HAWAII GEOTHERMAL

DRILLING GUIDE

Circular C 126

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State of Hawaii
DEPARTMENT OF LAND AND NATURAL RESOURCES
Division of Water and Land Development
Honolulu, Hawaii

January 1994

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ACKNOWLEDGEMENT

This document was prepared by R. A. Patterson & Associates, Kailua. Hawaii, for the Hawaii Department of Land and Natural Resources under Contract Agreement No. RCUH P. O. 4361021. The work was performed by **Ralph A. Patterson, William L. D'Olier, and Herbert E. Wheeler**. We wish to gratefully acknowledge the assistance of the staff of the Division of Water and Land Development, under the direction of **Manabu Tagomori**, and of the invaluable suggestions and assistance of all those who discussed the project with us.

Development of this Guide would not have been possible without the willing cooperation of many managers, technicians and professionals in the geothermal industry, various laboratories and academic institutions, and in other areas where their knowledge was helpful in presenting the review and recommendations of the Guide. The authors wish to acknowledge their help and candor, and their accumulated knowledge that has made our job easier.

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PREFACE

The drilling and completion of safe and effective geothermal wells in Hawaii is of vital importance for geothermal operators, drilling contractors, state and county regulators, and the general public. Improper drilling procedures can be costly and dangerous, may have a negative impact on surface and subsurface environments, cause resource waste, and develop unfavorable public perceptions of geothermal activity. These concerns are powerful incentives to operators and regulators to utilize all possible sources of information on the unique aspects of Hawaiian geothermal drilling.

This Hawaii Geothermal Drilling Guide has been prepared as a summary and ready reference for the key concerns and requirements that must be addressed for every geothermal well proposed.

This Guide should also encourage an informed flexibility in geothermal drilling practices, and to supplement State and County regulations, especially those pertaining directly to drilling permits and operations,[1]

This first Guide will be a likely candidate for revision as more drilling experience and information is gathered in the exploration and development of Hawaii's geothermal resources. The proven higher costs and uncertainties in Hawaiian geothermal drilling operations are sound reasons to make an extraordinary investment in well planning. Detailed planning is a must for each and every type of well because of the paucity of subsurface information and the small base of drilling experience to date.

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[1] Department of Land and Natural Resources (DLNR) Title 13, Subtitle 7. Water and Land Development; Chapter 183.

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SUMMARY

The Hawaii Geothermal Drilling Guide is a contribution by the Department of Land and Natural Resources (DLNR) toward the attainment of a safe, reliable and productive utilization of the geothermal resources in the State of Hawaii. It is expected that such utilization will be carried out by qualified private parties at their own costs and risks, that it will be beneficial to public interests, not abusive of the environment, and will contribute revenue to the State from leases and geothermal production royalties.

The first requirement to establish any geothermal energy asset in Hawaii is to achieve a successful practice of geothermal drilling operations in the dynamic, high temperature volcanic systems unique to the State. The DLNR regulates geothermal drilling operations with the intent that they will be both safe and successful.

Following a brief introduction and geothermal historical summary, the Guide presents well permitting and general requirements for drilling Operators. A description of the geothermal drilling environment in the volcanic rift zones reveals the need for a thorough process of detailed geothermal well planning. The Guide then treats the important drilling and casing program, which is critical for DLNR approval of the Geothermal Well Drilling Permit for each proposed well. Drilling monitoring procedures are discussed for the actual drilling to expected depths in the range of 4,000 to 10,000 feet. Well completion concepts are cited and a detailed process for geothermal well flow testing is presented. Finally, comments on drilling documentation and reporting, and on the slimhole drilling option, are included.

The DLNR presents this Drilling Guide as a supplement to existing drilling regulations, as cited in the Preface. Working jointly with the Operators, DLNR will support a continuous improvement in Hawaiian geothermal drilling operations.

I. INTRODUCTION

A joint effort between State. County and private industry continues to work toward the goal of safe and reliable utilization of geothermal electric power for Hawaii County. The drilling required to find and produce the geothermal energy is confronted by an active volcanic rift zone and by a respectable community opposition. With such challenges. it is clear that Hawaiian geothermal drilling requires detailed consideration, careful preparation and skilled execution. To those ends, this Guide is dedicated as a supplement to the State of Hawaii geothermal regulations.

It is of great concern to the authors of this Guide that each drilling party, hereafter identified as the "Operator", be successful in their Hawaii geothermal drilling operations. We believe that this success will be clearly related to reduced drilling time and costs, improved operational safety, reduction of accidents, and finally, increased well productivity and reliability. In Hawaii, adequate funding and strong technical competence are essential in geothermal drilling. However, every Operator will need to demonstrate extra measures of dedication, initiative and responsibility to be recognized as successful by the public and the regulators. The success of all Operators will eventually be a measure of the contribution of this Drilling Guide.

Certainly the key player from the developer side in this partnership is the "Operator." In a geothermal drilling context, an "Operator" can be defined as "any person (*a United States citizen of legal age, association of citizens, firms or corporations organized under the laws of the United States, any state or the District of Columbia and qualified to do business in the state, including any governmental unit, trust or estate.*) engaged in drilling, maintaining, operating, producing or having control or management of any geothermal well, or the development of geothermal resources. The Operator may be the landowner, the lessee, designated Operator, or agent of the lessee or holder of rights under a DLNR approved operating agreement" [1].

OBJECTIVES OF THE GUIDE

This Drilling Guide attempts to present a broad, yet complete discussion of Hawaii geothermal drilling practices and problems, as recognized from cumulative knowledge and experiences gained from 1975 through early 1993. It was not considered appropriate to attempt a comprehensive treatise on geothermal drilling that would approach Hawaiian issues in some disconnected sequence. Several comprehensive and recent publications on drilling technology, as practiced in the petroleum and geothermal industries, are cited in the Reference Appendix to this Guide. However, geothermal drilling operations are constantly evolving and improving worldwide; Hawaiian geothermal drilling will continue to evolve and improve as drilling techniques and technology change.

The objectives of the Guide are focused on Hawaii, and include the following:

1. Promote safety and proficiency in all geothermal drilling operations.
2. Assist drilling Operators, government regulators and the public to better understand geothermal drilling practices appropriate to the Hawaii resource. Sound practices elsewhere may be of marginal use in Hawaii.
3. Facilitate better discussions between Operators and regulators when subsurface conditions encountered require a change in the approved drilling program.
4. Promote conservation of all resources during geothermal drilling operations.
5. Lower the profile of geothermal drilling and its environmental intrusions, consistent with safety. Drilling operations can become an acceptable neighbor.

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[1] Department of Land and Natural Resources (DLNR) Title 13, Subtitle 7. Water and Land Development; Chapter 183.

GEOTHERMAL HISTORICAL SUMMARY

The most prospective area of Hawaii County for geothermal resources is the Kilauea East Rift Zone (KERZ). This is the only area in the entire state subjected to geothermal drilling operations as of early 1993. However, this historical summary properly opens with the 1881 visit of King David Kalakaua, the monarch of Hawaii, to Thomas Edison in New York. The King, seeing Edison's electric lamp, generator and boiler, immediately realized that Kilauea could power electric lamps in Hawaii. The King did not recognize the requirement for wells, rather he thought to set the boilers in Kilauea's hot lava throat. However, it is extraordinary that the essential concept of geothermal electric power was grasped by the King of Hawaii over 100 years ago.

Geothermal drilling in the KERZ commenced in 1961 when Hawaii Thermal Power Company, associated with Magma Power Company, drilled four shallow wells with a cable tool rig. The holes were located very close to the lava fissure vents that erupted in 1955, south of the town of Pahoa. These wells encountered high temperatures and some hot groundwater; however, none were judged to be of commercial interest and all were abandoned.

In 1975, following an extensive geophysical survey of the lower KERZ, the University of Hawaii, with federal, state and county funds, drilled the HGP-A well just south of Puu Honuaula, the initial vent site of the 1955 eruption, on the crest of the rift. The HGP-A well was drilled with a rotary rig and completed in 1976 to a depth of 6,450 feet. A bottom hole temperature of 676°F and a total mass flow of approximately 110,000 pounds per hour (50% steam) were recorded. Subsequently, in the 1982-1990 interval, this one well drove a 3 megawatt (MW) demonstration plant without any significant change in flowing pressure or steam fraction. All subsequent drilling in the KERZ is presented in Table IV-1, following page 12.

Consequent drilling on the Kapoho-State lease, immediately northeast of the HGP-A well, has prompted the construction of a 30 MW binary power plant. Rotary drilling operators are continuing, early in 1993, to provide a sufficient steam supply to this plant.

II. PERMITTING HAWAII GEOTHERMAL WELLS

INTRODUCTION

The permitting process for geothermal developments in Hawaii has been developed over a relatively short period of time, with few chances to test and revise the procedures based on actual experiences. Hawaii Revised Statutes (HRS) have placed geothermal drilling operations under the jurisdiction of the State Department of Land and Natural Resources (DLNR). Specific executive authority for these matters rests with the Director of the DLNR, and with the Chair of the Board of Land and Natural Resources (BLNR); these two positions are held by the same individual.

The administrative and regulatory staff for geothermal drilling matters is located in the DLNR Division of Water and Land Development (DOWALD) in Honolulu. Contact with the staff in this Division can be made at the following address:

Geothermal Project Manager
Division of Water and Land Development
Department of Land and Natural Resources

1151 Punchbowl Street
Honolulu HI 96813

P. O. Box 373
Honolulu HI 96809

Telephone: (808) 587-0259; FAX: 587-0390

The current DOWALD Manager-Chief Engineer is Mr. Manabu Tagomori; current Geothermal Project Manager is Mr. Hiram Young. Inquiries on geothermal drilling matters may be made to one of these DOWALD managers.

OPERATORS

Each geothermal drilling project must have a designated "Operator," whose responsibilities include the designation of a resident Hawaii Agent (to receive all orders, notices, etc.), and the obtaining of an indemnity bond for each geothermal well in the amount of $50,000, or $250,000 for **all** proposed wells.

The Operator of a geothermal project may also be the "Applicant" for permits. Applicants may be landowners of the properties to be developed, or may be lessees with demonstrated agreements to develop the lands - both surface and subsurface. In any event, the Operator must be designated to the BLNR/DLNR as a part of the permit process. The Applicant must also obtain a "Geothermal Mining Lease" from the State in most cases.

STATE AND COUNTY PERMITS

The primary source of permit rules and regulations affecting the Operator's interest in geothermal drilling and wellfield operations is the "Rules on Leasing and Drilling of Geothermal Resources."[2] Other State permits, primarily for the maintenance of air and water quality, are administered by the Hawaii Department of Health (DOH). Some of these DOH rules, and associated permits, will affect well drilling and operations; the specific permits are not discussed here, but their requirements are incorporated in the discussions of equipment and procedural requirements where appropriate.

County permits, where specific requirements have been adopted, are primarily land use permits. They also include administrative-type permits, such as grading and grubbing permits, building permits, lighting, noise limits, etc. These specific requirements also will not be discussed, although they too may have regulations affecting planning and drilling operations.

Permits can be basically categorized into those dealing with land uses - zoning, leases, etc. - and those dealing primarily with technical matters - drilling and resource protection, air

[2] Department of Land and Natural Resources Administrative Rules, Title 13, sub-title 7. Water and Land Development, Chapter 183.

and water quality maintenance, wellfield and power plant operations, and waste disposal. This Guide will deal with the latter type of permits, outlining the basic requirements for the combination of planning, procedures and equipment.

