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THE INDUCTION AND GROWTH OF FRACTURES IN HOT ROCK:
ARTIFICIAL GEOTHERMAL RESERVOIRS*

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OUTLINE

- I. Introduction.
- II. Magnitude of the geothermal resource.
- III. Approaches to exploitation.
- IV. Thermal stress cracking and computer simulations.
- V. Economics.
- VI. Proposed Experiment.

- App. A. Energy from a 15 mile diameter by 1 mile high cylinder of rock.
- App. B. Relative energy transfer of water and steam.
- App. C. Void volume generated per million BTU removed from rock.
- App. D. Temperature at which thermal fracture occurs vs. depth.

FIGURES

- Fig. 1 Circulation loop with concentric pipes.
- Fig. 2 Circulation loop with separate pipes.
- Fig. 3 Viscosity of water and steam vs. temperature.
- Fig. 4 Turbine/pump for use in concentric circulation loop.
- Fig. 5 Pressure difference between hot and cold water vs. depth.
- Fig. 6 Contours of equal porosity from computer calculation.
- Fig. 7 Power vs. time at constant circulation rate.
-
- Fig. B-1 Results of Steam Flow Calculations.

THE INDUCTION AND GROWTH OF FRACTURES IN HOT ROCK

R. Lee Aamodt and Morton C. Smith

I. INTRODUCTION

The consumption of energy in the United States has doubled every 28 years during this century, while the output of electrical power, other than hydro-electric, has doubled every 8 years. The environmental consequences of energy production are now causing much concern. Modern fossil fueled electric power plants are large and are usually located near the source of their fuel. Transmission lines are necessary to take the power to the consumer. These lines now occupy an area larger than the state of Connecticut¹. An equally large area has been devastated by strip mining, much of which was for coal². Obviously, the doubling process must stop soon, and better methods of generating and distributing electricity are needed. A much wider use of geothermal power would be helpful, but it is generally assumed that only a small part of our power will be geothermal. In a study made for the Secretary of the Interior by the National Petroleum Council³, it was estimated that geothermal power would be contributing less than 2% to our power production in 1985. The energy picture would change completely if geothermal power can be extracted from hot dry rock.

II. MAGNITUDE OF THE GEOTHERMAL RESOURCE

The slowly cooling intrusive mass below the Jemez Caldera⁴ near Los Alamos, New Mexico, provides a good example of the magnitude of the geothermal resource. It is roughly cylindrical and about 15 miles in diameter. If a one mile thickness of this rock were cooled an average of 250 °F, the energy removed would equal the entire world consumption in this year (App. 1). The western U.S. is underlain by accessible hot rock, and there are many thermal anomalies in eastern U.S. where geothermal power might be produced, as will be discussed later.

III. APPROACHES TO EXPLOITATION

A. Area of Rock-Water Interface Necessary for Power Production.

The idea of using the heat from slowly cooling lava beds is an old one. The difficulty of doing so is made clear in the well-known book on heat conduction of Ingersoll, Zobel, and Ingersoll⁵. They consider a spherical cavity with a radius of 4 feet, located deep in an old bed, where the temperature is 500 °F. Water is poured down a pipe extending from the surface to the cavity and steam is withdrawn through another pipe at a rate such that the water in the cavity is maintained at 300 °F. The power withdrawn decreases with time; after one week it is 7.09 kW. In order to produce 100 MW under similar conditions, the radius of the cavity would have to be 670 feet. This is not very interesting, but with a change in geometry, the same surface area can probably be produced quite easily by the process of hydraulic fracturing⁶.

B. Hydraulic Fracturing

Hydraulic fracturing is accomplished by pressurizing a section of a borehole by pumping water into it from the surface until a tensile crack is formed. The fracture grows as the pumping continues, and will continue to grow as long as water can be pumped in fast enough to overcome the leakage arising from the permeability of the rock. The process has not, to our knowledge, been performed in hot granite, but experts in the field are quite confident that it can be done. Computer modeling of the hydraulic fracture process at the Los Alamos Scientific Laboratory⁷ indicates that thermal stress cracking, caused by shrinkage of the rock as it is cooled by the inflowing water, will cause additional cracks, which may also propagate, so the crack pattern is expected to be more complex than it is in cold rock.

