HAWAII GEOTHERMAL PROJECT

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PHASE III - WELL TESTING AND ANALYSIS

PROGRESS REPORT FOR THE
FIRST QUARTER OF FEDERAL FY77

January 1, 1977

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Management
Geosciences
Well Testing and
Reservoir Engineering

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HAWAII GEOTHERMAL PROJECT
INITIAL PHASE III PROGRESS REPORT

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HAWAII GEOTHERMAL PROJECT MANAGEMENT-COORDINATION

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

1/1/77

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.

Below 4000 feet the drilling mud began to heat up rapidly, and subsequent downhole 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.

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, resulting in a noise level equivalent to that of a 747 jet aircraft at take off. Steam was discharged continuously for four hours on July 22, which verified that some natural flow into the well bore was taking place. The quality of the fluid from HGP-A was good -- surprisingly low in chloride content, but high in silica.

Because of the extremely high noise level generated during discharge, a silencer-separator was constructed before proceeding with a more comprehensive 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 have been raised by families in the area. Currently the project is shutdown while additional muffling and stiffening is built into the silencer. This should be completed by mid-January 1977, at which time a series of throttled flow tests will be conducted to provide better assessment both of the well and of the geothermal reservoir, and to obtain design data for a wellhead generator.

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 Pahoa Geothermal Field. Preliminary testing indicates that although some natural flow into the well bore occurs at depth, HGP-A is a relatively tight well -- whether due to low permeability of the reservoir or to skin damage in the vicinity of the well bore, it's premature to judge. Subsequent well testing and interpretation of current and future data will provide a better understanding both of the Pahoa Geothermal Field and of HGP-A, the well itself.

However, HGP-A already shows sufficient promise that every effort should be made to install an electrical generator at the well site as soon as possible. This would accomplish a number of objectives: 1) Provide near-total noise abatement and permit the removal of H_2S ; 2) Generate two to three megawatts of electrical energy, which could be fed directly into the Big Island electric grid; and 3) Permit long-range reservoir assessment. Negotiations with the University, the State and County of Hawaii, the electrical utility, private interests, and ERDA are proceeding to bring about the installation of this wellhead generator at HGP-A in the near future.

B. ACTIVITY OF THE MANAGEMENT-COORDINATION PROGRAM

October 1 through December 31, 1976

During the first 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.

To provide interaction at the local and national levels, the National Liaison Board (consisting of a dozen of the nation's leading geothermal scientists and engineers) and the 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) have been retained. Periodic reports were sent to both groups, and the next meeting of the Hawaii Advisory Committee is scheduled for February 2, 1977. It is unlikely that funding can be identified to hold a third meeting of the Liaison Board in Hawaii, but copies of all reports and publications will continue to be sent to each member. Their collective interest, advice, and support over the years has been a decided asset to the HGP.

The cooperation and joint support evidenced by all segments of government, the University, and private interests has carried over into Phase III, and seems to be reflected in preliminary negotiations that have taken place on a wellhead generator for HGP-A. The total support of \$3,417,000 received to date by the project and the half-dozen funding sources are listed on Page 2. Of this total amount, \$1,444,403 was required for the drilling subcontractor to complete the well to 6450 feet and conduct preliminary well tests. With the additional \$60,000 of drilling rig time contributed by Water Resources International, total drilling and related costs for HGP-A were slightly over \$1,500,000.

This makes it a very expensive well. However, a great deal of information was obtained and recorded on this first effort to drill in the Pahoa Geothermal Field. The Well Completion Report for HGP-A was assembled by KRTA, the New Zealand consultants to the project, and distributed late in this quarter. Much was learned on what should and should not be done in drilling subsequent wells in this area or in similar basaltic regimes throughout the world.

Table I presents a summary of the amounts awarded and expended by the HGP through the first quarter of FY 77. The total amount awarded by 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. However, only \$195,000 of this \$300,248 has been released to the project by ERDA-SAN as of January 1, 1977. The State of Hawaii has provided \$66,405 in FY 77 to assist with the well testing program.

The initial proposal to ERDA included provision to construct a silencer-separator which, among other things, was to reduce the noise level of the escaping steam to an acceptable level. A tried and true design, which had been developed in New Zealand and utilized both there and at Cerro Prieto, was followed. Although some benefit was realized, the high quality of the steam limited the effectiveness of this standard silencer, and the resulting noise level was still objectional to families living over a mile from the well. \$30,000 of additional funding was requested from ERDA and approved to build greater muffling and stiffening into the silencer, and to provide additional instrumentation and support services recognized as necessary during the two-week shakedown flow test. This supplemental budget as approved is shown in Table II, and these modifications will be made during the first half of January.

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

- Taken four trips to the Big Island to observe and advise on the project, to confer with County officials, and to discuss the project with planning commissions and citizens groups.
- Gone to Washington to discuss immediate and long-range aspects of the HGP with all interested parties in the Geothermal Division and in Solar, Geothermal, and Advanced Energy Systems.
- Developed a 10-minute 16-mm sound movie on the history of the project through the July 22, 1976, four-hour flow test. The movie has and will

TABLE I
FISCAL SUMMARY OF THE HAWAII GEOTHERMAL PROJECT FOR FY 77
December 31, 1976

<u>PROGRAM</u>	<u>AWARDED AMOUNT THROUGH 9/30/77</u>		<u>ESTIMATED COMMITTED EXPEN- DITURES THROUGH 12/31/76</u>		<u>ESTIMATED BALANCE AS OF 12/31/76</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		\$ 8,075		\$16,925	
Geosciences Tasks 2.1-2.7 & 4.1	141,975		47,640		94,335	
Reservoir Engineering and Well Testing Tasks 3.1-3.3	<u>133,273</u>	<u>\$66,405</u>	<u>65,278</u>	<u>\$19,147</u>	<u>67,995</u>	<u>\$47,258</u>
TOTAL	\$300,248*	\$66,405	\$120,993	\$19,147	\$179,255	\$47,258

* As of this date, only \$195,000 of this total amount has been released to the Project.

TABLE II

Supplemental Budget for the HGP-A
Well Testing Program

December 1, 1976

1. Silencing:

Muffling horizontal discharge	\$9,430
Stiffening vertical towers	<u>2,760</u>

\$12,190

2. Other modifications to separator/silencer
and wellhead:

Stilling basin at weir	\$ 575
Nozzle for calorimeter	115
Conical flange for probe	2,875
Lip pressure tap for 2" bleed line . .	1,150
Platform and ladder	<u>1,955</u>

6,670

3. Additional downhole clocks and instrumentation 3,140

4. Hourly labor for 24-hour surveillance of
site and recorders during flow tests 2,800

5. Additional interisland travel and living allowance 2,200

6. Contingency 3,000\$30,000

be shown extensively in Hawaii to legislative committees, technical organizations, and citizen groups. It was assembled primarily from two educational TV programs shot of the well at little expense to the project. Copies were given to ERDA-SAN and to the Geothermal Division.

