The Use of Slim Hole Drilling Technology in the Hawaiian Scientific Observation Hole (SOH) Program: A Case History

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ABSTRACT

Prior to the initiation of the Scientific Observation Hole (SOH) program of July 1, 1988, the geothermal potential of the Kilauea East Rift Zone (KERZ) on the Island of Hawaii was assumed to be approximately 500 megawatts of electrical energy. To test this assumption, the Hawaii Natural Energy Institute (HNEI) proposed a plan to assess Hawaii's geothermal resource potential by core drilling small diameter observation holes along the KERZ and the Haleakala Southwest Rift Zone on Maui. The goals of the SOH program, as defined by the enabling legislation, were to assess Hawaii's geothermal resource potential and stimulate geothermal exploration by the private sector. Approvals for geothermal activities in Hawaii must be coordinated with the Department of Health's Office of Environmental Quality Control, the Department of Land and Natural Resources, and the Planning Commission of the County in which the activity is planned. Required public hearings were held and agency approvals coordinated to ensure that all necessary permits were issued.

To assess the geothermal potential of the KERZ, an array of four holes, three of which were drilled, were sited along the long axis of the KERZ within existing Geothermal Resource Subzones (GRS). These holes were drilled by Tonto Drilling Services, Inc. using a Universal 5000 core/rotary drilling rig. Two holes were spaced to provide step-out coverage between or beyond existing and planned geothermal production wells, and two holes were located with the intent of "pairing" the SOHs with production wells to test for permeability across the rift zone. Successful drilling techniques, casing procedures, and a mud program were devised as the geologic formation became known and its characteristics noted.

SOH-4 was the first hole drilled and it provided information regarding thermal and permeability conditions along the eastern portion of the Truemid-Pacific Geothermal Venture (TMPGV) lease. SOH-4 was drilled to a total depth of 2,000.1 m in 151 days at a direct drilling and testing cost of $1,466,848 ($733.39/m), and recorded a temperature of 306.1°C at a depth of 1050.7 m.

The second hole, SOH-1, effectively defined the northern extent of the Puna Geothermal Venture (PGV)/HGP-A geothermal reservoir, doubled the "proven" reservoir size, and provided valuable data to PGV's lending institution for continued project funding. SOH-1 was drilled to a total depth of 1,684.3 m in 217 days at a direct drilling and testing cost of $1,643,544 ($970.80/m), and recorded a bottom hole temperature of 206.1°C.

The third hole, SOH-2, was drilled to a total depth of 2,073.2 m in 126 days at a direct drilling and testing cost of $1,106,684 ($533.80/m), recorded a bottom hole temperature of 350°C, and may have intersected a potential reservoir at a depth of approximately 1,495 m .

BACKGROUND

Although considerable geothermal activity and hitter permitting confrontations took place on the Island of Hawaii during the middle 1970s and early 1980s, by 1988 when the Scientific Observation Hole (SOH) program was initiated, geothermal development was not a major topic of contention. Operations at the HGP-A plant received continuing, but rather minor, complaints regarding the spread of unsightly surface settling ponds for the expended brine, rusting surface facilities, and occasional, but increasingly common, venting of H_2S because of plant breakdowns and poor maintenance at the abatement facility.

Opposition to geothermal development began to rise when the SOH program was announced and initial public information meetings were held in the communities in which the SOHs were to be drilled. (Olson and Deymonaz, 1991). Also, as the permitting process was beginning, litigation involving the land exchange and religious rights issues was resolved in TMPGV's favor, and PGV was sold to a consortium with sufficient financing to actively pursue development. Shortly thereafter TMPGV mobilized a drill rig from the mainland, cleared a drill site and access road in the rain forest, and began preparations to commence work on the initial *25* MW facility of a proposed 100 MW development. PGV began efforts to complete its permitting for a 25 MW hybrid binary cycle generating facility for which it had an existing steam sales contact with HELCO, the local utility on the Island of Hawaii. In addition, HECO, the Oahu utility, at this time published a Request For Proposals for the development of 500 MW of geothermal energy on the Island of Hawaii to provide electricity to the islands of Maui, Hawaii, and Oahu via a deep underwater cable transmission line.

The residents of the Island of Hawaii were rather suddenly faced with the perceived prospect of massive energy development and industrialization of the largely rural community in the Puna District and began mobilizing opposition to this recognized threat to their existing easy-going lifestyle. The State and County institutions and regulators at this time were untrained and inexperienced with geothermal development and were poorly organized, staffed, and equipped to effectively deal with this opposition. Permitting for the SOH program took place in this rapidly evolving, increasingly confrontational, environment.

PERMITTING

In general, permitting for geothermal activities in Hawaii State and County must be approved by the following lead agencies:

DEPARTMENT OF HEALTH (DOH), OFFICE OF ENVIRON MENTAL QUALITY CONTROL -- evaluates the environmental sensitivity of the project and determines if an Environmental Assessment (EA) or an Environmental Impact Statement (EIS) will he required. As geothermal development in Hawaii is controversial, State regulators and politicians determined that an environmental study would be required. Consequently, the University of Hawaii submitted a determination that an EA would be sufficient, which probably was accepted because it was overlooked by the opposition and not contested. This oversight probably will not happen again, and, realistically, EISs will be required on any future projects.

