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IN THE WESTERN UNITED STATES**

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THE POTENTIAL FOR HOT-DRY-ROCK GEOTHERMAL ENERGY
IN THE WESTERN UNITED STATES*

by

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ABSTRACT

The western third of the United States, comprising a geologically complex area which has been strongly influenced by regional plate tectonics and associated crustal thinning, is both seismically and thermally much more active than the remainder of the country. This fact is adequately demonstrated by the extensive evidence of recent volcanism extending from the Pacific Coast through the Rocky Mountain States.

Surface manifestations of deep-seated hydrothermal activity, such as geysers, thermal springs, and fumaroles, are widespread throughout this region. Based primarily on such surface indications, the U. S. Geological Survey has identified 1.8 million acres (2800 square miles) of western lands as "having a significant potential for geothermal development."

The Los Alamos Scientific Laboratory for the past 2 years has been actively investigating the potential for and problems associated with extracting geothermal energy from the much more numerous regions of the western United States containing hot, but essentially dry, rock at moderate depths. From a recent survey of all available regional heat-flow data, it has been estimated that about seven percent of the 13-state

area comprising the Western Heat Flow Province -- about 95,000 square miles -- is underlain, at a depth of 5 km (16,400 ft), by hot rock at temperature levels above 290°C (> 550°F).

In the Los Alamos concept, a man-made geothermal reservoir would be formed by first drilling into such a previously-identified region of suitably hot rock, and then creating within this hot rock a very large surface area for heat transfer using conventional -- albeit large scale -- hydraulic fracturing techniques developed by the oil industry. After forming a circulation loop by drilling a second hole into the top of the fractured region, the heat contained in this reservoir would be convected to the surface by the buoyant circulation of water, without the need for pumping. The water in the earth loop would be maintained as a liquid throughout by pressurization at the surface, both increasing the amount of heat transport up the second (withdrawal) hole, and enhancing the rate of heat removal from the fractured reservoir, when compared to steam.

Preliminary experiments and analyses indicate that thermal stresses resulting from the cooling of the hot rock in such a man-made reservoir may gradually enlarge the initial fracture system so that its useful lifetime will be greatly extended beyond the planned 10 to 15 years provided by the original reservoir. If these thermal stress cracks grow preferentially downward and outward into regions of hotter rock, as seem probable, the quality of the geothermal source may actually improve as energy is withdrawn from it.

INTRODUCTION

This report is intended to be an adjunct to the statement previously given by Morton C. Smith of this Laboratory before The Subcommittee on Water and Power Resources,* and will therefore be addressed more specifically to the potential for the development of hot-dry-rock geothermal-energy systems in the 13 western states encompassing the Western Heat Flow Province. These 13 states -- California, Oregon, Washington, Nevada, Arizona, Utah, Idaho, New Mexico, Colorado, Wyoming, Montana, North Dakota and South Dakota -- which represent over one-third of the total land area of the continental United States, possess by far the greatest potential for the utilization of geothermal energy as a viable adjunct to other more conventional forms of power generation in meeting the ever increasing energy demands of our nation.**

The western third of the United States, except for the west coast population centers, is also unique from several other standpoints which will directly affect the future development of any electrical power generation source.

1. The load centers are widely distributed and relatively small.
2. The availability of cooling water for steam condensers, particularly for power plant sites within the Rio Grande

*LA-UR-73-926, "The Potential for the Production of Power from Geothermal Resources," statement by Morton C. Smith, representing the United States Atomic Energy Commission, before The Subcommittee on Water and Power Resources, Committee on Interior and Insular Affairs, United States Senate, June 13, 1973.

**This and subsequent comments generally apply to Alaska, also.

and Colorado River watersheds, is already in short supply and may become critical in the near future.

3. The aroused citizenry of this vast region has already demonstrated -- witness the recent U. S. Supreme Court decision on air-quality standards -- that they will not tolerate any further degradation in the quality of their air resulting from increased use of the region's extensive coal deposits.
4. This portion of the United States, considering the abundance of natural resources, has a significant growth potential given adequate -- and widely distributed -- supplies of water and clean power.

THE HOT-ROCK GEOTHERMAL SOURCE

The heat contained in the earth's crust represents the largest supply of directly usable energy that is available to man. In many places, such as in the western United States, usefully hot rock is close enough to the earth's surface to be easily accessible using conventional drilling techniques. At present, however, energy from this source is used only locally in those relatively few places where the natural circulation of groundwater in permeable reservoirs overlying hot rock causes the heat to be convected upwards and then to be trapped in the form of steam or superheated water.