From the onset of interest in geothermal development in Hawaii, the sequence of permits (i.e. which permit, from which agency, in what order) has not been as clear as necessary. There is a logical hierarchy of permitting to consider issues and permitting conditions at the proper time, when sufficient planning and information are available to make reasoned decisions; for example, it is impractical to consider specific air quality permits and conditions for a given project until after the geothermal resource conditions are known, and the design of the power plant has reached a certain stage. This logical hierarchy begins with basic land use decisions and permits. The next phase of permitting considers exploration activities, facility locations, size and general design, and the general siting issues for exploration and development. It is only after some or all of these decisions have been made that many specific environmental and community issues can be decided. Next, development activities - production drilling, power plant construction, steam and electrical transmission systems, and testing activities - are considered; the final level is long-term operation of the project.

If this type of hierarchy is followed, all parties are afforded the chance to thoroughly examine pertinent issues before permits are approved. Previous permit actions lay the foundations for future actions, and public confidence in the whole process is improved.

APPROVAL PROCESS

In its own publication[3], the State admits that "Applicants for land and water [development] use permits and approvals are faced with an admittedly complex regulatory system... Activities regulated by the State focus on public health, welfare and the management

[3] "Applicant Guide to State Permits and Approvals for Land and Water Use and Development": Department of Planning and Economic Development, June 1986.

of natural and human resources. Counties regulate activities that are more directly related to land use, zoning and development of facilities... Regulatory [permitting] responsibilities in some instances overlap or are shared among the various regulatory agencies... A project may require the permission of only one or all three [Federal, State, County] tiers of government. This tends to complicate the permit process and may obscure the identity of appropriate regulatory agencies and the procedural sequence in which one can best obtain the necessary approvals."

This recognition that permit processing is complex should not deter Operators, as the Hawaii geothermal drilling process is similar to other states that have active geothermal drilling. The basic reference, which should be carefully studied by all Operator personnel associated with the planning, applications and actual drilling, is found in the State's "Rules on Leasing and Drilling of Geothermal Resources," in section 183-65 through 183-76.

The specific requirements for applying for a "permit to drill, modify, modify use, or abandon wells; permits" are found beginning in Section 65. Each application will include:

- Operator (applicant) name, address and signature.
- Owner of mining rights.
- Landowner (if applicant is not the landowner).
- Well designation and plot plans showing tax map key, well location, and elevation.
- Statement of purpose and extent of proposed work.
- Estimate of depths between which discovery, production, injection, or plugging will be attempted.
- Drilling and Casing Program description; this is the essential element for DLNR staff evaluation of the application. This element is discussed below in section VI., DRILLING AND CASING PROGRAM.
- A statement regarding the required bond.

- Statements of the applicant that all work will be performed in accordance with DLNR Rules and all Federal, State and County requirements.

Other requirements are presented in detail in the cited sections. Application processing and approval or disapproval by the Chairperson of the BLNR will be completed within 60 calendar days of receipt of a complete application; the approved permit to drill is then valid for a period of 365 days from the issue date. An extension of the permit for a further 180 days is possible upon application, review and approval by the Chairperson of the BLNR.

It must again be stressed that only a careful reading of the pertinent rules and regulations can assure an Operator that State, County (and sometimes Federal) requirements are met without undue restrictions on the exploration and development of Hawaii's geothermal energy potential.

III. REQUIREMENTS FOR DRILLING OPERATORS

Geothermal drilling operations in Hawaii present a major operational challenge and every Operator will need experience, commitment and solid financing. Detailed planning and a core group of dedicated experts, as required in any frontier class of drilling operation, are essential to safety, to success and to control of the high costs. Additionally, Hawaii drilling operations are exposed to full public scrutiny and occasional intrusions by opponents. Every Operator gets a basic education in moving through the specific Permit application process for the intended drilling operation. However, upsets in the actual drilling operations have resulted in adverse public reactions and consideration of shutdowns by regulatory authorities. Operators should maintain an active public relations campaign to support all active Hawaii geothermal drilling operations, particularly in the KERZ, until the benefits of reliable geothermal electric power are better recognized by the local community.

Drilling Operators remain on a learning curve in the KERZ. Only high quality, experienced professionals should assume the responsibility and immediate management/supervision. It is critical that an integrated team of geologists, drilling engineers and on-site drilling supervisors direct the actual operations in accordance with the approved drilling and casing program which they have prepared, or act in accordance with prudent practice when upset conditions occur. On site drilling supervision should not be less than excellent; this is every Operator's lowest cost, lowest risk, most promising path to a successful well completion. The Operator alone holds full responsibility for attaining the first class work and safety practices that can best protect the drilling operators from unanticipated events.

The drilling contractor should be carefully selected after detailed assessment of equipment capacity and condition, and personnel. The rig foremen and drillers should be highly experienced in geothermal drilling. The State of Hawaii may require that one technically qualified representative of the drilling contractor be licensed. Substantial directional drilling requirements should be anticipated; good margins of rig capacity and power are essential. The following minimum rig ratings are recommended:

Depth capacity: 10,000 feet	Draw works: 1,000 horsepower
Hook Load: 350 tons	Pumps: Two - 1,000 HP each
Mud system capacity: 1,000 barrels	

In addition, the Department of Health, or other permitting agencies, may require specific noise control measures on and around the rig that will affect the choice of equipment. Hawaii guidelines for noise control during drilling are strict; an Operator should expect to make modifications to the rig to accommodate these requirements.

The costs of drilling rig transport to and from Hawaii, and all of the costs under a day rate or footage drilling operations are not the proper approach. Choosing the low bid should be considered only after a careful evaluation of equipment, personnel and the challenges of the drilling proposed. High quality personnel and equipment provided under the drilling contract is the more prudent approach to effective cost control.

Drilling Operators must organize and manage logistics and support services, commonly from California and Texas sources. Marine transport schedules between Hawaii and California seaports control all bulk or heavy shipments. Air transport has been employed in emergency situations, but high costs and the physical size of some equipment are serious constraints on air shipping. Backup equipment and material inventories must be carefully evaluated and determined for Hawaii geothermal drilling operations.

IV. GEOTHERMAL DRILLING ENVIRONMENT

THE VOLCANIC DOMAIN OF HAWAII

The volcanic islands which exclusively comprise the lands of the State of Hawaii, were formed from nearly continuous eruptive vulcanism above a convecting mantle plume at a relatively fixed location under the northwestward moving Pacific Oceanic plate. The Hawaiian mantle plume has been operating as an energy and mass transfer mechanism for more than 70 million years. Each island of the State has been created sequentially and then transported northwestward from its birthplace. The newest island to surface, Hawaii County or the Big Island, which offers the most promising geothermal resources in the State, has been constructed only in the last one million years from five volcanic eruptive centers, which are progressively younger and more active from northwest to southeast.

The vigor of the volcanic processes under and within the Big Island are proven by its youth, and particularly by its size. The peaks of Mauna Kea and Mauna Loa stand more than 13,000 feet above sea level and 31,000 feet above the sea floor. Only 11 percent of the total erupted volcanic rock mass stands above sea level; 89% of this largest volcanic mountain on earth is hidden in the submarine realm. The Big Island and its older sister islands are composed of basalt lava flow sequences which are near horizontal and have a subsurface rock geometry of hard, crystalline flow rocks, interbedded with lesser amounts of highly varied rock debris. The common basalt flow sequences of Hawaiian bedrock are repeated in extensive rock outcrops and particularly in the water wells and collection tunnels which exploit critical fresh groundwater in support of agriculture and urban development on every island. The priceless groundwater resources of the State derive from persistent rainfall on higher elevations, immediate infiltration and long term underground storage in the flanking basalt flows.

THE RESOURCE CONCEPT

The geothermal resources, now under drilling exploration and initial development, wil likely help reduce the high costs and uncertainties of electric power on the Big Island. These resources are located in relatively small prospective areas which are strongly associated with active volcanism. The most prospective areas overlie the volcanic rift zones where deep subsurface conduits allow magma to move away from the volcanic centers to the subaerial and submarine flanks of the volcano. Hawaiian geothermal drilling to date has been confined to the Kilauea East Rift Zone (KERZ), which is a relatively linear, active magma transporting and lava erupting structure. In the KERZ the magma and lava processes attain very high subsurface temperatures (1900°F and higher). Both meteoric water (groundwater) and seawater, in abundant supply, can permeate the high temperature rock via extensive fracturing and faulting created continuously by high levels of seismicity and tectonic disruption along the rift zone.

The prospective KERZ geothermal reservoir targets appear to be situated in the roof rock above deep magma conduits that create the KERZ structure. The roof rock is exposed to a cross-rift tensional stress field which allows repeated upward intrusions of planar, near vertical sheets of magma from the deeper conduits, which cool to form dikes. The fluid magma input to this dike process is driven by the hydraulic head in the shallow magma chamber under Kilauea's active vent. These newly formed dikes, within the host basalt flow, probably contribute more thermal energy to the geothermal reservoir than does conduction from the deep magma conduit. Drilling and flow test data to date suggests that the greater mass of the high temperature basalt flow and dike rock complex, as penetrated below drilling depths of 4,000 feet, may have low permeability. However, significant fractures and major faults, due to a concentration of seismicity in the KERZ and the seaward gravity sliding of its southeast flank, have been encountered by recent drilling operations. The finding of open, major fault planes, charged with high pressure, 620+°F geothermal fluids, as recently encountered in Well KS-8, has raised new levels of technical challenge and provided opportunities for geothermal drilling operations.

KERZ DRILLING TO DATE

This Geothermal Drilling Guide draws its most significant information from experiences and results of drilling operations in 14 deep geothermal wells and 3 scientific observation holes in the KERZ between 1975 and 1993 (see following table and map). Rotary drilling rigs, of increasing depth capabilities, power and pump capacities, have been utilized in KERZ geothermal drilling. Well depths have ranged between 1,600 and 12,500 feet, true vertical depth. Directional drilling has been successfully employed in a number of primary and redrilling programs. A wide spectrum of drilling fluids are used; commonly, these fluids are moderately weighted muds, water, aerated fluids, and occasionally, foam and full air circulation. The Operators for well drilling have included five private resource companies and one public sector research unit.

The results of deep geothermal well drilling included the successful drilling and completion of the resource discovery well, HGP-A, in mid-1976, and its subsequent geothermal steam production to a 3 MW electrical generation demonstration plant from 1982-1990. As of late 1992, ten wells had penetrated prospective high temperature rocks and eight of these were flow tested or manifested high temperature fluids.

TABLE IV-1

KILAUEA EAST RIFT ZONE

STATE OF HAWAII

DEEP GEOTHERMAL WELLS 1975-1993

WELL	TOTAL DEPTH (feet)	BHT (°F)	COMMENTS
HGP-A	6,450	676	Produced about 110,000 lbs/hr of steam and brine. Supported 3MW plant from 1982-1990. Well is suspended.
Ashida 1	8,300	619	No permeability or fluids; plugged and abandoned.
Kapoho-State 1	7,290	642	Short test; 72,000 lbs/hr steam; plugged and abandoned.
Kapoho-State 2	8,005	648	Short test; 33,000 lbs/hr steam; plugged anc abandoned.
Kapoho-State 1A	6,562	572	17-day flow test; 65,000 lbs/hr steam anc 14,000 lbs/hr brine; converted to injectior service in 1992.
Lanipuna 1	8,389	685+	Low permeability, possible trace of fluids abandoned.
Redrill	6,299	300	379°F maximum uphole, no fluids; abandonec
Lanipuna 6	4,956	250+	Major L. C. zone below 4,285 feet; suspende
KS-3	7,400+	NR	Short test; 70,000 lbs/hr steam; converted injection service in 1992.
KS-7	1,678	NR	Hot pressured fluids vented after injection t at 1,678 feet; plugged and abandoned.
KS-8	3,488	NR	Blowout in June 1991 vented fluids for hours. Well killed, completed to production high pressure bottom zone. Supported P binary plant at 10 MW level briefly in Octc 1992. plugged and abandoned.

