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Geothermal Well Technology and
Potential Applications of Subterrene
Devices — A Status Review

by

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GEOTHERMAL WELL TECHNOLOGY AND POTENTIAL APPLICATIONS
OF SUBTERRENE DEVICES - A STATUS REVIEW

by

John H. Altseimer

ABSTRACT

The past, present, and some future aspects of the geothermal energy (GTE) industry have been reviewed with special attention given to geothermal well-drilling problems. Geothermal wells can be produced with present equipment and methods, mostly derived from the oil and gas industry, but costs are relatively high. Short-term improvements are needed in drilling rigs and auxiliary surface equipment, drill bits, bit-bearing lubrication systems, tubular goods, high-temperature muds and cements, logging and downhole sampling equipment, directional control equipment applicable to geothermal conditions, and in the use of a data bank for GTE wells to help optimize drilling programs. Two types of wells are needed: (1) small-diameter wells for exploration, reinjection, and disposal purposes, and (2) larger-diameter wells for production. To develop and greatly expand the use of GTE in the future, new methods and equipment are needed to penetrate hard abrasive rocks and to provide hole stabilization and support at the very high temperatures and other extreme conditions which can be encountered in GTE wells. New Los Alamos Scientific Laboratory concepts for penetrating rocks by use of rock-melting processes (called Subterrene concepts) offer potential solutions to some difficult GTE well-production problems.

I. INTRODUCTION

A. Objectives

A primary objective of this study is to present a summary status review of geothermal well technology, which includes drilling and operational problems. A secondary objective is to begin the analysis and evaluation of new concepts of making a hole by means of melting processes (called Subterrene concepts at the Los Alamos Scientific Laboratory) to improve the methods of producing geothermal wells. Besides the use of published literature and data, many personal discussions were held with people in various fields of the drilling and GTE industries in an effort to arrive at correct and objective conclusions. A list of the contacts made is presented in an appendix.

B. History of Geothermal (GTE) Exploitation

Man has made various uses of naturally occurring hot water for thousands of years. Indeed, Lieb¹

recalls Plato writing about ancient Atlantis in his Critias as follows: "Poseidon, as he was a god, found no difficulty in making special arrangements for the center of this island, bringing two streams of water from under the earth, which were caused to ascend as springs, one of hot water and the other of cold".

The first experimental attempts to produce electric power from GTE began in 1904 at Larderello, Italy, under the direction of Prince Piero Ginori Conti, general manager of the Larderello works. These works had been developed by a Frenchman, Francesco de Larderel, in 1818, primarily as a source of boric acid. In a paper delivered in 1924¹ Prince Conti reported that in 1905 a 20-hp engine was run by the natural steam supply to generate plant lighting power. By 1912, the development of a 250-kW steam turboalternator was initiated with subsequent success. In 1914, the erection of the

Larderello Power Station was begun, which housed three turboalternators of 2500 kW each, two operational and one spare. From these early beginnings the Larderello Power Station has increased its output to 384 MW in 1969.² With current technology, this output may be near the maximum for that location.

Larderello is a vapor-dominated reservoir. A similar reservoir exists at The Geysers in northern California. In 1960 The Geysers first became operational at 12.5 MW.³ Since then, several 110-MW complexes, each consisting of two 55-MW subcomplexes, have been developed. At the end of 1973, Pacific Gas and Electric Co. reported a total capacity of 412.5 MW for The Geysers,⁴ which became the largest producing GTE field in the world. More wells are being drilled including one completed at 2898 m which is the deepest producing steam well in the world. Current estimates of the total power production capability of The Geysers range from 1000 to 5000 MW(e). An indication of the private sector's evaluation of that area's potential is given by the results of the January 22, 1974, bids for 202 km² (50,000 acres) of Known Geothermal Resource Areas (KGRA's) in California. One 9.5-km² (2340 acres) KGRA brought a bid of \$3,200,000 or 337,000 \$/km² (1367 \$/acre), and the average for 12 KGRA's was 156,000 \$/km² (631 \$/acre).⁴

Encouraged primarily by Larderello successes, GTE interests sprang up all over the world. This was to be expected because GTE manifestations occur in many locations, being usually associated with volcanic activities and evidences of crustal plate phenomena. Thus, GTE activities occur from the Aleutian Islands and southern Alaska down the west coasts of the North and South American continents, westward under the Pacific through New Zealand and Oceania and up through Japan plus another volcanically active zone extending through Hawaii. Manifestations also appear through the mid-Atlantic Ocean, including Iceland, into the southern Atlantic, up eastern Africa, and into the Red Sea and Mediterranean areas with sizeable extensions eastward across Asia. At least 19 ongoing GTE power development projects are presently scattered around the world in the areas approximately outlined above.

C. General GTE Industry Status

Many oil companies are becoming interested in

GTE because oil-drilling technologies offer a convenient way of entering into these new enterprises. Union Oil became active at The Geysers in the 1960's while others like Signal, Standard Oil of California, Sun, Phillips, Occidental, Gulf, and Getty are all now active in the western United States along with a growing group of small specialty companies. For example, in the KGRA bidding in California, referred to previously, 17 companies submitted as many as 56 bids.⁵ Various problems in the past had slowed the growth of the GTE industry. Some problems are disappearing because of developments external to the industry and others are being taken care of by accelerated efforts of the involved organizations or agencies. A discussion of the important factors affecting the industry's growth follows.

1. Economic Incentives. The promise of generating low-cost electric power has probably kept the GTE industry alive, although the large-scale development of fossil-fuel industries with easy and predictable profits has greatly overshadowed GTE. Also, hydroelectric power plants were well understood and, where water was available, such plants were built. To further lessen the incentive to build GTE power plants, large nuclear plants were advertised as the solution to all power problems. It is, however, becoming evident that fossil and nuclear power plants have problems of cost, environmental pollution, and limited fuel resources, which make other complementing energy sources, e.g., geothermal and solar, look increasingly attractive. Finally, the power industry, because of heavy financial commitment requirements, is an extremely conservative industry which measures changes in decades rather than merely years.

A brief look at the economics of GTE is worthwhile. McMillan, who helped promote The Geysers development in the 1950's presented comparative cost data in a paper at Pisa, Italy.⁶ While now several years old the paper is valuable because it compares costs for different types of plants in the same geographic area. In 1968, in California, The Geysers' fuel and operating costs were 2.75 mills/kWh, compared with 5.78 mills for the Humbolt Bay nuclear plant and with 3.28 to 10.32 mills for all other power plants in the state, excluding hydroelectric. Using slightly different assumptions, Goldsmith⁷ estimates a GTE electricity cost of 5.33 mills/kWh,

which compares favorably with McMillan's data for other power plants (average, 7 mills/kWh, excluding hydroelectric). Included in a recent survey report by the State of Oregon Public Utility Commissioner's Office,⁸ R. Bowen, State Economic Geologist, shows that GTE power costs are 46, 61, and 82% of nuclear, coal, and hydroelectric costs, respectively. For dry-rock geothermal reservoirs being studied at the Los Alamos Scientific Laboratory, Brown et al.⁹ show in a preliminary study a power cost of 4.7 mills/kWh in 570 K rock in the New York area, compared with 11.8 and 13.3 mills for nuclear and coal, respectively. At Cerro Prieto in Mexico where a 75-MW plant with 15 supporting wells is operating by flashing superheated water, the Mexican Department of Geothermal Resources recently released cost data showing that the cost of the production installation amounted to 264 \$/kW.¹⁰ A previous release showed an electricity cost of 8 mills/kWh.¹¹ In Russia, where enormous reservoirs of hot water are known, Kremnjev et al.¹² also conclude that, in many cases, GTE is competitive with other types of energy systems.

Note that costs such as those quoted above are for small GTE installations and for very large coal or nuclear power plants. Power from these latter types would be even more costly if generated in small plants. Indeed, one advantage of GTE power generation is the possibility of distributing many smaller plants over the country in lieu of fewer very large installations with their attendant huge cross-country power-transmission lines and right-of-way land-area consumption. Another economic attraction is the short construction time for a GTE power plant. Goldsmith⁷ quotes Pacific Gas and Electric Co. as estimating only 28 months needed to build a 110-MW system at The Geysers, from approval and equipment purchase confirmation to commercial service. At Cerro Prieto, Mexico, drilling was recently started for a new 75-MW complex,¹¹ which is scheduled for power production in July 1976, or less than three years from initiation.

2. Geothermal Resource Data. A major factor in restricting the growth of the industry has been the lack of geothermal resource data, including detailed understandings of how various types of reservoirs behave and can best be exploited. The United States Geological Survey has been gathering resource data

for many years. One example is a detailed (3733 references) compilation by Waring et al.¹³ on the thermal springs of the United States and the world. However, national geothermal resource estimates in the literature differ by orders of magnitude, because different assumptions are made as to what is or is not economically feasible. The same phenomenon occurs in fossil-fuel resource estimates. Although total resources remain the same, proven reserve estimates change when, for example, oil prices rise and make formerly uneconomic and therefore unavailable resources suddenly economic and qualified as proven reserves.

