A NEW METHOD FOR EXTRACTING ENERGY FROM "DRY" GEOTHERMAL RESERVOIRS*

D.W. BROWN, M.C. SMITH and R.M. POTTER
Los Alamos Scientific Laboratory of the University of California

FOREWORD

Aware of the impending U.S. energy shortage and the growing concern over the adverse environmental effects of an exponentially-increasing rate of energy consumption, a group of scientists and engineers at the Los Alamos Scientific Laboratory has been working for over a year on the development of a practical, yet economical and environmentally acceptable, method of extracting thermal energy from the numerous regions of the earth's crust containing hot—but essentially dry**—rock at moderate depths. From preliminary studies, rock temperatures in excess of 160°C (320°F) at depths less than 6 km (~ 20,000 ft) appear to be suitable for present development.

This unique method of extracting geothermal energy is in reality quite simple, emulating the dominant heat-transfer mechanism occurring in natural vapor-dominated geothermal systems, where heat is convected from deeper regions of permeable hot rock to near-surface reservoirs by the convective flow of water (not unlike a heat pipe). In the proposed man-made geothermal system, a large fractured region of hot rock—created by hydraulic fracturing (a very common practice in the oil industry)—would be interconnected to a heat exchanger at the surface by a pair of drilled holes, forming a closed convective circulation loop. The water in this closed-loop system would be maintained as a liquid throughout by a suitable amount of surface pressurization. This is because, for a given hole diameter and driving pressure, considerably more heat can be transported from the reservoir to the surface by the flow of pressurized water than by the flow of steam. If, however, the imposed surface pressurization level resulted in intolerable reservoir leak-off rates, a downhole submersible pump could be used to maintain a liquid system in the ascending hot leg, allowing the fractured reservoir to remain at or below the pre-existing hydrostatic pressure level.

Preliminary experiments and analyses indicate that thermal stresses resulting from the cooling of the hot rock in such a reservoir may enlarge the initial crack system so rapidly that the useful life of the reservoir will be greatly extended. If these thermal stress cracks grow preferentially into regions of hotter rock, as seems probable, the quality of the geothermal source may actually improve as energy is withdrawn from it.

INTRODUCTION

In the recent National Petroleum Council (NPC) report to the Secretary of the Interior on the U.S. Energy Outlook[1], it is noted that naturally-occurring geothermal steam and hot-water reservoirs in California and Nevada, while potentially contributing up to only two percent of the total U.S. electrical generating capacity by the year 1985, could supply over *one-third* of the projected electrical power requirements for those two states (16,000 MW out of a total estimated requirement of 52,000 MW). The NPC projection, while close to a recent estimate by Dr. Carel Otte*** of a potential 20,000 MW of

* This work was performed under the auspices of the United States Atomic Energy Commission.
** Not containing significant quantities of recoverable hot water or steam—by far the most common case.
*** Manager of the Geothermal Division of the Union Oil Co. of California, the principal developer of the Geysers in northern California (the world's largest known dry-steam reservoir).

generating capacity by the year 1985, does neglect any significant contribution from other western states. However, other estimates of the U.S. geothermal potential[2-4] are considerably greater than those given above.

A very recent state-by-state geothermal *resource* evaluation[5] gives a total U. S. geothermal potential *several hundred times* greater than the NPC projection. However, this quite realistic evaluation is based on one additional premise not considered in the NPC projection: that a method can be developed for economically recovering the thermal energy contained in the much more numerous reservoirs of hot rock that are nearly impermeable to circulating ground water. One such method is the subject of this paper.

A PROPOSED COMMERCIAL SYSTEM

It is postulated that a commercial energy source, based on the Los Alamos dry geothermal energy concept illustrated in Fig. 1, would be developed in the following sequence of operations.

Site Selection

An accessible site (or sites) would be selected from within a region where the geology is favorable (free of major faults or other obvious structural complexities, and with reasonably competent rock at the projected reservoir depth), and where the heat flow has been determined to be adequate for the planned application. Since measured heat flow values are reasonably constant for surface displacements of many hundreds of feet (most definitely *not* the case when exploring for petroleum or geothermal steam), the plant location would be determined more by topography and ease of accessibility than by slight variations in heat flow. This measured heat flow might range from an acceptable value of 1.5 HFU (1 HFU = 1 μ cal/cm^2 - sec) for the eastern United States to from 3 to 6 HFU in the western United States—

