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DRAFT INTERIM REPORT:

EVALUATION OF GEOTHERMAL RESOURCES, STATUS OF EXPLORATION AND INFORMATION SOURCES

Volume II
(Appendices B-F)

for

DEPARTMENT OF BUSINESS ECONOMIC DEVELOPMENT & TOURISM

Honolulu, Hawaii

by

GeothermEx, Inc.
Richmond, California

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APPENDIX B

Review of Geophysics and Recommendations for Additional Work

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APPENDIX B

REVIEW OF GEOPHYSICS AND RECOMMENDATIONS FOR ADDITIONAL WORK

Overview. This review consisted of consultation of most of the original geophysical reports from the files of GeothermEx, followed by the examination of ENEL's evaluation of existing data for the KERZ.

Homogeneous coverage of the KERZ is afforded by only three kinds of geophysical data: passive seismic, aeromagnetic, and airborne EM (VLF). Other types of data, including ground-based geoelectrical, gravimetric, microearthquake, and ground noise, have been collected rather intensively in the Lower KERZ, east of Pahoa; however, these data are virtually non-existent for the Middle and Upper parts of the KERZ. Even within the Lower KERZ, however, the distribution of observing points has been very uneven; station positions have apparently been confined to the irregular, mostly sparse, distribution of roads.

Review of Geophysical Findings in the KERZ Gravity Surveys. A Bouguer gravity anomaly map that covers the entire island of Hawaii has been prepared (Kinoshita, 1965), but the Upper and Middle KERZ are devoid of gravimetric stations, and the contours shown in that area are merely inferred. The Lower KERZ has been surveyed in some detail (Furumoto, 1976), and the resulting Bouguer anomaly map reveals a strong, elongate high, parallel to the rift, in the western part of the Lower KERZ. The source of this feature has been modeled as a zone of high-density dikes and flanking sills, in which the top of the dike complex may rise to within 1.5 km of the land surface (Broyles, 1977). The high-density rock is believed to be composed of olivine-rich gabbro with a density of 3.1 g/cc, about 0.5 g/cc greater than the country rock. This density contrast is supported by high P-wave velocities (around 7.0 km/s) interpreted from refraction surveys.

In the vicinity of Puulena Crater and geothermal well HGP-A, this sharp gravity high appears to be offset along a NNW-trending belt in a left-lateral sense. This subtle offset might not have been noticed and discussed were it not for the existence of several successful geothermal test wells nearby. This and other features of the gravity data are correlated with aeromagnetic anomalies. However, the gravity data of themselves do not exhibit clear or definitive anomalies in the vicinities of proven geothermal targets.

Aeromagnetic Surveys

Aeromagnetic surveys were flown in 1966 and 1978 (Flanigan and others, 1986). The earlier survey was flown too high (4,000 meters a.g.l.) to have resolution useful in characterizing shallow structures of geothermal interest, while the later one was flown at only 300 meters a.g.l., with flight lines separated by 0.8 - 1.6 km. Because the regional (IGRF) field has a very small gradient (not more than 4 nT/km) in the area, it was not subtracted from the data in making the anomaly map. This survey shows steep linear gradients and associated dipolar anomalies alined with most of the length of the KERZ, and positioned along its southern flank. The orientation of the dipoles is in accord with a remanent magnetization of the source bodies which is close to that of the present geomagnetic field, with an inclination of around 35° N. This implies that the source bodies cooled below the Curie temperature within the current polarity epoch (beginning 20,000 years ago).

Flanigan and others (1986) have modeled the typical anomaly pattern in terms of a 2-dimensional prismatic body which is about 2.5 km wide and 2 km high, with top near the ground surface. This is considered to represent a complex of dikes that have higher magnetic susceptibility than the country rock. The model predicts that the anomaly extreme are approximately over the prism edges, so that the mapped extreme may be taken to locate the

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edges of the source. The magnetic susceptibility (K) contrast of the model is around 0.03 cgs units, with K higher in the source prism than in the country rock. This model agrees well with that put forward for the gravity anomaly prevailing in the Lower KERZ.

In the Puna area, the aeromagnetic data appear more complex than to the west, and some researchers suggest that an "offset" of the anomaly pattern is present, which may be related to and is supported by that of the Bouguer gravity anomaly. However, neither the so- called "offset" nor its relationship to the gravity data are obvious or compelling to the present reviewers. Although the aeromagnetic data appear to be effective in illuminating extensive structures, it seems that they cannot resolve geothermal targets, such as that in the Puna area.

Passive Seismic Data

Since the 1950s, the Hawaiian Volcanic Observatory (HVO) has operated a seismographic network, with stations located primarily in the vicinity of Kilauea and on the southern side of the island of Hawaii. The number and sensitivity of the seismographs have increased steadily since the network's inception: since 1969, virtually all shocks with magnitude 3 or larger on the island have been located; by 1985, the magnitude threshold of complete detection and location had dropped to around 1. Probably tens of thousands of small shocks have been detected and located by the HVO during the past 30 years.

The positions, source mechanisms, and rates of occurrence of earthquakes in relation to magmatic activity associated with Kilauea volcano and its rift zones, and with reference to the tectonics of the surrounding region, have been studied in great detail by a number of investigators. Scientific articles concerning these phenomena probably number several hundred, and this work cannot be totally characterized here. However, a few important features are considered: since 1960, many tens of thousands of small earthquakes have been detected and located beneath Kilauea as well as the KERZ and Southwest Rift, at depths from nearly 0 to more than 60 km; earthquakes associated with eruptive and intrusive magmatism occur in rather tight space-time clusters known as "swarms"; swarms shocks are small, with magnitudes that rarely exceed 4; shocks related to magmatism are caused by the fracturing that takes place when magma forces its way into and through brittle rock.

A recent review article (Klein and Koyanagi, 1989) presents an excellent, concise summary of the current understanding of seismicity in the southern part of the island of Hawaii. This includes a presentation of the spatial distribution of earthquake foci in a number of maps and cross sections, for the period 1970-1984. The report and map by ENEL (1990) does not adequately present this kind of information. A cluster of shallow shocks (depths of 0-5 km) is easily distinguished around Puulena Crater and geothermal wells, such as HGP-A. Shallow and deeper (depths of 5-13 km) clusters of shocks are centered north of Ka Lae Apuki, about 2 km east of a resistivity low shown by the airborne VLF survey discussed below. Other, less distinct, clusters seem to be present within the KERZ, but additional spatial analysis would be required to demonstrate or disprove their existence.

Microearthquake surveys have been carried out in the Lower KERZ, and one of the two reported by Suyenaga and others (1978) indicated clustering of small shocks near well HGP-A, predominantly at depths of 1-5 km. These workers conducted another survey, which indicated a cluster centered about 4 km north of Kehena, near wells GTW-1 and GTW-2. This is in the same area as a pronounced SP anomaly discussed below.

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Based on the experience outlined above, it is fair to say that passive seismic data are potentially useful in the delineation of geothermal targets in the KERZ.