In GTE, confusion about resources and reserves will continue until much more exploration and production technology is established. The most advanced GTE power systems today are probably the vapor-dominated types such as The Geysers. Yet, the exact nature of the thermal reservoir at The Geysers is not clear. The large energy resource in the Imperial Valley hot brine is still not being economically exploited because of technical difficulties. Methods for using the geopressurized GTE resources in the Gulf of Mexico are still quite speculative. Finally, the dry-rock concepts at the Los Alamos Scientific Laboratory which may make many of the high GTE reserve predictions come true are still in an early stage of research.

3. Environmental Pollution Awareness. Hopefully, the GTE industry will be able to maintain its claim of being environmentally acceptable. Environmental awareness is a new phenomenon that could benefit the industry. However, H₂S pollution instead of SO₂ pollution is not much of an improvement. Also, thermal pollution because of the lower thermal efficiency in GTE conversion to electric power (vis-à-vis fossil-fueled thermal systems) is a disadvantage. Conversely, direct use of thermal energy other than for electric-power generation could reduce the overall thermal pollution problem while making a significant contribution to efficient energy utilization.

4. Federal Support. Until recently, federal interest in GTE development has not been great. The Geothermal Steam Act of 1970¹⁴ was passed to facilitate the issuance of leases on public lands for the purposes of GTE developments. However, three years elapsed before the final regulations were issued on

December 21, 1973.¹⁵ While not a technical problem, lack of definitive federal guidelines put the private sector in a position where funding for GTE projects was inhibited. Federal funding of technology development has also been low and fragmented among ten different government agencies.¹⁶ Many problems are assuming lesser importance as regulations are defined, leasing competitions are held, and federal geothermal R&D funds are increased and coordinated.

5. State Support. All the western states are either accepting GTE as a viable energy source or seem to be rapidly becoming aware of its potentials. Active projects or studies are in progress in, at least, California, Oregon, Washington, Montana, Idaho, Utah, Nevada, Arizona, New Mexico, and Colorado. On the west coast, where large power-load centers exist, interest is high. Oregon and Washington have both recently issued state-sponsored studies^{8,17} of energy resources, and both states devoted a significant portion of their effort to geothermal energy.

II. GEOTHERMAL WELLS: CURRENT TECHNOLOGICAL AND COST STATUS

A. Exploration

1. Extent and Nature of the Resource. As noted earlier, GTE resource areas of the vapor-dominated or hot-water types exist throughout the world. Steam fumaroles or hot-water springs are indicators of such areas and occur from the Rocky Mountain States westward to the coast; hot spots are known to extend even out into the Pacific Ocean basin. Alaska has many hot-spring indications of GTE. Hawaii, because of its inherent volcanic nature, offers promise of having large GTE resources. Yet, Waring¹³ points out that Hawaii does not have many hot springs because the volcanic material is fragmented and porous, leading to a water table only a few feet above sea level. In the eastern United States, Waring lists numerous hot springs in Virginia and West Virginia, followed by Arkansas and Georgia. The above data are only rough indications of GTE resources because a significant GTE reservoir is a complex system depending on location and nature of the heat source, on water supply and recharging characteristics, on interrelation of permeable and nonpermeable strata, and on total volume of the system.

Another preliminary indicator of GTE is the measurement of near-surface heat flow in Heat Flow Units [HFU; one HFU being equal to $1 \mu\text{cal}/\text{cm}^2 \cdot \text{s}$ ($0.0418 \text{ W}/\text{m}^2$)]. Knowing the average or normal value of heat flow for a region, one can then detect the abnormal areas which may be suitable for extracting heat. Very approximately, the average HFU for the world is ~ 1.5 .¹⁸ In the eastern United States the value is ~ 1.3 , whereas in the western states it is ~ 2.0 . Thus, HFU considerations would lead to the conclusion that the western United States is a good place to search for GTE. Again, heat flow is only one indicator in a complex system.

Two United States Geological Survey (USGS) scientists, L. J. P. Muffler and D. E. White, have published estimates of GTE resources. In a 1965 paper, White¹⁹ calculated the amount of heat available in the outer 10 km of the earth to be $\sim 4 \times 10^{29} \text{ J}$ (10^{26} cal) or several thousand times the heat represented by total world coal resources. In a 1972 paper,²⁰ Muffler and White estimated the total stored heat in all geothermal reservoirs to a depth of 10 km, including reservoirs of molten rock, abnormally hot rocks of low permeability, and deep sedimentary basins of near-normal conductive heat flow such as the U.S. Gulf Coast and Kazakhstan in the U.S.S.R. They arrived at a value of at least $4 \times 10^{26} \text{ J}$ (10^{23} cal) or about equal to that of the world's coal resource. By assuming an efficiency value for converting the above GTE resource into electricity, Muffler and White conclude that GTE is unlikely to supply more than perhaps 10% of domestic or world electrical power. However, in favorable areas such power may be of major importance. They also conclude that knowledge and extent of our geothermal resources is still inadequate and new, and more efficient ways to use this resource are needed.

One of the new approaches to GTE is that of hydraulically fracturing hot dry rock and then extracting thermal energy with circulating water. This technique is in the research stage at the Los Alamos Scientific Laboratory (LASL). Potter²¹ at LASL estimated the total available United States GTE resource using the hot-rock method to be $2 \times 10^{27} \text{ J}$. (For comparison, this amount of heat is about 3000 times the $7 \times 10^{23} \text{ J}$ of total energy used in the U.S. in 1970.)²² He further estimated that $13 \times 10^{26} \text{ J}$ could be used directly as thermal energy and the

remainder to generate electric power equivalent to 488,000 GW-years. Using a gross averaging method, the latter is equivalent to a power output of 4,880,000 MW for an effective GTE lifetime of 100 years. The average value of 4,880,000 MW compares favorably with the estimated total U.S. electric-power requirement of 2,000,000 MW in the year 2000.²³ Noteworthy is the fact that the dry-rock method could be applied in every state.

In the vapor-dominated and hot-water reservoirs now known, the maximum well depths are 3 km, and in a good reservoir the temperatures might be between 470 and 570 K. The highest temperatures, 660 K, have been measured in the hot-water systems at Cerro Prieto, Mexico. In the vapor-dominated system at The Geysers, the downhole pressure is ~ 3500 kPa (500 psi) and at Cerro Prieto the pressures can be as high as ~ 12,000 kPa (1700 psi). The temperature characteristics in a conventional water-based reservoir have been explained by D. E. White.²⁴

Figure 1 is reproduced from this work and shows temperature-versus-depth changes for various conductive and convective heat-transfer conditions. Lines A, C, and B show data for temperature gradients in a purely conductive situation of 8, 25, and 50 K/km, respectively, and might be considered normal. Areas are known with abnormal gradients such as 75 K/km (line D) which would result in 500 K at 3 km depth. The Reference Boiling-Point Curve F is a plot of water boiling temperature at the hydrostatic pressure corresponding to the depths shown and includes a temperature correction for water density. Curve E illustrates rapid upflow of water starting at a moderate temperature at depth and boiling as it approaches the outlet and discharging at 373 K. Curve G starts at a high temperature similar to E but with a low upflow rate. Thus, the heat has time to conductively dissipate and the water arrives at a low surface temperature of 320 K. Curve H illustrates saline water in the Salton Sea system. At 550 K, Curve H crosses the reference boiling Curve F and then exceeds the reference temperature because of salinity effects on the boiling point. Because of the low-permeability sediments in the Salton Sea system there is a strong conductive-gradient effect on Curve H at shallow depths. Curve I illustrates a high-temperature system at depths similar to the systems observed at Wairakei, New Zealand, and at

Fig. 1. Temperature profiles controlled by conductive gradients within the "normal" range (A,B,C) and above "normal" (D), and by convective transfer of heat in hot-water systems of different subtypes, compared with reference boiling-point curve F (see text). (Taken from White.)²⁴

Yellowstone Park. These systems tend to be self-sealing due to mineral deposits forming near-surface restrictions to the flow and can build up pressures and temperatures exceeding those of Curve F. Curve J illustrates a steam-producing situation where steam is being generated in a deep brine-water body which exists below 1400 m. Higher steam temperatures and enthalpies may be obtainable as the brine becomes more concentrated and boiling occurs at greater initial temperatures.