● Presented oral reports on the status of the project to:

State Department of Planning and Economic Development

State Department of Land and Natural Resources
(The State Geothermal Regulatory Agency)

The Bishop Estate, a major land holder

Three technical and professional society meetings

The Puna District Planning Commission

State Legislative Committees -- two hearings are scheduled the first week in January

● Conferred with a wide variety of interests:

The State Energy Resources Coordinator

County of Hawaii administrators

County of Hawaii council members

State legislators

Hawaiian Electric Company

GEDCO, Natomas, Chevron

Office of Naval Research

TRW

A great deal of energy has been devoted to planning for the future of geothermal energy in Hawaii in general, and the future of the HGP in particular. The University does not wish to become a major developer of geothermal power, but does have a role to play in the identification and utilization of geothermal resources throughout the island chain, and would like to see HGP-A developed as the site for a prototype well.

The results of the current well testing program are crucial to further development of both the well and the field. Preliminary results led to consideration of obtaining a surplus low-pressure turbine generator from a sugar company and installing it at HGP-A quickly and inexpensively. This would provide near total noise abatement, generate a few megawatts of electricity, and permit long-range reservoir assessment. However, the minute quantities of H₂S in the steam, which are well below any safety standard thresholds, still are quite obnoxious to families located downwind from the well; and rather strenuous objections were raised by these citizens during the flow tests.

From the beginning of this project, the stated intent has been to make the first geothermal well environmentally acceptable, as an example that geothermal power can be generated with limited environmental impact. Therefore, it would be a mistake to install a surplus generator at HGP-A, without including provision for removal of the hydrogen sulfide. This would require installing a condenser, cooling towers, and a H₂S removal system -- all of which would add greatly both to the cost and to the lead time for power generation. Therefore, much of the advantage of going to a surplus sugar generator would be lost, and current thinking favors a new wellhead generator, designed specifically for the steam flow anticipated from HGP-A.

As throttled well testing proceeds during the second quarter to better define the design parameters for HGP-A, consultations will continue on future directions the project may take. There is a meeting scheduled on January 13 with the State Energy Resources Coordinator, the University, the Hawaiian Electric Company, and TRW to obtain agreement upon strategy for locating a wellhead generator and a non-electric test facility at HGP-A. Depending upon the outcome of this session and the next phase of the well testing program, a preproposal will be submitted to ERDA for continuing support to the project, with matching funds to be provided by the State and by the utility.

Parallel consideration is being given by private interests for drilling additional wells in the Puna Geothermal Field for power generation, and both the State and the County of Hawaii have begun planning on the socioeconomic implications of the development of geothermal resources. After four rather long years of research and development, the future of geothermal power for Hawaii is beginning to look bright -- although the legal and regulatory aspects could still cause additional delay.

Recent publications:

Shupe, John W., "Hawaii Geothermal Project Well A," Proceedings First National Geothermal Conference, Palm Springs, 1976 (In Press).

Shupe, John W.; Kamins, Robert M.; Yuen, Paul C.; "Geothermal Energy in Hawaii -- Hydrothermal Systems," Eleventh Intersociety Energy Conversion Engineering Conference Transactions, 1976.

SUMMARY OF GEOSCIENCES EFFORT FOR THE PERIOD

OCTOBER 1 TO DECEMBER 31, 1976

Charles E. Helsley

During the past quarter the primary activities of the Geosciences Subtask have been concentrated on acquiring new data about the subsurface conditions in and near the HGP-A well site. Emphasis has been placed upon the petrography and petrology of the samples collected during the drilling of the well and on the acquisition and analysis of fluids from the well that have been collected during the various engineering tests. These studies continue to indicate that the producing section within the HGP-A well is from highly altered basaltic volcanic rocks. These rocks have been extensively fractured and then the fractures filled with secondary minerals. Moreover, these observations suggest that the well produces from a series of relatively open fractures that intersect the well-bore in the lower part of the reservoir, but that these fractures may be fairly well sealed in the upper part of the reservoir.

Analyses of the fluids collected from the well indicate that the water has a generally low chloride concentration but a moderate amount of silica. The water quality is apparently the result of high temperature interactions with the host rock as evidenced by the moderate silica content and the low pH. The low salinity may be the result of high temperature interactions with the host rocks or it may be evidenced that there are permeability barriers between the reservoir and the ocean. The relatively low salinity of the fluids produced from the well is strong evidence in favor of reservoir recharge from a fresh water source.

Environmental monitoring has been carried out during each of the periods of well testing. The major potentially hazardous constituents in the fluid from the well are mercury and various sulphur compounds notably H_2S . The monitoring indicates that both of these occur at virtually negligible levels, and therefore present no concerns to the environment in the vicinity of the well. Background studies of the natural air mercury content indicate that the natural background level is quite variable within this region of the Puna rift zone and also indicates that a considerable amount of the variation that has been observed during testing may well be from natural sources rather than from the well itself.

Geophysical studies have also been continued during the past quarter with major emphasis being placed on the measurement of the physical properties of samples collected in the well as well as an interpretation and reinterpretation of some of the surface acquired geophysical data in light of the parameters actually

found in the well. Although an overall reassessment of the geophysical parameters is yet to be completed, it now appears that one of the most effective means of locating this particular reservoir is the distribution of local microearthquakes and the electrical self-potential anomaly observed on the surface. Both have quite similar locations. Perhaps this pair of techniques will prove to be the most effective method of locating geothermal resources within the basaltic volcanic regions. Verification of this hypothesis unfortunately will have to await additional exploration within the Hawaiian Islands and probably will not be fully verified until additional wells are drilled at other sites. More complete discussion of the accomplishments under each of the geosciences subtasks are summarized in the sections below.

Task 2.1
COORDINATION
Augustine S. Furumoto

For the past quarter the geophysical-geochemical program has primarily been concerned with the reduction of data gathered in earlier field studies. The process of interpreting and digesting the results obtained earlier is proceeding well and has yielded several manuscripts that are ready for publication.

The series of papers is being scheduled for publication as reports from the Hawaii Institute of Geophysics to serve as the records of the geothermal project. These reports will differ from journal publications in that there will be more tables and figures and the descriptions of field procedures will be more detailed. It is the intent that these reports will be useful to future investigators to avoid repetition of mistakes and to choose the most efficient way to achieve results.

In July the task leaders of the geophysical-geochemical program agreed to publish a joint multi-authored paper on the geoscience aspects of the geothermal project. The first drafts from the various authors have been collected and edited into a coherent paper. The compiled first draft has been sent back to the various authors for corrections and review. Changes being suggested appear to be minor and therefore we expect to complete the whole manuscript in February.

Two papers giving an overall view of the geoscience aspect of the geothermal project have recently seen the light of publication. A paper submitted to the Second United Nations Symposium on Geothermal Resources and Development has finally been printed and published (Furumoto, 1976). In a review paper on volcano energy utilization, a summary of the work on Kilauea has been included (Furumoto and Yuhara, 1976).

Upon the invitation of and under the sponsorship of the Japan Geothermal Energy Association, A.S. Furumoto presented a one hour public lecture on the geothermal project in Tokyo on December 10, 1976. The lecture was held at the new headquarters of the Association in Denki Building in the heart of the business district of Tokyo. There were more than 70 in the audience, eager to listen about the recent results and interpretations of the geothermal field in Puna.

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- A.S. Furumoto, 1976. A Coordinate Exploration Program for Geothermal Sources on the Island of Hawaii, Proceedings of the Second United Nations Symposium

on Development and Use of Geothermal Resources, San Francisco, Ca., 20-29, May 1975, Government Print. Off., pp. 993-1001.