C. Circulation Loop

Circulation of the working fluid used to extract the geothermal energy may be accomplished in several ways. One way is to use the same hole, drilled oversize for the purpose, that was used to create the hydrofracture, and arrange a concentric flow system. as shown in Fig. 1. This has the disadvantage of more complexity in the pipe string, but has the advantage that we know where the bottom of the return pipe is, and can assure that it is connected to the top of the reservoir by performing a series of overlapping small fractures from the bottom to the top of the uncased hole before the center pipes are emplaced. However, if it does not prove too difficult to drill a second hole and intersect the top of the fracture with the aid of directional drilling from a position perhaps 200 feet to one side, the two-hole circulation system show in Fig. 2 will probably be the one most used. There is one more case where the concentric string has advantages. This will be discussed under subhead D.

D. Working Fluid and Reservoir Tightness

If the crack system is capable of supporting the weight of the column of hot water to the surface plus the additional pressure needed to prevent boiling, a water cycle in which the hot water rises, passes through a heat exchanger at the surface, and is returned to the reservoir, may be used. In App. B it is shown that as much as 10 times more thermal energy may be transmitted up a given pipe if the working fluid is water instead of steam. A steam system, in which the condensate is returned to the cavity, is probably cleaner from an environmental viewpoint and can be used with "leaky" reservoirs but it is subject to clogging from precipitation of dissolved solids in the place where it flashes into steam. The biggest advantage of the all-water system is that the viscosity of water decreases as its temperature increases. This is shown in Fig. 3, where we also see that steam behaves in the opposite fashion.

This means that circulating water will tend to follow the hottest path, all else being equal, while steam will flow best through the coolest path. This will be especially important if the cavity grows by thermal stress cracking, which will be discussed further on.

The advantages of an all-water system need not be lost even if the crack system would lose too much water at the full pressure of an all-water system. Deep-well submersible pumps, hardened to withstand the high temperature, are probably within the state-of-the-art of pump design⁸. If such a pump is placed in the hot water line, the pressure on the reservoir may be reduced, while that at the surface is maintained. The water level in the cold-water-return pipe would be held at the appropriate level, compatible with the desired reservoir pressure.

Going back to the concentric geometry, we see the additional advantage mentioned above; the pump in the hot-water line may be driven by a turbine in the cold-water line, as shown in Fig. 4, with no additional power from the surface. There is a difference in pressure with depth in the hot and cold water lines, because of the difference in the density of hot and cold water. This difference is shown in Fig. 5, in which the pressure in the hot and cold lines at the surface is the same, 2896 psi. For the temperatures shown, the pressure difference is 2050 psi at a depth of 15,000 feet. This pressure difference is available to drive the circulation of the water, and the system will, according to the machine calculations, normally have to be throttled down by a valve in the cold-water pipe at the surface. The turbine-pump can be used if there is sufficient excess pressure to make up for the difference in the pressure drops in the hot and cold sides of the pump, which arises from the density difference and from inefficiencies in the pump.

E. Formation of a Crack System to Circulate Water Through Hot Rock.

1. Location.

An appropriate site would be selected for the development of a dry geothermal reservoir at shallow to moderate depth.

This would be in one of the known regions in which the geothermal gradient is abnormally high and hot igneous rocks are present not far below the earth's surface. There are many locations in the western United States that satisfy these requirements, including the one near Los Alamos, New Mexico.

2. Initial Drilling.

If, for example, a rock temperature high enough to be useful for power generation (say near 600 °F) were reached at a depth of 15,000 feet--as might be expected in the western third of the U.S.--then the geothermal reservoir would be entered by drilling to that depth. The hole would be cased with steel pipe, which would be cemented in place by conventional methods. Since the lower part of the hole would be in hot, igneous rock, these operations would be more difficult than the drilling and casing of conventional oil wells. However, with a fluid circulation sufficient both to cool the bit and drill string and to remove the cuttings, the drilling could be done with a conventional oil-field rotary drilling rig. Suitable casing and cementing materials are also available commercially.

To assist in understanding the subsequent fracturing behavior of the underground system, the character of the rock and of the hole would be investigated as fully as possible before the casing was inserted.