Geoelectrical Surveys

Only one geoelectrical survey provides homogeneous coverage of the entire KERZ, and this is the very low frequency electromagnetic (VLF EM) mapping reported by Flanigan and others (1986). Ground-based geoelectrical soundings and surveys have been carried out in the Lower KERZ and are of the following types: bipole-dipole, pole-dipole and time domain electromagnetic (TDEM) or EM transient surveys (Skokan, 1974; Keller and others, 1977); vertical electrical soundings (VES or Schlumberger) and EM soundings (Kauahikaua and Klein, 1977; Kauahikaua and Mattice, 1981); a mise-al-a-masse survey (Kauahikaua and others, 1980); and a self-potential (SP) survey (Zablocki, 1977). By far, most of the ground-based work has been conducted in the area extending easterly from the road between Pahoa and Kalapana to Kapoho Crater. A small number of bipole sources and VES spreads were located north of Pahoa, to near Kurtistown, and three bipole sources were positioned near Kilauea Crater.

The ENEL report (1990) makes a useful contribution in its compilation of a map showing transmitter sites for the various active geoelectrical surveys and soundings; however, receiver sites are shown only for the TDEM work, and not for the direct-current surveys. Also, the ENEL report includes a map compilation showing major results of the geoelectrical work, although it appears to oversimplify data which show great variability in electrical structure over distances of a few kilometers.

Most of the soundings (both direct-current and EM) have indicated a dry, highly resistive (100s to 1,000s of ohm-m) surficial layer above the water table, underlain by a saturated, more conductive layer (1 to 600 ohm-m) with variable thickness; this is underlain by more resistive (electrical "basement") material. The most significant variability is in the depth, thickness, and resistivity of this second, conductive layer. These factors appear to be controlled by the salinity and temperature of the ground water, possible lenses of meteoric water over sea water (brine), and, to a lesser degree, by clay alteration. Except for the Puna area, the spatial density of sounding points has been insufficient to permit resistivity mapping with really useful resolution.

Because of their very uneven and frequently non-coincident spatial distribution, it is difficult to compare or synthesize results of the many ground-based geoelectrical surveys and soundings. Only the EM transient (TDEM) survey, with 24 soundings in the Puna district, had sufficient spatial density of observation points to allow a useful mapping (that is, with horizontal resolution better than about 5-10 km) of shallow, second-layer resistivity; this is shown in ENEL report (1990, Plate 7). Of the 24 soundings, 17 were interpreted in terms of a layered model. The data indicate an ENE-trending low, some 3 km wide, extending from the vicinity of well Ashida 1 to Kapoho Crater (ENEL, 1990, Plate 7). This has resistivity of about 2-4 ohm-m for a second layer with a thickness of 500-1,000 m.

The various surveys (bipole-dipole, pole-dipole, mise-a-la-masse) using fixed current sources and distributed receiver sites portray surficial resistivities at close range and second-layer resistivities at greater distance, making it quite difficult to combine the data. Only two bipoles were close enough to HGP-A to illuminate that area; they indicated apparent resistivities of around 10 ohm-m at HGP-A, and that the well is positioned away from the lowest apparent resistivities (2 to 5 ohm-m); the depth of current penetration and true resistivities are unknown. The mise-a-la-masse survey, which used the casing of well HGP-A as one current electrode, showed a

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similar situation. The investigators speculated that these high apparent resistivities at HGP-A are the result of fresh water impounded upgradient of dikes.

The most interesting of the geoelectrical investigations is the self-potential (SP) survey carried out in the Puna district (Zablocki, 1977). The survey revealed four anomalies, of which at least two appear to be significant in relation to geothermal targets. One is a narrow monopolar (positive) anomaly centered near well HGP-A, with amplitude of 450 mV, and long axis alined with a 1790 fissure. Another is bipolar, with peak-to-trough amplitude of nearly 800 mV, with positive peak directly over steaming vents formed during the 1955 eruption; wells GTW-1 and GTW-2 are on this anomaly. It is modeled as the result of an asymmetric convective plume, buttressed on its south side by an impervious dike. A third anomaly is located about one kilometer to the northeast of HGP-A, and strikes northwest, cross-cutting fissures. It is noted that the ENEL (1990) report (Plate 7) does not completely represent the SP data. For example, closed positive and negative anomalies are associated with GT1 and GT2 and should be discussed.

Each of the data reports listed above included speculations on the depth, temperature, and geothermal significance of circulating ground waters. In our view, these remain simply speculations.

The airborne VLF EM survey had flight lines draped at 100 m a.g.l. and spaced at 1-2 km, trending NNW, transverse to the trend of the KERZ. An apparent resistivity map was prepared for a transmitter frequency of 18.6 kHz, with attendant skin depth of 30-400 m, depending on actual shallow resistivity. This map reveals three major lows which appear as troughs, about 2-6 km in width, that cross-cut the KERZ. The most easterly of these runs northerly from Opihikao through the Puna area to a point about 5 km north of HGP-A, and has apparent resistivities of 25-600 ohm-m. It is thought that this trough reflects shallow circulation of ground water, and perhaps clay alteration, enhanced by faults and fractures which cross-cut the KERZ, and along which several productive geothermal wells are found. The middle and western troughs run northerly from Kupapau Point and Ka Lai Apuki, respectively, and no other geophysical or structural geologic features appear to be correlated with their positions.

Reiterating, it appears that the self-potential method, and perhaps resistivity soundings, may be useful in selection of geothermal targets in Hawaii.

The Kilauea Southwest Rift Zone (KSWRZ). The data available for this review were quite incomplete for the KSWRZ, and so this very brief evaluation is subject to revision. Gravity and aeromagnetic data for this area exist but were not reviewed. The HVO seismographic network has revealed abundant seismicity in the KERZ. The VLF EM mapping (Flanigan and others, 1986) reveals no low-resistivity features along the KERZ. Further review of data available for the KERZ is underway for these tasks (1 and 3).

Utility Ranking and Recommendations for Obtaining Additional Geophysical Data. A utility ranking is presented, which considers the logistical problems (physical access to land areas), expense, and ability to resolve a geothermal target. The geophysical methods are listed in order of decreasing priority and explanations are given below:

1. Self potential (SP) surveys over selected areas
2. Detailed spatial analysis of existing HVO seismicity data
3. Airborne VLF EM surveys in selected areas
4. Resistivity soundings (VES/Schlumberger or TDEM)
5. Gravimetry, resistivity surveys, and aeromagnetics

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1. Self Potential Surveys

Self potential surveys in selected areas, not larger than approximately 50 km^2, have a good likelihood of identifying geothermal resources, should they exist, with a precision better than 1 km. SP surveys, including that in the KERZ, have shown a good capability of resolving geothermal targets, because they can detect the streaming potentials often associated with shallow hydrothermal plumes. Among the geoelectrical methods, SP surveys are probably the easiest to conduct on foot, as one man can backpack the required receiver, porous pots, and a small reel of wire for short spread lengths. Portable global positioning receivers are now available, making it easy to establish precise coordinates for remote observing stations. Off-road portability of equipment and locatability are critical considerations for ground-based exploration in the KERZ, as most of the area has no road access, and land surveying is quite inconvenient in the dense tropical forest. Selection of new areas in which to make SP surveys can be based on several other types of available data, including passive seismic (HVO data), VLF EM mapping, surficial geologic structure, locations of historically formed fissures and steam vents, and results from recently drilled SOH and exploration wells. The initial survey field data should be replicated first to see whether this method provides consistent and applicable results. There may be changes since the Zablocki (1977) survey, but the presence of anomalies and relationship to successful geothermal wells is important to consider.