A.S. Furumoto and K. Yuhara, 1976. On the Status of Research Leading toward Volcano Energy Utilization. Critical Review in Environmental Control, v. 6, no. 4, pp. 371-402.

Task 2.2
MAGNETICS
R. Norris

Work on the magnetic subtask for the past quarter has primarily been the preparation of manuscripts for publication for all of the field work is finished and the analysis essentially complete. The initial manuscript has been prepared and is undergoing final editing and revision of several of the figures.

Although the ground-level magnetic measurements over the lower east rift do not show a simple ridge-and-trough (or line-of-dipoles) anomaly, there is a discernable linear trend in the complicated pattern of small anomalies which lies over the rift. The short wavelength anomalies, 1/2 to 3 km in width, which make up the pattern are due to intrusions which approached the surface and cooled, while the linear pattern of the anomalies is interpreted as the magnetic expression of present and past magma transport routes from Kilauea's central vent. The Leilani anomaly, the largest (about 3 km wide) of the pattern is still thought to be a good site for a geothermal test well.

Task 2.3

SEISMIC STUDIES

Augustine S. Furumoto

The seismic task has addressed itself to two distinct jobs in the past quarter. The first is the wrap up of the passive seismic experiments carried out over the past years and the second is a seismic refraction survey to outline the subsurface structure of the east rift of Kilauea.

The results of the drilling have brought about a reinterpretation of the microearthquake data. Around the geothermal well HGP-A, a region of shallow earthquakes was noticed. The shallow earthquake area formed an ellipse, 3 km on the long axis and 2 km on the short. The depths of the earthquakes varied from 1 to 3 km. In no other place was a cluster of shallow earthquakes found.

We now prefer the interpretation that the shallow earthquakes outline a confined geothermal reservoir. The reservoir is embedded in the dike complex system, and probably is a relatively permeable region due to fractures in the rock. The microearthquakes are probably caused by groundwater of meteoric origin percolating into the region of fractured rocks.

As for the second job, the seismic refraction survey is scheduled for the week of January 10-15, 1977. Shots will be fired at sea and recordings will be made on land. The shots and recording points will be located on the east rift as determined by surface line of vents and by gravity data.

According to plans, there will be 19 recording points. Of these 13 will be in line along the rift zone, the others will be on the side to check lateral variation of velocity.

Shots are also planned to shoot perpendicularly across the rift zone. For this part of the experiment, the geophones will be aligned perpendicular to the rift zone and will cut across the rift.

Task 2.4

GEOELECTRIC SURVEYS

D. Klein, E. Sakoda

The past quarter has been devoted to evaluating the geoelectric field experiments on the lower East Rift of Kilauea Volcano. Several reports, which include: (1) "deep" electromagnetic transient results, (2) "shallow" electromagnetic and d.c. sounding results, (3) "reconnaissance" bipole-dipole results, and (4) self-potential results, are scheduled to be completed by the end of February. The first listed of these is a condensed version of J. Kauahikaua's M.Sc. thesis (accepted in December, 1976). In the third and fourth listed are G.V. Keller's (Colorado School of Mines) and C. Zablocki's (U.S. Geological Survey) contributions. These data have been presented in numerous previous progress statements, for instance (Klein, 1975, 1976; Zablocki, 1975) and won't be repeated here. However, a brief comment on our evaluation does seem appropriate. First, it is noteworthy that the self-potential anomalies along the East Rift (Zablocki, 1975) have seemed to provide the most dramatic and apparently least ambiguous indications of hydrothermal activity. The physics of this phenomena remains unexplained to our satisfaction and definitely needs further theoretical investigation.

Second, the "deep" electromagnetic transient soundings, which indicated an anomalously low resistivity zone ESE of the drill site, HGP-A, has not, in retrospect, seemed to have sensed the primary geothermal reservoir. This data indicated the possibility of 90-150°C water at depths of less than about 1200 m, which is above the producing zone which begins at about 1500 m. At these shallow depths the surface measured resistivities 3-7 ohm-m and the a-priori (using sea water salinity) implied temperatures 90-150°C agree well with the downhole measurements, but the downhole fluid salinities, which are equivalent to about 1/10 that of sea water, would require us now to estimate temperatures much higher than those measured. This discrepancy means, either that the Archie's law assumption is invalid, or that the downhole fluid-sample salinity is not representative of the bulk of fluids saturating the strata. The latter could be true if the geothermal reservoir was a narrow, linear, dike-confined fresh water body. The former could be true if ionic exchange processes (or similar conductivity enhancement processes) were important in the in situ conductivity mechanism. The data available do not allow us to make a choice.

Finally, our evaluation of the electromagnetic experimental method indicates future experiments should be designed to provide roughly an order of magnitude better precision. Our limitation was in the frequency spectrum (0.1 to 35 Hz) of the transient signal and in the low (about 10) signal-noise ratio. An adequate frequency range can probably best be obtained by designing a multi-frequency-domain system (10 kVA, 10-20 Ampere, 10^{-2} to 10^3 Hz). This is a major undertaking but feasible. It is also quite feasible to improve to signal gain by at least 10 by using better signal-conditioning electronics. Both of the requirements might be met if natural source signals (magnetotellurics), properly processed, were employed rather than using controlled source signals. We hope to test magnetotellurics in this area soon.

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Task 2.5

PETROGRAPHY, PETROLOGY AND GEOCHEMISTRY

P. Fan, C. Stone, D. Palmiter

The past quarter of geochemistry research has consisted of finishing petrographic examination of core thin sections, writing a petrographic report on the results for inclusion in the multi-author HGP-A paper, and sample preparation for major and trace element analyses.

The most significant features found in the cores by thin section examination include:

1. Core 4 (2230-2240 ft) and Core 5 (2876-2886 ft) both exhibit a lithologic change. Above the contact in Core 4 feldspar phenocrysts are unaltered and comprise less than one percent of the rock. Below, the feldspar phenocrysts constitute nearly 18 percent of the rock and they exhibit slight alteration. Vesicles are completely filled with secondary minerals above, but are only rimmed with them below the contact. The lower portion of Core 4 is more coarse-grained than other cores from the well with the exception of Core 9 (6031-6041 ft). The lithologic contact in Core 5 is marked by a change in crystallinity. Above the contact the rock is hypocrystalline with numerous vesicles, both filled and unfilled. The bottom of core 5 is nonvesicular, with a hyalopilitic texture.

2. Core 6 (3666-3676 ft) differs markedly from all other cores in that it is holocrystalline, nonvesicular, and equigranular throughout.

3. The first signs of alteration, corroded olivine, appear in Core 3 (1412-1422 ft). Alteration of olivine to montmorillonite first occurs in Core 4 along with the first occurrence of vesicle-filling secondary minerals and a very slightly turbid appearance to the matrix. Alteration increases in intensity with depth in the well.

Considerable effort has gone into sample preparation for various geochemical studies. The majority of the effort has gone into the hand separating of the freshest rock chips from cutting samples at approximately 400-ft intervals. Where fresh glass is abundant, the glass has been selectively separated for analyses as it is assumed to represent chilled flow margins and, therefore, the original magma composition. For seven cutting samples, at approximately 1000-ft intervals, the rock chips have been separated into least- and most-altered samples for separate analyses.