However, the reservoir of geothermal energy represented by essentially dry hot rock is so vast, so broadly distributed,

and in many accessible places so hot that it is now at last being given the serious technical attention that it deserves.

In a recent report by R. M. Potter of this Laboratory,¹ the subject of heat flow within both the Eastern and Western Heat Flow Provinces has been studied in considerable detail. In this study, the effects of heat generation within both the basement crystalline rock and the overlying sedimentary layers, due to the decay of the associated uranium, thorium, and potassium radioisotopes, has been considered in a quantitative way. Using the well-established regional deep-seated source heat flow values -- a constant for each of the heat flow provinces -- in conjunction with the spatial distribution of these three radioactive elements, some rather broad predictions can be made about heat flows in specific areas. From these derived heat flow relationships, and with a knowledge of the geologic section for the area of interest (the rock types, their measured thermal conductivities, and the depth of the sedimentary section), the temperature variation with depth can be estimated.

Using the analytical techniques developed in the above heat-flow study, the temperature variation at a specified depth for any given region can be estimated without a specific knowledge of the corresponding near-surface heat-flow values. However, as shown in Fig. 1, there is a fair amount of measured near-surface heat-flow data for the 13-state region comprising the Western Heat Flow Province.

Fig. 1. Contour map of heat flow in the western United States (after Roy et al.² with modifications in the north-western and northeastern portions -- data points with tails are from the recent work of Combs and Simmons³). The contours delineate regions of high and low heat flow with average values of flux that would be measured in rocks with heat production within the range of granodiorite. Pluses represent observed heat flow values in the range 0-0.99; white circles, 1.0-1.49; dotted circles, 1.5-1.99; black circles, 2.0-2.49; black triangles, 2.5-2.99; and black rectangles, >3.0. Units are 10^{-6} cal/cm²-sec.

Therefore, using these measured heat-flow values in conjunction with the temperature vs depth predictive techniques discussed above, one is in a position to estimate, in a semi-statistical fashion, the probability of finding a given temperature at a given depth, for this portion of the country. Obviously, then, a technique is available to attempt to quantify the very large hot-dry-rock geothermal-energy potential for the western United States.

Table I lists the estimated probability, in the form of a percentage distribution, of a given temperature range for two specified depths -- 5 and 6 km (16,400 and 19,700 ft) -- for the 13-state region being considered. A mean depth to basement of 2.5 km (8200 ft) was used, along with appropriate mean-thermal-conductivity values for sedimentary and crystalline basement rock,* in deriving the temperature ranges listed in this table.

From an examination of Table I, one can conclude that a hot-rock reservoir temperature level in excess of 290°C (550°F) -- a very appropriate reservoir temperature level for a surface electrical power generating plant -- can be achieved by drilling to a depth of about 5 km anywhere within a 95,000 square mile broadly distributed region of the western United States. This area is over 30 times greater than the total "Known Geothermal Resource Area" listed by the U. S. Geological

*0.005 cal/cm-sec-°C for sedimentary rock, and 0.007 cal/cm-sec-°C for crystalline basement rock.

TABLE I

PROBABLE DISTRIBUTION OF HOT ROCK RESERVOIR TEMPERATURES
FOR THE WESTERN THIRD OF THE UNITED STATES^a

<u>Probable Areal Distribution</u>	<u>Heat Flow Range HFU^b</u>	<u>Reservoir Temperature Range Corresponding to a Drilled Hole Depth (Deeper Hole) of:</u>	
		<u>5 km (16,400 ft)</u>	<u>6 km (19,700 ft)</u>
20%	< 1.6	< 158°C (316°F)	< 180°C (356°F)
30%	1.6-2.1	158-203°C (316-397°F)	180-233°C (356-451°F)
33%	2.1-2.6	203-248°C (397-478°F)	233-285°C (451-545°F)
10%	2.6-3.1	248-293°C (478-560°F)	285-337°C (545-639°F)
7%	> 3.1	> 293°C (560°F)	> 337°C (639°F)

^aBased on a mean sedimentary thickness of 2.5 km overlying the top of the crystalline basement rock.

^bHFU - $\mu\text{cal}/\text{cm}^2\text{-sec}$, corrected for Pleistocene climatic effects.