2. Surface Prospecting Techniques. To start a GTE exploration one must determine an objective, e.g., is a low-grade or a high-grade heat source required? Some examples: (1) heating of buildings, greenhouses, mines, etc., can be done with 350 K, (2) industrial processing such as water desalination could be done with 450 K, (3) electric power generation requires 450 K and preferably higher, and (4) a multitude of new applications would open up if temperatures > 670 K were to become available by means of new heat-extraction techniques. The next steps would usually be literature surveys and field surveys. Noteworthy, for GTE literature, is an extensive bibliography of worldwide GTE reports,

sponsored by the National Science Foundation and published by the New Mexico Institute of Mining and Technology, Socorro, New Mexico in 1971.²⁵ Another current project, using all available well data, is to map subterranean temperature conditions across the North American continent. This is being done by the Amercian Association of Petroleum Geologists, Tulsa, Oklahoma. Methods used for field tests are listed below.

a. Geochemical Analyses. The geochemical analyses of hydrothermal waters produce data on water condition at depth (steam or liquid), temperature at depth, source of the water, chemical composition at depth, and character of the water to be handled at the surface. D. E. White²⁶ described geochemical methods at the U. N. Meeting in Pisa, Italy. Geochemical indicators of subsurface temperatures are sometimes called geothermometers, the use of which are described by Fournier, White, and Truesdell.²⁷ Fournier and Truesdell have also studied the problem of mixing hot and cold waters.²⁸

b. Thermal Measurements. Aerial infrared surveys of large areas have been used by the United Nations in Ethiopia and Kenya to delineate above-normal surface temperatures.²⁹ The USGS has also detected some warm areas by this method. This technique has severe limitations, the signal-to-noise ratio making it difficult to accurately detect heat-flux anomalies less than about 100 to 150 times the normal;³⁰ however, the contrast needed may be much less, depending on the terrain being surveyed.

Using boreholes, thermal gradients with depth are measured and heat flows calculated. Very shallow (~1-m-deep) holes are usually not worthwhile because of near-surface effects. Holes to 150 m have been more successful although the data must always be evaluated for effects of ground-water movement. Typical boreholes are drilled 100 mm (4 in.) in diameter with a 20- or 25-mm (0.7-to 1-in.) pipe cemented into the hole. The pipe is filled with water and capped, and after equilibrium is established a temperature traverse is made from the top down.³¹ Combs³⁰ writes about gradient and flux-calculation results of 20 HFU average in a New Zealand field, 120 times normal near Steamboat Springs, Nevada, and of at least 67 HFU at Yellowstone's Firehole Basin.

c. Geophysical Methods. One of the most useful geophysical tools is the measurement of deep-sounding electrical resistivity, which is primarily dependent on the effective porosity, temperature, and salinity of the interstitial water at depth.³⁰ This method is fast and convenient, and can be used to probe down to at least several kilometers. It has been demonstrated to be very effective in New Zealand. Meidav³² reviewed the method at the U.N. 1970 meeting in Pisa, Italy. Recent developments in electromagnetic methods may become especially useful in geothermal areas of low resistivity. At least three different types of electromagnetic apparatus are being developed. Aeromagnetics have also been used in attempts to locate hot plutons where water can cause changes leading to reduced magnetic properties.³³ Gravimetric measurements are also normally made across an anomalous area.

d. Seismic. For the exploration of hot water or vapor-dominated reservoirs, active seismic methods are only indirectly useful, active seismic data being used primarily to define subsurface geologic structure and basement-rock depths and configurations.³⁴ However, if future drilling capabilities allow exploitation of very hot intrusions or magmas then the active seismic methods could become much more interesting and applicable. Some success along these lines is indicated by Furumoto.³⁵

Passive seismic methods are directly useful for defining water or vapor reservoirs, one use being to detect micro-earthquakes which seem to be prevalent in geothermal reservoirs. Also there is usually an abundance of background noises caused by water or gas movements. Exceptions to this statement are possible, however--the most notable current example being the high-heat-flow area being studied at Marysville, Montana, which is one of the most quiet spots known in the U.S.¹⁸

3. Exploration and Discovery Wells. With all the exploratory methods available, the presence of a viable GTE reservoir must still be proven by drilling. These exploratory holes should be used, according to Combs and Muffler,³⁴ for measurements of temperature and pressure profiles, permeability, porosity, lithology, stratigraphy, fluid compositions, other geophysical logs, and production tests. They further state that these data, which can only be obtained from a borehole, are essential in:

"1. Estimating the ability of the geothermal reservoir to produce sufficient energy over a sufficiently long time to be economically attractive. 2. Distinguishing between different models of the geothermal system, with the aim of accurately predicting production characteristics under varying exploitation conditions. 3. Calibrating and refining geophysical and geochemical methods for recognizing and delineating geothermal systems."

The above described uses of exploration holes are consistent with today's capabilities for drilling, downhole measurements, and logging. An additional desirable capability, not yet available, is that of continuing drilling economically past the anticipated production zone towards the source of heat that drives the reservoir. This could mean penetrating into hard igneous and metamorphic rocks at very high temperatures. The objectives would be to gain a better understanding of the basic system and to determine whether reinjection fluid, or even additional fresh water, might be added at the lower hotter depths to percolate upward into the production zone. The latter could greatly augment and artificially stimulate both the production and useful life of the reservoir. At the Geothermal Resources Research Conference in Seattle, in September 1972,³⁶ two recommendations were that high priority be given to immediate improvement of exploration methods and to the development of cheaper drilling methods in high-temperature formations. These improvements would result in improved reservoir and economic models which, the conference attendees also concluded, were sorely needed.

4. Costs. Let us start this discussion on costs with a look at average costs for oil and gas wells as presented in the 1972 Joint Association Survey Report on drilling costs³⁷ and presented in Table I.

For a number of reasons the costs of geothermal wells are greater than those of average oil and gas wells. Greider³⁸ of Chevron Oil compiled cost data on geothermal exploration wells as follows: Wells to depths of 1.5 km (5000 ft) in most geothermal provinces in sedimentary basins in the U. S. average 65 to 100 \$/m (20 to 30 \$/ft). In remote areas or in those with interbedded volcanic rocks, costs run from 100 to 200 \$/m (30 to 60 \$/ft). To run casing

TABLE I
AVERAGE DEPTH AND COST PER DEPTH
TOTAL UNITED STATES IN 1972*

Average Depth, km	Type of Wells & Average Cost** per Meter, \$/m			Total Weighted Average
	Oil	Gas	Dry	
1.3	44.10	45.10	25.10	35.90
(4300)	(13.40)	(13.80)	(7.70)	(11.00)
1.9	52.95	53.80	34.80	45.20
(6200)	(16.10)	(16.40)	(10.60)	(13.80)
2.6	68.00	82.90	54.40	65.00
(8500)	(20.70)	(25.30)	(16.60)	(19.80)

*Numbers in parentheses are ft and \$/foot.

**Includes drilling and casing.

and to prepare for production in these 1.5-km wells, costs 33 to 50 \$/m (10 to 15 \$/ft). Thus, costs of geothermal wells range from 100 to 250 \$/m (30 to 75 \$/ft) or approximately two to five times higher than the average costs of oil or gas wells given in Table I. Greider presented other cost data: Surface exploration costs run from \$75,000 to \$90,000 per typical area of interest. Only one out of four of these areas would probably justify an exploratory hole, resulting in \$300,000 to \$380,000 per drillable prospect. Only one of four of these prospect wells would be worth running pipe and completing for extensive testing. The three unsuccessful wells would cost ~\$100,000 to \$200,000 each and the completed wells ~\$150,000 to \$250,000. The net average cost for each prospect worth completing and testing extensively is then \$650,000. Perhaps one of four of the completed prospect wells would result in the discovery well of a reservoir large enough to be commercially attractive. The ratio of total wells drilled to each discovery well is 16:1. Greider feels that this is a realistic ratio as the industry matures after the large easily located reservoirs are drilled. Axtell³⁹ of Phillips Petroleum Corp. agreed that 16:1 is reasonable and cited historical data showing five discovery wells out of 75 exploration geothermal wells for a 15:1 ratio. Greider's definition of a good discovery well is one defining a reservoir capable of 275 MW(e) power output. A summary of his cost model is shown in Table II

TABLE II
COST TO PRODUCE A DISCOVERY WELL
FOR A 275-MW(e) RESERVOIR

	Cost,\$	% of Total
Land acquisition (nontechnical leasing, bonus, rentals, etc.)	3,580,000*	45
Drilling (12 unsuccessful + 4 completed holes)	2,600,000	32
Surface exploration (geology, geochemistry, geophysics)	1,840,000	23
Total	8,020,000	100

*Considering the recent high bids made at the Jan. 22, 1974 KGRA competitions in California, these costs are probably low.