Selected samples have also been taken for trace element analyses and these have been acid and ultrasonically cleaned, hand ground, and digested in

teflon-lined bombs. Dilution to volume for atomic absorption analyses is currently underway, with AA work to begin in January. Major element analyses will be made in the next quarter as well as more definitive textural analyses of rocks penetrated by the well, based on thin section examination of cutting samples.

Task 2,6

HYDROLOGY AND HYDROTHERMAL GEOCHEMISTRY

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Surface water samples have been collected since the well first flowed on June 24 (Table 1). These samples are currently being studied in an attempt to learn the source and characteristics of the well waters. In general the water has a low chloride ion concentration but very high silica value. The concentration of silica and possibly other water quality parameters is caused by high temperature exchange with the host rocks. The geochemistry of the rock-water interactions will be discussed in more detail after the analyses of the cores is completed.

Downhole samplings have been conducted on three separate occasions to characterize the water quality variation with depth before well flash and to ascertain the depth zones of active recharge (Table 2). The samples were collected using a Klyne sample bottle which is designed to collect downhole water at temperatures lower than actually encountered in this well. Despite our attempts to change the gaskets the sampler still occasionally leaks as noted in Table 2. The downhole data show that the low pH (~2) is consistent with high values of sulfides (up to 370 mg/l). Silica values as high as 630 mg/l were encountered. Dissolved mercury is exceedingly low ($< 1 \mu\text{g/l}$) except at the 100 ft level. The majority of the mercury present is in the particulate fraction. Rock samples cored from the bottom of the cased part of the well (2270 ft) also had a very high mercury content of 244 $\mu\text{g/Kg}$ compared to about 70 $\mu\text{g/Kg}$ for the rest of the cored samples (Table 3).

The above data, a single tritium water age, pre-flash well head evidence of the water level, and related general geology known for the area, support the following conclusions:

1) There are likely dikes or dike-like impermeable subsurface formations located between the ocean and the HGP-A well. The occurrence of dikes would account for the low salinity, chloride and electrical conductance measured in the well water.

2) The HGP-A well water is drawn in part from dike impounded high-level ground water which is recharged by recently infiltrated rain water. The annual rainfall for this area is on the order of 125 inches and furnishes a sizeable source of fresh water for groundwater recharge.

TABLE 1

HGP-A Well Head Samples

Water Quality Parameters
(Concentrations in mg/l except as noted)

	#	pH	Cl	SO ₄	HCO ₃	Na	Mg	Ca	K	SiO ₂	Hg (µg/l)	δ ¹⁸ O(‰) (SMOW)	S ²⁻	F	T.U.
Average Seawater 1%			553.0	77.5	4.1	307.0	37.0	11.8	11.1	3	0.06				
Water used in drilling	I-1		6.3	16.1	.6	15.8	1.8	2.1	2.7	35.6	3.5	-			
First H ₂ O flow 06/24/76	I-2 I-5 ave. I-9		552.0	176.0	1.0	407.0	1.2	5.0	52.0	-	0-6 (I-5)	-			
After steam 07/03/76	II-1	6.5	610.0	160.0	27	350	-	-	-	151	<.1	-		.8	7±2
Before flash 07/22/76;11:15	G1-A		757									-3.7 _{steam}			
Just before production 07/22/76;13:40	G1-B											-2.0 _{H₂O}	300		
1 hr into test 07/22/76;15:30 condensate	G1-C		94.5			50.9		1.3	7			-6.5 _{steam}	110		
After production test 07/23/76;09:20	G1-D	6.6	166	72	81					220		-3.9 _{H₂O}	626		

Sample II-1 of 07/03/76: Nitrate-Nitrite .04; total solids = 2322; suspended solids = 289; volatile solids = 34; turbidity (NTU) = 85, lead = 0.30, Ca and Cr <0.1.

TABLE 2

HGP-A Down Hole Samples

Water Quality Parameters

(Concentrations in mg/l except as noted)

Depth (feet)	Date	pH	Cl	Conductance (μ mho-cm)	Si	S ²⁻	Total Hg [†] (μ g/l)
Surface	08/04/76	5.1	880	3050	200	-	-
	08/12/76	5.5	930	2900	240	-	-
	08/19/76	5.2	1000	3250	370	-	-
1,000	08/19/76	5.6	830	2700	210	190	44.4
	10/12/76	4.9	725	1980	220	250	26.3
2,270	08/17/76*	5.3*	950*	3200*	300*	-	2.4*
	10/12/76	1.4	730	3450	620	-	3.6
	10/30/76	2.3	685	3650	630	210	0.95+0.48
3,000	08/18/76	2.3	710	4450	530	-	-
4,300	08/19/76*	5.3*	900*	2950*	270*	300*	3.5*
	10/29/76	2.7	685	2700	630	210	0.82+0.41
5,500	10/12/76*	1.9*	735*	3050*	650*	-	7.5*
5,800	08/19/76	2.5	800	4400	340	-	3.2
	08/19/76	3.5	780	2550	430	-	-
	10/29/76	3.4	850	2600	630	210	0.50+0.64
6,300	08/19/76	3.0	660	2800	190	-	1.6
	10/30/76	3.5	440	1650	630	370	.72

† ~85% as particulate except at 2270 and 4300 feet where particulate:soluble ratio is ~1:1.

*Due to the extremely high down hole temperature we suspect that the "Klyne" sample bottle occasionally leaks.

TABLE 3

Mercury Content of HGP-A Core Samples

Depth (feet)	Mercury ($\mu\text{g} \cdot \text{Kg}^{-1}$)
456	46
1057	98
1412	100
2230	68
2231	125
2876	244
2877	56
3666	70
4447	62
5396	80
6029	28
6446	88

3) The HGP-A well water would derive its salinity and other water quality parameters from other sources than from the percolating rain water alone. The geothermal source that heats up the HGP-A well water evidently can help create these sources; the possibility of contact with unknown saline water sources cannot be excluded at present.

Task 2.7

PHYSICAL PROPERTIES OF ROCKS

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During the first fifteen months of this project (June 1975-September 1976), we completed the following measurements:

1. Bulk density and porosity of about 200 samples which included the core samples from the HGP-A and Keller's holes, and the field samples.
2. Compressional (V_p) and shear wave (V_s) velocities in the above samples under dry and saturated conditions at ambient pressure.
3. Resistivity (ρ) of these samples saturated with four different saturating solutions (a) tap water ($\rho = 24.4 \Omega\text{-m}$), (b) 1 part seawater and 3 parts distilled water ($\rho = 0.66 \Omega\text{-m}$) and (c) 1 part seawater and 1 part distilled water ($\rho = 0.35 \Omega\text{-m}$) and (d) seawater ($\rho = 0.21 \Omega\text{-m}$).
4. ρ as a function of pressure for about 30 samples saturated with the above four solutions, as the pore pressure being nearly zero.
5. Conductivity as a function of temperature ($\sim 1500^\circ\text{C}$) for some of the samples.
6. Thermal diffusivity of some 25 analyzed field samples.