2. HVO Seismicity Data (Passive Seismic)

Detailed spatial analysis of the enormously large set of earthquake locations available for the Kilauea East and Southwest Rifts offers a relatively inexpensive means of identifying shallow (0 - 5 km deep) seismicity that may be linked to significant, ongoing hydrothermal activity in

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the upper crust. No field work is required to conduct this study. Analysis would rely primarily on preparation of maps and cross sections of earthquake hypocenters within selected rectangular crustal blocks; it would be useful to apply moving time-of-occurrence windows to identify swarms, which appear to be more related to geothermal activity than non-swarm events. Location of targets may have a precision of about 1 km. Detonation of a few "calibration shots" in the KERZ (and perhaps also in the Southwest Rift) could be used to significantly improve the accuracy of hypocentral locations (by appropriate reprocessing of hypocenters already located). The USGS might cooperate in such a venture; some of the analyses and indeed calibration shots may have been done and maps and cross sections may be available to inspection by interested scientists at The Volcano Observatory. Short-term microearthquake surveys with state-of-the-art equipment (PASSCAL portable seismographs) may be appropriate following thorough analysis and interpretation of available data. In this way structural and earthquake source features developed from HVO data may be methodically selected and investigated.

3. Airborne VLF EM Surveys

The existing airborne VLF EM mapping reveals three interesting low-resistivity troughs that cross-cut the KERZ. The easternmost of these transects the Puna area and includes the geothermal resource in the vicinity of Puulena Crater. It is obvious that parts of the troughs also extend outside of the areas of the geothermal reservoir, but geology and other geophysical methods enable exclusion of these parts of the troughs from consideration for geothermal exploration. It would probably be worthwhile to conduct additional VLF EM surveys, with higher resolution (using closer-spaced flight lines) and incorporating lower frequencies (to provide deeper penetration) than the existing survey, in selected areas. Selection of areas for future exploration may be guided by the locations of the two resistivity troughs lying west of the Puna area, by locations of seismicity clusters, and, of course, by surficial geologic features.

4. Resistivity Soundings

Resistivity soundings are rather cumbersome to make, and are not practical without road access. It may be worthwhile to fill-in some gaps left by previous sounding efforts (TDEM and VES) in the Puna geothermal area, where there is relatively good road access. Such work could help to better define extent of the Puna geothermal reservoir. Additional data review would be required to specify worthy locations.

5. Resistivity Surveys, Gravimetry, Aeromagnetics

Based on experience to date, none of these methods is considered capable of providing sufficient resolution of geologic structure in all-volcanic terrain, or in detection of hydrothermal plumes, to be clearly useful in geothermal exploration, namely, siting wells, on Hawaii. However, gravity data in the Puna area are confined to a few roads; the available Bouguer gravity map (Furumoto and others, 1976) interpolates these data. Several gravity stations were located along an approximate east-west traverse through the geothermal district. It may be useful to make several or many more observations (fill gaps) along this traverse and to model all data (old and new). Otherwise no further work is recommended at this time.

References

References are listed in the main report.

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APPENDIX C

Review of Geochemistry and Recommendations for Additional Work

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APPENDIX C

REVIEW OF GEOCHEMISTRY AND RECOMMENDATIONS FOR ADDITIONAL WORK

Overview. Geothermal resource assessments may be undertaken with the focused goals of resource exploration, exploitation and management, the broad objectives of scientific research, or some combination such as doing basic science to assist developing tools for technology.

This review of geochemistry mainly concerns assessments to locate, define and, if possible, utilize the resource, from the viewpoint of cost effectiveness and the broad objective of economic assessment.

Methods and technologies which are most likely to give direct and useful information about the resource are therefore favored over methods which tend to give indirect information. For example, temperature and pressure logs and fluid samples from a drillhole, correctly obtained and analyzed, give direct knowledge of current rock temperatures in a hydrothermal system. By comparison, fluid inclusion homogenization temperatures may reflect current rock temperatures, or otherwise represent conditions (*i.e.* salinity) at some time in the past. While data concerning historic temperatures are interesting from a scientific viewpoint, they contribute less to the type of assessment addressed herein, than to an understanding of system evolution over geologic time.

Geochemical studies in an economic assessment may have various immediate objectives:

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A. detecting "hidden" reservoirs (exploration targets) which are not connected to known hot springs, steam or gas vents and wells, but which release trace amounts of certain substances, such as ^{222}Rn (radon isotope 222), Hg (mercury), NH_3 (ammonia), and/or CO_2 (carbon dioxide) into shallow groundwaters and soils;

B. classifying and ranking exploration targets by fluid type and geochemical temperature, at locations where thermal manifestations are known to exist and water, steam/gas and solids samples can be collected;

C. defining the hydrogeologic model of the reservoir, for example its zone(s) of upflow, internal circulation and outflow, by classifying and showing relationships between the fluids and solids compositions at various wells and springs which tap into the hydrothermal system;

D. predicting and allowing design-stage engineering to manage: scaling, corrosion, fluids releases to the environment and/or fluids behavior upon injection back underground;

E. assisting long-term reservoir and production engineering by monitoring changes in fluids chemistry which have been caused by production and injection;

F. classifying the background chemistry of the natural environment in the vicinity of the resource, and monitoring changes caused by production.

These studies typically are coupled with parallel geological, hydrological and/or geophysical studies, which are desirable/necessary to aid the interpretation of the data and avoid errors resulting from single-discipline conclusions.

Review of Prior Geochemical Work and Possibilities for Additional Surveys.

Several reviews of geochemical studies in the Kiluaea East Rift Zone (KERZ) and its surroundings have been published (*e.g.* Cox, 1980; Cox, 1981; ENEL, 1990; Iovenetti, 1990; Thomas, 1986; Thomas, 1987; Thomas, 1989). These, along with discussions with scientists and private operators recently active in the area, form the basis for the following observations and conclusions.

Soil Surveys (Objective A)

Exploration to detect trace chemical emissions from "hidden" reservoirs (objective A, above) has been reported by Cox (1980, 1981), who conducted soil surveys for Hg and ^{222}Rn with reconnaissance-level sample spacings of about 0.5 to 0.8 km (Hg) and 1 to 1.5 km (^{222}Rn), in the lower KERZ (lower Puna area). Reducing the Hg data to remove strong background effects of soil chemistry was particularly difficult; the reduced data presented "a pattern of anomalous Hg overall (which) indicates Hg leakage in ground gas from fractures within the rift zone and tends to reinforce the model of a rift-controlled reservoir" (Cox, 1981, p.70). There were localized variations some of which may be related to the influence of specific fractures, but most of which appeared to be a function of the problems with data reduction. The major anomaly included the location of well HGP-A.