DEEP GEOTHERMAL WELLS 1975-1993 (Continued)

WELL	Total Depth (feet)	BHT	COMMENTS
TRUE 1	12,500	932±	High pressure steam entries encountered deep in vertical hole and in 3 redrills. Steam flows not sustained in flow tests; suspended. Deepest vertical penetration was 12,500 feet; total 28,000 feet of hole drilled.
KS-4	6,800+	NR	Completed in November 1992 for injection service.
KS-9	NR	NR	Spudded December 1992. Flow tested and supplying steam to plant-April 1993.
KS-10	NR	NR	Spudded 1993. Flow tested and supplying steam to plant-June 1993.
SOH 4	6,562	583 MRT	No adequate permeability shown by injection in completion interval of 1,991-6,562 feet; suspended.
SOH 1	5,526	403 MRT	Adequate permeability not shown by injection interval of 4,103-6,802. Some injectate loss at ± 4,600 feet, where 341°F was recorded; suspended.
SOH 2	6,802	661	Inconclusive; funding limits imposed stopping at 5,526 in rising BHT; suspended.

Notations: BHT - Bottom Hole Temperature as measured by wireline tools

NR - Not Reported

MRT - Maximum Reading Thermometer

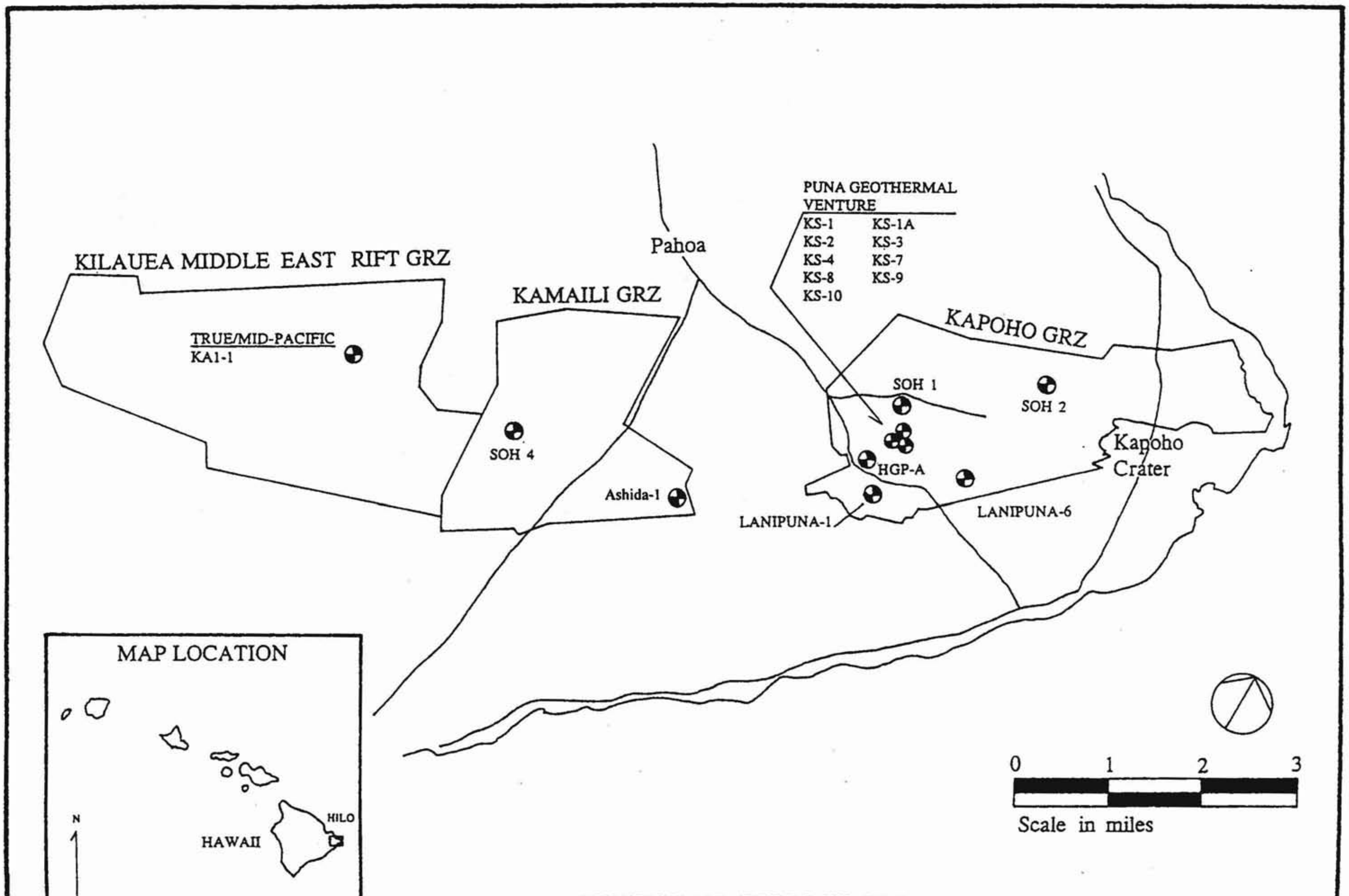


Figure 1. GEOTHERMAL WELLS IN THE KILAUEA EAST RIFT ZONE

Two of these wells incurred casing-contained blowouts in 1991 upon unexpectedly encountering high pressured geothermal fluids at depths shallower than anticipated. Well KS-8, finally completed to production consequent to the blowout, actually drove the on-site binary plant at 10 MW generating capacity briefly in October 1992.

Three deep scientific observation holes (SOH) were drilled as continuously cored exploratory slimholes to 5,500-6,800 foot depths in the 1990-1992 interval. These SOH's helped to prove that favorable high temperatures prevail over a ten-mile interval along the KERZ.

WELLSITE SELECTION AND PROTECTION

An excellent summary of the surface hazards attending Hawaii's active volcanism is presented by Mullineaux et al. 1987 (see reference in Appendix B). Active lava flows constitute the primary concerns for the selection and long term protection of geothermal wellsites. The entire prospective trend of the KERZ has been included in Zone 1 (see Mullineaux) with the highest order of lava flow hazard. This reality drives several considerations of risk reduction for the development and lower cost maintenance of a Hawaiian geothermal wellfield, especially in the KERZ.

1. The thicker and slower moving a'a lava flows will be controlled by topographically low courses on the land surfaces. These courses are easily identified in the recent and detailed new topographic maps available for the KERZ. A'a flows will advance over ground surface at rates between 100 to 200 feet per hour, with frontal thicknesses between 20 and 35 feet. Consequently, naturally elevated drill sites and well pads offer the most effective offset to surface lava flows. With careful consideration of the site elevation and probable lava flow courses in the topography, wellsites can be optimally designed, raised or bermed on an up-slope exposure.

2. Analysis of surface lava flow risks for an intended Hawaii geothermal wellfield, its dual production and injection functions, and its pipeline requirements, will drive development toward the use of elevated large wellsites with clustered wellheads and extensive directional drilling. Large berms of volcanic cinder can be placed on the flow risk perimeter of such bigger multi-well pads. Such cinder berms will establish an effective barrier for stopping actual lava flows by cooling and solidifying the first arriving lava front, thereby increasing the protection of the wellsite. Additional cinder supplies and the reliable availability of large capacity bulldozers may be critical elements to successful stoppages of the worst possible case lava flow event(s).

3. To date, much discussion has been raised on the Hawaii practice of placing geothermal wellheads in deep cellars at significant cost and at additional risk of H_2S gas entrapment. The clear requirement of heavy, intricate and tall, full BOP stacks, as recommended in the **Hawaii Geothermal Blowout Prevention Manual** (1993), indicates a continued preference for deep wellhead cellars. Additionally, deep cellars appear to add significant protection against a worst case lava flow. Strong steel mesh gratings, which close the cellar throat at ground level, should be able to support a protective volcanic cinder pile that could be placed around the exposed low profile wellhead as a final protection tactic. It would be part of a sound defensive strategy to minimize the possibility of a lava flow causing multiple wellhead destruction, blowouts and resource waste.

4. The deep wellhead cellars used on the Kapoho-State lease in the KERZ are constructed of concrete with reinforcing bars, and have internal dimensions of 10 feet or more on each side wall, and floor depths of 10 feet or more below ground level. Consideration of larger cellars is appropriate for safer access to the cellar floor and the lower components of the wellhead installation.

The southeastern portion of Hawaii County is the most active seismic area in the State. Earthquakes are frequent along the KERZ; however, the common range of magnitude 4 to 5.4 is not considered to be of significant risk to geothermal drilling operations. Larger magnitude earthquakes have occurred (magnitude 7.2 event in 1975) but are rare in the KERZ historical record. California has a more serious exposure to major earthquakes, yet they have not proven to be significant risks to the more active and extensive geothermal, oil and gas drilling operations there.

SUBSURFACE CONDITIONS

Wellbore temperatures ranging from 600-700°F, and higher in several wells, have been encountered in the KERZ. Rotary drilling in this range of high temperature basalt flow and dike rocks is efficiently accomplished with various circulating fluids, usually water, aerated muds or moderately weighted muds. Production well completion targets are specific major fault planes, intersections of predicted fault planes, or concentrations of intense fracturing. The primary heat source for the geothermal reservoirs seems to be the young, near vertical, planar dikes. These newly formed dikes may be more common on the seaward edge of the KERZ structure. Drilling data is not yet sufficient to accurately characterize cross rift temperature profiles in the prospective production intervals.

The hydrology and subsurface water processes in active rift zones has not yet received detailed studies. Broad spectrum scientific efforts in the KERZ by the Hawaiian Volcano Observatory (U.S. Geological Survey) have mainly focused on volcanic gases and have long deferred the hydrologic sector. Nearly nine years of geothermal fluid production from the HGP-A discovery well has made a preliminary indication of what may be an extraordinary interplay between fresh water, seawater and geothermal fluids in the KERZ. The obvious elements of hydrology include heavy precipitation and infiltration of rainfall in the KERZ, a major fresh groundwater resource moving down Mauna Loa's eastern flank and then feeding into the geothermal fluid regime, and a limitless seawater supply pressing all along the southeast boundary of the rift. Both freshwater and seawater participate in the geothermal fluid regime, as proven by well production and flow testing.

The combination of high rainfall and its nearly total infiltration acts to maintain a relatively cool and fresh groundwater body just above sea level along the KERZ. The thin freshwater cap floats on a deeper, denser saline water body which appears to extend to drilled depths below 2,000 feet in the Kapoho-State geothermal wellfield. Strong evidence of geothermal fluid leakage, occurring naturally from the deep hot core of the rift, is found in both high salinities and anomalously warm (>100°F) temperatures in KERZ water well drilling, most of which predates the recognition of the geothermal resource potential in the early 1970s. Within the context of this natural leakage it can be recognized that the more mobile gas components of the geothermal fluids will readily escape upward and into the bottom of the saline groundwater body. The large H_2S component in these gases, mixing in the cooler saline water, may present a particular external corrosion risk to the cement sheaths and casing strings in the 2,000-2,500 foot depth range (bottom of saline waters under Kapoho-State leases). If this proves to be a significant general condition, improved cementing procedures and higher grade steel casing may be required for long term integrity of the intermediate casing strings in KERZ geothermal wells.