In Table II, drilling amounts to 32% of the costs and is significant. Table II can also be used to indicate the possible overall exploration drilling costs to, e.g., the year 2000. Recalling Muffler and White's estimate that GTE might supply 10% of the nation's electrical power (see Section II, A 1) and the AEC prediction²³ of a total U.S. power capacity of 2,000,000 MW(e) by the year 2000, one arrives at 200,000 MW(e) supplied by GTE in 2000. This is low compared to the estimate³⁶ of 395,000 MW(e) by 2000 made at the 1972 Seattle Geothermal Research Conference. However, using the 200,000-MW(e) estimate, 727 of Greider's 275-MW(e) plants would be needed. Neglecting any effects of capital costs and inflation, the total costs for exploration drilling only for the 727 plants would be $\$2,600,000 \times 727 = \1.89×10^9 . This simple calculation of exploratory drilling costs indicates that the costs are high enough to easily justify the cost of research leading to lower exploration drilling costs. The much higher costs associated with the production and reinjection wells will be discussed later.

A factor worth noting is that the hole size of an exploratory well is almost always the same as if it were a production well, the reason being that a successful discovery well can then be easily converted to a production well. With current cemented-casing methods it is not feasible to drill a smaller, more economical well and later enlarge the well to production size. A possible method for enlarging small exploratory holes to production size is

given in Section III where rock-glass-lined holes are discussed.

B. Problems in Completing Geothermal Wells

1. Dependence on Oil-and Gas-Drilling

Equipment and Methods. The methods used in making geothermal wells are essentially the same as those for oil or gas wells. Indeed, this very fact somewhat impedes GTE development because geothermal well drillers are forced to use materials and equipment that are not necessarily best for geothermal wells with their higher temperatures and corrosive conditions. Problem examples are: (1) only oil-well tubular goods and bits are available, (2) muds and cements are not checked out for high-temperature use because suitable high-temperature laboratory equipment is not available, and (3) bit-bearing lubrication systems are not designed to withstand GTE temperatures. This dependence is designated as an important consideration in the NSF-sponsored study of impediments to geothermal development⁴⁰ being done by Bechtel Corp. for The Futures Group, Inc.

2. Geological Factors. The geological character of The Geysers, a vapor-dominated reservoir, is described by Cromling.⁴¹ The area is underlain by the Jurassic-Cretaceous Franciscan formation -- an eugeosynclinal sequence of graywacke, shale, basalt, and serpentine. These Mesozoic rocks were uplifted and complexly faulted into a series of horsts and grabens and during Pleistocene time, volcanic rocks were erupted onto the then eroded surface. The Geysers is at one end of a graben with Franciscan graywacke overlain by basalt, which is then overlain by serpentine. In some places the basalt and serpentine have been downfaulted into the underlying graywacke, the geometry of the faults indicating that the thermal areas are located on the fissures closest to the serpentine body. The Quaternary volcanic rocks indicate the presence of young hot magma at depth. The rocks are hard and badly jointed.

Not all geothermal areas have the character described above. For example, large sedimentary basins can provide hot water. In Hungary, Boldizsar⁴² describes the Hungarian Basin of the Danube River system as being filled with several kilometers of sand and clay sediments spreading over an area of 92,000 km². No volcanic activity occurred in

this area during the Cenozoic Era, but the heat flow is higher than normal -- between 0.084 and 0.142 W/m^2 [2.0 and 3.4 HFU ($\text{kcal/cm}^2 \cdot \text{s}$)] -- and thermal gradients are 50 to 70 K/km. Water free-flows at 357 K from wells of 1.8 km average depth and is used for heating buildings and greenhouses. The Imperial Valley, California, is a sedimentary basin with static water temperatures approaching 670 K.

The large sedimentary basins are usually characterized by above-hydrostatic pressures.³⁴ Although these strata may be easier to penetrate with rotary drills than The Geysers type rocks, operations can be complicated by hot corrosive water at high pressures.

Wunderlich⁴³ described how present orogenic activity may be an important factor in influencing the heat-flow distribution of the earth and the location of GTE anomalies, in addition to volcanism, highly permeable sedimentary basins, and rocks of high heat conductivity such as rock salt. He states that "Some of the interesting zones of abnormally high heat flow show a characteristic position relative to young orogenic belts. Usually, orogenic fronts are combined with low heat flow values in the foreland and high heat flow behind the front." Further development of Wunderlich's thesis may furnish guidance for locating new "hot spots" associated with young mountainous regions.

3. Surface Sites and Equipment. Because geothermal anomalies are often located in volcanic and mountainous terrain, the drilling sites can cause problems and abnormal expenses. Cromling⁴¹ describes his drilling-site problems at The Geysers very well. He cites rugged, mountainous terrain; very small drill sites; blasting required often; little top soil and that little sloughing readily; steep roads requiring tractor towage; pits on various levels, etc. His site costs run from \$10,000 to as much as \$40,000. The latter cost is corroborated by Hutchinson of Standard Oil of California.⁴⁴ Cromling also reports that at The Geysers the drill rig should be overdesigned for the job so as to withstand the excessive torque and shock loadings.

Of significant economic importance to the GTE exploratory drilling industry is the lack of a modern, easily moved drilling rig capable of penetrating to depths of up to 4 km and adequately

equipped for rapid changes in drilling procedures as hole conditions change.⁴⁵

Another type of surface capability lacking in GTE work is the so-called Optimized Drilling "concept". This concept has been developed in the oil industry and is described by Lummis.⁴⁶⁻⁴⁸ The concept envisions the establishment of a standardized data-acquisition system ultimately resulting in a well-drilling data bank used to analyze and optimize the drilling of new wells. The data would cover the mud program, drilling hydraulics, bit types, bit rotation, depths, formations, etc. Comparable data are relayed to the data-bank location for analysis from an active drilling rig. Computer programs would continuously analyze the data and optimize the modes of operation to minimize total overall cost. Kennedy⁴⁹ reports cost savings of 30 to 40% on a 14-well program in Wyoming, using the Optimized Drilling concept. Another example is a 25% savings on two North Sea wells linked by satellite with an "Op-Drilling" headquarters in Tulsa, Oklahoma.

4. Drilling. In current geothermal wells, drilling is easy in some sedimentary basins and is very difficult in hard, fractured rocks found, e.g., at The Geysers. The latter results in high bit wear and often in failures of bit bearings due to a combination of temperature, stress, corrosion, and fatigue effects. Cromling⁴¹ describes typical actual penetration rates of 3 to 6 m/h, using mud, and of 3 to 11 m/h using air as the circulating fluid for 310-mm (12-1/4 in.)-diam holes. In the final 222-mm (8-3/4 in.) hole into the production zone (on air), rates of 7 to 23 m/h are attainable. Of course, the overall effective penetration rate can be considerably less than the actual drilling rate, as illustrated by the detailed drilling data given by Matsuo⁵⁰ and shown in Table III. He states that in Japanese steam fields, rock hardness, lost circulation, and other conditions unique to geothermal wells cause drilling of steam wells to be slower than drilling for oil or gas at depths ranging from 500 to 1300 m and working at downhole temperatures of about 370 to 510 K.

To broaden our understanding of factors affecting geothermal well drilling we have studied the activity logs⁵¹ for 125 geothermal wells drilled in California. The majority of the data were

TABLE III
AVERAGE DRILLING RATES FOR SIX
GEOTHERMAL WELLS IN JAPAN
(Data from Matsuo⁵⁰)

Well Designation	Type Well	Total Depth, m	Average Penetration Rate When Drilling		Average Overall Rate to Total Depth	
			m/d	m/h	m/d	m/h
Shikabe HGSR-1	Production	500	13.9	0.58	10.0	0.42
Matsukawa R-3	Production	210	17.3	0.72	11.4	0.48
Ohnuma R-1	Production	850	25.0	1.04	12.8	0.53
Onikobe GO-10	Production	1350	18.2	0.76	10.9	0.45
Takinokami	Survey	403	16.1	0.67	11.5	0.48
Takenoyu	Survey	309	15.2	0.63	8.9	0.37

either from the general Geysers area or from Imperial Valley, California, and are here designated Steam, Hard Rock (SHR); and Hot Water, Sedimentary (HWS); respectively. The data include 92 SHR and 33 HWS type wells. Their depths are indicated in a frequency of occurrence-versus-depth plot in Fig. 2. Selected depth intervals are 300 m. About 40% of the Imperial Valley wells ranged in depth from 1300 to 1900 m (4300 to 6200 ft). In the Geysers 50% of the wells are in the 1900- to 2500-m (6200- to 8200-ft)

range. A similar plot is shown in Fig. 3, but for overall average penetration rates where the average includes total time from spudding-in to total depth. In the Imperial Valley the penetration rates peak at about 1.5 to 2.5 m/h (4.9 to 8.2 ft/h) for 42% of the wells analyzed. In The Geysers, 52% of the rates peaked at 1 to 2 m/h (3.3 to 6.6 ft/h), somewhat lower than the peak rates in the Imperial Valley.