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The ^{222}Rn survey was regarded as somewhat more successful in defining zones of possible deep permeability and thermal activity. There is an anomaly which encompasses the locations of well HGP-A and the Puna Geothermal Venture (PGV) well, and several other anomalies, all within the KERZ. The anomalies are interpreted as defining zones of both high temperature and structural permeability, allowing ground gas movement (outgassing of deep vapor bearing ^{222}Rn) which is detectable near the surface (Cox, 1980). However, Don Thomas (oral communication, 1991) suspects that the anomalies are created by variations in local shallow subsurface permeability, and do not necessarily indicate good exploration targets.

Both surveys have established correlations between soil anomalies and the KERZ, and show that an anomaly exists at the proven HGP-A and PGV wellfield. The HGP-A discovery was made without the benefit of these data, and the PGV discovery wells probably also were sited using other criteria. The unproductive deep holes just south and southeast of the wellfield are at the edge or outside of the anomaly. This encourages siting exploration wells within the Rn anomalies, the Hg data being too uncertain. However, the actual utility of the soil chemistry data as a tool for siting wells and proving deep, productive reservoir(s) remains to be established. Data from drilling into the other Rn anomalies are needed.

From reviews of the prior work, it appears that additional Hg surveys would be of little benefit for exploration and scientific values.

Regarding Rn, we recommend considering only:

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1) detailed surveys around SOH holes or any other exploration step-outs which discover high temperature and/or high permeability, to investigate whether anomalies exist at these locations. This work also merges into the realm of research, but may have practical applications at a future time.

This additional survey work is a low priority. It should again be considered if future deep drilling in some way confirms the anomalies already discovered.

There are other techniques intended to detect "hidden" reservoirs, such as sampling and analyses to find anomalies of NH_3 and CO_2. These depend upon the presence of shallow groundwater to concentrate and carry the specie being analyzed, and would not apply to the rift zone environment.

Classifying and Ranking Targets, Defining the Hydrogeologic Model (Objectives B and C)

Thermal springs and fumaroles are absent from the KERZ, so this method of exploration to classify and rank targets (objective B) is impossible. Furthermore, the small number of deep exploration holes and data therefrom in the public domain, except from HGP-A, limits possibilities for more than a sketchy definition of the hydrogeologic model (objective C).

Groundwater studies have identified thermal fluids at shallow (<300m) and cool to warm (<100°C) boreholes and wells, and at coastal springs, in and south of the lower east rift zone (ENEL, 1990; Iovenetti, 1990; Thomas, 1986). The number of shallow boreholes and wells in the area is quite small. ENEL (1990, pl.2) reported 15 locations, but only 6 with temperatures above 30°C. OESI has since drilled two monitor holes and two water wells (one recently completed; 29 Aug. 1991).

Only one sample from a coastal warm spring was tabulated by ENEL (1990, annex A table 1, Isaac Hale Spring). The same report (pl.2) shows the temperatures and approximate locations of 10 springs along the coast south of the rift, and one to the north. Temperatures exceed 30°C only at Allison, Isaac Hale and Opihikau springs. Don Thomas (oral communication, 1991) reports that Isaac Hale and Opihikau are the only locations where hot water discharge can be sampled before it mixes with seawater.

Fluids compositions at several of the holes indicate mixtures of dilute shallow groundwater with heated seawater and/or with deep thermal reservoir water. ENEL (1990) tends to view the warm waters as mixtures of dilute groundwater with heated seawater, whereas Iovanetti (1990) has interpreted the same samples as mixtures of dilute groundwater with thermal reservoir outflow.

As ENEL (1990) has pointed out, much of the chemical data that ENEL examined are fragmentary, incomplete, and often marginal in quality. Sample locations are often ambiguous and samples from single locations collected years apart sometimes differ. Most analyses lack trace elements such as Li, Rb, Br and Cs, and the stable isotopes of oxygen and hydrogen. One-half of 94 major element analyses reported by ENEL (1990; annex A, table 1) show major element ion imbalances of more than 10%. ENEL may not have obtained all available information from the USGS and State of Hawaii.

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Major ion balances of analyses from well HGP-A, tabulated by ENEL (1990) and also published elsewhere, are quite satisfactory. The HGP-A chemical data include numerous weir samples, and liquid, steam and gas samples collected at the same pressure, but do not include stable isotope analyses. The well was not precisely flow metered, so total flow enthalpy and relative steam-water flow rates are not well-known.

Discussion and Recommendations for Obtaining Additional Fluids Geochemical Data.

Considering the work already accomplished and the results we recommend:

1) collect new samples where necessary at all of the shallow wells and coastal springs in and south of the east rift zone, at the newer water wells and monitor holes drilled by OESI, at the SOH program holes, and at any other new holes which become available. At a minimum, the older locations should include the GW-3 hole, the Allison well, the Malama Ki well, and the Kapoho hole (if accessible). Downhole samples can be collected at holes which cannot be flowed.

   Temperature-spinner logs of shut in holes sampled downhole are also recommended, to detect interzonal flow. Sample analyses should include major and trace elements, and stable isotopes. It would be best for the samples from all sources to be analyzed at the same laboratory, with very careful quality controls.

This work should be done to help define the hydrogeologic model of the thermal system, and in particular the patterns and causes of heating in the shallow groundwater system in and south of the rift. Results should be integrated with data from well HGP-A and private deep exploration holes, as such data become available. This work also should be done in connection with long-term monitoring of the environmental background, which is discussed below.

At least some of the recommended locations were sampled in August 1991, by personnel of the U.S. Geological Survey, but a list of locations is not yet available (R. Mariner, oral communication, 19 August 1991). The U.S. Geological Survey recently started a 3 to 5 year long project to study the entire hydrologic and hydrogeologic system of Kilauea volcano, from the summit of Mauna Loa, to Hilo, to South Point. The study team includes a hydrologist, two geologists, a geophysicist, and two hydrogeochemists; the project chief is J. Kauahikaua of the HVO. The work is described as a regional hydrogeology project. Project work started in mid 1991 with meetings at the HVO to define the scope of work. The project geochemists then spent two weeks in the field, collecting samples of rainwater, surface water, spring and wellwater, from throughout the project area, for chemical and isotopic analysis. The U.S.G.S. also obtained, in late 1989, samples from some of the hot groundwater sources in the rift zone, including well GW-3. (C. Janek, oral communication, 30 August 1991).

Engineering Design and Production Engineering (Objectives D and E)

Public-domain studies related to these objectives have not been done, except for reports on corrosion and scaling at well HGP-A. This work is largely the domain of field developers and operators, except to the extent that failure to manage corrosion can be a matter of public safety, and injection problems such as undesired contamination of non-thermal aquifers, gas break-through and thermal degradation may result from failure to select appropriate locations, depths, fluid composition and pressure.