The greater number of deep geothermal wells and boreholes (15 out of 17 total) prove that normal hydrostatic pressures prevail in most of the high temperature realm in the KERZ. Normal subsurface fluid pressure gradients should range between 422 psi per 1,000 feet of drilled hole in a freshwater realm, and 433 psi per 1,000 feet in a saltwater realm. However, overpressured geothermal fluid conduits are present in the KERZ due to recurring fault and fracture penetrations deep into the geothermal fluid regime. These newly opened faults and fractures will immediately transfer high pressured, high temperature fluids upward to new locations in lower pressured, lower temperature conditions. Rapid secondary mineralization sealing the new fluid locations create the hot fluid overpressures in the open fault conduits, which now present both well completion targets and blowout prevention challenges.

The chief risk to KERZ geothermal well drilling is the unexpected penetration of mineral sealed fault planes and fractures containing overpressured geothermal fluids. Two recent wells have made such penetrations and sustained blowouts which were subdued at major additional costs and eventual loss of the intended well function. Two important analytical procedures must be refined to bring these overpressured containments out of an initial sense of unpredictability. The structural response to the stress fields and seismicity of the KERZ must be more accurately identified by detailed correlation of wellbore data, and to the major findings of the U.S. Geological Survey - Hawaii Volcano Observatory scientific studies. Detection efforts before drilling, as discussed in detail in Section VII, DRILLING MONITORING PROCEDURES in the **Hawaii Geothermal Blowout Prevention Manual** (1993), should be rigorously applied at every active drilling rig. Both the reward of high well productivity and the penalty of blowouts will drive the need for prediction and detection of the high pressured fluid conduits.

A significant additional concern for KERZ geothermal wells follows from the weakness of the near surface volcanic rocks. Open lava tubes, cinder and rubble deposits, and contraction fracturing in hard, crystalline lava flows, contribute to low rock strengths, vulnerability to hydraulic fracturing and high vertical permeability. These weaknesses may extend to depths of 1,500-2,000 feet and can pose special problems for the cementing of surface and intermediate casing strings and for the reliable anchoring of the full BOP stack required for drilling into the geothermal zones.

A comment regarding the presence of the H_2S gas component in the KERZ geothermal fluids: Operators drilling with mud and water do not run significant risks in penetrating the prospective high temperature zones and the unwanted release of H_2S, as long as well control is maintained. Drilling with aerated fluids or air will require careful monitoring and possibly mitigation, under the provisions of the drilling permit. In every Hawaii geothermal well, H_2S safety and rescue training should be completed by all drilling crew members and renewed annually. Flow tests in KERZ geothermal wells have identified an H_2S range of 800-1300 parts per million in the noncondensible gas component; API and California Division of Oil and Gas references cited in Appendix B are pertinent on this issue.

SUMMARY

Hawaii geothermal drilling will continue to encounter unique features and problems. The geothermal resource promises to be a powerful one if it can be developed with drilling practices and well designs to safely control its character.

V. GEOTHERMAL WELL PLANNING

INTRODUCTION

The proven higher costs and uncertainties in Hawaiian geothermal drilling operations are sound reasons to make an extraordinary investment in well planning. Detailed planning is a must for each and every type of well because of the current paucity of subsurface information and the small base of drilling experience to date.

WELL PLANNING OBJECTIVES

Safety The concept of safety must be carefully applied for all workers and activities at the wellsite and for the public. A blowout prevention strategy is a crucial part of any successful practice of safety in geothermal drilling; it is a necessity in Hawaii (see **Hawaii Geothermal Blowout Prevention Manual**, 1993). Proper personnel supervision and training are essential to any safety program; the rules of workplace safety must be clear and understandable to all who may frequent the wellsite.

Well Function Geothermal wells, if beneficial development is to be attained, must convey and control very large quantities of fluid and energy, hopefully for the greater part of the 30-year life that is expected in electric power systems. The HGP-A discovery well demonstrated a reasonable performance in the production mode from 1982 to 1990.

Reasonable Cost Hawaiian geothermal wells are in the very costly category; perhaps $2,500,000 per well is a representative minimal cost (1992$) if no significant problems impact a good drilling plan. Competent planning might cost only 1 or 2% of the total cost of a successful well. High quality well planning will assure a greater degree of safety and improved well functions. Proper well planning will allow the Operator to be more confident in responding to the upset conditions that can't be avoided and actual drilling performance can be better assessed for continued improvements in future Hawaiian geothermal wells.

DRILLING TARGETS AND WELL TYPES

Geothermal drilling targets in Hawaii can be organized into three simple classifications:

Exploration targets - to discover the resource, are generally identified by a favorable combination of subsurface data indicating heat, fluids and fractures (voids). Targets that can attract drilling funds, but which present a high risk exposure, are classified as exploratory by the Operator and participants.

Reservoir targets - to develop the resource, are generally qualified by high temperatures, indicated fault planes and fracture systems, or by nearby well production data. The probability of penetrating both high temperatures and fluid producing permeability intervals is high. Hawaiian geothermal reservoirs are of the hydrothermal type (the predominate type now in worldwide utilization.)

Supplemental targets - to conduct research on the resource, are comprised of scientific and/or observation objectives which can contribute to a better understanding of a geothermal resource and its subsurface environment.

At the present level of knowledge in Hawaiian rift zones, no class of geothermal drilling target can be confidently said to have lower blowout risks. Off rift geothermal drilling targets may offer the perception of lower drilling risks, however, no such drilling has been undertaken as of 1992.

Geothermal wells can be categorized as to function and several additional features. The common types of wells include the following:

Exploration well. Any well drilled to evaluate a prospective geothermal resource target, usually at some significant distance from an established or proven geothermal reservoir. Hard, nearby subsurface data are not likely to be available for a full drilling plan: diligent drilling monitoring procedures (see Section VII) and casing plan flexibility are essential in exploration wells.

Production well. Any well designed to exploit the energy and fluids of a geothermal reservoir for beneficial use or demonstration purpose. Plans for production wells can be better specified to more confidently known subsurface conditions.

Injection well. Any well designed to return the geothermal effluent to the reservoir or other deep disposal zones.

Slimhole. This type of geothermal well is identified by its small diameter borehole, 6 to 4 inches, compared to the 17½ - 8½ inch hole diameter range commonly used worldwide in the geothermal industry. The slimhole technology, presently surging in evaluation and use in the petroleum industry, has been safely introduced in the KERZ when the Hawaii Natural Energy Institute (HNEI) accomplished three continuous boreholes between 5,500 and 6,800 foot total depths in its Scientific Observation Hole (SOH) Program (1989-91).

Deep versus shallow wells. These are terms of convenience in their general usage; however, regulations may impose a legal definition on them.

Vertical versus deviated wells. It appears that Hawaiian geothermal wellfields will be extensively developed with deviated wellbores. General planning, equipment selection, monitoring procedures, and blowout prevention requirements are not significantly altered in any type of geothermal well by the vertical or deviated course of its wellbore.

CASING AND CEMENTING CONSIDERATIONS

Casing. Selection of casing sizes starts with deciding on a desirable hole size through the production interval. This then determines the hole sizes and casing sizes for conductor pipe, surface, intermediate (possibly more than one), and production casings. At present, the common and accepted casing sizes (outside diameter) used in Hawaii are 30 inch conductor, 20 inch surface pipe, 13-3/8 inch intermediate, 9-5/8 inch production casing and 7 inch liner (See figure 2). Casing for geothermal wells comes from oil and gas industry tubular goods and the selection of sizes is generally dependent on what is commonly used and available. Drilling bit size selection is the same. The availability and the logistics of getting it to Hawaii become important considerations in casing size selection. Also, an Operator must be flexible In the design so that changes can be made to accommodate changing hole conditions. For instance, lost circulation zones may necessitate an additional intermediate casing string.

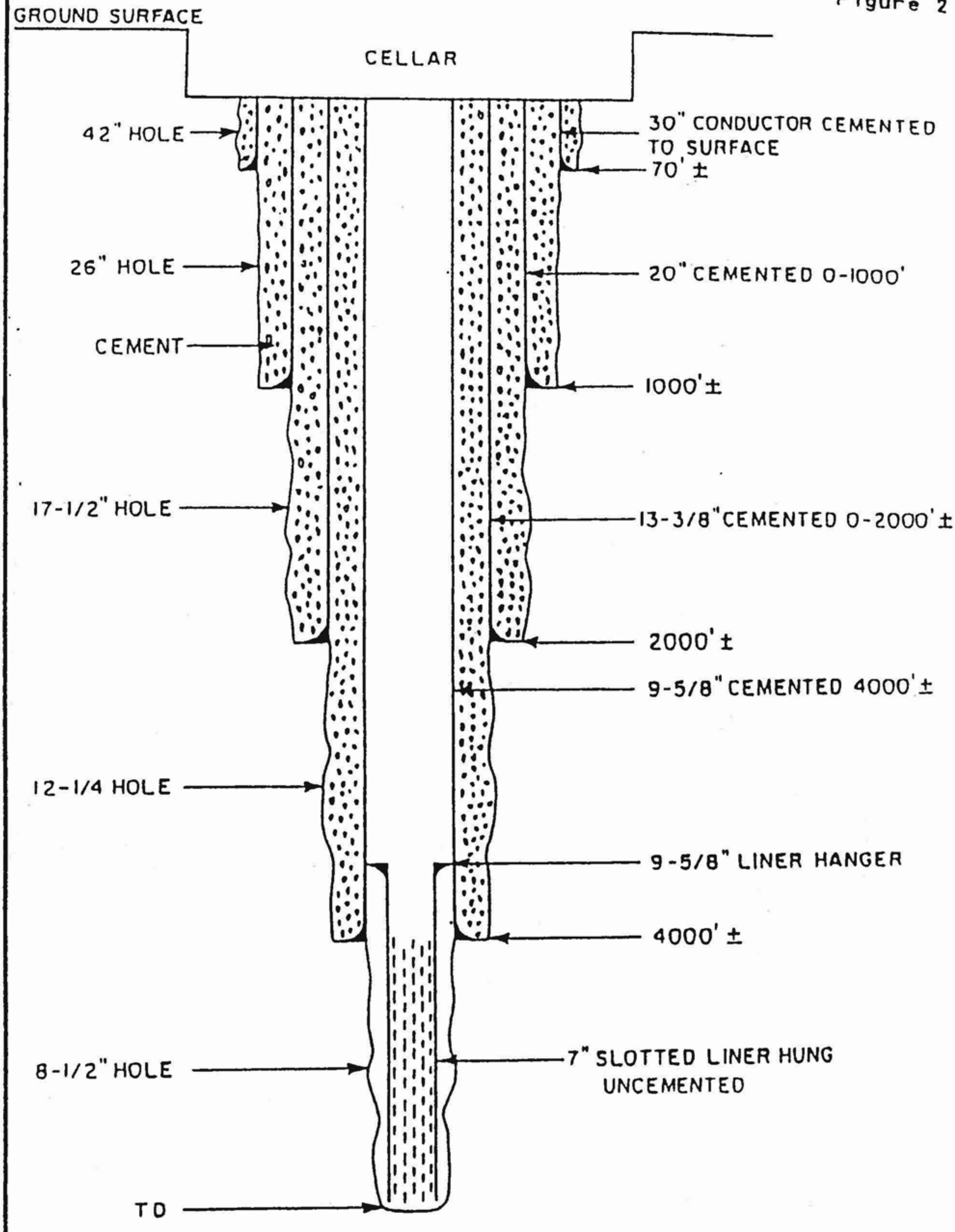
Selection of casing weight, grade and joint threads will be based on tension, burst and collapse pressures. Common safety factors in use are 1.125 for collapse, 1.5O for burst and 1.75 for tension. In addition to this, weights and grades of steel should be selected to obtain the maximum resistance to corrosion from fluids, and $C0_2$ and H_2S gases. There is a potential problem in Hawaii with the mechanical integrity of wells that have produced high temperature fluids and are then shut in for long periods of time. Temperature decreases imposed by shallow ground waters can accelerate H_2S corrosion.