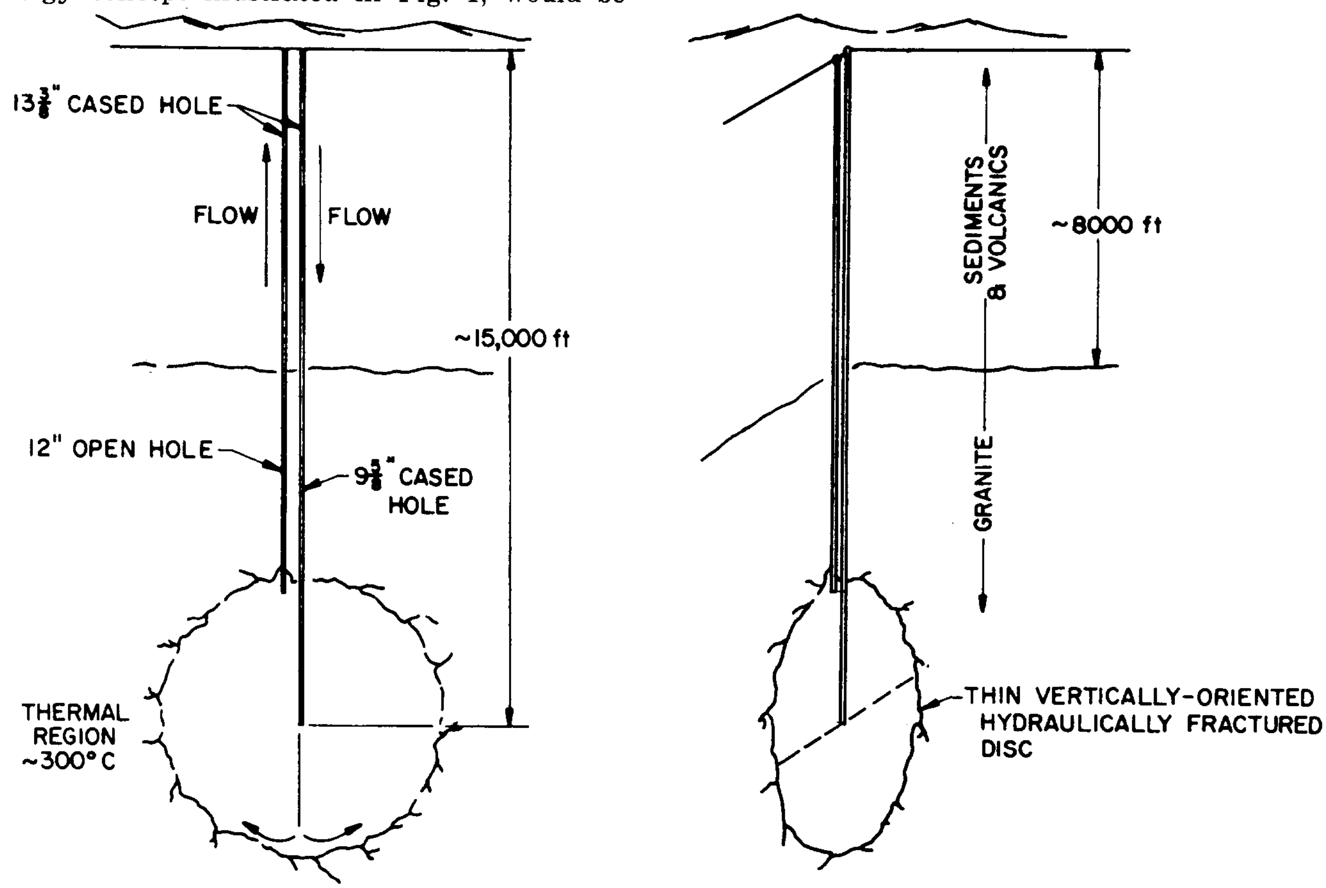

FIG. 1—A PROPOSED SYSTEM FOR DEVELOPING A SHALLOW, DRY, GEOTHERMAL RESERVOIR AS A COMMERCIAL ENERGY SOURCE

west of the eastern slope of the Rockies.

Drilling the Deeper Hole

The first (deeper) hole would be drilled to the projected depth, and then logged to obtain geologic, stratigraphic and reservoir rock physical property and diagnostic data—which would, of course, include a measurement of the relatively undisturbed bottomhole (reservoir) rock temperature. The hole would then be cased with steel pipe to within the planned upper limit of the reservoir, and the casing cemented in place.