DEPARTMENT OF LAND AND NATURAL DEVELOPMENT (DLNR) -- evaluates the technical aspects of the project and determines the technical conditions of the permit and land usage conditions on property classified as "conservationland." Although initial permitting required considerable time and education of the DLNR Board that reviewed the permit applications, permit conditions, although stringent, were essentially straight forward and reasonable.

COUNTY OF HAWAII PLANNING COMMISSION -- evaluates permit activities with regard to social impacts, land usage plans, zoning regulations, and other provisions and determines operational conditions on property classified as "residential and agricultural." County regulations provide for "Mediation", if requested, in the event that the permit application meets considerable opposition. As the SOH application hearings were contentious, one meeting was recessed until the police were called to provide security for the Commissioners who had been physically threatened by a member of the opposition and mediation was requested. Mediation was often heated, did not involve any concessions by the opposition, and was used by the opposition only to voice greater demands, to obtain further operational restrictions, and to harasses the project managers. A local driller, who was not selected in the bidding process, was able to require a drilling and casing plan more suitable to full-scale production wells then to scientific observation holes. The Geothermal Resource Permit application, when finally approved, contained three general and 26 specific conditions (1989). Although many of the conditions were straight forward and reasonable, the remaining conditions served only to increase the regulatory burden, to reduce operational flexibility, and to raise overall project costs, while detracting from the efficiency and safety of the project.

General permit conditions are as follows:

1) Geothermal development activities will not have unreasonable adverse health, environmental, or socioeconomic effects on surrounding residents or property, and
   - drill sites will not exceed approximately 1/4 acre in size;
   - ground water will be protected by casing to sea level;
   - sites will be relocated to avoid endangered species and archeological sites, and undesirable impacts;
   - geothermal emissions will not be vented to the atmosphere;
   - sites will be located to take advantage of natural conditions to minimize impacts on local residents; and
   - drilling sites will be designated as "hard hat" areas to which the general public is excluded.

2) Geothermal development activities will require no provisions from public agencies to provide roads and streets, sewers, water, drainage, or school enlargement or improvements, and only the normally afforded police and fire protection will be expected. Any necessary access roads will be constructed by the SOH program, and all drilling water will be purchased or supplied by the driller.

3) Environmental, noise, and H_2S monitoring will be conducted at all times during drilling operations and will comply with all federal, state, and local rules regarding environmental monitoring.

The Special Permit conditions were mostly straight forward and reasonable, causing little difficulty in compliance. However, several conditions imposed by the geothermal opposition limited the effectiveness of the program, increased costs, and served as the basis for continuing harassment during operations. In addition, these conditions produced "trip points," violation of which could have caused the program to be shut down.

The most onerous of the special conditions included:

A noise limitation of 55 dBA during daylight hours (defined as 7 a.m. to 7 p.m.) and 45 dBA during the night, measured at a residence "receptor." For practical purposes a "receptor" was defined as a sound monitor at a complaining neighbor. To provide for "spike" noises such as clanging of pipes or "revving" of the diesel motor while tripping the provision provided that guidelines could be exceeded by 10 dBA for not more than two minutes during any 20-minute period. Noise guidelines were not exceeded throughout the entire program, but were the cause of continual harassment as the opposition called in noise complaints every time rig noises could be heard in order to increase costs related to verifying the complaints, and to establish a record of noise complaints. At the rig, continual efforts were made to reduce noise impacts of any kind by aligning the rig to direct the broadcast of sound away from the neighbors most likely to be impacted, to construct noise barriers on and around the rig, and to reschedule or cancel high noise-emitting rig activities such as tripping or cementing to minimize noise impacts at night.

Limit large-vehicle traffic to daylight hours. This condition, at times, severely restricted drilling activities and increased costs. During nighttime rotary drilling at SOH-4, lack of water required shutting down the rig until water could be delivered in the morning. This problem was partially solved on subsequent SOHs by securing a local source of water that did not require haulage.

A provision that SOH-4 would be drilled first and a status report of drilling activities through the setting of the surface casing submitted to the Planning Commission for review to verify compliance of the initial drilling activities, prior to drilling below a depth of 200 feet at the next SOH site. This provision was imposed because the opposition convinced the Planning Commission that the drilling activities could not operate within the permit conditions, even though the Planning Director had the authority to suspend the drilling permit for non-compliance of the permit conditions. Although the status report was submitted to the Planning Commission after the casing was set, the Commission did not act on the report at a public meeting until after the rig had set up on the SOH-I site and drilled to a depth of *200* feet causing the rig to be shut down for a period of nearly a week and incurring down-time charges of approximately $30,000.

SOH PROGRAM

The Hawaii Natural Energy Institute (HNEI) successfully drilled three SOHs between December 1989 and May 1991 to assess and characterize the geothermal resources potential along a portion of KERZ in an area composed of rain forest, small farms, and scattered residences in several loosely organized communities located in the environmentally sensitive and developmentally opposed Puna District of the Island of Hawaii. The program was able to be completed because great care was taken to select drill sites that were as unobstrusive as possible and a drill rig as small and quiet as possible while still having the capability to drill to the targeted depths. Great care was also taken to select a drilling company with a record of environmental sensitivity and compliance and a highly competent staff of drillers and supervisors who were instructed as to the environmental sensitivity of the program and the need for caution and common sense in the drilling practices. The rig was further modified prior to mobilization to the project site to reduce operational noise, and at each site noise surveys were taken so that noise buffers could be strategically located to reduce noise impacts to a minimum.