The temperature stresses in Hawaii related to 700+°F reservoir temperatures must be considered when selecting casing. The effects of these high temperatures on the modulus of elasticity for different grades of steel is significant.

The current practice in Hawaii is to use higher casing weights and lower casing grades to obtain the strength for collapse, burst and tension. Joint threads being used generally are Buttress, Seal-Lock and VAM. The Operator must select casing and joint threads only after thorough investigation of recent experience and performance and must consider new changes in technology In the area of corrosion resistant steels and premium thread couplings.

Cementing. It has become evident that there is nothing more important in the construction of geothermal wells In Hawaii than the quality and integrity of the cement job on each casing

Figure 2



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string. Tension and collapse failures of casing in geothermal wells have been found to be caused by improperly cemented casing. Thermal expansion of voids or pockets of water in the cement sheath, due to high temperature, can cause casing failures.

In addition to that kind of failure, it is suspected that an acidic condition can be formed outside the casing due to H_2S. If the cement sheath does not properly protect the casing, corrosion failure can occur. Proper cement slurry design is crucial for maximum protection from external corrosion and should be indicated by the physical characteristics recorded on the drilling mud log (see Section VII, page 32).

It is especially difficult to obtain competent cement jobs through areas of lost circulation. The operator must make every effort to overcome this problem. Cementing techniques have become quite sophisticated and the Operator must use a cementing program adapted to the specific conditions at hand. Consideration must be given to:

1. The cement additives, including lost circulation materials, and the proper mix of slurry for different temperatures and hole conditions and for the prevention of cement strength degradation during the future life of the production or injection well.
2. The use of light weight cements.
3. The techniques of multiple stage cementing and/or the use of tie-back strings.
4. The amount of excess slurry.
5. The importance of centralizing casing and reciprocating during cementing.

CASING AND CEMENTING PROCEDURES

The intended function of the proposed well will be a factor in casing design and cementing procedures selected. However, the best available subsurface data sets on geology, hydrology, pressure and temperature profiles, formation failure thresholds (fracture gradient), together with the wellsite elevation, comprise the basis for increased safety in drilling and quality of construction. The subsurface conditions and wellsite elevation are unique to each wellbore; the proposed casing and cement plan must reflect a reasonable response to these conditions.

1. Surface casing (commonly 20 inch diameter) is preferably cemented below the groundwater table. Where the groundwater table is within 600-800 feet below the surface, an approximate 1,000 foot length of surface casing would meet this objective. It may be difficult to obtain a good cement sheath on surface casing because of the presence of lost circulation zones and incompetent rock in which to cement the casing shoe. Where the groundwater is deeper, as much as 2,000 feet of casing may be required. Prudence suggests that it is better to obtain a quality cement sheath on a shorter length of surface casing.

2. Intermediate casing (commonly 13-3/8 inch diameter) may be set at depths between 1,000-2,500 feet below the surface casing shoe if no unexpected geothermal fluids or anomalies are encountered. The intermediate casing shoe depth should optimally be below the major groundwater body. It should also be below extensive fracturing that may reach up to the groundwater table, frequent occurrence of lost circulation zones, and less competent volcanic rock. Because the intermediate casing provides the critical attachment for the complete BOP equipment stack required to drill to total depth, it is critical that the cement sheath in the open hole (17½ inch diameter) annulus be of the highest possible quality. The findings in the 17½ inch drilled hole should be carefully studied. Any adverse downhole conditions can be mitigated by cementing the bottom portion of the intermediate casing as a liner in the open hole interval (lapped at least one hundred feet into the bottom of surface casing). The upper portion can be run and cemented as a tie back string inside the surface casing. Each of the two cement jobs required should be of enhanced quality, should offset the external natural hazards and should optimize the anchor for the complete BOP equipment stack.

3. Production casing (commonly 9-5/8 inch diameter) run in 12 inch hole may be set at depths of 4,000+ feet, at the top of the producing zone. As with the intermediate

string, it should be cemented back to the surface with a high quality cement and with every attempt made to insure a competent cement sheath between casing and formation. The preferred method is to overlap the 13-3/8 inch casing by at least 100 feet and then run a tie-back string to the surface. As with the intermediate string, hole conditions will dictate whether a tie back string or stage cementing is desirable. The production casing should be landed in an expansion spool at the surface.

4. Slotted or perforated 7 inch liner is hung in open hole below the production casing. Two successful production wells to date indicates that KERZ geothermal wells can be completed in the reservoir interval without full liner protection over the entire interval of 8½ inch drilled hole. The amount of rock debris discharged in recent initial flow tests suggests that open hole completion intervals remain intact without liners.

DRILLING FLUIDS

The subsurface conditions encountered within the KERZ are prompting the use of many drilling fluids ranging from moderate to low density muds, water, aerated muds and water, to foam, and air. Additionally, the ability to switch drilling fluids promptly is being recognized as a cost effective advantage in greater well control. The diversity and flexibility of drilling fluid utilization in Hawaii is encouraging, not only because all fluids can be controlled by available BOP equipment, but because this approach should lead directly to advanced safety margins, reduced drilling times and lower costs.

VI. THE DRILLING AND CASING PROGRAM

INTRODUCTION

This section discusses this most important document, which will be included in each Application for Permit to Drill presented to the DLNR. Each proposed geothermal well requires a Drilling and Casing Program (DCP) specific to the known and predicted circumstances at and under the selected drillsite. This document is to be prepared by the Operator with professional expertise consequent to completing a very careful process of geothermal well planning, as discussed in the preceding section. The Operator, as the applicant for the Drilling Permit, is exclusively responsible for the DCP. The format and details are selected by the Operator; however, the DCP must contain the essential information which will allow the DLNR to make an informed analysis of the application and decision for approval or disapproval. The DCP may be supplemented by tables, figures, and other details, however, the document should be clear and concise in its content, sequence and proposed procedures. The DCP is submitted with other requirements of the Application for Permit to Drill, as discussed in Section II of this Guide.

PROGRAM CONTENT

The DCP should be a separate typewritten document. The following minimum content and sequence of information is recommended:

HEADING

1. Well designation and purpose (production, injection, other).
2. Well location and elevation at ground level, wellbore course (deviated or vertical).
3. Total depth and expected completion interval.

MAIN ELEMENT

This should be a numbered presentation of the sequential key procedures required to construct the well. Commonly a DCP is segmented into depth intervals relating to the specific requirements for surface, intermediate, production casing stages and finally for completion. Operators have preferred formats and depth of detail for the contents of the DCP; any clear and logical presentation would be acceptable. Importantly, the sequential key procedures should include consideration and integration of the following basic concerns:

1. Drilled hole sizes and projected depths.
2. Drilling fluid selection for each wellbore segment.
3. Drilling monitoring procedures for each wellbore segment, including proposed logs.
5. Casing specifications and cementing procedures for each wellbore segment.
6. Blowout prevention equipment, procedures, strategy, and testing for each wellbore segment.
7. Completion interval and liner.

The DCP should be illustrated by a graphic diagram showing the vertical section of the well, which presents hole sizes, casing, and liner configuration from the surface to total depth. This will provide a ready reference for an understanding of well construction.

SUMMARY

The DCP is the most fundamental document required for the DLNR's consideration and approval leading to issuance of the Permit to Drill for every individual geothermal well. Consequent to DLNR approval and the commencement of drilling operations, the DCP is the departure baseline for all additions or changes that may be forced by the actual conditions encountered downhole. Both Operators and regulators are aware that the conditions encountered may modify or largely preclude the execution of any DCP even when it is carefully prepared on the basis of competent geothermal well planning. However, the better the quality of work behind each DCP, the better it will allow upset conditions to be addressed, should they occur.

VII. DRILLING MONITORING PROCEDURES

INTRODUCTION

The actual drilling process on geothermal wells worldwide, is commonly monitored with special concerns for rock penetration and drilling rig performance. Both the Operator and the drilling contractor require a continuous stream of data on the rocks, formation liquids and gases. pressure, and temperatures being encountered by the drill bit. Mechanical and hydraulic parameters are recorded for every combination of hole size, drilling assembly and drilling fluid circulation to help determine an optimal drilling penetration mode for each rock type. Drilling monitoring procedures can be defined as the continuous sensing actions which identify the subsurface conditions in the rock formation and in the wellbore as the drill bit advances.

MONITORING RATIONALE FOR HAWAII

Geothermal wells drilled within the prospective, active volcanic rift zones of Hawaii. merit carefully planned and integrated monitoring procedures. This view is supported by two primary concerns.

First, the subsurface geology, hydrology, temperatures and pressures in the rock roof above the deep magma conduits, which create the rift zone, are only partially known. Only 15 deep geothermal bores (12 wells and three scientific observation holes) have provided hard, factual subsurface data as of the end of 1992.

Secondly, two geothermal wells have demonstrated that fault or fracture conduits, charged with high pressure, high temperature fluids can extend upward to relatively shallow depths from a deeper subsurface domain of >600°F temperatures. These near vertical and planar conduits present both new production potentials and some additional blowout risk. One recent KERZ well, KS-8 (see Table IV-1) demonstrated a 10-MW level of geothermal fluid production briefly in October 1992, after surviving a significant blowout. Drilling monitoring procedures can play an important additional role in the blowout prevention strategy, which must be established by every Operator (see Section VI, **Hawaii Geothermal Blowout Prevention Manual**, 1993).

VITAL MONITORING SECTORS

Monitoring focuses on three vital sectors during the drilling of a geothermal well:

1. Physical properties and resource potential of the newly penetrated rock formation. The array of information gathered in this sector is commonly presented in a continuous "mud log" graphic record over the entire interval drilled. The mud log includes, but is not limited to, the continuous and automatic analysis of formation gases such as methane, carbon dioxide and hydrogen sulfide, as well as the geologist's description of the lithology and associated alteration minerals at various depths.
2. Drilling penetration rate and drill bit performance measurements. The penetration rate, commonly measured and recorded in feet per hour, indicates the mechanical progress of drilling in the host rock. Weight on bit, rotational speed and torque are additional measurements that are made to better understand the variations of the drilling penetration rate.
3. Drilling fluid circulation in the wellbore which clears the newly made hole of drilled rock debris, cools and lubricates the rotating bit, and drilling string. Importantly, the density and hydrostatic pressure gradient of the drilling fluid are commonly used to control the formation fluids and pressures encountered. Drilling fluid losses and gains, as well as fluid temperature in and out of the wellbore, are of special significance as forewarnings of upset conditions.

The information products from the sectors discussed above have important potential well construction applications. Possible immediate improvements might be indicated in drilling procedures, drilling fluid properties, casing and cementing programs, and completion plans. Enhancements in well design, drilling programs and/or cost reductions can be determined for future wells.