With respect to corrosion, it may be assumed that the current operators are well aware of the potential corrosivity of the fluid (high H_2S, Cl) produced by the existing wells. Some wells have shown a tendency to produce only steam, which presents a very severe corrosion potential if the steam carries HCl. This corrosion can be managed using existing technology. To our knowledge, adequate analyses to detect HCl corrosion potential still do not exist. Steam sampling to monitor for HCl can require special techniques of sample collection and analysis, which are not routinely applied.

With respect to injection, we propose that strategies and actual injection must be monitored. We are not aware of locations where deep geothermal injection has mixed into shallow aquifers. However, the relatively unique hydrologic environment of the rift zone will need to be considered, as well as possible effects of injecting large amounts of non-condensible gases, as proposed by OESI. Gas injection in excess of solubility may result in breakout and vertical travel if unconfined zones exist. Injection is a subject of study which will require integrated modeling, which also considers production from the geothermal reservoir.

Chemistry of the Environment and Production Effects (Objective F)

As discussed above, the chemistry of the cool to hot shallow groundwater system in and south of the lower east rift zone is not well-documented. For this reason, a re-sampling has been recommended. We further recommend that this work be carried out on a regular, routine basis for 2 or 3 years, to allow establishing solid background data and detecting any seasonal changes in shallow groundwater chemistry which may be occurring. Such changes are not common, but if they occur, they would interfere with detecting and analyzing injection effects. Shallow groundwater sources close to the northern edge of the rift zone should also be included. Samples should be collected about 6 times/year the first year, and 4 times/year or less thereafter, depending upon variability. Species to be analyzed can be limited somewhat to avoid excessive costs, but should include trace elements and isotopes at least at the start.

Summary of Recommendations. The following techniques are proposed as the highest priority items for future work.

1. Resample (or obtain information from the U.S.G.S.) cool to warm shallow groundwater sources in the lower east rift and to the south, and sample new sources, to obtain analyses of trace elements and isotopes along with better analyses of the major elements. Collect downhole samples at wells which cannot be flowed; obtain temperature-spinner logs at these same holes.

2. Continue sample collection at the same locations on a periodic basis for about 2 years, to establish solid environmental background data, and document seasonal changes, if any.

3. Carefully monitor plans of location, depth, pressure, chemistry and volume proposed by operators for water and gas injection from the production areas, the rational for choice of injection locations, and precise injection plans.

4. Consider Rn surveys at detailed scale in the lower rift, if future drilling in the lower rift shows that existing anomalies correlate with producible deep thermal aquifers.

References

References are listed in the main report.

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APPENDIX D

Analysis of Reinjection

Memorandum

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MEMORANDUM

To:	Mr. Gerald Lesperance Department of Business, Economic Development and Tourism State of Hawaii (DBEDT) 130 Merchant Street, Suite 1060 Honolulu, HI 96813 Fax: (808) 586-2536	*Date:*	October 23, 1991
From:	Subir K. Sanyal Vice President	*Page:*	1 of 6
Subject:	Geothermal Development in the Kilauea East Rift Zone-- Status of Reserves Assessment and Injection Strategy		

This memo addresses some basic concerns regarding the status of reserves assessment and the development of an injection strategy for waste water and gases from any power plant to be developed within the Kilauea East Rift Zone (KERZ).

It is generally agreed that a considerable amount of exploitable geothermal reserves exist in the KERZ and possibly in the other rift zones of the Big Island. For example, the Puna Geothermal Venture (PGV) has been able to convince sophisticated investors and major financial institutions that at least a 30 MW (gross) power plant could be supported for 30 years from the reserves within a 500-acre portion of their leasehold. In fact, the Scientific Observation Holes (SOH) program of the State of Hawaii has confirmed the existence of a much larger geothermal system within the KERZ than had been proven before by commercial developers.

Figure 1 shows the temperature distribution at the -4,000 foot datum (below sea level) within the PGV's leasehold before the SOH wells were drilled. In figure 1, from a report written in 1990, the temperature contours on the western flank of the rift are dashed indicating the extrapolated, and therefore unverified, nature of the contours, because no wells then existed on the western side of the rift; for this reason, in 1990 the only proven reserves were considered to exist on the eastern side of the rift and over a few hundred acres of the leasehold in the vicinity of the HGP and the Kapoho State wells. Figure 2, drawn in 1991, shows the temperature distribution within the KERZ, at the -4,000 foot level, after the SOH wells had been drilled. Comparing figures 1 and 2 one can conclude the following:

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- Well SOH 1 confirmed the prior temperature extrapolations to the western side of the rift, thereby nearly doubling the proven thermal anomaly in the vicinity of the PGV project area.

- Well SOH 2 extended the high temperature anomaly, in the northeast direction along the rift zone, several miles beyond the PGV project area.

- Well SOH-1 also indicated the presence of a reservoir boundary on the western flank of the rift, symmetrical to the reservoir boundary indicated by well Lanipuna 6 on the eastern flank.

Besides confirming the existence of a large thermal anomaly, these SOH wells also encountered fractures, thereby proving the existence of exploitable reserves. These wells have confirmed and substantially expanded the proven and probable reserves within KERZ. Thus, the State funds in support of the SOH program have played a major role in establishing the extent of commercial geothermal resource prospects within the KERZ, as well as helping define the boundary of the reservoir, which needs to be known for planning geothermal fluid injection areas.

The best injection strategy for the commercial development of the KERZ is yet to be decided upon. For example, an optimum injection plan for the PGV project has not yet been clearly established. As regards the PGV project, the need for injection (of 100% of the produced mass) is primarily for environmental reasons: the disposal of the waste water and gases from the power plant. The production wells would not rely on injection pressure support.

The original plan of PGV had called for injecting the waste water and gases in a well (or wells) outside the southeastern boundary of the reservoir in the vicinity of well Lanipuna 6; this is a "dry" hole, and therefore, assumed not to be in communication with the reservoir. Lanipuna 6 was known to have encountered a relatively shallow (below 2,000 ft depth) zone of apparently high flow-capacity, which could be used for the disposal of waste water and gases through a well or wells to be drilled into this zone by PGV. The assumption underlying this plan was that the reservoir pressure could be maintained at an acceptable level without any injection into the reservoir; however, this assumption has not yet been validated by numerical modeling of the reservoir behavior. GeothermEx is scheduled to conduct such modeling on behalf of Credit Suisse in a few months.

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Assuming that the reservoir would not need injection pressure support, the above-mentioned plan appears reasonable. Normally, injection outside the reservoir over a long period would not be feasible because the injection pressure would continue to rise due to the lack of any reservoir depletion by production. Fortunately, in this case, injection outside the producing reservoir appears feasible because of two reasons:

- The very high flow capacity of the target zone.
- The relatively small volumetric flow rate (about 1,200 gallons per minute) of waste water requiring disposal.

The original plan for injecting outside the reservoir was meant to eliminate the possibility of cooling due to any premature breakthrough of the cooler injected water to production wells. The plan for injecting the gases as well as waste water from the production wells into the subsurface was based on the desire to eliminate the following:

- major cost of abatement of the noxious component (H_2S) from the non-condensible gases, and
- emission of the residual gases (mainly CO_2), after H_2S removal, to the atmosphere.