Nevertheless, even with a record of program accomplishments while successfully meeting the permit conditions, future programs probably will be more difficult to fund and permit, because of the intense opposition to geothermal development by the vocal minority. Although this opposition is carried under the guise of public safety, the environment, and native Hawaiian rights and religion, the real issues are "not in my backyard" (NIMBY), "locally unpopular land usage" (LULU), and, more importantly, social and political control. The case for energy development in Hawaii has passed beyond the realm of science and fact and is now being argued in terms of perception and politics, and unfortunately sufficient techniques of opposition are now sophisticated enough and the democratic process subverted to the point that most projects can be stopped even though the project is permitted and in compliance with all conditions. Although geothermal developments on the Island of Hawaii have been successfully operated, further development of Hawaii's most abundant indigenous natural energy resource may have to wait until radical changes are made to the present political and regulatory environment.

The SOH program was planned and implemented by HNEI, a division of the School of Ocean and Earth Science and Technology, at the University of Hawaii at Manoa to provide an assessment of the geothermal potential of the KERZ on the Island of Hawaii and the Haleakala Southwest Rift Zone (HSRZ) on the island of Maui within existing GRSs. The SOH program was initially funded to drill six SOHs to a nominal depth of 1,200m **(4,000** ft). four on the Island of Hawaii and two on Maui, to "confirm and stimulate the geothermal resources development in Hawaii." Initial attempts to permit the two SOHs on the island of Maui, however, met with such intense local opposition that the two holes scheduled to be drilled in the HSRZ were withdrawn from further consideration (Olson et al., 1990, Olson and Deymonaz, 1992a). Figure 1 shows the location of the volcanic features, the KERZ, and areas with geothermal potential on Maui and Hawaii. The location of the SOHs, the GRSs, as well as the production wells drilled by PGV and T/MPGV along the KERZ are shown on Figure 2.

Prior to the initiation of the SOH program, preliminary geothermal surface exploration was completed during the work that resulted in the Geothermal Resources of Hawaii Map, (Thomas, et al., 1983). Active volcanoes and obvious geothermal heat sources were known, rift zones were identified and mapped, and areas of geothermal potential defined. Parts of the KERZ had been studied by mapping surface geology and by surface geophysical and geochemical surveys. The immediate area at and surrounding the State of Hawaii HGP-A, 3-MW demonstration electrical power plant had been tested by seven production size geothermal wells. Of these, the HGP-A

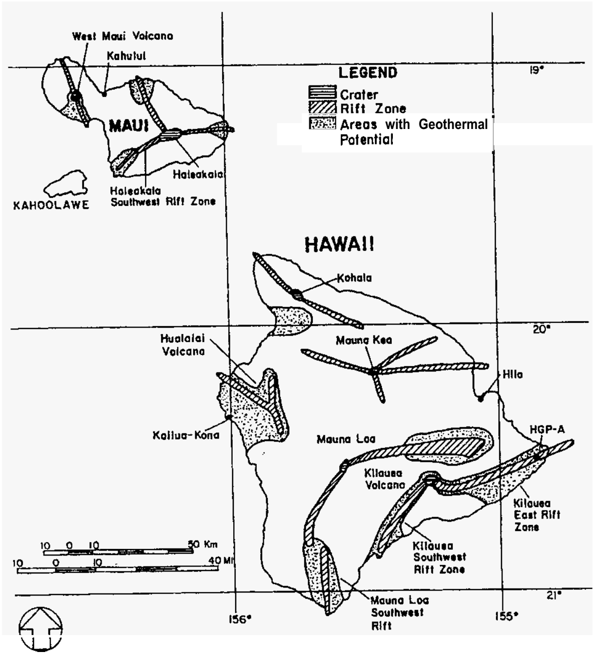

FIGURE 1. Volcanic Features and Areas with Geothermal Potential on Maui and Hawaii. After Thomas, et al., 1983.

well had produced at a rate of about 2.5 MW for approximately six years, and three wells had intersected an economically viable reservoir but had not been adequately flow tested. These three wells could not be produced because of casing damage. Two wells were hot but dry and were shut in without undergoing extensive flow testing. The remaining well intersected a meteoric recharge zone, and, although potentially productive, was not thought to have sufficient temperature for electrical generation. Surface geochemical and geophysical exploration surveys gave results which could not be interpreted to define subsurface drilling targets. Temperature surveys of the exploration wells indicated that shallow temperature gradient holes drilled to <600 m (2,000 ft) could not define drilling targets, and because the cap rock above the reservoir in the HGP-A area was at a depth of about 900 m (3,500 ft), drilling to a depth of approximately 1,200 m (4,000 ft) would be needed to identify other potential reservoirs in the area. The State of Hawaii, however, was interested in quickly assessing the geothermal potential of the KERZ, and so it was determined that the assessment could be accomplished most economically and efficiently by drilling a number of deep, scientific observation holes to a nominal depth of 1,200 m (4,000 ft) within the known resource areas along the KERZ.