Initial Hydraulic Fracturing

Following postcementing hole cleanout operations, the uncased portion of the hole below the casing would be hydraulically fractured using methods that are common in the oil well service industry. This would be done, using a high-pressure pump at the surface, by pumping water down a high-pressure line extending through a seal (packer) inserted in the annulus between this line and the bottom of the casing string. Hydraulic pressure (of the order of 7000 psi above the hydrostatic head) would be exerted against the rock adjacent to the wellbore, developing tensile stresses in this rock sufficient to cause fracturing.

The stress required to extend a crack is, in general, much less than that needed to form it. Therefore, once breakdown (cracking) had occurred at the wellbore, pumping would continue at a reduced pressure until the principal cracks had been extended to the desired radius. Mathematical analysis agrees with field experience in indicating that the resulting crack would be in the form of a thin, vertically-oriented disc of elliptical cross-section, as suggested by Fig. 1.

Following the initial fracturing operations, the crack system would be allowed to collapse by slowly reducing the system pressure by back-flowing through a pressure control valve. This procedure is necessary to preclude the dangers inherent in intersecting a large volume of superheated water during the air drilling of the second (shallower) hole.

From diagnostic measurements obtained during the hydraulic fracturing operations, the orientation (azimuth) of the fracture system would be determined. Typical of the diagnostic measurements that might be used for this purpose would be impression packers, downhole pressure transducers and geophones, and surface arrays of seismometers.

Drilling the Second Hole

The second hole would be located several hundred feet away from the first (deeper) hole, on a line normal to the orientation of the fracture system formed at the bottom of the first hole. This hole would be essentially the same size as the first hole, but several thousand feet shallower. It would be drilled parallel to the first hole until adjacent to the upper portion of the fracture system, and then slanted (whipstocked) to intersect this fracture system using directional drilling techniques. During the directional drilling operations, the deeper hole would be periodically pressurized to test for communication between the two holes.

Final Hydraulic Fracturing

After sufficient communication has been established through the fracture system connecting the two holes (which may require additional fracturing from the bottom of the second hole), the fracture system would be enlarged to its final dimensions by additional pumping down the deeper hole.

Pressurized Water Circulation

Following the final fracturing operations, the previously filled and pressurized surface system—heat-exchangers, water-treatment system, valving and surface piping—would be plumbed into the flow loop, and circulation initiated by an auxiliary pump. Circulation would be down the deeper hole, through the fracture system, up the shallower hole, through the heat-exchangers and water-treatment system, through the flow-control valve, and finally back down the deeper hole. Once a moderate temperature difference had been established between the ascending and descending legs, the auxiliary pump would be bypassed and then valved off. From this point on, the earth-loop flow would be maintained by natural convection, no circulating pump being required. However, for some eastern U.S. systems working on a smaller temperature difference—say an earth outlet temperature of 150°C (302°F) and an earth inlet temperature of 40°C (104°F)—some auxiliary pumping might be required to obtain adequate water flow rates.

If water entered the underground system at 65°C (149°F) and left it at 280°C (540°F), the difference in water density in the two legs would produce a pressure difference sufficient to maintain natural convective circulation at the rate of about 610 lb/sec (4500 gpm) for the hole sizes shown in Fig. 1 . If permeability of the hot rock for this system was low enough to permit it, a pressure of approximately 2000 psia would be maintained in the heat-exchangers, which is safely above the vapor pressure of water at 280°C—930 psia. This overpressure would keep the flow system liquid throughout, maintaining a negative temperature coefficient of viscosity in the heat-transfer medium—which relative to steam, offers a very large heat-transfer advantage in extracting thermal energy from thin cracks in the hot rock—and greatly increasing the rate at which energy can be transported through a pipe of a given diameter. It would also permit the operation of the system at higher water temperatures if spontaneous extension of the cracks occurred and hotter rocks were encountered.

COMMERCIAL POWER PLANT

It was realized many years ago that naturally-occurring hot geothermal waters were potential energy sources. Until recently, however, no attempts have been made to utilize these low-enthalpy waters for electric power generation. Now, with a growing interest here and abroad in organic binary cycle* power plants[6-8] and the apparent availability of more suitable downhole submersible pumps,[9] the situation appears to be changing. However, common to all proposed (or operating) geothermal energy systems based on circulating pressurized water as the heat source, and using heat exchange to a separate vapor-cycle working fluid, is the following unique problem: A large temperature drop in the circulating geothermal water is required to vaporize a significant amount of the power cycle working fluid. The advantages of a low-boiling-point working fluid over water are obvious for such a geothermal water heat source, particularly if the earth outlet temperature level is below about 200°C (392°F), (as would be the general case for "dry" geothermal energy applications in the eastern United States, if electric power generation was the objective).