The total volume of gas emission to the atmosphere from this project would be small compared to many other geothermal projects because the fluid at the KERZ appears to have a relatively small amount of total dissolved gases. However, the cost of H_2S abatement would be a significant burden because, even though the total gas content is small, the H_2S content in the KERZ fluid is high compared to other geothermal projects.

There are two obvious questions as regards the above-mentioned injection plan:

- Would the water flow rate in the injection stream be sufficient to allow injection of the gases?
- Would the gases or the injected water find their way to the ground water system or even to the ground surface?

Injection of gases in a well requires a minimum amount of simultaneous water injection; otherwise the injection pressure would become impractically high. It is expected that the available waste water injection rate would be nearly enough for gas injection. However, some make-up water from ground-water wells would have to be used to augment the injection stream. Fortunately, PGV appears to have an abundant ground-water supply.

We believe that the danger of gases or injected water appearing on the ground surface or in ground-water aquifers is very small for two reasons:

- The targeted injection zone is much deeper than the local ground-water aquifers.
- The gas concentrations would be diluted by mixing with the subsurface water in the injection zone and partially consumed by reaction with subsurface fluids and rocks.

It is theoretically possible, but largely impractical, to model the possible interaction between the gases and water injected into the target zone and the overlying ground-water aquifers, because of the following reasons:

- No practical numerical modeling approach exists that can simultaneously model the fluid flow, heat transfer and complex interactions between the gases, water and rocks in a non-isothermal ground-water system.
- No information exists on the hydraulic as well as chemical nature of the target injection zone or the exact chemical nature of the injection water and gases.

We have recently learned that PGV is reconsidering its original plan and now intends to inject into wells KS-3 and KS-4 and perhaps KS-1A, located within the production area, instead of in wells outside the reservoir. This plan has two advantages:

- It eliminates any potential leakage of gases or waste water into the ground-water aquifers.
- It would provide some pressure support to production wells.

However, it also has two potential disadvantages:

- Possible cooling of production wells due to the breakthrough of cooler, injected water, and
- possible breakthrough of the injected non-condensible gases at the production wells.

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We consider the second disadvantage to be a more serious concern.

The only geothermal field in the U.S. where non-condensible gases from production wells are being injected into the production reservoir is the Coso Hot Springs field in California. At Coso Hot Springs, the injected gases have broken through at several production wells. This has caused the following problems:

- The power generation level has declined due to the increase in the gas content of the steam.
- The capital cost has increased because of the need to install an H_2S abatement system not originally planned for.
- The operations and maintenance costs have increased due to the need for H_2S abatement.
- A gas discharge permit had to be obtained from the local air pollution control district which was not originally planned for.

It is possible that these problems would occur at the KERZ given the new injection plan.

It is theoretically possible to forecast the extent of the cooling and gas-breakthrough problems by reservoir modeling; but given the complexity of the problem, the scanty knowledge about this geothermal system and the relative lack of data, such modeling is difficult, if not impossible, at this time. GeothermEx will, however, develop such a model on behalf of Credit Suisse after the PGV's drilling and well-testing activities are completed. Because of our substantial experience in modeling this aspect of the Coso Hot Springs field, we anticipate being able to accomplish this difficult modeling task.

PGV points out that while the production and injection wells at the KERZ are closer to each other than at Coso Hot Springs, the vertical distance between the production and injection zones would be higher. However, this fact cannot be fully assessed until well KS-8 is tested and PGV updates their production/injection strategy.

Finally, it is worthwhile considering the steps that can be taken by the DBEDT to improve the confidence in the geothermal energy reserves underlying the KERZ and to help define an optimum production/injection strategy. We believe that the most practical step that the DBEDT can take at this time is to help finance drilling and testing of exploratory wells, either slim holes or production size wells. We do

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not believe that other technical activities, such as surface exploration, laboratory studies or computer modeling, by themselves, would be effective in improving the confidence of investors in the geothermal development prospects in Hawaii.

After 15 years of geothermal exploration and the construction and operation of a demonstration power plant for 7 years, only 30 MW (gross) of power is under development in Hawaii. If the ultimate goal of 500 MW of power on the Big Island is to be realized, a minimum investment of 2 billion dollars would be necessary, not counting the enormous cost of a subsea cable. This amount of investment obviously cannot be funded either by the State or the Federal government. Major financial institutions and most equity investors would be willing to fund a power plant development only after the reserves are confirmed by drilling and testing of wells; exploration activity cannot be debt-financed. Surface exploration, laboratory studies or computer modeling, without a simultaneous program of drilling and well testing, would not have any attraction to potential debt-financiers or even most equity investors, and therefore, would not provide any impetus towards geothermal development in Hawaii. Indeed, because they are not "bankable," such studies would serve only to delay commercial geothermal development in Hawaii. By contrast, an impetus from the DBEDT is all the more necessary now that the drilling, environmental and public relations problems in the PGV and True-Mid Pacific projects have cast a shadow on the future financing prospects for geothermal development in Hawaii.

If you wish, I would be prepared to explain and amplify the above ideas, illustrating them with comparable case histories of several other fields, and answer any related questions in a meeting of the DBEDT and other concerned parties.

Best regards.

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APPENDIX E

Analysis of SOH Cores

Memorandum

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REVIEW OF CORE DATA FROM STATE OF HAWAII SCIENTIFIC OBSERVATION HOLES, SOH-1, SOH-2 AND SOH-4

Purpose of the Work

This review was undertaken to determine the adequacy and consistency of core descriptions from the subject holes, to determine what additional detailed analysis of rocks and hydrothermal minerals should be carried out and to outline a form in which the drilling results can be summarized and made usefully available to both industry and the scientific community in the near future.

Method

The cores, core photographs and core descriptions were selectively examined with the assistance of René Evans, project geologic technician. Frank Trusdell, formerly associated with the SOH project, and now with the U.S. Geological Survey, was able to participate in the discussion of these of his activities carried out while he was an employee of the State. This review was conducted in the period from October 28 through November 1, 1991, at the Pahoa core storage facility.

Conclusions and Recommendations

1. Adequacy and Consistency of Core Descriptions.

Extensive intervals of core from SOH-4 were examined and compared to the log sheets. Similar intervals from SOH-1 and SOH-2 were examined and compared to SOH-4. Both the description detail and the consistency of description of

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similar rock types within a well and between wells appear, from hand specimen examination, to be good. However,

(a) so much detail is recorded on the core data sheets as to be excessive, and a composite log, outlined below, is recommended for easier access to the salient fractures of the wells.

(b) The verbal summaries on each log sheet should be re-checked and edited by Ms. Evans so that the descriptions format is consistent and routinely mentions important features such as vuggy porosity, character of the fracturing and other features related to amount of porosity.

(c) RQD figures should be checked to eliminate artifacts of logging such as discing and recoring which occur in a few intervals.