As the SOH drilling program expected to meet with considerable environmental and community opposition during the permitting process, a primary consideration in designing the project was to minimize the environmental and sociological impact. This objective was achieved by selecting equipment and drilling techniques requiring only a limited work area (less than 1/3 acre), and, that would be as quiet as possible, would have low water consumption, would not require a high volume of heavy truck traffic, and would be conducted in a professionally safe manner with as little impact on the neighboring community as possible. Prior to selecting the sites, several aerial reconnaissances of the KERZ were made to obtain a feel for the regional geology, topography, existing road network, vegetation, and use patterns, and to determine the location of residences and possible access roads. Possible drill site locations then were carefully selected, based on results of prior work in the area, and checked on the ground to eliminate the need for new road construction, to reduce environmental impacts, to maintain as much distance as possible from residences, and to use the natural terrain to reduce the visual and audible impact on the community. State regulations and land zoning restricted drilling to existing GRSs. During the public permit hearings extremely restrictive conditions were placed on noise, fluid emissions, and operating activities, and pumping or flow testing of ground water and reservoir fluids was prohibited. Bailing adequate fluid samples from the SOHs was not effective, and because of the operating restrictions it was not possible to collect uncontaminated water or reservoir samples, (Olson and Deymonaz, 1992b).

Tonto Drilling Services Inc. of Salt Lake City, Utah was chosen as the drilling contractor for the SOH program. Tonto provided a crew experienced in geothermal core drilling and a Universal 5000 core/rotary drilling rig, which was uniquely suited to the drilling conditions encountered during the program. The rig weighs approximately 42,900 kg (94,600 lb), and is mounted on a 3-axle trailer. The rig was extensively modified for geothermal work and to meet the stringent noise level limitations mandated by the county of Hawaii. A self-elevating jack-up system permits raising the rig and placing a 3.2 m (10.5 ft) high substructure under the mast. The substructure carries the weight associated with drilling, serves as a working floor, and permits the above ground installation of blow-out prevention equipment (BOPE).

Depth rating of the Universal 5000 depends on the size of the drill rods used, drilling conditions, and other factors. For NQ drill rods, which were used to complete the SOHs, the theoretical maximum depth is over 5,180 m (17,000 ft). Hole size drilled with an NQ bit is 75.7 mm (2.98 in) in diameter.

SOH DRILLING RESULTS

Because of the parallel fracturing and diking along the KERZ, permeability, initially, was assumed to exist along the axis of the rift. Cross-rift permeability was basically unknown and untested and was thought to be restricted to areas of cross fracturing or related to structures, such as subsurface plugs or buried volcanic necks, that could cause local fracturing across the rifts.

To most efficiently assess the KERZ, the SOH drill sites were laid out in a fence along the KERZ. Two of the SOHs were step-outs at a distance from any previous drilling to assess untested segments of the rift, and two of the SOHs were "paired" with existing or planned production wells to test cross-rift permeability conditions. The SOH program also was designed to be more practical, or applied, rather than scientific or academic, and attempted to emphasize the drilling of as many holes and as much footage and ground truth as possible, rather than the collection of basic scientific information. In addition, an attempt was made to obtain indications of reservoir potential by injection tests after the well had been drilled by calculating possible flow from a production-sized well at the same site from the measured downhole temperature, and the pressure required to pump a known volume of water down the hole during injection.

Despite continuous opposition from well organized and funded special interest groups, the SOH program was highly successful and met the University of Hawaii's stated mission to provide scientific information and technology transfer to the private sector for utilization and commercialization and to stimulate private development of Hawaii's geothermal resources. Although all the necessary permits were approved for the fourth hole, SOH-3, the State of Hawaii decided to defer the drilling of SOB-3 because of political pressures and funding shortages, and to apply for additional SOHs at a later date when the SOHs could be permitted with amended provisions to allow pumping or flow testing of the holes to obtain fluid groundwater and reservoir samples.

Drilling problems were anticipated because of possible high temperatures, and much thought was given to designing a mud program capable of operating in these austere conditions. A satisfactory program was designed as the program progressed with minimum experimentation, and successful drilling techniques, casing procedures, and drilling fluids mixtures were devised as the rock section became known and its characteristics noted. At relatively shallow drilling depths, above 600 m (2,000 ft) at temperatures usually below 100°C (212°F) thin mixtures of bentonite and polymer, with thicker mixtures of mud and loss circulation material **(LCM)** or cement or both in loss circulation zones, provided satisfactory drilling results. At temperatures above 130°C (270°F) a complex stearate was added to the drilling fluids to maintain lubricity. Above 165°C (330°F) a mixture of soda ash, high temperature polymer, complex stearate, and sepiolite virtually eliminated high torque and vibration problems frequently associated with high temperature drilling. This mixture gave satisfactory results in temperatures as high as 350°C (662°F).

SOH-4

The first hole, SOH-4, was drilled to a total depth of 2,000.1 m (6,562 ft) and recorded a bottom hole temperature of 306.1°C (583°F). Although evidence of fossil reservoir conditions were found, no zones with obvious reservoir permeability were encountered. No problems were encountered in core drilling the upper section of subaerial basalt flows and dikes; however, severe rotary drilling problems with lost circulation and reaming were encountered in the upper 610 m (2,000 ft) of the hole, resulting in large drilling cost overruns.