The same data are shown in Fig. 4 and 5 as

Fig. 2. Depths of geothermal wells drilled in two geothermal regions.⁵⁰

Fig. 3. Overall average penetration rates in typical geothermal wells.⁵⁰

Fig. 4. Overall average penetration rate vs depth for sedimentary hot water wells.⁵⁰

Fig. 5. Overall average penetration rate vs depth for steam-dominated, hard-rock wells.⁵⁰

penetration rates-versus-depths plots. For the Imperial Valley, three widely scattered points were discarded, and the remaining 91% of the data lie in an area as shown. Similarly, 99% of the data are enclosed in Fig. 5 for the Geysers. The data trends indicate a decrease in penetration rates with depth in the Imperial Valley and a lesser decreasing trend in the Geysers. In the Imperial Valley the wells are drilled to total depths with muds and at higher temperatures and pressures than at The Geysers where the drillers use air (which is simpler to handle than hot muds) for much of the well in more competent rock and at lower temperatures. The difference in drilling techniques may account for the fact that, even though the strata at the two locations are vastly different, the penetration performance is not. The Imperial Valley data average 1570 m (5160 ft) depth and 1.82 m/h (5.97 ft/h) penetration rate. Corresponding averages for The Geysers are 1890 m (6230 ft) and 1.98 m/h (6.49 ft/h). However, well costs at The Geysers, according to Greider³⁸ and Cromling,⁴¹ are ~1.5 to 2.0 times higher, probably because of higher costs due to difficult siting conditions; erosion by high-velocity air and steam flow; and high bit failure rates in hot, hard, jointed rocks.

The lost-circulation problem mentioned earlier is typical of The Geysers and other locations where low ground-fluid pressures exist in badly fractured or highly permeable formations. Cromling⁴¹ and Budd⁵² both verify this problem at The Geysers. A similar problem occurred in the Jemez Mountains at the Los Alamos Scientific Laboratory's second hot-dry-rock experimental well, GT-2, where excessive lost circulation in the sedimentary section was encountered in the first 600 m. This problem is often solved by changing the drilling fluid from mud to air. The use of air in a steam well, however, results in excessive erosion of the drill stem and of all other metal parts in contact with the mixture of air, steam, and cuttings being blown out of the well. The flow rate of the air is fixed by the bit-cooling and debris-removal requirements, but steam entering the well anywhere above the bit adds to the total volumetric flow rate to create the excessive-velocity flow condition.

The lack of adequate directional control equipment in hard rocks is a problem. Cromling⁴¹ states

that directional drilling at The Geysers is expensive and adds as much as \$100,000 to the cost of a well in difficult situations. Matsuo⁵⁰ and Suter⁵³ both confirm the desire for good directional control and point out the difficulties of attaining it in hot hard-rock formations. For production wells, especially where the surface sites are expensive and difficult to set up, directional control would allow three or four wells to be drilled from one central surface area. Currently available directional downhole motors are inadequate in geothermal wells because of high temperatures and also because water or mud is often used to drive the motors, whereas the drilling fluid may usually be air.

5. Casing and Cements. The presence of hydrogen sulfide is not new to the drilling industry and is relatively common in GTE projects. Dench⁵⁴ reviewed the problems of casing design in the geothermal fields of New Zealand and described the problem of cold, damp hydrogen sulfide in contact with casing at high tensile stresses causing fracturing in all grades of casing steels tested. In one case, failure occurred at only 25% of the normal ultimate strength. Due to thermal expansion and contraction effects the casing joints can be loaded either in tension or in compression. Cromling recommends buttress joints, which cause increased casing costs, for wells at The Geysers. Another temperature-caused problem is brought up by Suter who states that casing wear occurs in The Geysers wells because rubber drill-pipe protectors, used to centrally locate the drill pipe in the well, fail due to temperature and allow the drill pipe to rub against the casing. A problem of high operating pressure requiring either new high-strength materials or very heavy casing walls was noted by Bealaurier⁴⁰ for geopressurized wells under both static and dynamic flow conditions.

In geothermal wells, one function of the casing cement is to prevent the detrimental intrusion of cold water into the well. It was found early that common cement at high temperatures suffered strong retrogression effects and became highly permeable, as reported by Nakajima.⁵⁵ Special cement mixtures capable of setting up properly at higher temperatures have been developed and will need further improvement as temperatures in future GTE developments become higher. Nakajima mentioned the frequent

need for cement squeezing, i.e., the special application of high pressure to force the cement back of the casing, to recement channeled areas, or to correct cement-deficient zones. Cromling reports requiring squeezing in about 50% of the wells at The Geysers. Dench listed four possible failure modes,⁵⁴ which may result if the cementing operation leaves a length of casing not bonded to the hole: (1) water in the annulus expands when the well goes into production causing high temperature/pressure buildup and casing failure, (2) compressive failure of a joint due to heating, (3) tensile failure of a joint due to cooling, and (4) failure of the well-head connection. An example of the first type of failure is the Matsukawa Well R-4 in Japan where the casing collapsed at 35 m depth.⁵⁰ Matsuo reports that such repairs are very difficult and expensive. Matsukawa Well R-3 also had a casing failure for some undefined reason when casing fragments began to be blown out of the well after seven months of production followed ten months later by blowout of a large quantity of casing fragments.

One possible reason for the latter type failure and casing disintegration is the fact that, typically, a GTE steam well uses the stepped casing as the production-flow passage, which is constantly directly exposed to the high-velocity steam flow. In oil or gas wells, on the other hand, an inserted production tube of constant diameter is normally used which is easily removed for maintenance, if necessary. A well-drilling system that would produce a hole of constant diameter to total depth would facilitate the use of a production tube. Also, it would avoid sudden turbulent expansion conditions across a step that can cause precipitation of salts from the expanding fluid and their deposition on the casing walls.

6. Drilling Fluids and Muds. The use of air as the drilling fluid and the resultant erosion problem have already been noted. Water is another readily available and easily handled drilling fluid, which can be used if the downhole fluid pressure is not above hydrostatic and if lost circulation, should it exist, can be compensated for by either having sufficient makeup-water flow capacity or by pumping all the water and debris directly into the formation with zero return to the surface. However, if the ground

fluid pressures are above hydrostatic then special drilling muds must be composed, which are compatible with high temperatures and meet the following requirements: The mud must have the density needed to hydrostatically balance the downhole pressures and to otherwise stabilize the hole; its surface tension must be adequate to transport the bit cuttings out of the hole; it must serve as a good bit coolant; it must not dry out and bridge flow passages during cementing (leading to casing failures); and it must not dry out or change chemically during time-consuming operations such as changing bits. There are many references in the literature to the high-temperature mud problems in geothermal wells. Recently, Greider⁵⁶ of Chevron Oil wholeheartedly endorsed the development of high-temperature muds and cements. Also, the Bechtel Corp. study⁴⁰ lists 588 K as the current limit for muds.

7. Downhole Measurements and Samples. The early exploration and modeling phase of a GTE reservoir requires taking many downhole measurements and samples of the rock and general fluids. Witherspoon,⁵⁷ who is involved with studies of the national geothermal resources, feels that equipment and methods for obtaining the required downhole data leave much to be desired. Cores are used to obtain data on the type of strata being encountered, on fracture orientation, and on other phenomena. However, cores are taken in insufficient intervals and the taking of many more core samples would be highly desirable. The alternative and perhaps ultimate approach to this problem is to develop new downhole diagnostic techniques. Ground-water samples are also very important, if they can remain chemically undisturbed between the time of in situ sampling and the time of chemical analysis. In a water-based GTE reservoir assessment program the data should, at a minimum, be sufficient to determine downhole temperatures and pressures, porosity, permeability, fluid chemistry, and GTE producibility.

8. Costs. Cost data for a typical exploratory geothermal well have been presented in Section II, A.4. According to Greider's data for large-scale development of 275-MW(e) GTE complexes, the cost of 50 production wells per complex would, with careful planning, average \$7,500,000; and the cost

of 25 reinjection wells would amount to \$3,000,000 to \$3,500,000. Thus, the total cost for production and reinjection wells would be ~\$10,750,000 per complex.

These costs, which average 94 \$/m (29 \$/ft), are reasonable considering that only about one in twenty geothermal fields²⁴ would be in a vapor-dominant field like The Geysers, where drilling is most expensive. Then, continuing the example started in Section II, A.4, the total costs of production and injection wells to develop a complex with 200,000 MW(e) power output would be $727 \times \$10,750,000 = \7.28×10^9 . This, added to the previously derived exploratory drilling cost of $\$1.88 \times 10^9$, gives us the total drilling expenditures, $\$9.7 \times 10^9$, just for finding and setting up the wells. Clearly, GTE drilling with current techniques could be very costly (e.g., running into tens of billions of dollars) making it quite worthwhile and cost-effective to develop new, cheaper techniques and equipment. Note, again, that the initial assumption of 200,000 MW(e) may be low.