Survey for potential natural hot water or steam geothermal development. Further, the additional 10% of the West where hot rock reservoir temperatures are estimated to vary between 248°C (478°F)* and 293°C (560°F) for a hole depth of 5 km (as shown in Table I) have been neglected in the above comparison.

Obviously then, if a practical, yet economical method of extracting energy from these known reservoirs of hot rock can be developed, as appears probable based on the results of the Los Alamos Program so far, this hot rock geothermal resource is very large. For instance, if only one 100 MW(e) hot-rock geothermal power plant were to be installed for every 10 square miles of this widely distributed 95,000 square mile area with the highest reservoir temperature potential, there would be more electrical power generation capacity available than the projected requirements for the western United States for the year 2000.

POWER PLANT SITE SELECTION AND DEVELOPMENT

A commercial energy source, based on the Los Alamos Hot-Dry-Rock Geothermal-Energy Concept as illustrated in Fig. 2, would probably be developed in the following steps:

1. Initial Heat Flow and Geological Surveys

The accessible -- and available -- land within say 100 km (60 miles) of the specified load center would be surveyed

*The geothermal steam temperature at The Geysers in northern California is only about 460°F.

Fig. 2. Typical dry-rock geothermal-energy system produced by drilling and hydraulic fracturing.

to locate regions with suitably high near-surface heat flow and favorable geology. From a geological standpoint, it would be desirable for the potential power plant sites to be in areas free of major active faults or other obvious structural complexities, and with reasonably competent rock at the projected reservoir depth. However, given the 12,000 square mile area covered by the initial survey, locating a number of geologically and thermally suitable areas should pose no real problem.

2. Site Selection

From among the potential power plant sites identified above, one or more would be selected for eventual development. The final site selections would probably be made based on additional factors such as the proximity to the load center and existing power line right-of-ways, environmental considerations, economic factors such as land costs, site accessibility and topography.

3. Drilling the Deeper Hole and Hydraulic Fracturing

After drilling the first (deeper) hole to the projected depth, a large hydraulic fracture would be formed at or near the bottom of the hole 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 just above the bottom of the hole. Mathematical analysis agrees with field experience in indicating that the resulting fracture would be in the form of a thin, vertically-oriented disc

of elliptical cross section, as suggested by the sketch in Fig. 2. From diagnostic measurements obtained during the hydraulic fracturing operations, the orientation (azimuth) of the fracture system would be determined.

4. Drilling the Second Hole and Final Hydraulic Fracturing

The second hole would be located several hundred feet away from the first (deeper) hole, on a line perpendicular to the orientation of the fracture system formed at the bottom of the first hole. This hole would be the same diameter 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.

After sufficient communication had been established through the fracture system connecting the two holes, the fracture system would be enlarged to its final dimensions by additional pumping.

5. Pressurized Water Circulation

Following the final fracturing operations, the surface system 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 surface system, 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. From this point on, the earth-loop flow would be maintained by the density difference between the water in the cold and hot legs, without the need for pumping.

A pressure of approximately 2000 psia would be maintained at the surface to keep the flow system liquid throughout. This is because, relative to steam, water offers a very large heat-transfer advantage in extracting thermal energy from thin cracks in the hot rock, and greatly increases the rate at which energy can be transported through a pipe of a given diameter.

COMMERCIAL POWER PLANT

For a typical commercial man-made geothermal-energy source for the western United States as shown in Fig. 2, a dual-cycle power-generation system may be appropriate. One such 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. 3.

For applications in the West, where water availability is already becoming critical, forced-draft air-cooled condensers are specified. Although adding 10 to 20 dollars/kW to the capital costs of such a plant,⁴ 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.

POSSIBLE DUAL-CYCLE POWER GENERATION SYSTEM

Figure 3

Further, the economics for this type of geothermal power plant are so favorable (as discussed later) that the additional 0.2 and 0.4 mills/kWH in generating costs associated with the air-cooling requirement can easily be absorbed.

HYDRAULIC FRACTURING

Hydraulic fracturing is a very common production stimulation technique used in the oil industry to improve reservoir flow characteristics, by creating a set of cracks in the producing formations adjacent to the well bore.⁵ Although there does not appear to be any depth limitation, hydraulic fracturing has normally been done only in sedimentary rocks. However, a series of rock mechanics experiments recently completed by the Los Alamos Scientific Laboratory, in the open-hole section of the crystalline basement rock exposed at the bottom of the deep exploratory hole drilled during the Spring of 1972, have demonstrated that hydraulic fracturing works equally well in igneous and metamorphic rocks.