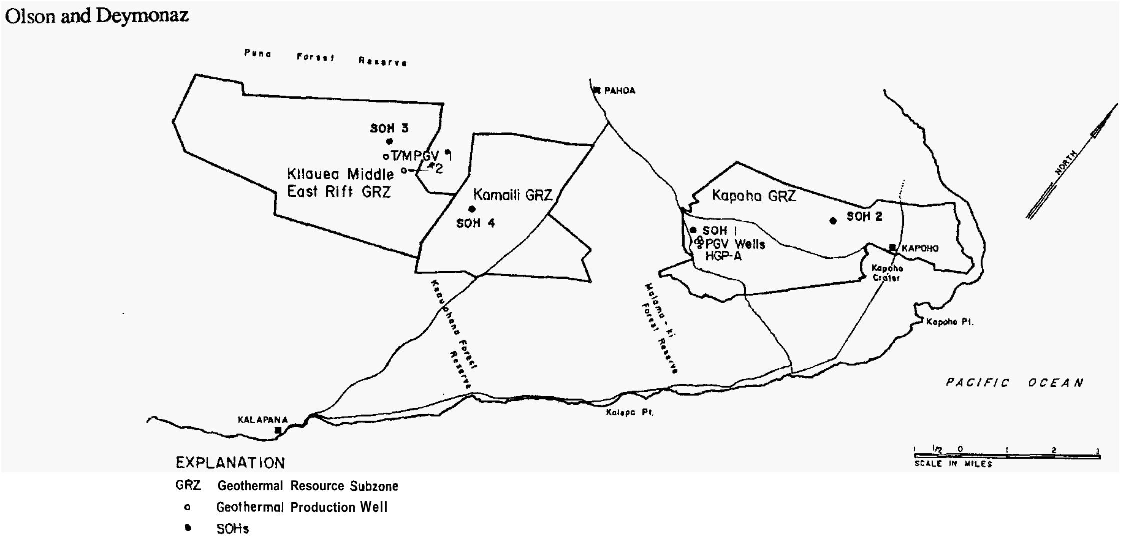

FIGURE 2. Location of the Geothermal Resource Subzones, Production Wells, and the SOHs on the Island of Hawaii.

The initial drilling and casing plan called for opening the core hole to 17-1/2 in in diameter to a depth of 30.5 m (100 ft) and cementing 13-3/8-in casing to the bottom of the hole. This was accomplished by drilling with an 8-1/2-in bit to open the hole, followed by a 12-1/4411bit, and finally with a 17-1/2-in bit, because the drill rig did not have sufficient torque to open the hole to full width in one pass. Each time circulation was lost, drilling stopped and circulation was regained with high viscosity mud and LCM, and the casing was set without trouble. The hole was then cored to a depth of 306.9 m (1,007 ft). This interval was then opened to a diameter of 12-1/4 in by first drilling with an 8-1/2-in bit followed by a 12-1/4411bit. This interval encountered multiple lost circulation zones which were plugged by high viscosity mud and LCM or with LCM and cement. Upon opening the hole to 12-1/4 in, however, circulation was usually lost at the same intervals as encountered with the 8-1/2411bit, resulting in much lost time cementing and waiting for cement to dry. It was soon discovered that the rig had sufficient torque to open the hole to 12-1/4 in in one pass, and that the hole would stay open after loosing circulation for an additional 45 to 90 m (150 to 300 ft) by drilling slowly ahead and conditioning the hole carefully. Subsequently the hole was opened, and the 9-5/8-in casing set and cemented in this manner. The hole was then cored to a depth of 609.6 m (2,000 ft) and then opened to 8-1/2 in by slowly and carefully drilling blind through lost circulation zones instead of cementing whenever circulation was lost and by using thin cement mixtures to regain circulation. The 7-in surface casing was then set and cemented, and core drilling proceeded with only minor problems to the bottom of the hole in a heated section of submarine basalts. Figure 3 shows the drilling/casing plan used for SOH-4.

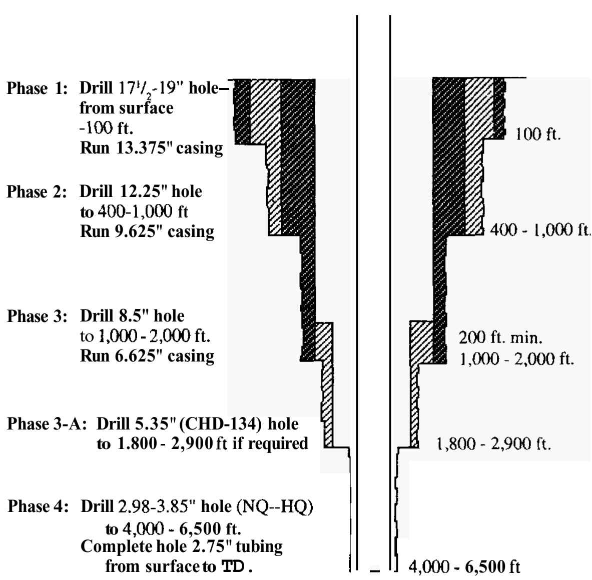

FIGURE 3. SOH-4 Casing Plan

At a depth of approximately 1,220 m (4,000 ft), state officials approved the deepening of the hole to a depth of approximately 2,000 m (6,500 ft) because temperatures of 200°C (400°F) or higher had not been recorded during drilling. At this time, the other scheduled SOHs also were targeted to depths of approximately 1,825 to 2,000 m (6,000 to 6,500 ft). Total direct drilling costs for SOH-4 were $1,466,848, ($733.39/m, $223.54 /ft).