For a typical commercial man-made geothermal energy source for the western United States as shown in Fig. 1, and with an earth outlet temperature level of 280°C (536°F) as discussed above, a dual-cycle power generation system would be appropriate. Such a proposed system, using a conventional steam cycle for the higher source temperatures, and an isobutane vapor cycle for the lower source temperatures, is shown in Fig. 2.

For applications in the western United States, where water availability is already becoming critical, forced-draft air-cooled condensers were specified. Although adding 10 to 20 dollars/kw to the capital costs of such a plant,[10] the resulting freedom in site selection and the absence of thermal pollution problems (at least as now generally applied only to the heating of bodies of water or rivers) appears to justify this choice. Further, the economics for this type of geothermal power plant are so favorable (as discussed later), that the additional 0.2 to 0.4 mills/kwh in generating costs associated with the air-cooling requirement can easily be absorbed.

FEASIBILITY EXPERIMENT

If funding becomes available, our group is planning for a concept feasibility experiment to begin February 1974. This experiment would be performed in a region referred to as the Jemez Plateau, in north-central New Mexico. This area, on the western side of the Jemez Mountains and about 20 miles from Los Alamos, is within the Santa Fe National Forest and therefore under federal control. Detailed geological and geophysical investigations of this area over the past year, and the drilling of an exploratory hole into the basement crystalline rock during May and June of this year, confirm the suitability of this site for an initial experiment.

The planned experimental configuration and operating conditions are shown in Fig. 3. For this experiment, the crack size (a 1500-ft radius)

* Using low-boiling-point hydrocarbon or fluorocarbon working fluids in a vapor-cycle power generating system, with a primary heat exchanger using hot pressurized water as the heat source (i.e. *binary* cycle).