Besides characterizing the various physical, thermal, elastic, and electrical properties of Hawaiian basalts under varying P, T and saturation conditions, the main conclusions reached were:

1. The Archie Law holds well.
2. There is good correlation between the elastic, thermal and electrical properties.
3. The laboratory data on the electrical conductivity can be used to infer the surface temperatures from the field electrical data.
4. Thermal diffusivity of basalts are largely dependent on porosity.

During the period October-December 1976, we have concentrated on the laboratory investigation of the HGP-A core samples. We have obtained about 25 core samples from the HGP-A hole. Table 1 gives the summary of the measurements made from ten core samples at various depths.

I. Ultrasonic velocity measurements at room pressure

Both V_p and V_s have been measured in dry and saturated samples. The saturated V_p value is generally higher than the dry value, irrespective of the degree of porosity of basalts, whereas saturated V_s value is higher for samples having a porosity of $<5\%$; for $\phi > 5\%$, saturated V_s is lower than dry V_s .

Table 1. Ambient physical, electrical and elastic properties of core samples (tholeiitic basalts) from the HGP-A hole.

Depth, ft.	Degree of Alteration and Accessory Minerals	Bulk Density, gm/cm ³	Porosity (ϕ), %	Resistivity (ρ), ohm meter				Bore Hole Resistivity, ohm meter	Dry V _p , km/sec	Saturated* V _p , km/sec	Dry V _s , km/sec	Saturated* V _s , km/sec
				Tap water	1:3:: S.W.: D.W.	1:1:: S.W.: D.W.	S.W.					
457	No alteration (plag., clinopyrox. mag., olivine)	2.75	6.4	978.7	122.7	66.6	39.9		4.61	5.46	2.92	2.88
1062	Same as above + some pyrite	2.78	4.0	3457.0	895.1	384.1	219.6		5.24	5.99	3.20	3.35
1417	Altered + chlorite, goethite siderite	1.99	23.1	261.3	48.5	27.1	14.4		4.55	4.72	2.51	2.43
2235	Altered (chlorite, goethite siderite, pyrite, clay minerals)	2.59	7.0	104.5	81.1	70.2	45.9	4 - 8	4.49	4.85	2.82	2.68
2878		2.46	13.5	28.9	20.3	16.6	13.5	2.5 - 8	4.06	4.66	2.33	2.47
3669	Altered (common minerals + pyrite, quartz, clay minerals)	2.60	8.6	93.7	61.9	47.7	32.7		4.66	4.93	2.77	2.82
4452	Highly altered (pyrite, quartz, chlorite, kaolinite, clay minerals)	2.52	14.5	89.6	38.0	23.3	15.2		4.16	4.40	2.56	2.38
5398	Same as above + some amphiboles, hematite, vermiculite	2.79	5.4	450.6	243.8	153.2	108.1		4.94	5.47	3.08	3.08
6034	Same as above but no amphibole	2.84	3.7	1383.5	518.4	302.6	210.7		5.35	5.84	3.17	3.25
6451	Highly altered (amphibole, zeolite gibbsite, siderite)	2.31	18.0	429.3	21.2	10.6	6.4		3.95	4.05	2.45	2.28

* Tap water saturated.

Note: S.W. = sea water, D.W. = distilled water.

Figure 1 shows the relationship between formation factor and V_p for all the basalts studied to date. In spite of the scatter, the velocity, in general, increases with increase in f . Figure 2 shows a good correlation between resistivity and V_p for the HGP-A core samples. Such a relationship can be used in estimating resistivity from velocity data, and vice versa.

II. Thermal diffusivity

Temperature dependence of the thermal diffusivity (k) for selected HGP-A core samples is shown in Figure 3. As expected, k decreases with increasing T . At $\sim 425^\circ\text{K}$, the value of k falls in the range of $5-9 \times 10^{-3} \text{ sec/cm}^2$. From our knowledge gained from last year's research, the value of k is strongly dependent, besides alteration, on porosity. In Figure 3, the apparent increase in k with depth (depth in feet shown in the parentheses) is due to increase in density (decrease in porosity) of basalt. Figure 4 shows the relationship between k at 100°C versus density for all the HGP-A core samples. Since the density does not always increase with depth (porosity can be higher at greater depths) there is no systematic trend of k with depth.

III. Electrical conductivity at high temperature

We have measured electrical conductivity σ of about 10 basalts (representing a wide range of chemical composition--e.g., nephelinite with 38.92 wt % of SiO_2 to trachyte with 60.85 wt % SiO_2) to 1500°C , to understand the dependence of electrical conductivity on temperature and chemical compositions.

Figure 5 shows data for some typical basalts. The σ increasing gradually with temperature up to solidus temperatures; sharp rise in σ is related to the onset of melting.

Figure 1. Relationship between formation factor and saturated V_p for Hawaiian basalts.

Figure 2. Resistivity versus saturated V_p for the HGP-A core sample. The depth (in feet) is given in parentheses.

Figure 3. Temperature dependence of thermal diffusivity of the HGP-A core samples. The depth (in feet) is given in parentheses.

Figure 4. Thermal diffusivity versus density for the HGP-A core samples. Depth (in feet) is indicated adjacent to the data point.

Figure 5. Temperature dependence of electrical conductivity σ for alkalic olivine (full circle) and olivine tholeiitic (cross) basalts.

Task 4.1
GEOTOXICOLOGY
B. Siegel, S. M. Siegel

The results of the Geotoxicological studies at HGP-A were highlighted in a September 1976 report (Kamins, et al., "Environmental Baseline Study for Geothermal Development in Puna, Hawaii"). This account concluded by reporting a surprising rise in the air mercury (Hg) at the drill site during the brief flashing trial of 22 July 1976.

Although the absolute evaluation of this situation was difficult because the air quality standards for Hg are far from settled, the capacity for an elevation of air levels by nearly ten-fold in one hour warranted close surveillance during future thermal well tests. Reflecting on their more than five years of attention to natural thermal emission of mercury in Hawaii and its biogeochemical implication, the co-investigators did not consider this data to be a cause for alarm, however.

Following a nearly three month shutdown, a new flowing experiment was planned for the beginning of November. The brief report which follows summarizes aerometry carried out in conjunction with that test.

Measurements were carried out using battery-operated volume samplers drawing 30-60 liters of air through gold foil and nitric acid traps for mercury, barium chloride traps for S-oxides and MSA detector tubes for H₂S and CO (1-2 liter samples).

Additional tests for Hg were made by analyzing copper grids and vegetation exposed directly to the steam plume. Preliminary tests for arsenic were also carried out.