SPECIFIC CONCERNS

As noted in the discussions under ***Subsurface Conditions*** in Section IV, **Geothermal Drilling Environment**, and under ***Casing and Cementing Procedures***, item 2 in Section V, **Geothermal Well Planning**, there is cause for concern about fracturing and permeability in the KERZ, combined with the poorly known character of the bottom of the saline groundwater body in the depth interval of 1,000 to 3,500 feet. This is the interval commonly selected for the emplacement of 13-3/8 inch diameter intermediate casing in 17½ inch open hole. Considerations for appropriate upgrades in casing selection and cementing procedure for the intermediate casing need the particular careful evaluation of drilling monitoring procedures in the interval. A detailed, integrated analysis of the mud log and the lost circulation record would be essential for this purpose.

Drilling monitoring procedures, particularly in the detection of sharp increases in bottom hole temperatures coincident with an increase in mineralized rock and anomalous gas entries, must be accepted as the best available indicators of the possible approach to sealed conduits of high pressure geothermal fluids. These can yield production wells of very large capacity. The publicly released **Independent Technical Investigation** of the June 1991 KS-8 blowout reported a bottom hole temperature increase, coupled with significant CO_2 and H_2S gas entry, drilling fluid gain and minor well flow at 3,401 feet. All of these perturbations were encountered 75 feet above the major 12 foot void at 3,476 to 3,488 feet, which resulted in a blowout promptly after draining the mud column from the wellbore. It can be expected that the KS-8 mud log and other monitoring records, in the minimum 75-foot seal thickness indicated, contain additional clear evidence of an impending major upset. Certainly it is not known if every major geothermal conduit in the KERZ will present this many precursors 75 feet away from every salient production zone. However, the KS-8 well record offers the reasonable promise that competent geologic-engineering teams can make effective and safe production casing settings on these exceptional completion targets. Obviously, big well completions are the preferred way to reduce drilling requirements and costs.

All of the products of drilling monitoring procedures should be carefully integrated and assessed in making a confirmed or revised selection of the production casing setting depth. Isolation of the production or injection zone within the geothermal reservoir is commonly intended, but may not be achieved in the context of the downhole conditions actually encountered. Additionally, the drilling monitoring products should be closely examined for details that may enhance the completion design or procedure for the successful well. Longer or shorter perforated liner intervals may be appropriate to the actual completion zone features found, rather than as stipulated in the written drilling and casing program.

Importantly, the drilling monitoring results indicate the hard facts and reality of the wellbore penetration. These results may provide a convincing confirmation of the predrilling prognosis or they may reduce relevance of the drilling and casing program. It is likely that the findings and sound interpretation of the monitoring procedures would be one of the primary causes of necessary changes to the approved drilling and casing program. Should a program change be required for this reason, it can be expected that the DLNR would want to examine the monitoring data and interpretation with the Operator before approval is granted.

VIII. COMPLETED WELL CONCEPTS

WELLHEAD EQUIPMENT

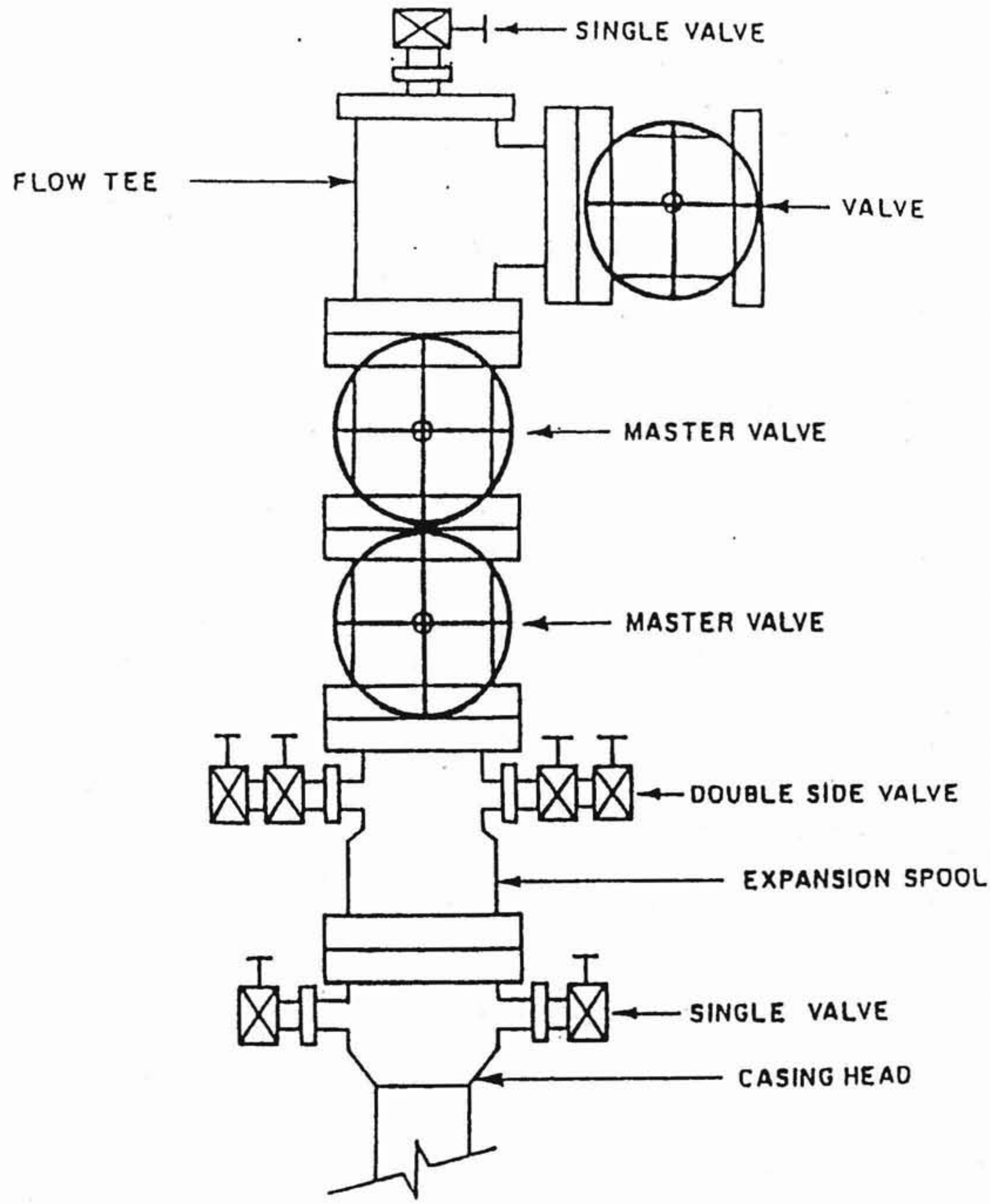
A typical basic completed wellhead, or tree, in use in Hawaii (see Figure 3) consists of casing head, expansion spool for the production casing, dual master valves, flow tee and single wing valve. It has side outlets on the casing head (for observation) and expansion spool. and a valve on top of the tree for wireline access into the wellbore. The design of the wellhead should include a consideration of the following elements:

1. Selection of a pressure rating with an adequate margin of safety, taking into account the best available information on expected maximum temperature and the pressure rating degradation of steel due to high temperature. Given the high temperature Hawaiian resource, and the potential corrosion problems, it appears that a 5000 psi minimum pressure rating should be considered.
2. The design of the wellhead should be such that it is possible to change any part(s) if it becomes necessary.
3. The wellhead should be readily adaptable to either production or injection capability.
4. The design and strength of the wellhead should minimize the exposure to natural surface conditions and the possibility of vandalism.
5. The additional equipment beyond the wellhead itself, such as chokes, flow lines. bleed lines, manifolds for diverting flow to stacks or mufflers, all have an impact on the design and configuration of the wellhead. An important part of the wellhead design may be its ability to convert to a constant bleed mode during periods of flow line shut down.

COMPLETION ZONE CONFIGURATIONS

Successful geothermal wells, completed to either production or injection service, will

Figure 3



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probably employ similar casing and liner configurations. Open holes of 12¼ inch diameter will have 9-5/8 inch casing run to the top of the production or injection interval and should be carefully cemented to isolate this permeable interval from all uphole rock, fluid and other conditions. An 8½ inch diameter open hole through the permeable interval will sometimes be protected with a 7 inch perforated steel liner which is hung in place and not cemented. The liner length, in both production and injection completions, would be determined by the fractures and/or permeable zones encountered.

The injection well would likely be completed with a protective, solid steel liner hung down from the wellhead to the top of the 7 inch perforated liner. For additional protection, the annulus between the protective liner and the 9-5/8 inch casing can be charged with an inert fluid.

WELLBORE MULTIPLE USE OPTIONS

At very substantial costs, an investment in quality casing and proficient cementing must be made in the KERZ for both production and injection wells completed in the geothermal reservoir. However, reservoir performance under exploitation, which includes both production and injection, is only poorly known at this time. This suggests a need to thoroughly consider being able to switch functions at every well. The initial determination of production or injection service for each well depends on the best available data. As the reservoir reacts, with the new well supporting the wellfield exploitation scheme, performance data may indicate a better alternative use of the existing completion (injection versus production), or a redrill and recompletion to the same or alternate function. Until the internal dynamics of KERZ reservoirs are better known, all successful geothermal wells, at any performance decline in either deviated or vertical bores, should be carefully evaluated for redrilling options.

WELL ON SHUT-IN STATUS

A high level of corrosion, which may lead to casing failure, is present in those KERZ geothermal wells which have tested at high temperature fluid flows, and then are placed in a full shut-in status. Fluid convection can operate inside the wellbore in full shut-in conditions, building highly concentrated H_2S gas caps. Prior to placing a high-temperature well on shut-in status for extended lengths of time, the Operator may pump a caustic water solution down the wellbore to abate any H_2S and protect the well from acidic corrosion. This column of caustic water solution can be pressurized with nitrogen to keep any remaining H_2S gas in solution. This would prevent a highly concentrated H_2S gas cap from forming while the well is on shut-in status. As an option for long term well shut-in, the H_2S gas cap may need to be periodically bled off, properly abated, to the atmosphere.

IX. WELL FLOW TESTING

INTRODUCTION

Each successful geothermal well operation has three critical stages before the well can be properly identified as a production asset. The wellbore must first penetrate the geothermal reservoir; drilling monitoring procedures should reveal many important specific features of the production zone, possibly the fluid entry points. The well must then be completed with a casing and liner configuration that isolates the production zone and maximizes its fluid yielding capacity. It is fundamental in geothermal energy exploitation that wellbores be designed to attain very large fluid mass flows with safety and reliability. Finally, the completed well must be cleaned out and then flow tested to measure its production capacity. These initial flow measurements become a critical index to a significant number of additional concerns; the efficacy of the well design, the total well cost per pound-hour of geothermal steam found, and the initial state physics and chemistry of the produced effluent. The completion flow test is a critical task that provides the first indications of real energy cost delivered to the power plant and the probable future wellfield operations and maintenance (O & M) costs. It is common to see geothermal drilling costs identified as a high and uncertain negative factor in many economic comparisons of geothermal electric power with other energy supply options. It is important that the benefit to cost ratio be identified promptly and accurately by flow testing all successful Hawaii geothermal production wells.