The above discussions of cost centered primarily on wells in conventional GTE areas where maximum depths may not exceed 3 km. For hot dry rock and perhaps geopressurized developments the depths and drilling costs could be considerably higher. Costs increase very rapidly with depth, as illustrated in Fig. 6. The average oil and gas-well costs are shown shaded; typical The Geysers and Imperial Valley geothermal costs are shown as 160 \$/m (50 \$/ft) and 80 \$/m (25 \$/ft), respectively; for depths of 15 km, costs could be ~\$20,000,000 to \$26,000,000 per well.

9. Summary of Current Drilling Problems. It has been amply demonstrated that naturally occurring hot-water or vapor-dominated geothermal reservoirs can be penetrated by rotary drilling methods that have been developed for oil and gas wells. However, there are factors in geothermal fields such as high temperature, corrosive fluids and gases, unfavorable siting conditions, and, in many cases, hard abrasive rocks, which combine to make the average rotary-drilled geothermal wells more expensive than the average oil or gas wells of comparable depth. High well costs could significantly impede the expansion of geothermal energy sources

Fig. 6. Cost of wells per meter vs depth.

to the level where they could contribute substantially to our national energy supply.

There are many applications for geothermal temperatures less than 660 K, which is about the upper limit measured at well bottom to date. To attain the higher temperatures desirable or required for many heretofore unexploited GTE applications, one has to consider penetration either into deep hot zones or close to or directly into magmas. Current drilling methods (especially the use of muds and cemented casings for hole control and support) will thus be severely strained technically and will probably make the wells excessively expensive.

An evaluative summary of the various current drilling problems in geothermal wells is shown in Table IV.

C. Production Operational Problems

1. Production Loss with Time; Reinjection; and Augmentation. Only limited data are available on production loss with time. Even though Larderello has been producing power since 1912 it is

still not clear whether maximum output has been reached. Also, complete monitoring of production performance at Larderello has been initiated only recently. Indications are that some Larderello areas have reached the maximum because steam yields per well have been declining.³ However, successful drilling is being done at the previous margins of the field, indicating that the total heat resource is not completely understood.

Budd⁵² presented productivity data starting from 1967 at The Geysers for wells feeding Generating Unit 3. Two typical wells showed a drop to 50% of the original production rate in five years. These wells are spaced at 50 per km² (one per 5 acres). Koenig⁵⁸ considers that four or five times fewer wells per area is more typical. Well interference was also established, and a sharp production decrease was measured with more closely spaced wells.

Another effect of high production rates without reinjection for sustained periods of time is surface subsidence, especially in hot-water fields. The most notable data on subsidence are for Wairakei, New Zealand, as reported by Hatton.⁵⁹ At this field, which has been monitored since 1956, the maximum subsidence rate was 0.4 m per annum (1.3 ft per annum) and, as of 1970, a total subsidence of greater than 3 m (10 ft) is indicated. In New Zealand, the expended water was not initially reinjected because disposal on the surface was permitted, but now reinjection is being tested, also.

Reinjection of spent fluids has several objectives: First, to dispose of the fluid especially in hot saline fields where salt disposal is a large problem; second, to help prevent subsidence; third, to help recharge the reservoir. However, because known reservoirs are not completely understood, the proper recharging procedures are not well established.

One concept envisions adding more than just spent waters back into the reservoir by injecting additional water from some other convenient source. For example, it has been suggested that in some way water from the Gulf of California might be used to recharge the Imperial Valley.

2. Large Surface Piping. Because each well might supply steam for only 5 to 10 MW(e) of power

TABLE IV
SUMMARY OF CURRENT GEOTHERMAL DRILLING PROBLEMS

Item	Type GTE Field		Symbols and Problem Descriptions
	Sedimentary Hot Water	Hard, Igneous Vapor Dominated	
Surface locations	---	G	G: Difficult geological conditions typical of many GTE fields, including sites, hard rocks, caving formations, etc.
Drilling-rig design	R,X	R,G,X	R: Rigs of high mobility are needed, adequately equipped to handle rapid changes in hole conditions.
Other surface equipment	T,C,X	T,C,E,X	X: Dependence on oil- and gas-industry materials and equipment, competition for supplies.
Bits and drillability	T,C,D,X	G,T,C,D,X	T: Temperatures up to ~660 K cause rubber, elastomer, metallurgical, mud, cement, and electronic problems.
Mud-circulation systems	T,G,F,X	T,G,F,X	C: Corrosion problems caused by ground fluids and gases.
Hole support and control	G,T,F	G,T,F	E: High stem, casing, and surface-equipment erosion by air + steam + rock cuttings.
Cements	T,X	T,X	D: Directional drilling equipment not available for hard rock at high temperatures.
Downhole measurements	T,X	T,X	F: Hot saline waters contaminate drilling muds. Also, muds can reduce or kill well productivity or may hydrate clays.
Tubular goods	T,C,X	T,C,X	O: Lack of organized GTE wells drilling-data bank and ways to use such data to optimize drilling programs.
Optimized drilling	O	O	H: Costs are typically high because of interrelating effects of items listed above.
Costs of geothermal wells	H	H	

production the collecting system of a power complex must clearly consist of a considerable array of steam and hot-water lines. Budd described how the lines at The Geysers vary from 300 mm (12 in.) to 900 mm (36 in.) in size in the surface installation. Directional drilling capability might be useful to help minimize the problems of deploying surface lines by concentrating several well heads in one area.

3. Corrosion and Scaling. In hot-brine fields the corrosion and scaling of surface equipment are very severe problems. The problem also exists for production wells, and wells should therefore

be designed to facilitate rework and maintenance. Such rework might include cleanout of the scale and keeping the production zone clear to allow the fluid to enter the well. A failed cemented steel casing cannot now be repaired easily or cheaply and could result in abandonment of a well.

4. Desirability of Higher Electric Power Generating Efficiency. Due to the approximate temperatures of 470 to 620 K in conventional GTE reservoirs the thermal efficiency for generating electric power is only about 14 to perhaps 25% compared with approximately 33 to 40% for nuclear and fossil-fueled plants, respectively. If GTE were

to become a large source of electric power then thermal pollution could also become a significant problem. The efficiency could conceivably be increased by the development of advanced drills that can penetrate very hot GTE resources such as magma or very deep, hot, dry rocks, increasing the power-plant operating-temperature levels. Such advanced drilling devices are discussed in the next section.

5. Summary of Current Operational Problems.

- The decrease of well productivity with time has been observed in existing geothermal fields. This might be prevented with proper reinjection or augmentation techniques. Surface subsidence has also been observed and might be expected if widespread water withdrawals are made without replacement.
- Because each well has a steam production rate equivalent to only 5 to 10 MW(e), a considerable number of wells are needed to generate, e.g., several hundred megawatts of power; hence, the surface array of piping becomes rather complex.
- There are corrosion and scaling problems in geothermal wells, which require that the installation be designed for long-term maintenance and replacement of components subjected to these problems.
- The thermal efficiency of geothermal electric power plants is lower than that of nuclear or fossil-fueled plants. This is not an economic problem but relates to long-term thermal pollution of the earth and needs to be addressed before geothermal electric power plants are developed on a large scale.

III. CONCEPTUAL APPLICATIONS OF SUBTERRANE DEVICES TO GEOTHERMAL WELLS

A. Subterrene Program History

Rock-melting penetrators (Subterrenes) are under development at the Los Alamos Scientific Laboratory (LASL) to produce self-supporting glass-lined holes in rock and soil (Fig. 7) by

Fig. 7. Cross section of hole melted in tuff.

progressive melting with a non-rotating, hot bit rather than by chipping, abrading, or spalling.⁶⁰ Rocks and soils melt at temperatures that are relatively high: e.g., common igneous rock melts at ~ 1500 K, almost the melting temperature of steel (1500 to 1800 K). Thus, the melting penetrators utilize refractory metals such as molybdenum (Mo) and tungsten (W), which melt at 2880 and 3650 K, respectively, and which, in addition, have low creep rates at the rock-melting temperatures.

Excavation by rock- and soil-melting offers potentially new and novel solutions to the three major areas of the excavation process:

- Making the hole or breaking up the rock.
- Providing structural support for the borehole.
- Removing or displacing the debris or cuttings.

The liquid form of the rock- and soil-melt produced by a heated penetrator introduces new solution concepts into the latter two areas:

- The liquid melt can be formed into a glass lining to seal or support the walls of the borehole, and

- Any excess liquid melt can be chilled and formed into glass rods, glass pellets, or rock wool (Figs. 8 and 9); or used to form a glass-cased core that can, for example, be removed by present wire-line methods.

The LASL development program in rock- and soil-melting techniques has already demonstrated in laboratory and field tests an attractive advancement in practical excavation technology for the production of short, horizontal, small-diameter holes. This experience has been partially developed through the extensive testing of melting-consolidating penetrators (MCPs).⁶¹ The tests consisted of:

- Melting 50-mm (2-in.)-diam, glass-lined drain holes in Indian ruins⁶² at Bandelier National Monument (Fig. 10).
- Melting a 50-mm (2-in.)-diam glass-lined vertical hole in Los Alamos volcanic tuff to a depth of 26 m (82 ft) in a single run.⁶³

Fig. 9. Debris from basalt hole made by extruding penetrator showing rock wool and glass-pellet constituents.