Sample collections at HGP-A followed the schedule:

- 31 October - Pre-warmup
- 1-2 November - Warmup
- 3 November - Flashing

Fixed gases: Sulfur dioxide and hydrogen sulfide levels potentially hazardous to plants and animals are attained from time to time at natural emission sites such as the Sulfur Banks (Table I), but the general level at HGP-A is quite low. There are at present no Federal ambient air quality standards for H₂S, but the 8-hour weighted average for occupational health

TABLE I
Fixed Gas Aerometric Data, June - November 1976
at HGP-A and Other Hawaiian Sites

Date	Site	Status	Gas Content (ppm)		
			H ₂ S	SO ₂	CO
24-26 June	Sulfur Banks	Comparative	6.4	18.0	<0.5
31 October	Sulfur Banks	Comparative	2-4	3.5	ca 1
24-26 June	HGP-A	Pre-warmup I*	<0.2	<0.5	<0.5
31 October	HGP-A	Pre-warmup II	<0.2	<0.5	<0.5
1 November-	HGP-A	Warmup II			
2 November		At well head	<0.2-1.5	<0.5	<0.5-1.5
		30 meters**	<0.2-0.9	<0.5	ca 0.7
3 November	HGP-A	Flashing - 4 hrs.			
		In plume - 10 m**	3.1	<0.5	ca 1
		In plume - 100 m**	0.8	<0.5	<0.5
		Outside plume - 10 m	0.6	<0.5	<0.5

* Prior to flashing of 22 July

** From well head

limits is 10 ppm, with 20 ppm allowable for 5 minutes. During recent test operations, although the odor of H_2S was clearly evident, the measured level 6-7 feet above ground did not exceed 3.1 ppm directly in the plume and was much lower in the general area.

Mercury: The only Federal air quality standards currently on record for Hg are (a) a stationery point emission limit of 3200 g per day and (b) OSHA limits of $10 \text{ ug}\cdot\text{m}^{-3}$ for Hg-alkyls and $50 \text{ ug}\cdot\text{m}^{-3}$ for all other forms. The EPA has recommended that a 30 day average of $1 \text{ ug}\cdot\text{m}^{-3}$ (all forms) be used as a guideline for general public safety (Fed. Reg. 14 Oct., 1975).

Our 5-year average for natural thermal sites in Hawaii Volcanoes National Park exceeds the guideline for ambient air by some 15-fold, and peak measurements in the Park approach the OSHA standard for maximum allowable occupational limits.

Prior to the 22 July HGP-A ambient levels did not exceed $1 \text{ ug}\cdot\text{m}^{-3}$, however, as noted above, the first flashing of the well was accompanied by a marked rise in air Hg (Table II). The level on 31 October during the prewarmup phase was $16.1 \text{ ug}\cdot\text{m}^{-3}$ and is significant because this level cannot be associated with geothermal operations at the site. This is reinforced by the absence of a significant charge during subsequent warmup and steam production.

Furthermore, the Puhimau thermal area on the Chain-of-Craters which was venting steam free of sulfur gases on 30 October, yielded an air level comparable with that at HGP-A on the following four days.

Other observations:

1. In spite of the high rate of steam on 3 November, Cu-grid Hg collectors in the plume and ca 30 meters distant yielded similar values of about 0.20-0.25 ug, whereas prewarmup figures of 0.25-0.45 ug were recorded on 31 October.

2. Vegetation samples - fern, Ohia and nutgrass - were comparable with or lower than those collected during the preceeding 18 months.

3. Fern and Ohia in the plume showed no significant rise in leaf Hg content during the 4 hours of direct exposure.

4. Except for the large quantity of particulate (sulfide) mercury (ca $26\text{-}42 \text{ ug}\cdot\text{l}^{-1}$) found in 1000 ft. well samples, these waters average ca $1 \text{ ug}\cdot\text{l}^{-1}$ (3 samplings in August and October by P. Kroopnick), approximately the level found in the Puna District aquifer.

TABLE II

Mercury Aerometric Data, June - November 1976
at HGP-A and Other Hawaiian Sites

Date	Site	Status	Hg Content ($\mu\text{g}\cdot\text{m}^{-3}$)		
			Hg ⁰ (reduced)	Oxidized	Total
24-26 June	Sulfur Banks	Comparative	8.6	38.9	47.5
30 October	Puhimau	Comparative	-	-	14-18
24 June*	HGP-A	Pre-warmup	-	-	<1
22 July*	HGP-A	1st Flashing	1.7	8.2	9.9
31 October	HGP-A	Pre-warmup	2.8	13.3	16.1
1-2 November	HGP-A	Warmup	2-8	8-16	16-18
3 November	HGP-A	Flashing			
		1st 2 hrs.	3.0	15.8	18.8
		2nd 2 hrs.	4.3	4.3	7.0

* Prior to this date measurements in May 1975 and May 1976 yielded total air mercury levels of ca $1\mu\text{g}\cdot\text{m}^{-3}$.

5. Separator discharge waters fell from a 1 November figure of $\text{ca } 1.6 \mu\text{g}\cdot\text{l}^{-1}$ to a 3 November level of $0.1 \mu\text{g}\cdot\text{l}^{-1}$ four hours after the well was flashed.

6. Although the Hg-bearing particulates in well waters contain arsenic in the low ppm range (after nitric acid digestion) none was detected in the steam.

Conclusions from the November tests

1. The only potential toxicant identified at HGP-A thus far is mercury.

2. The source of most of the Hg found at nor near the site is not related to geothermal operations. It represents, rather Hg accumulated during the geological history of the area in combination with current natural emission. Thus, any potentially hazardous Hg concentrations found so far in the HGP-A area reflect the volcanic character of the environment and are not amenable to air quality regulations.

3. Surveillance for Hg and other possible toxicants should be continued both in steam and water effluents until it can be established that there are no cumulative effects in air, waters, soils or vegetation.

Additional observations were made in the vicinity of HGP-A prior to and during the start-up of the December test on November 30 - December 1, 1976. This sampling was carried out at HGP-A Puna approximately one month after the test flowing and flashing of 1 - 3 November, and two weeks following shutdowns.

From pre-warmup through well-flowing and four hours of flashing, the air Hg level and HGP-A ranged up to $\text{ca } 16 \mu\text{g}\cdot\text{m}^{-3}$. A similar range was noted at that time in the Puhimau hot spot in Hawaii Volcano National Park.

Our most current measurements 2 weeks after shutdown show HGP-A air values of $13\text{-}29 \mu\text{g}\cdot\text{m}^{-3}$ and Puhimau levels of $2\text{-}15 \mu\text{g}\cdot\text{m}^{-3}$.

Copper grid Hg collectors after 3 weeks at Puhimau carried up to $2\text{-}3 \mu\text{gHg}$, whereas those exposed at HGP-A for 30 days carried no more than $0.32 \mu\text{g}$. During the same period, grids placed at the Heiheiahulu hot spot, on the East Rift near the drill site, collected up to $9 \mu\text{gHg}$ in one week. Our contention that most although not all drill site mercury originates elsewhere (in the East Rift) is supported.

Steam condensate samples provided by Kroopnick contain $1.5 \mu\text{g}\cdot\text{l}^{-1}$ of Hg. This means that peak emission to date is $\text{ca } 1 \text{ g of Hg/24 hr}$.

No changes in other gases (H_2S , SO_2) have been noted.

Task 3.1

NUMERICAL MODELLING

Ping Cheng and Kah Hie Lau

During the past quarterly period, the task effort has been concentrated in two major areas:

1. Simulation of the Puna Geothermal Field

The computer programs developed for the past few years under the Hawaii Geothermal Project are being specialized for the simulation of the Puna geothermal field. Using the data from core samples obtained during the drilling phase, we now assume that the aquifer consists of three horizontal layers with different permeabilities. Instead of ocean recharge, the model assumes that the aquifer is recharged by rainfall from the top. The efficiency of the computer code is much improved as a result of using a new direct method rather than the interactive method for the numerical solution of the pressure equation. Some preliminary results for heat and mass transfer characteristics for the Puna geothermal field have been obtained.