(d) The visual identifications of rock textures, rock alteration and of fracture and vug-filling minerals is in some cases, uncertain. In view of the significance of some mineral species to the analysis of the hydrothermal regime, it is strongly recommended that the present identifications be confirmed by more detailed work. This should include:

    (1) About 60 <u>rock</u> samples of typical intervals, selected from among the three wells, should be submitted for petrographic or the appropriate studies, to confirm the revised descriptions.

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(2) About 60 samples of vug or fracture-filling minerals should be submitted for identification by XRD or other means, as appropriate. Care would be taken not to use all of the mineralized material in any core, assuming that some sample material remain for later use.

In order to be of value in the phase of the project, this mineral and rock analysis work must be carried out immediately in a timely fashion.

To assist in carrying out the sample selection and ultimate description editing when the analyses are available, it is recommended that René Evans be given the opportunity to review the recent literature on hydrothermal mineralization in geothermal systems and to confer with the persons carrying out the laboratory identifications.

2. <u>Preparation of a summary report covering SOH-1, SOH-2 and SOH-4 holes</u>.

A summary report needs to be prepared as soon as possible to make the findings of the project drilling available to the interested public and to assist in planning future project work. This report will be an elaboration of the work already done for the Reno GRC meeting poster session display.

(a) a composite log should be prepared for each well, at a vertical scale of 1 inch = 100 feet. This log should be in an easily reproducible form and include the following:

(1) Lithologic log (using symbols).

(2) Summary rock descriptions.

(3) RQD log, annotations in zones of poor core recovery, zones of lost circulations, fluid entry, notable vesicularity, vugs and fracturing).

(4) Temperature log.

(5) Hydrothermal mineral distribution.

(6) Annotations indicating hole size and casing.

(7) Legend for log symbols.

(8) Brief notes giving a short well construction history, status, and so forth.

(9) A log heading giving location coordinates and elevations. Any other well data suitable for graphic presentation and useful in understanding the well should be evaluated for inclusion (such as gamma ray log, geolograph, etc).

(b) A summary report should be prepared to accompany the composite logs. This report should include:

(1) Statement of the purpose of the project, sources of funding, dates of operations and current status, accompanied by a location map showing <u>all</u> wells in the area, on a topographic base.

(2) Brief description of the geologic setting, with a geologic map on which wells are plotted.

(3) Summary of conditions found in each well, emphasizing conditions in which porosity may be present, and temperature conditions. (Refer to the composite logs).

(4) Comparison of rock units, temperature profiles, alteration zones, etc. between the three wells. Note any anomalies in correlation which might imply structural discontinuity. Support the text with small scale cross-section diagrams.

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(5) Utilize the data from these three holes, plus all available data from other wells in area, to define the selection of future SOH drillsites .

(6) Utilize the experience gained from these holes to refine operational and geological wellsite procedures in future drilling operations.

(7) Comment on the degree to which the project has meet its scientific goals.

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APPENDIX F

Recommendation for SOH and Geothermal Assessment Program

Memorandum

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MEMORANDUM

To:	Gerald O. Lesperance DBED, State of Hawaii Fax: (808) 586-2536	*Date:*	October 11, 1991
		Page:	1 of 5
From:	Murray C. Gardner		
Subject:	Recommendations for SOH and Geothermal Assessment Programs		

In 1988, the Hawaiian Program for Confirmation and Stimulation of Geothermal Resource Development listed three general goals:

1. identify subsurface target conditions;

2. emphasize subsurface truth, rather than collect basic scientific information; and

3. determine reservoir potential.

These goals still seem appropriate. There are, of course, basic scientific data that would help identify subsurface targets as well as improve calculations of reservoir potential. The program outlined below attempts to reach project goals within time and budget constraints. The requirements of the State (DLNR) to manage resource development, review the subzoning process and participate in environmental and regulatory programs are considered, as were supplemental funding sources, such as other State agencies and commercial operators:

1. SOH Holes (Program 2)

Four SOH wells were planned on the Big Island and two on Maui for program 1, but just three were drilled due to permitting constraints. Therefore, the drilling program is behind schedule. Program 2 should accomplish drilling and testing a minimum of four wells. Ideally those will be permitted for flow testing, but the principal goals can be accomplished by injection testing. Permeability can be determined; only the capability of a well to flow cannot be demonstrated directly by injection tests. Funds should be budgeted and reserved for drilling and testing four wells.

The SOH project team should examine property maps, make field inspections and select the locations of the four new holes. Data from the TRUE-mid-Pacific holes, which are no longer confidential, should be obtained by DLNR and examined before those sites westward of SOH-4 are finally selected. That environmental work for permitting which is exclusive of EIS work should be contracted and initiated.

2. <u>SOH Holes (Program 1): SOH Holes 1, 2 and 4</u>.

A. After review of core descriptions, limited intervals should be selected for further study and archiving. One hole may be selected for splitting and archiving against future scientific investigation, and the costs for this work assessed against the potential value.

Further study of the intervals selected, based on lithology and temperature, should include detailed structural analysis of fractures, dikes and veins, petrography and petrology, XRD, rock chemistry, fluid inclusion chemistry and physical properties (magnetic susceptibility, thermal conductivity) analysis.

By the selection process, the bulk of the core may be reduced by geological review to about 25 percent of the total available footage. About 30 percent of the footage drilled in the zones with temperatures above 400°F (<1,000′ in SOH-1; 1,500′ in SOH-2 and 1,500′ in SOH-4) and about 15 percent of the footage drilled in the zones with temperatures less than 400°F may be sufficient for the additional laboratory work.

The HNEI geologist and principal investigator should make the first selection of intervals using either SOH-2 or -4. The effectiveness of this technique can then be appraised before work on the other holes is begun. A standard practice is to work outward from inspection of central zones of hydrothermal alteration into unaltered rock and select intervals including the major mineralogic changes, and to additionally select a small number of typical, unaltered flows and make laboratory tests of margins and interiors.

The boundary between lava flows originating at Mauna Loa and those originating at Kilauea is of special interest, and the best estimates of the depth to this boundary zone for each SOH location should be made. From this, chemical/isotopic analyses should be made to relate to existing analyses of the rocks from the two sources.

B. Additional temperature and pressure runs should be made in the holes.

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SOH-2: The temperature in this hole has not been measured while fully equilibrated. Conditions downhole need to be inspected; temperature and pressure measurements should be made (as well as a spinner log during a short injection run if proper equipment is locally available.) It is not possible to isolate any parts of the slotted zone for injection at present. However, indications from the preliminary injection surveys are that in each of the SOH wells the injection loss is constrained to a single zone. Afterward, depending upon hole condition, a downhole chamber should be placed to monitor pressure during future production from other geothermal wells in the KERZ. Although SOH-2 is distant from production wells, baseline data collection should be instituted.

SOH-1, -4: Chambers should be installed in these holes to obtain pressure data; SOH-1 should be instrumented in advance of production by OESI; SOH-4 should be instrumented, if possible, well in advance of planned drilling and testing by TRUE. This data would be useful and it is advantageous to get it at a time when legal constraints may prevent use of the geophysical tools from the USGS truck and emplacement of geophysical monitoring devices.