As a rule, core drilling costs, usually expressed as footage charges, tend to increase with depth, even if hole size is reduced, resulting in lower bit costs, because of increased trip time for core recovery and bit changes, and for other problems such as increased risk of twist-offs associated with depth. Drilling performance is shown graphically for depth versus cost for all the SOHs in Figure 4 and for depth versus time for all the SOHs in Figure **5**. The temperature gradient of SOH-4 and the other SOHs is shown in Figure 6. The drilling activity cost summary for SOH-4 and the other SOHs is shown on Figure 7.

Interestingly enough, SOH-4 was initially considered to be a "failure" by state officials because (1) the bottom hole temperature was not as high as the 358°C (676°F) encountered in the state HGP-A well, (2) the large cost overrun, as compared to the cost estimated for the original 1,200 m (4,000 ft) depth planned for the hole, and (3) the hole did not encounter a reservoir. This misunderstanding on the part of the state officials resulted in renewed efforts to educate the officials to the realities of drilling economics, programmatic goals, and expected results.

SOH-1

The second hole, SOH-1, was drilled to a total depth of 1,684.3 m (5,526 ft) and recorded a bottom hole temperature of 206.1°C (403°F). The drilling and casing plan for the upper 610 m (2,000 ft) was modified, utilizing the experience gained in the drilling of SOH-4, by omitting the 13-3/8 in and the lower 305 m of 9-5/8-in casing, and using 7-in casing from the surface to a depth of 610 m (2,000 ft). Figure 8 shows the revised drilling/casing plan used in drilling SOH-1 and SOH-2. The revised drillinglcasing plan resulted in rapid progress with only infrequent and minor drilling problems and a cost savings of approximately $240,000 as compared to SOH-4 at a similar depth. When coring resumed below the casing, however, very severe drilling problems were encountered because of highly fractured, cool (<38°C or <100°F) submarine basalt, sands, and dikes, in the interval between 610 and 1,370 m (2,000 to 4,500 ft), resulting in short bit life, short (15 to 45 cm or 6 to 18 in) core runs, stuck drill rods and massive cost and time overruns. The fractured submarine basalt and dikes broke off during drilling into small fragments around and in front of the bit. The rock fragments rolled around the drilling surfaces, wearing the bit face matrix and gouging out the diamonds. The exterior gauge of the bits was reduced and the interior gauge enlarged, resulting in short core runs which were caused by sticking drill rods, and rock stuck in the core barrel. Thus it was necessary to redrill frequently to reach bottom. Bit life averaged between 3 and 6 m (10 to 20 ft), and resulted in constant tripping of the rods to replace bits. Below 1,370 meters (4,500 feet) the temperature increased rapidly, resulting in normal drilling runs, core recovery of nearly 100%, and long bit life, as a

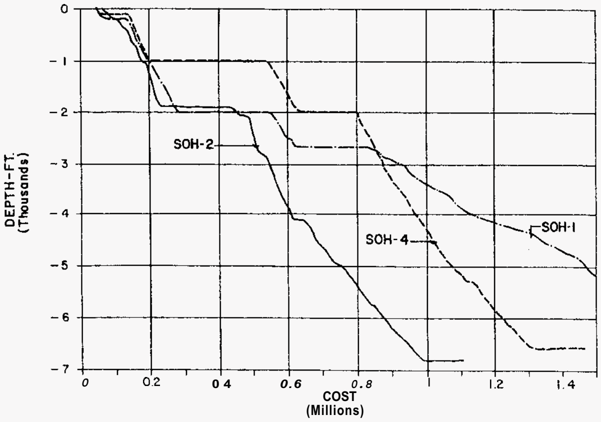

FIGURE 4. SOH Drilling performance, Depth vs. Cost.

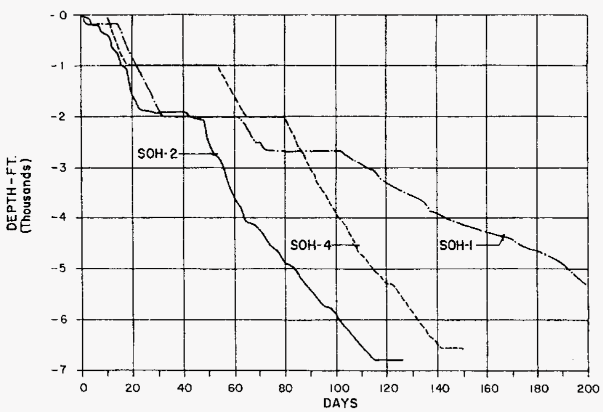

FIGURE 5. SOH Drilling Performance, Depth vs. Time.