2. Dynamics of Ghyben-Herzberg Lens

A numerical model for coastal geothermal reservoirs with a free surface at large Rayleigh numbers has been developed. For low Rayleigh numbers, the numerical results agree within 15% with the previous model by Cheng and Lau (1974) which is applicable only to low Rayleigh numbers. A preliminary report of this phase of work will be presented at the forthcoming National Heat Transfer Conference.

More detailed descriptions of recent work on this task are contained in the following publications:

1. Cheng, P. & Lau, K.H., "The Effect of Steady Withdrawal of Fluid in confined Geothermal Reservoirs," Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources, 1591-1598 (1976).
2. Cheng, P. & Chang, I-Dee, "Buoyancy Induced Flows in a Saturated Porous Medium Adjacent to Impermeable Horizontal Surfaces," Int. J. Heat Mass Transfer, V. 19, 1267-1272 (1976).
3. Cheng, P., "Buoyancy Induced Boundary Layer Flows in Geothermal Reservoirs," presented at the 2nd NSF Workshop on Geothermal Reservoir Engineering, Dec. 1-3, 1976, Stanford, California.
4. Lau, K.H. & Cheng, P., "Steady State Free Surface Flow in a Geothermal Reservoir," to be presented at the 1977 National Heat Transfer Conference.

5. Cheng, P., "Constant Surface Heat Flux Solutions for Porous Layer Flows," submitted for publication to Letters in Heat and Mass Transfer.

Future Work

The work on the simulation of the Puna geothermal field and the study of the dynamics of the Ghyben-Herzberg lens will be carried to its completion during the next period.

Tasks 3.2 & 3.3

WELL TEST & RESERVOIR ENGINEERING

Paul Yuen, Bill Chen, Deane Kihara, Patrick Takahashi

With the completion of the drilling of HGP-A on April 27, 1976, and indications of extremely high bottom-hole temperatures, a well testing program (Task 3.2) designed to determine the properties of the well and the fluid, and a reservoir engineering program (Task 3.3) to determine the properties of the reservoir were initiated. The objectives of these programs are to:

1. determine well and reservoir characteristics,
2. obtain data useful for drilling future wells and for power plant design,
3. determine problem areas, if any, and possible solutions relative to well production,
4. determine possible environmental problems,
5. remedy skin damage, if any.

Progress on these two tasks is reported together this quarter since results from the several tests are important to both programs. A chronology of well testing activity for this period is listed on the next two pages.

HGP-A has been flashed several times for varying periods beginning on July 2. A four-hour discharge was made on July 22 to obtain preliminary values for wellhead pressure and temperature, and total mass flow rate. An air-lifting procedure was used to artificially induce the well to discharge. Air from two 100-psi, 175 cfm air compressors was injected into the water column, emulsifying it and causing the fluid level to rise and eventually reach the surface where it flowed out via a bleed line. As the colder upper water was removed at the surface, the hotter water from below replaced it. This reduced the density of the column, the height of which, of course, remained constant. Eventually, a portion of the column at depth reached the saturation pressure for its temperature and boiled. The water column density then was lowered even further, causing more water to flash into steam. Once started, the process continued so that the flow now proceeded without the aid of the air compressors.

Surface measurements of lip and wellhead pressure and temperature were taken and are shown in Figures 1 and 2. If the enthalpy of the discharge

HGP-A
CHRONOLOGY OF WELL TESTING EVENTS
October to December 1976

1976

- Oct. 6 Casing integrity test conducted to determine whether casing has collapsed at any point; results negative.
- Oct. 12 Water samples taken downhole. Temperature profile made on lower half of well.
- Oct. 13 Water influx test conducted to determine whether production regions might be at 2090', 4320', and 5747'; clock failure led to inclusive results. Temperature profile made on upper half of well.
- Oct. 21-28 Silencer/separator installed. Instrument shack erected. Dry well excavated. Kicker installed.
- Oct. 29-30 Water Samples taken downhole.
- Oct. 31 Temperature/pressure profiles measured. Second water influx test made at same depths but clocks failed again.
- Nov. 1-2 Well casing heated up slowly by means of 2" line.
- Nov. 3 Start of 2-week flow test. Measurements made of:
 sound level
 wellhead temperature & pressure
 lip pressure
 weir height & temperature
 rise of wellhead
- Nov. 8 Security fence completed. Lighting and electrical lines installed.
- Nov. 13 Ten foot dummy probe sent downhole while well was flowing to determine whether temperature/pressure profiles can be measured during flow. Probe caught in wellhead.
- Nov. 17 Shut-in of well at end of 2-week flow test and beginning of pressure buildup test with wellhead pressure as variable.
- Nov. 18 Dummy probe removed.
- Nov. 19 Temperature/pressure profiles measured. Water depth measured.
- Nov. 20 Water depth measured.
- Nov. 21 Temperature/pressure profiles measured. Water depth measured.
- Nov. 22-28 Water depth measured.
- Nov. 30 Temperature profile measured.

Chronology of Well Testing Events (continued)

Dec. 1 Water depth measured.

Dec. 2 Water samples taken downhole. Water depth measured.

Dec. 3 Water depth measured.

Dec. 4 Temperature profile measured. Water depth measured.

Dec. 5 Water depth measured.

Dec. 6-7 Water depth measured.

Dec. 8 Temperature profile measured. Water depth measured.

Dec. 9 Water depth measured.

Dec. 10 Airlifting used to induce well to begin flowing.

Dec. 11 Well flowing through 2" line.

Dec. 12 One-week discharge test started.

Dec. 14 Probes lost while making downhole measurements.

Dec. 15 Flow throttled to a lip pressure of ~4 psig.

Dec. 16 Temperature/pressure profiles measured with lip pressure of 4 psig.

Dec. 17 Temperature/pressure profiles measured with lip pressure of 4 psig.

Dec. 19-20 Well shut-in and pressure buildup test started. Clock failed so well had to be opened and flow resumed. After well flow had stabilized well was shut-in. Pressure probes were continually dropped downhole for pressure measurements.

Dec. 21-30 Downhole pressure and water depth monitored daily.

Figure 1

HGP-A FLOW TEST, JULY 22, 1976 VARIATION IN WELLHEAD & LIP PRESSURE WITH TIME

Figure 2

HGP - A FLOW TEST
VARIATION IN WELLHEAD & LIP TEMPERATURE
WITH TIME JULY 22, 1976

fluid is estimated to be 600 Btu/lb, the Russell James formula¹,

$$G = \frac{11,400 P_c^{0.96}}{h_o^{1.102}}$$

where G = flowrate in lb/(ft²-sec)

P_c = lip pressure, psia

h_o = stagnation enthalpy, Btu/lb,

for a 6" pipe at a lip pressure of 23 psig, gives a flowrate of 227,880 lb/hr. The equivalent electrical production rate is about 5 megawatts, assuming a conversion efficiency of about 15 percent. If the enthalpy is estimated to be 1000 Btu/lb, a flowrate of 129,842 lb/hr is calculated. However, the potential electrical production is now 7 Mw, because of a higher steam quality (80% vs 38%).