The observed breakdown pressure levels for these rocks were of the order of the corresponding overburden compressive stress -- about 1 psi/foot of depth. The resulting fractures appear to be essentially vertical and more importantly, capable of containing pressurized water -- with little if any observed leakoff -- at pressure levels sufficient to keep the fracture system open (for this particular case, at a surface pressurization level of from 1000 to 1300 psi).

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.

THERMAL STRESS CRACKING

Extraction of heat from rock penetrated by the hydraulic fractures 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.⁶ 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.⁷ 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. Figure 4 shows for one specific reservoir calculation, the geothermal power variation with time, indicating the power recovery phenomenon discussed above.

ECONOMICS

The economics of an electrical power generating system for the western United States, based on the Los Alamos Hot-Dry-Rock Geothermal-Energy Concept, appear to be very favorable from a preliminary analysis. However, since no dual-cycle power plant has ever been built, the estimated costs are indeed speculative. Geothermal power generating plants operating at turbine inlet steam conditions somewhat lower than those shown on Fig. 3 are now operating in both the United States and Mexico,* with capital costs presently running about \$110/kW of installed capacity.

No actual cost data are available for organic vapor-cycle power-generating plants since none of these type power plants have been built in the United States. However, the Rogers Engineering Company of San Francisco has made such a power plant study for Magma Energy, Inc.,⁸ using isobutane as the working fluid. Their projected capital costs, for a 100 MW(e) plant size, are \$125/kW of installed capacity (1970 dollars).

*A 290 MW(e) power complex at The Geysers in northern California, and a 75 MW(e) power plant at Cerro Prieto in northern Mexico.

Fig. 4. Power vs time at constant circulation rate.

The estimated capital costs for a 100 MW(e) dual-cycle power plant, as shown in Fig. 3, are \$185/kW for a power plant coming on line in 1975. The associated drilling and fracturing cost, for two pairs of holes* is estimated to be \$6.2 million, giving an overall capital cost of \$247/kW.

Table II compares the preliminary estimated costs 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 center during the mid 1970's. The latter information is contained in a recent New York State Public Service Commission report.⁹

*To depths of 4.2 km (13,000 ft) and 5 km (16,400 ft), respectively.

TABLE II

**COMPARISONS OF PLANT AND GENERATING COSTS
FOR THE YEAR 1975**

<u>Power Plant Type</u>	<u>Power Plant Size MW(e)</u>	<u>System Capital Cost Dollars/kW</u>	<u>Generating Cost Mills/kWH</u>
Dry Rock Geothermal Energy Source			
($> 290^{\circ}\text{C}$ rock, dual cycle, 4 drilled holes):	100	247	6.3
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.

REFERENCES

1. R. M. Potter, "Geothermal Resources Created by Hydraulic Fracturing in Hot Rock," paper presented at the Geothermal Research Conference (sponsored by NSF through a research grant to Walter J. Hickel), Battelle Seattle Research Center, Seattle, Washington (Sept 1972).
2. R. F. Roy et al, "Continental Heat Flow," in The Nature of the Solid Earth, E. C. Robertson, Editor (McGraw-Hill, Inc. 1972) pp 506-543.
3. J. Combs and G. Simmons, "Terrestrial Heat Flow Determinations in the North-Central United States," J. Geophys. Res. 78, No. 2 (Jan. 10, 1973).
4. T. C. Elliott, "Air-Cooled Heat Exchangers - New Growth?," Power, pp 88-90 (Aug 1971).
5. B. C. Craft, W. R. Holden, and E. D. Graves, Jr., Well Design: Drilling and Production (Prentice Hall, Inc., Englewood Cliffs, N. J. 1962).
6. A. H. Lachenbruch, "Depth and Spacing of Tension Cracks," J. Geophys. Res., 66, 4273 (1961).
7. F. H. Harlow and W. E. Pracht, "A Theoretical Study of Geothermal Energy Extraction," J. Geophys. Res. (Aug 1972).
8. "Magma Max Power Generating Plant Feasibility Study and Preliminary Cost Estimate," prepared for Magma Energy, Inc., by Rogers Engineering Co., Inc. (Sept 1970).
9. Nucleonics Week, p 6 (Jan 20, 1972).