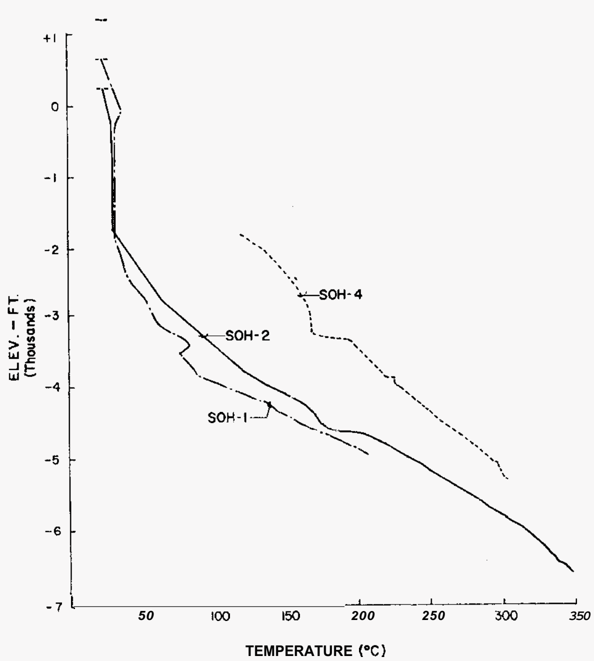

FIGURE 6. SOH Temperature vs. Elevation.

SOH Drilling Activity Cost Summary

SOH-4 Activity		Cost ($)
Site construction. MOB & Setup		42,297
Core 101mm (0-112 ft) in Type II		13,703
Open hole to 17-1/2" (0-112 ft)		53,847
Casing (13-3/8" 0-112 ft) cmt/rig BOPE		31,886
Core 101mm (112-1,008 ft) in Type II		65,930
Open hole to 12-1/4" (112-992 ft)		283,609
Casing (9-5/8" 0-992 ft) cmt/rig BOPE		53,617
Core 101mm (1,008-2,000 ft) in Type II		89,452
Open hole to 8-1/2" (992-2,000 ft)		78,311
Casing (7" 0-2,000 ft) cmt/rig BOPE		82,249
Core HQ (2,000-5,290 ft) in Type II		326,956
Core NQ (5,290-6,562 ftj in Type II		205,311
Completion & testing		139,680
Total	$1,466,848	$733.39/m
SOH-I Activity		
Site construction, MOB & Setup		42,916
Core, open to 12-1/4" (0-202 ft)		35,129
Casing (9-5/8" 0-202 ft) cmt/rig BOPE		31,843
Delay, County of Hawaii permits		29,061
Core 101mm (202-1,995 ft) in Type II		136,457
Open hole to 8-1/2" (0-1,996 ft)		175,593
Casing (7" 0-1,996 ft) cmt & rig BOPE		93,149
Core 101mm (1,996-2,671 ft) in Type II		84,463
Fish, ream over stuck drl rods & open hole to 5-5/8" (1,996-2,671 ft)		201,709
Core 134mm (2,671-3,022 ft) in Type I		73,047
Casing (4-1/2" 0-3,022 ft) & spot cmt		23,026
Core HQ (3,022-4,325 ft) in Type I		360,154
Core NQ (4,325-4,880 ft) in Type I		165,440
Core NQ (4,880-5,526 ft) in Type II		93,549
Completion & testing		98,008
Total	$1,643,544	$975.80/m
SOH-2 Activity		
Site construction, MOB & Setup		66,170
Drl 12-1/4" hole (0-202 ft)		35,192
Casing (9-5/8" 0-202 ft) cmt/rig BOPE		18,548
Drl 8-1/2" hole (202-1.904 ft)		227,442
Casing (7" 0-1,896 ft) cmt/rig BOPE		98,555
Core HQ (1,909-2,044 ft) in Type I Rx		27,997
Rotary 5-7/8" hole (2,044-2,785 ft)		51.062
Core HQ (2,785-2,830 ft) in Type I Rx		18,261
Rotary 5-7/8" hole (2,830-4,103 ft)		89,978
Casing (4-1/2" 0-3,022 ft) uncemented		22,733
Core HQ (4,103-4,988 ft) in Type II Rx		97,760
Core NQ (4,988-6,802 ft) in Type II Rx		243,716
Completion & testing		109,259
Total	$1,106,684	$533.80/m

FIGURE 7. SOH Drilling Activity Cost Summary.

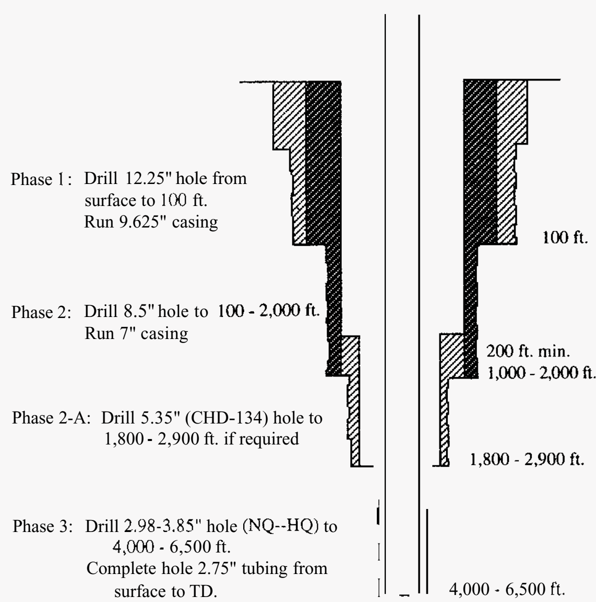

FIGURE 8. SOH-1 and SOH-2 Revised Casing Plan.

result of fracture filling or bonding of the fractures by thermal metamorphism.