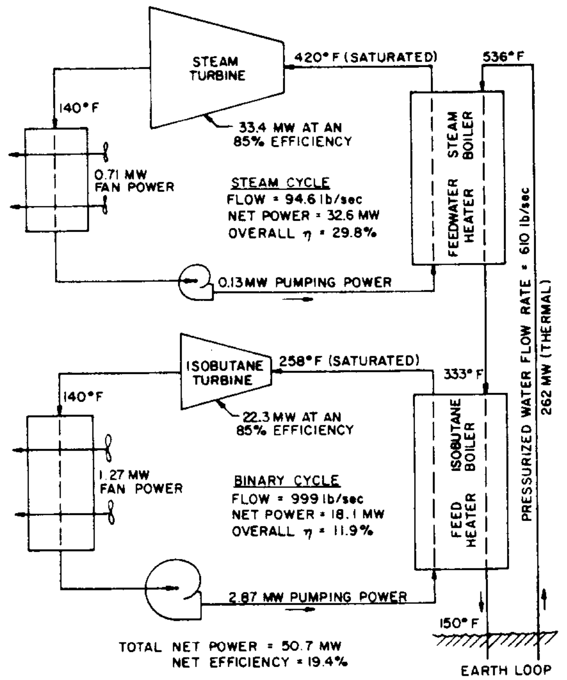

FIG. 2—POSSIBLE DUAL-CYCLE POWER GENERATION SYSTEM

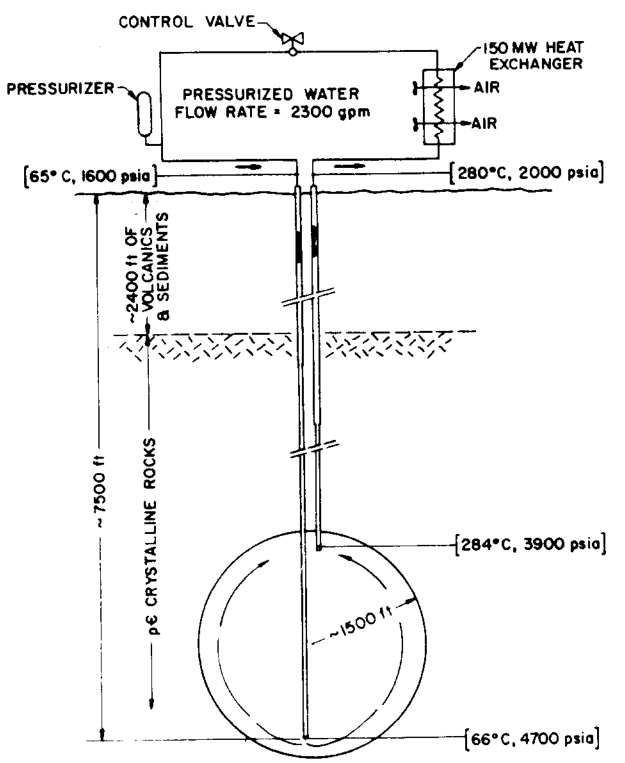

FIG. 3—EXPERIMENTAL CONFIGURATION AND OPERATING CONDITIONS

and the pressurized water flow rate (315 lb/sec, or about 2300 gpm) have been so selected that the artificial geothermal reservoir should be depleted in less than a year, if no reservoir enhancement due to thermal stress cracking were to occur.

HYDRAULIC FRACTURING AND THERMAL STRESS CRACKING

Hydraulic fracturing is a very common stimulation technique used in oil and gas fields to improve reservoir flow characteristics, by creating a set of cracks in the producing formation(s) adjacent to the wellbore.[11] This is normally done by inserting temporary seals above and below the zone to be fractured, and then using a high-pressure pump at the surface and a high-pressure line extending through the upper seal, to produce a hydraulic pressure (normally with water) in the isolated zone of the order of a few hundreds to a few thousands of psi above the existing hydrostatic pressure. A crack system is created which may extend for many feet from the wellbore, the resulting increase in volume being accommodated locally by natural porosity and by elastic compression of the uncracked rock.

Although there does not appear to be any depth limitation, hydraulic fracturing has normally been done only in sedimentary rocks. However, the strengths and elastic properties of some of the sedimentary formations that have been successfully fractured closely approach those of igneous rocks. For example, Halliburton[12] cites hydraulic fracturing at depths of 12,000-15,000 ft in the Ellenburger formation of West Texas, a strong massive limestone having properties very similar to those of a granite. The theory and practice of hydraulic fracturing are well developed, and representatives of two commercial service companies specializing in fracturing have predicted that the required fracture system for our application can be produced without difficulty, using standard techniques. Hydraulic fracturing evidently offers a method of producing a large surface area for heat transfer even in hard, competent rock, and is proven and relatively inexpensive.

Extraction of heat from rock penetrated by the hydraulic fracture will create thermal-contraction stresses that should eventually be sufficient to extend the initial crack system in three dimensions. Initially, the cooler rock next to the fracture surfaces will be restrained from contracting by the adjacent hot rock. These restraints will cause tensile stresses to be developed which, after sufficient cooling has occurred, will exceed the tensile strength of the rock. New cracks will then form along the surfaces of the initial hydraulic fracture system that will undoubtedly propagate far beyond the cooled region.[13] Both the amount of heat-transfer surface and the total amount of heat available to a fluid circulating through the crack system should therefore increase continuously as energy is withdrawn from the geothermal reservoir.

This very important potential of the proposed development method has recently been verified by computer modeling of the reservoir behavior.[14] These calculations indicate that the new crack volume and heat-transfer surface opened by thermal-stress cracking will, following an initial reservoir thermal drawdown period, make additional heat available to the circulating water more rapidly than it is removed by the cooling that creates the thermal stresses. Figures 4 and 5 graphically show the results of one specific reservoir calculation, where the thermal-stress crack spacing was about two inches. Figure 4 shows the geothermal power variation with time, indicating the power recovery phenomenon discussed above. Figure 5 shows reservoir contours of equal porosity for several selected times which, as expected, show the reservoir growing preferentially downwards and sideways with increasing time.