Geothermal well flow testing can present technical issues and problems that may rival and possibly surpass those encountered in the drilling operations. Mature and confident flow testing procedures evolve where large numbers of wells can be completed in a single reservoir, such as The Geysers and Coso geothermal fields, or where the regional character of the geothermal resource is reasonably well identified, as in the Imperial Valley. However, each resource is unique, and successful flow test practices in one area may not be appropriate everywhere else. Certainly, the real character of the resource in the KERZ, with only twelve wells tested or productive of geothermal fluids to date, cannot be considered as adequately determined. Many more successfully flow-tested wells will be required.

RATIONALE FOR FLOW TESTING

A KERZ geothermal well, successfully drilled and completed without serious problems. may represent a minimum $2,500,000 investment. Some common questions asked are: what was achieved; what is the wellhead product; how effectively will it contribute to electrical generation? A carefully designed well flow test program that is safe, accurate in measurement. and adequate in duration is the only procedure that can yield factual data for the following:

1. Correlation of well productivity and well design. Was the completion interval optimally selected and isolated; is production casing appropriate and integral for reliable production service? Ideally, the maximum flow capacity should be demonstrated in the well flow test.

2. Measurement, sampling, and chemical identification of the produced effluents. Steam, brine and non-condensible gas (NCG) components should be evaluated with precision for comparison with designed fluid partitioning and paths in separators, turbines, heat exchangers, cooling, and injection facilities. The initial flow test provides the baseline parameters of these produced fluids. These parameters, expected to change over the well's productive life, can guide operating and maintenance practice for wellfield, plant, and reservoir management for more reliable electrical generation throughout the project's life.

3. Production performance over time. It is very important to obtain continuous flow at fixed wellhead conditions over some reasonable time duration to determine if production volume and flowing pressure stabilizes or decreases with time. Of equal significance, many new wells attain increased volumes in the flow mode. The initial flow testing seeks to prove a stable well flow volume at a fixed wellhead flowing pressure which is higher than the turbine entry

pressure.

4. Determination of optimal flow rate and deliverability for each well. Three or more step rate flow measurements, at different well head pressures, commonly within and near the pipeline and turbine entry pressure ranges, will assist the balancing of multiple wells in production service.

FLOW TEST PREPARATION

A safe and reliable practice has evolved in certain areas for obtaining well flow tests promptly upon completion, with the drilling rig yet standing over the well. This has worked at The Geysers, where a meaningful well flow test can be obtained before rig release, because the production intervals have been air drilled and the 100% geothermal steam entries are cumulatively vented, even before well completion. There are advantages to well flow testing under the drilling rig, where it can be quickly and safely accomplished with reliable results. However, it is unlikely that this will come to be an early practice on Hawaii geothermal wells that are successfully completed. More intricate testing facilities are required for the two phased fluids, and long duration flow modes are necessary for performance determinations.

All of the following discussions of Hawaii geothermal well flow testing are predicated on prior release of the drilling rig, unobstructed access to the wellhead and adequate space on the location for the requisite test facilities. The flow test preparation may include a completion zone evaluation with water injection and related wellbore surveys. Preparation of a flow test program must be based on sound mechanical and reservoir engineering considerations and the selection, installation, and check-out of test equipment and facilities. The main components of the equipment-facilities are flow control valves, the separator, the metering runs, H_2S gas and noise abatement, and disposal of residual liquids. Additional tasks would include the preparation of any observation wells, confirmation of adequate water supply for backup control options, and notifications to appropriate agencies of the actual flow test schedule.

FLOW TEST SEQUENCE

The following information derives from one successful and uninterrupted initial flow test made on a KERZ geothermal well. It is provided as a guide to the detailed features and sequence of activity in flow testing. The features of each well and its completion zone best dictate the design of each flow test. Many more flow tests in the KERZ will be required to define an appropriate, generalized, optimal flow test plan.

A. Water Injection.

Immediately after drilling equipment removal, a water injection procedure can be utilized to confirm fluid entry points and locate other permeable intervals in the completion zone. Water injection data should not be expected to provide more than rough indications of a well's expected flow capacity and cannot be considered as a meaningful alternative to flow testing. An initial pressure-temperature survey of the completion zone in the static (shut-in) mode should be made before injection is initiated. Pressure, temperature and spinner surveys can be run between, during and after each injection phase; suitable water pumping capacity, a wellhead lubricator and about a 2000-barrel water supply are required. The fluid entry points should be identified with reasonable precision by temperature kicks and their relative flow capacity by the spinner responses. Additional multi-rate water injections can provide data for estimation of reservoir transmissivity and of wellbore skin effects. It should also be noted that production wells completed in a single, high capacity fluid conduit, such as well KS-8 encountered, would not be candidates for injection evaluations.

B. Thermal Recovery.

Upon conclusion of injection, the completion zone must rebound from the imposed temperature suppression. A series of wellbore temperature surveys and tracking of the water level rise in the wellbore should reveal the pace of thermal recovery and its correlation with preparation of the testing equipment and facilities. The thermal recovery can be accelerated, to the threshold of flowing, by injecting a gas column into the well, thereby suppressing and more rapidly heating the wellbore liquid column. The gas column can be maintained for several days and then vented to observe if the water level surfaces and initiates actual flow. The air injection tactic can be repeated if required. When the well attains a ready to flow condition, all test equipment and facilities should be installed and verified to be operable as required in the continuous flow mode.

C. Wellbore heat-up.

It is recommended that a conservative wellbore heat-up procedure be used to reduce thermal shock to the new casing and cement sheaths in accommodating the first high temperature geothermal fluid flow. Bleed lines of steel pipe can vent an initial small water flow from the wellhead (15-20 gpm). Low water flow should be increased gradually to achieve a gentle temperature rise over the full vertical extent of the wellbore. The increase of temperature should be restrained by water flow control (reduce to a small bleed) in a gradual approach to a well head temperature of 400°F which can be the starting condition for the continuous, long duration flow phase of the test.

D. Initial Well Venting/Cleanout.

The safest, most technically rewarding flow test is obtained with clean, continuous geothermal fluid flows over a time interval required to accurately measure a new well's productive capacity and character. However, the production zones of KERZ geothermal wells may discharge a major quantity of rock debris and sharp edged mineral particulates in their initial flows, initiating a cleaning action in the whole rock mass opened to the wellbore. Rocks, debris and minerals enter the wellbore in the completion interval and then accelerate in the high velocity uphole fluid flow. At the wellhead, this mixture is a highly erosive product that can quickly begin to cut any steel surface it strikes, and require shutting in the well for repairs to surface equipment. Such interruptions in a flow test can rapidly degrade the quality of the technical information obtained.

The safest response to this transient hazard is to vent the well, with hydrogen sulfide abated, to the atmosphere. This initial well cleaning should be accomplished in approximately four hours or less. Only such a wellbore flow can ensure effective cleaning of the rock completion interval and establish the conditions for continuous, long duration and safer flow over the intended test interval. If this venting process is not performed, both the flow test program and the wellhead, field piping and separator facilities in early production service, may be exposed to the risk of mechanical failures if the rock and mineral debris unloads from the wellbore. The recommended initial well cleanout applies a safe, short and mechanically focused response to the cleanup requirement for all new or redrilled geothermal wells.

E. Continuous Flow Mode.

The critical objectives of continuous flow testing are to detect any increase or decrease of flow rate with time and, finally, to confidently determine a measured production rate for a new (or reworked) well. For a test of this type, clean resource product is directed, at a constant wellhead flow rate, to the separator for breakout of steam, liquid and NCG fractions, then through orifice meter runs, sampling ports, H_2S and noise abatement, and disposal. The continuous flow should extend over ten days or more, depending on the magnitude and vigor of the total mass fluid flow.

F. Step Rate Flows.

The end of a satisfactory continuous flow mode presents an excellent opportunity to put the flowing well through step rate flow tests at 3 to 5 different wellhead pressures that straddle expected pipeline and turbine entry pressures. Resultant data, plotted as a deliverability or productivity curve, will reveal the changes in steam and water fractions that attend changes in wellhead flowing pressure and total mass flow. This data will assist refinements in plant and surface facility design, operation or modification. Finally, with step rate flows accomplished, a brief sequence of 100% well closure and reopening can provide a confirmation of the stabilized flow rate determined in the continuous flow mode.

G. Shut-in and Buildup.

With final well closure in a successful flow test, a very important data collection program should be initiated in the wellbore. Repeated pressure, temperature and spinner surveys should monitor the transition from the flow mode to a temperature-equilibrated shut-in status. This sequence of temperature profiles will reveal the cooling impacts of the saline and groundwater external to the upper wellbore. and spinner surveys may show active inter-zonal flows within the completion interval. This post flow wellbore data, coupled with chemical analyses of the steam. brine and NCG fractions, is essential to devising long-term protection procedures for corrosion control as a first concern in prolonging well life, particularly if the new well is not to be promptly placed in production or injection service. Newly completed KERZ wells which are shut-in for extended time intervals have exhibited casing corrosion rates at problem levels. Lastly, pressure buildup data provides vital information on the geothermal reservoir dynamics and response to exploitation. The data gathered at each well completion is crucial to informed reservoir analysis, improved production-injection practices, and long-term reservoir management for optimal energy yields.

H. H_2S and Noise Abatement.

The active flow phases of the flow test, following the well cleanout to obtain clean, safe, total mass flows, must be accomplished in full compliance with regulations controlling gas and noise emissions. H_2S abatement is now an available, reliable technology that is readily applied to well flow testing. Venting during well cleanout flow tests requires noise abatement which can best be accomplished by exhausting the steam into perforated pipe chambers (rock mufflers) under beds of volcanic cinders.

I. Geochemistry.

Detailed and repetitive fluids sampling is an integral part of the flow testing. The conductivity, pH and chemical species of the steam condensate and brine are of greatest importance. With the high incidence of H_2S in the KERZ and the stringent 25 parts per billion emissions limitation imposed on the geothermal operations, the procedures for its detection and measurement need to be elevated to a consistent reliable practice accepted and understood in detail between Operator and regulatory personnel. With respect to all chemical analyses of geothermal fluids and materials employed, it is essential that Operators use reputable laboratories that have a geothermal expertise. Regrettably, a significant number of analytical facilities are failing in accuracy due to the demand of work driven by the surge in environmental problems.

X. DRILLING DOCUMENTATION AND REPORTING

Complete documentation of drilling activities, particularly in the active area of the KERZ, is important if sufficient information is to be at hand for planning future wells. Although each Operator will determine what daily records, logs, testing and post-drilling reports are appropriate for each project, there are some records that are needed for all wells. Hawaii **Rules on Leasing and Drilling of Geothermal Resources**[4] require that "all physical and factual exploration results, logs, and surveys which may be conducted, well test data, and other data resulting from operations....." must be furnished to the Board of Land and Natural Resources.

TYPES OF REPORTS

A number of reports and logs have been developed by the worldwide geothermal industry in support of drilling operations; not all logs and reports are appropriate to each project, but in general, it may be said that more types of records are better than fewer, especially in the KERZ, where a complete understanding of the resource and conditions is not yet available. The basic records and logs that must be kept include the following:

1) Daily Drilling Reports. The daily drilling, or tour, reports kept by the drilling crew on the rig are the most valuable source of information on the actual drilling operations and accomplishments in each geothermal well. The most widely used form in both the geothermal and petroleum industry is the **IADC API Official Daily Drilling Report Form**. Frequent review of the accuracy and completeness of these reports should be made by the Operator's drillsite supervisor. A complete set of the Daily Drilling Report, for every geothermal well drilled, must be

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[4] Department of Land and Natural Resources Administrative Rules, Title 13, sub-title 7. Water and Land Development, Chapter 183.

preserved by the Operator as the primary historical record of well construction.