- Melting a 50-mm (2-in.)-diam glass-lined horizontal hole in Los Alamos volcanic tuff to a length of 16 m (50 ft), Figs. 11 and 12.

Fig. 8. Hole melted in granite specimen with an extruding penetrator. Note debris.

Fig. 10. Modular Subterrene field demonstration unit melting drain holes at Bandelier National Monument.

Fig. 11. Consolidating Subterrene penetrator "holing through" a 16-m (50-ft)-long horizontal hole.

Fig. 12. Stem and service head in position to melt a 50-mm (2-in.)-diam horizontal hole.

- Melting a sequence of 76-mm (3-in.)-diam glass-lined holes in volcanic tuff in the laboratory (Fig. 13).
- Melting stable 50-mm-diam glass-cased holes in shales, adobe, and alluvium (Fig. 14).

In addition, the prototype test program has developed a universal extruding penetrator (UEP) designed for hard, dense rock.⁶⁴ Tests with this unit have recently demonstrated the capability to penetrate basalt at a 620 K temperature with enhanced performance compared to cold rocks.

The modularized, mobile field-test and demonstration unit⁶⁵ (Fig. 10) that was used successfully at Bandelier National Monument will be used for additional field tests and for demonstration of improved consolidation and extruding penetrators. The most recent addition to the field-test equipment is shown in Fig. 15 and is a trailer-mounted rig for use in the near future to make a 30-m-deep demonstration hole in basalt.

Fig. 13. Consolidating penetrator after melting a 76-mm (3-in.)-diam hole in Los Alamos tuff.

Fig. 14. Exterior view of self-supporting glass-lined hole melted in unconsolidated alluvium.

Fig. 15. Rig for vertical Subterrene hole production.

In addition, LASL has conducted preliminary tests on a 114-mm (4.5-in.)-diam, consolidating, coring penetrator designed to produce a 63-mm (2.5-in.)-diam glass-encased core.

B. Basic Subterrene Technology

1. Basic Types of Penetrators. To illustrate basic technology, the design features of three devices that have been used in rock-penetration tests are described below.

a. Melting Consolidating Penetrators (MCPs).

These penetrators utilize density consolidation for melt disposal, such consolidation relying upon the porosity of the parent rock or soil. The process

is illustrated in Fig. 16, which shows how the rock melt is formed into a glass lining and how the larger hole diameter is melted to accommodate the lining. The need for debris removal is completely eliminated. The ratio of outer-to-inner glass-lining radius can be related by conservation-of-mass considerations to obtain:

$$\frac{r_m}{r_p} = \frac{1}{\sqrt{1 - \frac{\rho_R}{\rho_L}}}$$

where r_m is the outer radius of the glass lining, r_p is the radius of the penetrator or inner glass lining (hole radius), ρ_R is the unmelted rock density, and ρ_L is the glass-lined density. Figure 17 is a design sketch of a MCP which has been tested successfully at LASL. The various components are designated.

Fig. 16. Schematic of density consolidation in porous rock.

Fig. 17. Design sketch of the Melting Consolidating Penetrator (MCP).

b. Universal Extrusion Penetrators (UEPs).

The UEP development was primarily directed toward melting holes in dense rock. However, because these devices can be used in most other rocks or soils, they are termed "universal". A sketch illustrating the UEP concept is shown in Fig. 18. The mechanical design is similar to that of the MCP. The molten rock confined by the unmelted rock and by the hot face of the penetrator is extruded continuously through a hole (or holes) in the melting face. This material is chilled and freezes shortly after the circulating cooling fluid impinges upon the extrudate exiting from the extrusion region. If frozen quickly, the material will be in the form of frozen glass rods, pellets, or rock wool. The flowing coolant can then transport these small fragments up the stem to the exhaust section. Typical pellets and rock wool that were formed from frozen extrudate and were removed by the cooling fluid during a basalt test were shown in Fig. 9.

c. Consolidating Coring Penetrators (CCPs).

The concepts incorporated in the MCP and UEP

Fig. 18. Design of the Universal Extruding Penetrator (UEP).

designs described above have been expanded to include a technique for obtaining continuously retrievable, oriented, and geologically interesting core samples from the material being penetrated. The coring concept utilizes an annular melting penetrator which leaves an unmelted, but glass-encased, core in the interior that can be removed by conventional core-retrieval techniques. Although the concept is applicable to either the extrusion or consolidation mode of melt-handling, initial program emphasis has been placed on a consolidating-coring penetrator as illustrated in Fig. 19. A 114-mm-diam consolidating corer for alluvial soils has been tested in the laboratory. The core diameter is 64 mm, and the molybdenum melting body is fabricated as a single structural component as shown in Fig. 20. The water cooling system represented a departure from previous gas systems and performed successfully. Minor adaptations to commercially available core-extraction tools are visualized.

2. Other Coring Designs. To further illustrate the design of a Subterrene coring device, refer to Fig. 21, which shows the elements of the "Geoprospector". The Geoprospector's purpose is to core and geologically

Fig. 19. Design concept of consolidating-coring penetrator.

Fig. 20. Photograph of 114-mm-diam consolidating-coring penetrator.

Fig. 21. Geoprospector conceptual design.

explore horizontal tunnel routes, but its design is illustrative of devices which may be used to produce vertical wells.⁶⁶ This design has been developed in considerable detail at LASL. It requires 150 kW of electric power to melt a 300-mm-diam glass-lined hole while removing a 200-mm-diam glass-encased core. The stable hole lining allows the use of a packer-thruster unit located in the hole-forming assembly. Provision is also made for an orientation-sensor package and for a guidance unit. A hollow, flexible stem contains the electric-power, coolant, and instrumentation lines and provides a passage for debris removal. The core is removed through the flexible stem with conventional wire-line core-retrieval hardware.

3. Rock Glass Hole Linings. The Subterrene's capability to continuously form rock-glass liners provides intriguing possibilities for a well-making device. Figure 7 shows a 50-mm-diam hole made in tuff by a consolidating penetrator where the liner volume is slightly greater than the hole itself. For larger sizes, liners would be made only as thick as necessary to meet structural, leakage, and advance-rate requirements.

Figure 22 illustrates a liner deliberately kept thinner by utilizing a UEP in porous tuff. Excess debris in the form of glass rods was removed, as shown. A typical glass liner for hard dense rock, formed by a UEP in granite, is shown in Fig. 8. Figure 23 shows a liner formed in permafrost alluvium

Fig. 22. Hole in tuff melted by UEP. Note rods of extrudate and thin glass hole lining.

Fig. 23. Sample of glass-lined bore melted in simulated arctic permafrost.

by a consolidating penetrator. The moisture close to the penetrator body was forced into the alluvium and away from the penetrator during liner formation. The Subterrene's liner-forming capability might also prove useful in preventing methane, which is pervasive in sediments, from leaking into the hole and becoming an explosive hazard during hole production.

C. Problems That Subterrenes Might Help Solve or Eliminate

We do not intend to imply that rotary drilling methods in geothermal fields should be completely superseded by nonrotating, rock-melting devices. Rather, a new Subterrene technology would open up options for obtaining the most economically and technically suitable methods for any particular set of conditions and requirements. For example, it could very well be most economical to use rotary drills for making holes rapidly in known, easily penetrated formations. Then, in hot, hard zones, the tools and methods might change to Subterrene technology to complete the job.

Listed below are categories of current rotary drilling problems in geothermal wells followed in each case by a discussion of how the use of Subterrene devices might either help solve or eliminate the problems.

- Problem: Hole stabilization in unstable formations.

Subterrene: The optimum well hole production process minimizes excavation damage to the inherent structural integrity of the ground or rock and is then followed by the continuous installation of a structural support and seal to prevent the inflow of ground fluids. This process may well be accomplished by a Subterrene system which makes the hole by melting and simultaneously forms a structural rock-glass liner.

- Problem: Rock bit wear and temperature-induced failures.

Subterrene: A Subterrene depends upon melting, not on cutting or mechanical fragmentation, and therefore eliminates this problem. Also, high rock temperatures would enhance the performance of the Subterrene bit because the bit has to supply less thermal energy to melt the rock.

- Problem: Muds at high temperatures.

Subterrene: Subterrene cooling and debris-removal system can be isolated completely or almost completely from detrimental effects of the ground or rock. Therefore, the cooling and debris-removal fluid could be, e.g., simply water or any other fluid that is easily made compatible with the static temperature conditions.

- Problem: Cements at high temperature.

Subterrene: Steel casings may not be necessary if good structural rock-glass hole linings can be made. If steel casings are used, the relatively smooth surface inside the glass lining should facilitate the flow of the cement. Also, the requirements that the cement be both strong and impermeable should be lessened because of the presence of the glass lining.