3. Hydraulic Fracturing.

Using methods which are common in the drill industry, the well casing would be perforated at a point several hundred feet above the bottom of the hole, and a temporary seal would be inserted just above that level. By use of a high-pressure pump at the surface and a high pressure line extending through this seal, a fluid pressure sufficient

to produce hydraulic fracturing would be developed in the sealed-off section of the hole. Through the perforations and in the open section of the hole, this pressure (of the order of 7,000 psi above the hydrostatic pressure at that point) would be exerted against the rock adjacent to the hole, developing tensile stresses in the rock eventually sufficient to cause it to crack. The stress required to extend a crack is in general much less than that needed to form it. Therefore, once breakdown (cracking) had begun, pumping would continue at 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 is suggested by the sketch of Fig. 2. Since the crack will be filled with water, fluid pressure in the crack is expected to hold it open without support.

4. Second Drilling.

At a distance of about 200 feet from the first hole, a second hole of the same size would be drilled, intended to intersect the upper part of the crack system created by hydraulic fracturing in the first hole. The orientation of the crack may have been determined by listening with strategically placed geophones to noise generated at points on the rim, as the crack grows intermittently at various places⁹. If not, the orientation at the start of the hydraulic fracturing operation can be determined. If, for some reason, the crack system were not intersected by

*In hot rock this may not be correct, see sec. IV-B.

directional drilling from the second hole, then--after this hole was cased and cemented--hydraulic fracturing could be repeated from the bottom of the second hole, to produce a second crack system that would intersect with the first.*

5. Water Circulation.

A pump located at the surface would be used to force cold water down the deeper hole, through the completed underground fracture system, and up the shallower hole. Once a moderate temperature difference had been established between cold water descending in the first hole and hot water rising in the second hole, circulation through the system would be maintained by natural convection, and pumping would be discontinued except for injection of any additional water required to keep the system full. In App. C it is shown that 1/4 to 1/2 cubic feet of void space is formed for each million BTU withdrawn from the rock. The void space formed each day when 100 MW of thermal energy is being drawn from the rock will require 25,000 gallons of make-up water even if there is no underground leakage from the reservoir.

*Several variations of the hydraulic fracturing procedure have been suggested, including: hydraulic fracturing from the bottom of the first hole, to insure communication between this point and the crack system established by previous fracturing at a high level; hydraulic fracturing simultaneously from the two holes; and hydraulic fracturing from an open (uncased) section at the bottom of the first hole. Selection among these and other possibilities must await more detailed analysis, and agreement among drilling and hydraulic-fracturing specialists. However, experts in the field agree that the relatively straightforward procedure outlined above has a very high probability of producing the interconnected crack system that is required.

6. Power Potential.

It was shown in section III-A that an area equal to the surface area of a sphere 670 feet in radius was required in order to get 100 MW of thermal power from a relatively cool (500 °F) rock mass. A crack with a 1,000 foot radius is slightly larger than necessary. If a 3,000 foot radius crack can be formed in rock which is at 570 °F, it has been calculated that an average power of 89 MW (thermal) could be extracted for 20 years through the initial crack faces¹⁰. Such calculations are probably too conservative, however, because of thermal stress cracking, which will be discussed in the next section.

IV. THERMAL STRESS CRACKING AND COMPUTER SIMULATIONS

A. Thermal Stress Cracking.

In App. C, a calculation is made of the void volume resulting from removal of one million BTU of heat from rock. This volume is, at least to a first approximation, independent of the magnitude of the decrease in temperature. In App. D, it is shown that, if the temperature increase is linear with depth, rock must be cooled to a certain fraction of its initial temperature in order to fracture it by thermal contraction, and that the fraction is independent of depth, again at least to first order. The fraction is close to 1 if the thermal gradient is large, but may become so small, if the thermal gradient is small, that thermal fracture will not take place, or will proceed very slowly. Some geologists have expressed doubt that granite rock would fracture when cooled; the alternative suggested was an increase in porosity, which would not necessarily increase permeability. However, when a cube of granite about one foot on a side was slowly heated to about 600 °F over several days, the oven was removed, and water applied to one face, large tensile fractures appeared in about 20 minutes¹¹.