3. Hydrogeochemistry and Hydrogeology

A. KERZ

The program of sampling water sources - shallow wells and springs - for analysis of major and trace elements and limited isotopes (H_2: H_3, O_{16}: O_{18}) should be organized and expedited. A schedule for sampling and data presentation should be established. The sampling should be completed by field measurements of temperatures, water levels and conductivity. Replication of sampling should be scheduled quarterly and data reports submitted to DBED and DLNR within six weeks of sampling runs. Suitable equipment for continuous measurement of selected water points should be purchased and installed. Results of this work should not await presentation at scientific meetings, in journals or by theses.

Some of this activity is clearly redundant with work planned by the USGS. If the legal constraint from the USGS is removed, negotiation for shared activity, funding, support of graduate student(s), etc., should proceed to relieve the State of some costs. Also, this work may relate to EIS studies and funding may devolve from agencies concerned with the EIS task. This work will be useful for assessment of the hydrology of the KERZ but there should be a clear understanding that different approaches need to be undertaken in modeling the groundwater system, the geothermal system and for contamination forecast.

B. Other Areas the Big Island

The many wells that have been drilled to supply new and old resort construction should be sampled for chemical analysis of major and trace elements, and measurements of temperature as part of island-wide assessment of hydrology. Owners and drilling contractors who control access should be solicited by DOH and/or DLNR to obtain cooperation from these parties. This action is of high priority both to obtain baseline data and to identify any new potentially significant geothermal resource areas before they become densely populated and unavailable for classification, exploration and possible development.

4. Surface Geophysical

A. KERZ

Gravity surveys should be started to complete, add detail and improve published surveys. The principal objective is to define the structure of the KERZ and map the high-density dike system in greater detail than topography and geology can provide. The "offset" of the Puulena gravity high should be tested by detailed traverses. The gravity station data can now be calibrated to the densities of rocks in the SOH wells and operator's wells. The gravity data should be modeled and tested against the subsurface truth before surveys are extended to other rift zones. The planning of station densities in other areas will depend upon usefulness of the model in the KERZ.

B. Other Areas of the Big Island

Gravity surveys should await the results of work in the KERZ, since the purpose is to prove exploration techniques and not a general geophysical survey program.

5. Modeling

Modeling of the deep geothermal system in the Puna District (KERZ) in a primary task for the operator(s). Professional reservoir engineering is normally conducted by operators and validated by an independent reservoir engineer (consultant) for financial institutions and/or government agencies. In the KERZ, the reservoir engineering by OESI, TRUE and others would be reported to DLNR.

One of the tasks presently assigned to GeothermEx by DBED under the technical advisory contract is to provide a conceptual hydrogeologic model of the geothermal system and volumetric estimates of the reserves within the boundary of the geothermal reservoir. This work has started.

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The present scope of work does not include numerical modeling (determination of initial state, simulation of heat transfer, fluid flow, thermodynamic behavior of the system based upon exploration drilling and production/injection data, forecast of reservoir and well behavior). DLNR may elect to separately hire staff to review the model or rely upon a consultant from industry or an institution. If a qualified reservoir engineer were hired by Hawaii to eventually make a numerical model and maintain it through field development, it would be a unique State in that respect. A reservoir engineer would find it difficult to work isolated from others in his/her discipline, especially without a significant background in handling field data from diverse geothermal reservoirs. The State will have to make this basic decision. In any event, it is premature from the data at hand to attempt to accomplish complete numerical modeling of the geothermal reservoir.

6. Acquisition of High-Temperature Downhole Logging Instruments

For use in existing and future SOH wells and possibly for renting to operators, the State should acquire a hoist and cable, with hydraulic controls, and downhole tools including: temperature, caliper, spinner, electrical and radioactive. If the USGS truck and its effective tools can be acquired, and the outmoded analog instrumentation completely gutted and replaced by modern, highly reliable, simple electronics, the State should do this. A system comprised of a computer to convert voltage, resistance and pulse information from down-hole instruments to digitized information is ideal. The circuity exists commercially and should not need to be reinvented. We understand that the refurbishment work has begun; we recommend expeditious completion and testing of the rebuilt logging truck.

It is not recommended that the State fund a development program for tools except for special circumstances. The USGS, LASL and experienced commercial companies have expended decades of work and considerable funds in this research and development effort with few significant successes.

The foregoing represent the principal exploration and scientific investigation techniques that are recommended at this time as part of the SOH program. In addition, the State should consider the usefulness of work associated with environmental and regulatory programs.

7. Other Geophysical Surveys

Certain geophysical work has not been discussed because the State is isolated by legal decree from access to USGS assistance and cooperation. This includes use of data from aeromagnetic and passive seismic surveys. An island-wide aeromagnetic survey and TDEM surveys would await reestablishment of the cooperative programs. At such time as coordinated programs can be negotiated and cost-shared, we consider that HVO seismicity data should be analyzed and possibly used for the location of drilling targets, and that it be coordinated with downhole passive seismic surveys. Also calibration of aeromagnetic data with magnetic susceptibility data from cores should await USGS assistance.

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MEMORANDUM

To:	Gerald O. Lesperance DBED, State of Hawaii Fax: (808) 586-2536	*Date:*	October 15, 1991
		Page:	1 of 2
From:	Murray C. Gardner		
Subject:	Recommendations for SOH and Geothermal Drilling Assessment Programs		

Events at the Technical Advisory Committee (TAC) meeting of October 14, 1991, demonstrated that there remain some serious differences of opinion about what investigations should be undertaken as part of the SOH-Geothermal Assessment Program. The discussions about the subject tasks recommended in my memorandum of October 11, 1991, on the same subject indicated that resolution of the principal issue, namely, what work will be selected at what costs, remains unresolved. I suggest that resolution of the problem be dependent upon the principal representatives of DBED and the SOH management convening to systematically approve a work program. A similar recommendation was made at the TAC meeting. I recommend that this management meeting, to include Drs. Olson and Thomas and DBED designee(s), be held within the next ten days. The objective should be accomplished in plenty of time to inform the TAC one week or more prior to its next scheduled meeting.

The essential conditions for success of the meeting of DBED-SOH is that the proponent(s) of the various investigations arrive with clear proposals. The proposals need be no longer than one page for each. Each proposal should include these minimum items:

1. Proposed work description.
2. Brief statement of hypothesis of the relevance of the work to SOH-Geothermal Assessment.
3. Identification of investigators, including staff as well as principal.
4. Tasks included in the scope of work.
5. Work schedule and date of completion.

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6. Deliverable products.

7. Budget, with line items for personnel, equipment and other costs.

If the proponents of some program(s) cannot prepare such a proposal, the work should be deferred or denied at this time. I think that each proposal should be judged on its merit and should have clear, intrinsic value for the overall SOH-Geothermal Assessment program. There should be total funding ceilings, including both for drilling of new SOH wells and for the group of ancillary geotechnical programs. However, proposals should not be accepted and funded to absorb part of some total available funding. We remain available to assist DBED with this work in anyway you may find useful.