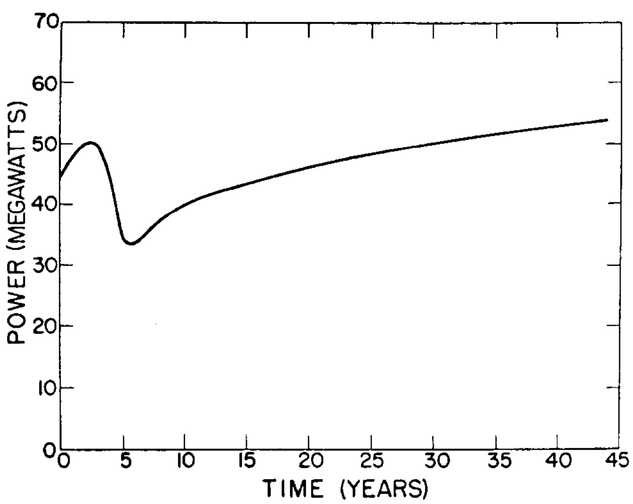

FIG. 4—POWER VS TIME AT CONSTANT CIRCULATION RATE

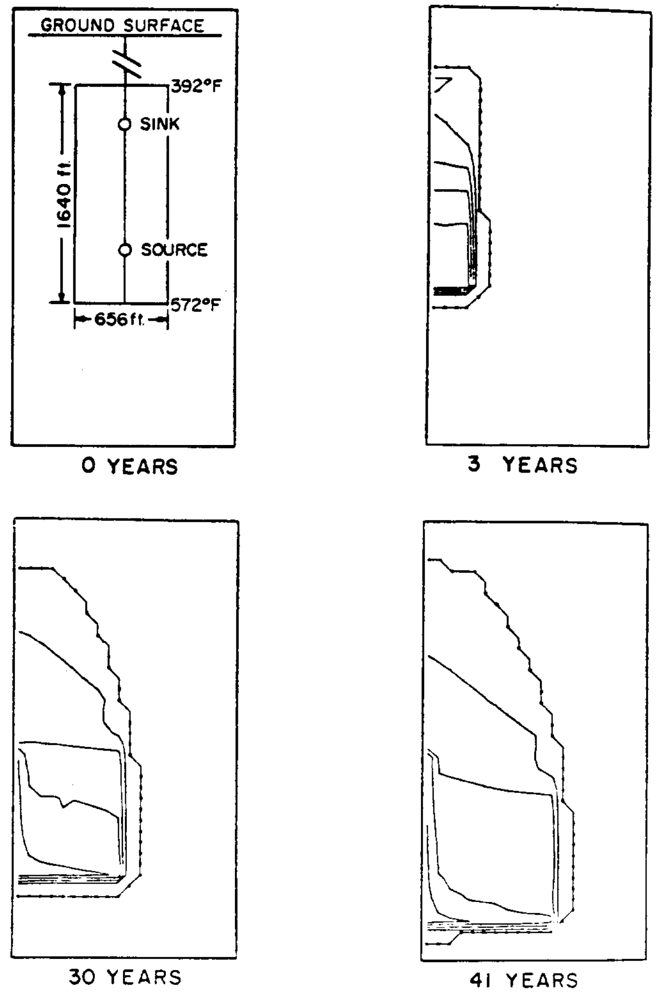

FIG. 5—CONTOURS OF EQUAL POROSITY FROM COMPUTER CALCULATION

ECONOMICS

The economics of a power generating system based on the Los Alamos "dry" geothermal energy concept appear to be favorable now, and may possibly improve in the years to come. These improving economics may result since the only "fuel" costs for such a man-made geothermal power system would be in the form of maintenance charges, while conventional power plants (both nuclear and fossil-fueled) are expected to experience continually increasing fuel costs, especially for oil-and-gas-fired systems.

Since no organic vapor-cycle power-generating plants have yet been built in the United States, the plant costs for such a system are not well-known. However, the Rogers Engineering Co. of San Francisco has recently made such a power plant study for Magma Energy, Inc.,[15] using isobutane as the working fluid. In addition, the San Diego Gas and Electric Co. announced in August plans to go ahead with construction of just such a power plant in the Imperial Valley of southern California (to be completed by the summer of 1973), so better isobutane power plant cost data should be available soon.

In any event, 50-60% of the capital charges for a power plant based on the Los Alamos "dry" geothermal energy concept would be attributable to the drilling, casing and hydraulic-fracturing operations associated with the formation of a sufficiently large thermal reservoir. Since the costs associated with the drilling and casing of conventional-sized holes are very well-known, the importance of the more speculative estimates required, relative to the total capital charges for such a power plant, are correspondingly reduced.

Table 1 compares the cost for power plants based on the "dry" geothermal energy concept, to conventional nuclear-and-coal-fired power plants to be installed near the New York load centers during the mid 1970's. The latter information is contained in a recent New York State Public Service Commission report.[16]

TABLE 1—COMPARISIONS OF PLANT AND GENERATING COSTS

Plant Type	Plant Size MW (e)	Plant Cost dollars/kw	Generating Cost mills/kwh
"Dry" Geothermal Energy Source:			
300°C Rock, dual-cycle, 4 holes	100	186	4.7
175°C Rock, isobutane, 10 holes	100	316	8.0
New York Area for the Mid 1970's:			
Nuclear (PWR)	950	350	11.8
Coal-Fired Steam	950	250	13.3

Basis: 0.17 Annual capital charge rate
Use Factor = 80% of rated capacity

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