- Problem: Abrasion and erosion due to steam-plus-air flow.

Subterrene: This problem arises because the amount of air is presently determined by bit-cooling and cutting-removal requirements and because steam leakage into the borehole is unpredictable and uncontrollable. Subterrene designs can isolate the bit working fluid from any steam inflow. Also, the glass lining should minimize steam inflow.

- Problem: Production-zone hole completion.
Subterrene: The Subterrene could penetrate the production zone with a glass-lined hole. This penetration would not kill or impair the zone's production capability because drilling fluid, cuttings, and lost-circulation material would not be pumped into the zone. Also, the sealing action of the lining would facilitate stem and bit changes, if necessary. Several ways to ultimately complete the well and to allow the hot water or steam to flow into the well are conceivable: One might be to shatter the glass liner with a linear explosive; another, to conventionally perforate the liner with shaped charges; and still another might be a system in which liner porosity is controlled while the liner is formed.
- Problem: Corrosive environment.
Subterrene: The corrosion problems will change because different materials will be used. Any drilling system must live with the corrosive materials encountered in the earth. However, Subterrene-produced holes should be more effectively sealed from the corrosive materials. Also, stem and bit need not rotate so that protective coatings should be easier to maintain.
- Problem: Formation evaluation and sampling.
Subterrene: The Subterrene offers the possibility of extracting a continuous, oriented glass-encased core. The glass hole lining eliminates the problem of making logging measurements through a heavy steel casing or through variable depths of mud invasion. Because the glass-lined hole interior is better protected than the unlined hole, the possibility of developing continuous down-hole logging may be enhanced.
- Problem: Directional drilling in hot, hard rock.
Subterrene: Hot, hard rock does not bother the Subterrene bit. Directional change is possible by either mechanical means or by controlling the temperatures circumferentially around the bit.

- Problem: High torque and shock loads on long drill stems in deep wells.
Subterrene: Subterrene bits are not rotated and therefore the torque requirements are eliminated.
- Problem: Difficult surface site conditions in some GTE fields.
Subterrene: Since such large components such as mud ponds and rotary equipment are not needed, the surface installation may be simplified and more compatible with the terrain conditions.

D. Potential Subterrene Applications in Geothermal Wells

Potential applications of Subterrene devices for making geothermal wells are summarized in Table V. The four major types of geothermal fields are listed as hot-water or vapor-dominated, the LASL hot-dry-rock type, magmas and lavas, and geopressurized reservoirs. Two basic well functions, exploration and production, are indicated.

In exploration and currently urgent resource assessments Subterrene devices might make small-diameter, shallow (e.g., 50-mm-diam by 150-m-deep), self-cased holes for thermal-gradient measurements. Many such holes will be needed in the near future. Subterrenes could also be useful for economical exploration of deep heat and water reservoirs where high static temperatures prevail.

For production wells and systems there are two specialized backup or auxiliary devices that could be used in conjunction with conventional rotary drilling systems: First, a hole-stabilization tool for use in caving formations, hydrating or swelling clays, or lost-circulation zones. This tool would be a thermal device producing either a rock-glass lining or injecting structurally stabilizing materials into the bore-hole walls. Second, the tool would be used for completing holes into production zones where high static temperatures and hot fluids are encountered and where reservoir contamination is not desirable.

In certain water or steam reservoirs, or in magmas and lavas that are difficult to penetrate with rotary drills, Subterrene systems could be used to produce entire production wells. Production

TABLE V

POTENTIAL SUBTERRENE GEOTHERMAL WELL APPLICATIONS

Basic Function	General Requirements	Types of Geothermal Field			
		Water or Vapor-Dominated Reservoir	Hot-Dry-Rock Systems	Magma and Lavas	Geopressurized Reservoirs
EXPLORATION	• Small and economical.	• Thermal-gradient holes.	• Thermal-gradient holes.	• Thermal-gradient holes.	
	• Directionally controllable.	• Heat-anomaly probes.		• Heat-anomaly probes.	
	• Formation evaluation capability.	• Discovery wells.			
	• Holes enlargable to production size, if desired.				
PRODUCTION	• Large enough to achieve optimum production flow rates.	• Special hole-stabilization tool, backup to rotary drills.	• Special hole-stabilization tool, backup to rotary drills.	• Special hole-stabilization tool, backup to rotary drills.	• Special hole-stabilization tool, backup to rotary drills.
	• Directionally controllable.	• Production wells.	• Hole-completion tool in very hot rocks.	• Production wells in very hot rocks.	• Hole completion in very hot rocks.
	• Hole made can be reworked and maintained.	• Reinjection disposal holes.		• Production wells in molten rocks.	
		• Production-augmentation holes.			

fields would probably include waste-water reinjection wells and injection wells for production-augmentation purposes. These latter type wells, of smaller diameter than the production wells, could have the same diameter as the exploration wells.

Note that one of the desirable requirements for small exploration boreholes is that the holes be readily enlargable, if desired, to the size of a production well. With conventionally cased holes, such an enlargement is very difficult and costly because the casing is very securely cemented into place. In a glass-lined hole the lining might be either reamed out with a rotary bit or it could be melted and the hole enlarged with a Subterrene bit. Glass-lined holes, in general, might be readily reworked or maintained with Subterrene melting tools.

E. Subterrene Program Accomplishments Still Required

Although the general feasibility of the Subterrene concept has been proven, the establishment of Subterrene devices as accepted hardware for commercial use in the drilling industry has not yet been achieved. Extensions of work already under way include the development of higher penetration rates for applications where this is economically advantageous, more testing and development of the compatibility of hot bit materials with actual in situ environments, refinement of penetrator designs to maximize lifetimes, incorporation of more efficient bit heating devices such as heat pipes, and elaboration of systems and cost studies for specific applications. New work is required on such technical aspects as the determination of rock-glass lining

performance under downhole conditions, development of operating controls for producing linings meeting variable in situ requirements, and the development of power feed systems for deep holes.

LASL has continuing program plans leading to the development of geothermal well devices such as those indicated in Table V. In the immediate future LASL efforts will concentrate on the production of shallow holes (e.g., up to 300 m depths for measurements of exploratory data such as geothermal gradients), and the development of the hole-stabilization tool.

IV. CONCLUSIONS

- The use of geothermal energy, although exploited on a small scale for millennia, has not yet developed into a mature industry.

- Geothermal wells can be produced with conventional oil- and gas-well drilling techniques. However, the unique combinations of GTE conditions of temperature, pressure, hard fractured rock, and corrosion raise the cost of average geothermal wells two to five times above the national average for equally deep oil or gas wells.

- With current techniques, the drilling of exploration, production, and reinjection wells needed for an electric-power capability of 200,000 MW(e) (10% of projected demand in the year 2000) would cost $\sim \$10 \times 10^9$ in current dollars. Thus, R&D expenditures for cheaper drilling equipment and methods are justified.

- Short-term improvements in current drilling equipment are needed as follows:

- A standardized drilling rig with 4-km depth capacity, especially designed for mobility and equipped to adapt rapidly to changes in drilling plans.

- Longer lifetimes for bit cutting edges and bearings.

- Stem and casing materials that are more readily available than standard oil and gas tubular goods and that can stand up better to GTE temperatures and corrosive conditions.

- Muds and cements able to withstand high temperatures.

- Better methods to measure downhole temperature, pressure, porosity, permeability, fracture orientation, and general lithology plus the means of

obtaining undisturbed fluid samples. Sampling methods that do not delay the drilling operation would be very desirable.

- An electronic network in communication with drilling projects which would implement the concept of optimized drilling by means of centralized computer programs and geothermal-well data banks.

- Two basic types of geothermal holes or wells are needed:

- Small and economical: For shallow or deep exploratory probes into hot reservoirs; for waste water disposal; or for reservoir production augmentation by injecting water into strategic reservoir locations.

- Large diameter (e.g., 300-mm-diam): Needed to handle large hot-water and steam flow rates for many years of production operation.

- Advanced drilling systems are needed for both exploration and production, which can

- Penetrate hard, abrasive rock formations.

- Be compatible with high rock temperatures up to approximate magma temperatures, ≥ 1300 K.

- Provide a hole stabilization and support system that is compatible with high geothermal temperatures and pressures.

- The Subterrene concept, i.e., forming a hole by rock or soil melting, has the potential of greatly improving the art of making geothermal wells. For the near term, conceivable applications are heat-flow measurement holes, hole stabilization where conventional methods are inadequate, and completion of final production holes. Over the longer term, applications may encompass the production of both exploratory and production holes, especially in very hot and hard rocks.

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APPENDIX

CONTACTS MADE TO DISCUSS GEOTHERMAL WELL DRILLING PROBLEMS

The following people were willing to discuss drilling problems and contribute data that were useful in assembling this report, for which the author is appreciative:

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