Immediately after the well was shut in, temperature and pressure measurements were obtained and are shown in Figure 3, together with a plot of the boiling point curve. Figure 4 is the temperature profile for HGP-A immediately after flashing, and one week, two weeks and three weeks later. There was rapid temperature recovery. Figure 5 contains plots of the pressure profile at various times after the well was shut in.

Because the results of this short test showed promising temperatures and mass flow rates, a series of tests of longer duration was planned to obtain additional data on the well and the reservoir. Figure 6 is a sketch of the equipment and instrumentation which was designed, constructed, and installed for the longer-term discharge test. As shown, the method uses twin cyclone separators for noise reduction and separation of steam and water, and the James technique for measuring total mass flow rate. A 90° V-notch weir is used to measure the liquid flowrate, permitting steam quality and specific enthalpy to be calculated. In addition, a calorimeter provides an independent measurement of the specific enthalpy. A 2" twin cyclone sampler is used to obtain gas and vapor samples for chemical analyses and a recovery tube is mounted on the wellhead to permit the insertion of a probe during the flow tests to obtain temperature and profiles. Gauges and recorders are used to

¹James, Russell, "Measurement of Steam-Water Mixtures Discharging at the Speed of Sound to the Atmosphere," New Zealand Engineering, pp. 437-41, October 1966.

Figure 3

TEMPERATURE vs PRESSURE
FOR HGP-A
July 22, 1976
After Four-Hour Discharge

Figure 6
HAWAII GEOTHERMAL PROJECT
FLOW TEST EQUIPMENT AND INSTRUMENTATION

measure and record lip pressure, wellhead pressure and temperature, and weir temperature. An instrument shed was built next to the wellhead to house the instrumentation and tools, a security fence with lighting installed and a portable van was placed a hundred feet away to provide project personnel with protection from inclement weather.

Following the installation of the equipment, a two-week discharge was run from November 3-17 to test the equipment and instrumentation and also to determine whether the well would produce for that length of time. Test data on well performance were recorded and are plotted in Figures 7 to 9, which give lip pressure, wellhead pressure, and wellhead temperature as functions of the duration of the well production. As shown, following an initial transient flow during which the wellbore was discharged, the pressures settled into the expected straight-line variation on a semi-log plot. The wellhead temperature was read with a precision of about a degree and was subject somewhat to the ambient weather. The water flow as measured by the height of the water in the weir notch remained essentially constant at 24,000 pounds per hour throughout the flow except for the initial period.

Figure 10 is a plot of the total mass flow rate as derived using the Russell James method. At the end of the two-week period, total mass flow was 74,000 pounds per hour. Figures 11 to 14 give enthalpy, steam flow, steam quality, and thermal power as functions of time. The apparent discontinuity at 192 hours is probably caused by an error in the lip pressure readings. Vibration of the instrument shed resulted in a leak in the lip pressure line and a consequent false lowering of the lip pressure reading. The leak was detected and the line tightened.

Wellbore conditions were monitored after the well was shut in. Figure 15 contains four temperature profiles which show the manner that the wellbore temperature approached its quiescent equilibrium condition. Figure 16 shows a pressure profile, which is essentially a hydrostatic one. Figure 17 shows the buildup of the water column level after shut-in of the well.

A 6 1/2-day variable-discharge test was run from December 12-19. During the period when the control valve was wide open, test data could be compared with the November test data. These show that wellhead temperature and pressure values as well as total mass flow rate were significantly higher in the December test. Also, while in the previous tests, the steam flow rate,

Figure 7
LIP PRESSURE VS. TIME

Figure 8

WELLHEAD PRESSURE VS. TIME

Figure 9
WELLHEAD TEMPERATURE VS. TIME

Figure 10

TOTAL MASS FLOW VS. TIME

Figure 11

ENTHALPY OF DISCHARGE VS. TIME

Figure 12
STEAM FLOW VS. TIME

Figure 13
STEAM QUALITY VS. TIME

Figure 14

THERMAL POWER VS. TIME

Figure 15
TEMPERATURE PROFILES AFTER NOVEMBER DISCHARGE TEST

Figure 16
PRESSURE PROFILES FOUR DAYS AFTER TWO-WEEK DISCHARGE TEST

Figure 17. WATER COLUMN LEVEL VS. TIME AFTER WELL SHUT-IN

enthalpy and steam quality decreased with time, these three quantities increased with time in the December test. Table 1 gives a comparison of output characteristics 7 and 25 hours after start of discharge in both tests.

Temperature and pressure profiles were measured during the December discharge tests and are given in Figures 18 and 19, respectively. While the temperature profile is probably accurate, considerable doubt has been raised about the validity of the pressure profiles despite the fact that they were taken with two different pressure gauges, including one just received directly from the Kuster Company. This is because the two sets of data taken together indicate that the bore is filled with superheated steam (but there is a considerable amount of water at the wellhead) and because a check of the gauges at the ground level where the pressure was known indicated the possibility of a partial leak into the outer portion of the Bourdon tube.

Future Work

The pressure build-up test, begun after the well was shut-in after the December discharge test, will be completed. Analyses will be made of the data from the pressure drawdown during the November test and the pressure build-up after the December discharge. Information on reservoir transmissibility (product of permeability and height), mud damage effects, and approximate size of the reservoir should be obtained.

A study to better determine the proper description of the well will be continued. It is expected that information will be obtained regarding depths, temperatures, pressures, and fluid state of the producing layers. Much of these data should be available for presentation on February 15, 1977 at the 18th ERDA-DGE Geothermal Coordinating Group Meeting at China Lake, California.

In order to obtain engineering data necessary for power plant design, a series of tests is planned in which the well will be discharged at various controlled flow rates, and wellhead and borehole temperatures and pressures are measured and recorded. These tests should begin in the last part of January after modifications are made to the wellhead equipment to remedy shortcomings discovered during earlier discharge tests. To reduce the noise level a steam muffler will replace the 24" horizontal discharge line, and circular stiffeners will be welded at two heights on each vertical stack. Leaks in the stacks will be sealed, and the stilling basin for measuring weir height will be moved to a location more convenient for reading the water level.

TABLE 1

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

	<u>After 7 Hours</u>		<u>After 25 Hours</u>	
	November	December	November	December
Wellhead Pressure (psig)	55	66	47	53
Wellhead Temperature (°C)	150	157	146	150
Lip Pressure (psig)	11.1	10	7.9	10.1
Weir Height (inches)	3-1/2	4-3/4	3-1/2	4
Weir Temperature (°F)	203	207	203	205
Water Flow Rate (Klb/hr)	24	52	24	34
Enthalpy (BTU/lb)	912	725	888	833
Mass Flow Rate (Klb/hr)	97.3	120.0	87.9	103.4
Steam Flow Rate (Klb/hr)	73.2	68.3	63.8	70.0
Steam Quality (%)	75	57	73	68
Thermal Power (Mw)	26.0	25.5	22.9	25.2

Figure 18
TEMPERATURE PROFILES DURING DECEMBER TEST

Figure 19
PRESSURE PROFILES DURING DECEMBER TEST

A steel platform will be built and installed at the wellhead to replace the present, hastily-built wooden one which does not meet OSHA standards. To facilitate the insertion and removal of the double-gauge probes for temperature and pressure measurements during discharge tests, a six-foot spool will be placed above the vertical valve and a suspended pulley and a winch will be added to the platform.