The volcanic rocks encountered during drilling were classilied to reflect their drilling characteristics. Submarine basalts above the zone of thermal alteration are extremely difficult to core drill and neither time nor cost effective. Rotary drilling in this section, however, does not pose any significant difficulties except for loss of drilling fluids and minor stability problems. These rocks were classified as Type I. Subaerial basalts could be efficiently core drilled and opened to larger diameters by rotary drilling methods and rotary drilled with a single pass. Submarine basalts, which exhibited extensive thermal alteration resulting in loss of permeability, also could be core or rotary drilled with few problems. These rocks were classified as Type II.

Total drilling costs for SOH-1 were extremely high at $1,643,544 ($975.80 /m, $297.42/ft), which caused the hole to be stopped approximately 300 m (975 ft) short of its targeted depth.

SOH-2

The third hole, SOH-2, was drilled to a total depth of 2,073.2 m (6,802 ft) and recorded a bottom hole temperature of 350.5°C (663°F). The drilling plan was again modified to incorporate the lessons learned in the drilling of the first two holes. To reduce drilling costs, the upper 580 m (1,900 ft) of the SOH was rotary drilled with no coring. Casing was set approximately 30 m (100 ft) higher in SOH-2 than in the other two SOHs because of a sudden 4° deviation in the hole in an 8.2 m (27 ft) interval at a depth of 567 to 575 m (1,860 to 1,887 ft), which resulted in several drill collar twist-offs and fishing jobs. After the casing was set, coring encountered difficult, time consuming, and expensive drilling conditions similar to those encountered in SOH-1.

At that time a decision was made not to attempt to fight the hole down by coring, but to rotary drill to a depth of approximately 1,250 m (4,100 ft). As circulation was lost at the surface, only a few scattered rock samples were collected in the upper rotary portion of the hole; however, the dogleg caused by the sudden hole deviation, persisted through the casing, and drilling continued to be plagued by repeated twist-offs to the bottom of the hole. Luckily all the twist offs occurred inside the casing and fishing, although time consuming and costly, did not result in major delays or loss of the hole. Temperature at a depth of 1,250 m (4,100 ft) was 132.7°C (270.9°F) which was sufficient to bond the fractured submarine basalts (or the section previously had been subjected to high temperatures with the same results), and coring proceeded rapidly and smoothly to the bottom of the hole. Subsequent injection testing indicated that a permeable interval between 1,488.3 and 1,505.7 m (4,883 to 4,940 ft) with a temperature of 210.3°C (410.5°F) can be designated as a possible "discovery." Additional drilling in the vicinity of SOH-2 possibly could intersect fracture permeability below a depth of 1,825 m (6,000 ft) with fluid temperatures in excess of 300°C (572°F).

Total drilling costs for SOH-2 were $1,106,684 ($533.80/m, $162.70/ft), which represents a savings of greater than $300,000 while drilling 73 m (240 ft) deeper than SOH-4, and greater than $460,000 while drilling 389 meters (1,276 ft) deeper than SOH-1.

SOH PROGRAM RESULTS

Results from SOH program indicate that:

- Core (slim) holes can be successfully drilled to depths in excess of 2,070 m (6,800 ft) and can be used to assess geothermal resource potential at substantial savings in drilling and permitting costs and environmental impact. Initial drilling results indicate that SOHs in Hawaii can be most efficiently drilled by a combination of rotary and core drilling techniques.

- Analysis of the drilling results indicates that the key to reducing costs involves more than just drilling faster. Over the long run, staying out of trouble usually results in faster penetration rates and lower drilling costs. Consequently, after the experience with the twist-offs in SOH-2, a decision was made to core-drill future, cool, unmetamorphosed, subaerial basalts and then to open the hole by rotary drilling, which will probably result in a straight hole and more data, rather than to attempt to reduce costs by not coring and running the risk of twist-offs and possible loss of the hole.

- It was not possible to collect uncontaminated ground water or reservoir fluids in the SOHs in a cost effective manner by bailing. To obtain reliable fluid samples the holes must either be pumped or flowed. As ground water and reservoir fluid chemistry is vital to the assessment of the geothermal potential of an area, future SOHs must be permitted to allow the sampling of downhole fluids by pumping or flowing. Wellhead abatement equipment will probably be required to reduce possible noise and H_2S emissions.

- The geothermal potential of the KERZ has not been proven, and additional production and assessment drilling must be completed before a reasonable estimate of the size and characteristics of the resource can be made.

- Although high temperatures probably are continuous along the KERZ, a single large geothermal reservoir (or several relatively large reservoirs) probably does not exist within the KERZ. The geology of the geothermal reservoirs that do exist probably will be highly complex, and the reservoirs may be relatively small and discontinuous.

- SOH-I essentially defines the northern boundary of the HGP-A/PGV reservoir, which has produced between 2 and 3 MW of electrical power with a plant factor of greater than 90% for over 7-1/2 years. Utilizing published data from HGP-A, the KS wells drilled by Thermal Power in the early 1980s, and SOH-I, reservoir conditions at a depth of 1,250 m (4,100 ft) and a cutoff boundary of 200°C (392°F) indicate a narrow, easterly dipping resource approximately 800 m (2,600 ft) wide that is open to the west.

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