2) Additional reports to be submitted to DLNR. (See Chap 13-183; paragraph 85). Upon completion, suspension or abandonment of every geothermal well, the Operator must provide, within six months, and in accurate, complete and final form, the following well reports to DLNR:

a) Well summary report, which indicates location,casing depths, completion interval, completion date, and production test results, if available.

b) Well history report, which is presented as a daily chronological description of the entire drilling operation from spud date to completion date. This is a detailed record of well construction procedures actually employed.

c) All drilling logs, such as the mud log, which presents continuous profiles of all lithology, fluids, and temperatures encountered from the surface to total depth. Any electric logs and descriptions of any cores obtained should be included in this wellbore data package.

d) A wellbore directional survey from surface to total depth, if the well has been drilled as a deviated hole, or redrilled or deviated courses from an original vertical hole.

All of the documents and reports cited above are important baseline information to both the Operator and to the DLNR. These comply with the basic requirements of the laws and regulations. They also provide a critical basis for evaluations of drilling operations and for future improvements in well design, construction, safety, reliability and cost control.

XI. SLIMHOLE DRILLING OPTIONS

The high costs of Hawaii geothermal drilling operations are a valid reason for retaining an awareness of the slimhole drilling options for both exploratory and development objectives. This drilling technology is presently being applied and rigorously evaluated by the petroleum industry in worldwide efforts. Leadership has come from both American and French petroleum companies. Amoco's Slim Hole Advanced Drilling System proceeded from 1987-1991 and obtained over 70,000 feet of continuous rock cores in the U.S. Mid Continent area. This program researched the entire scope of equipment and process and importantly included well control requirement. (see **Hawaii Geothermal Blowout Prevention Manual**, Section XI., *Blowout Prevention in Slimholes.*) A newly designed slimhole rig, which incorporates the Amoco findings is rated for 7,500 feet in 6 inch hole and 10,000-12,000 feet in 4.38 inch hole.

The slimhole concept has been used and evaluated in the KERZ in the Scientific Observation Hole (SOH) Program operated from 1989-1991 by the Hawaii Natural Energy Institute (HNEI). Three SOHs reached total depths between 5,500 and 6,800 feet with HQ (nearly 4 inch diameter) core holes. Excellent core recovery and high borehole temperature profiles were obtained in the deep prospective zones (see Table IV-1 for details). This initial program was costly; however, new approaches to the drilling-coring sequence were evaluated and can be incorporated for significant cost savings in any future Hawaii SOH program.

Many Operators, regulators, and reservoir engineers believe that it is better to invest in a more producible borehole, rather than in the slimhole option. However, for initial exploration in new areas, the slimhole allows a low cost, first penetration of a prospective target. If the conditions are proven favorable, a subsequent full hole exploration well could be more confidently designed to test the target at much lower risk and costs. Slimholes could similarly assist development drilling programs in the KERZ.

APPENDIX A

PROCEDURES FOR GUIDE REVIEW AND REVISIONS

APPENDIX A

REVIEW AND REVISIONS

Geothermal drilling experience in Hawaii, as of the end of 1993, has been quite limited. Only 15 deep geothermal boreholes had been drilled, and these were located on only one prospective feature, the KERZ. Reasonable increases in geothermal drilling in the KERZ, and perhaps other areas, can be anticipated. New operational and regulatory experiences should accumulate in the next few years.

This Drilling Guide can best be accepted as a first edition. Ideally, it should serve as a working reference for operators and regulators in a cooperative approach to the achievement of more efficient,safer drilling practices.

It is recommended that this Guide be reviewed and revised within 5 years of its date of issue by DLNR. Such a time interval seems ample for the collection of new operating information and for a reasonable application of the procedures reviewed in the Guide. Frequent and informed discussion of procedures between Operators and regulators could prove to be one of the most important consequences of the use of this Manual.

APPENDIX B

REFERENCES

APPENDIX B

REFERENCES

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NOTE: **GRC - Geothermal Resources Council, Davis, CA.**

APPENDIX C

GLOSSARY

APPENDIX C

GLOSSARY

A limited glossary of terms used in this Guide, and/or common to the geothermal industry is presented in this Appendix. Further terms are defined in the references listed in Appendix B.

A

API *abbr*: American Petroleum Institute

B

BHP *abbr*: bottom hole pressure.

BHT *abbr*: bottom hole temperature.

blowout n; A blowout is an uncontrolled flow of formation fluids or gas from a well bore into the atmosphere or into lower pressure subsurface zones. A blowout occurs when formation pressure exceeds the pressure applied by the column of drilling fluid.[1]

blowout preventer n: the equipment installed at the wellhead to prevent or control the escape of high pressure formation fluids, either in the annular space between the casing and drill pipe or in an open hole (i.e., hole with no drill pipe) during drilling and completion operations. The blowout preventer is located beneath the rig at the surface. See annular blowout preventer and ram blowout preventer.

BOP equipment n: The entire array of equipment installed at the well to detect and control kicks and prevent blowouts. It includes the BOP stack, its actuating system, kill and choke lines, kelly cocks, safety valves and all other auxiliary equipment and monitoring devices.

bottom hole temperature n: The temperature of the fluids at the bottom of the hole. While drilling, these temperatures may be measured by minimum reading temperature devices, which only record temperatures above a designed minimum, and may not provide an accurate bottom hole temperature. Bottom hole temperature readings should be recorded after a period of fluids circulation at a particular depth, in order to stabilize the reading.

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[1] Rotary Drilling BLOWOUT PREVENTION Unit III, Lesson 3; Petroleum Extension Service, The University of Texas at Austin, Austin Texas, in cooperation with the International Association of Drilling Contractors, Houston Texas. 1980; 97 pages.

BOP *abbr*: blowout preventer

BOP stack n: The array of preventers, spools, valves and all other equipment attached to the well head while drilling.

borehole n: the wellbore: the hole made by drilling or boring.

C

casing n. steel pipe, cemented in the wellbore to protect it against external fluids and rock conditions, and to facilitate the reliable and safe production or injection of geothermal fluids.

cap rock n: 1. relatively impermeable rock overlying a geothermal reservoir that tends to prevent migration of formation fluids out of the reservoir.

cellar n: a pit in the ground to provide additional height between the rig floor and the wellhead. and to accommodate the installation of blowout preventers, rathole, mousehole, and so forth. It also collects drainage water and other fluids for subsequent disposal.

cementing n: the application of a liquid slurry of cement and water to various points inside or outside the casing.

competent rock n. (in wellbores) any rock that stands without support in the drilled wellbore can be described as *competent*. Beds of ash, or loose volcanic clastics, are vulnerable to failure in open wellbores, and are thus considered to be *incompetent rock.*

complete shut off n. a full closure and containment of wellbore fluids and pressure at the wellhead.

conductor n: 1. a short string of large-diameter casing used to keep the top of the wellbore open and to provide a means of conveying the up-flowing drilling fluid from the wellbore to the mud pit.

CSO *abbr*: complete shut off.

D

drilling fluid n: a circulating fluid, one function of which is to force cuttings out of the wellbore and to the surface. While a mixture of clay, water, and other chemical additives is the most common drilling fluid, wells can also be drilled using air, gas, or water as the drilling fluid. Also called circulating fluid. See mud.

drilling spool n: a spacer used as part of the wellhead equipment. It provides room between various wellhead devices (as the blowout preventers) so that devices in the drill stem (as a tool joint) can be suspended in it.

drill pipe n: the heavy seamless tubing used to rotate the bit and circulate the drilling fluid. Joints of pipe are coupled together by means of tool joints.

drill string n: the column, or string, of drill pipe with attached tool joints that transmits fluid and rotational power from the kelly to the drill collars and bit. Often, the term is loosely applied to include both drill pipe and drill collars. Compare drill stem.

F

flange n: a projecting rim or edge (as on pipe fittings and opening in pumps and vessels), usually drilled with holes to allow bolting to other flanged fittings.

formation pressure n: the force exerted by fluids in a formation, recorded in the hole at the level of the formation with the well shut in. Also called reservoir pressure or shut-in bottom-hole pressure. See reservoir pressure.

J

joint n: a single length of drill pipe or of drill collar, casing, or tubing, that has threaded connections at both ends. Several joints, screwed together, constitute a stand of pipe.

K

kick n: an entry of water, gas, or other formation fluid into the wellbore. It occurs because the hydrostatic pressure exerted by the column of drilling fluid is not great enough to overcome the pressure exerted by the fluids in the formation drilled. If prompt action is not taken to control the kick or kill the well, a blowout will occur.

kill line n: a high pressure line that connects the mud pump and the well and through which heavy drilling fluid can be pumped into the well to control a threatened blowout.

L

L.C. *abbr*: lost circulation

log n: a systematic recording of data, as from the driller's log, mud log, electrical well log, or radioactivity log. Many different logs are run in wells to obtain various characteristics of downhole formations. v: to record data.

lost circulation n: the loss of quantities of any drilling fluid to a formation, usually in cavernous, fissured, or highly permeable beds, evidenced by the complete or partial failure of the fluid to return to the surface as it is being circulated in the hole. Lost circulation can lead to a kick.

which, if not controlled, can lead to a blowout.

M

mud n: the liquid circulated through the wellbore during rotary drilling and workover operations. In addition to its function of bringing cuttings to the surface, drilling mud cools and lubricates the bit and drill stem, protects against blowouts by holding back subsurface pressures, and prevent loss of fluids to the formation. Although it was originally a suspension of earth solids (especially clays) in water, the mud used in modern drilling operations is a more complex, three-phase mixture of liquids, reactive solids, and inert solids. The liquid phase may be fresh water, and may contain one or more conditioners. See drilling fluid.

mud logging n: the recording of information derived from examination and analysis of formation cuttings suspended in the mud or drilling fluid, and circulated out of the hole. A portion of the mud is diverted through a gas-detecting device. Cuttings brought up by the mud are examined to detect potential geothermal production intervals. Mud logging is often carried out in a portable laboratory set up near the well.

mud weight n: a measure of the density of a drilling fluid expressed as pounds per gallon (ppg), pounds per cubic foot (lb/ft^3), or kilograms per cubic meter (kg/m^3). Mud weight is directly related to the amount of pressure the column of drilling mud exerts at the bottom of the hole.

P

permeability n: 1. a measure of the ease with which fluids can flow through a porous rock. 2. the fluid conductivity of a porous medium. 3. the ability of a fluid to flow within the interconnected network of a porous medium.

pressure n: the force that a fluid (liquid or gas) exerts when it is in some way confined within a vessel, pipe, hole in the ground, and so forth, such as that exerted against the inner wall of a tank or that exerted on the bottom of the wellbore by drilling mud. Pressure is often expressed in terms of force per unit of area, as pounds per square inch (psi).

R

reservoir pressure n: the pressure in a reservoir under normal conditions.

S

surface casing n: the first string of steel pipe (after the conductor) that is set in a well, varying in length from a few hundred to several thousand feet.

survey n: a continuous wellbore measurement of a parameter such as pressure or temperature.

W

wellbore n: a borehole; the hole drilled by the bit. A wellbore may have casing in it or may be open (i.e., uncased), or a portion of it may be cased and a portion of it may be open. Also called borehole or hole.

wellhead n: the equipment installed at the surface of the wellbore. A wellhead includes such equipment as the casinghead and tubing head. adj: pertaining to the wellhead (as wellhead pressure).