Similar results were obtained with basalt. It is expected, therefore, that the void formed by cooling will expose fresh hot rock by cracking, and, if the new fractures are sufficiently permeable, the life of the reservoir will be greatly extended. A given amount of empty space can be distributed through the rock in many ways. If it occurs as parallel cracks, the permeability is proportional to the square of the distance between cracks⁷. The decrease of viscosity with temperature should be helpful in inducing circulation through newly created cracks. Growth of the reservoir should be fastest at the bottom, where the coldest water overlies the hottest rock.

B. Computer Simulation of Reservoir Behavior.

Although the processes taking place when water circulates throughout a mass of broken rock are individually simple, their interaction makes the situation complex. Such problems are well suited for numerical solution with a computer, and a program which included the flow of heat through the rock, its cooling and shrinkage, fracture, and the growth of the reservoir, was devised by F. Harlow and W. Pracht at Los Alamos⁷. The problem also included heat transfer to the water, its temperature, density, viscosity, and velocity. Unknown factors such as crack spacing were absorbed into parameters which could be varied and the sensitivity of cavity behavior to these unknown factors could be determined. As expected, the calculations show the reservoir growing preferentially downward and sideways, unless the crack spacing is made too small, about 1/2 inch or less. Fig. 6 shows contours of equal porosity at various times, for a crack spacing of about two inches. Fig. 7 shows the variation of power output with time--an initial rise as the top of the cavity is warmed from below, a period of decreasing power output, which is finally overcome by cavity growth with a subsequent rise to more than the initial power level. In this calculation, the flow rate was held constant at 26.5 gallons per second, or about 2.3 million gallons per day.

Some calculations were made for the case of the single thin crack, without allowing thermal fracture to take place, verifying that such cracks could indeed supply many tens of megawatts of thermal power for several tens of years. However, the rock is undergoing cooling while the initial fracture is being formed. Thermal fracture will create new cracks, preferentially near the source of the first one where the water is coldest, and these cracks may propagate also under the high pressure at that point. Thus, the reservoir may resemble a cylinder rather than a thin flat crack when the initial fracture is completed.

C. Geochemical Complications.

Most natural minerals have significant solubility in hot water, and their solubilities increase with temperature and pressure. This fact may have both favorable and unfavorable consequences. If the reservoir does truly grow downward and the temperature of the circulating water increases above the initial temperature of the rock in the initial reservoir, the thermal fractures would close again if it were not for solution and perhaps re-precipitation of minerals. The water rising to the surface will contain minerals which may be expected to cause problems of corrosion and plugging of the heat exchanger. However, some of these minerals will have commercial value and recovery of these from the water may be profitable. Certainly intensive study must be made, both in the laboratory and in the field, of the solubility and precipitation of minerals in solution under realistic conditions of temperature and pressure, in order to exploit the thermal cracking process. In some cases such a system may be utilized solely for mining.

V. ECONOMICS

No one would argue with the proposition that if, from any point on the earth's surface, a hole were drilled downward to a sufficient depth, it would eventually reach rock hot enough to constitute a potentially useful energy source. The thermal reservoir represented by the earth's crust and mantle is unimaginably large, and it exists everywhere beneath the earth's surface. A general method of extracting energy from this source has been outlined above, which uses only existing engineering techniques--although in a new combination. The principal question that remains is whether this method, or some variant of it, can be used to extract energy from hot dry rock in a usable form, at a usefully high rate, at a cost that is comparable with that of energy from other sources.

Water at 200 to 300° F has many important uses, including space-heating, water-distillation, and chemical processing. In many cases, such uses could be served economically by relatively low-grade geothermal energy (as, indeed, they are already served in several parts of the world). However, the major present interest is in new nonpolluting sources of electrical power. Therefore, in considering the economics of man-made geothermal energy systems, it has been assumed that thermal energy will be useful only if it is brought to the surface at a temperature high enough to operate generating equipment. The minimum temperature required for a steam power plant has here been assumed to be 550° F, although lower-temperature systems are operating, and that for an isobutane cycle to be 340° F.

It has also been assumed that, in the present state of the drilling art, it would probably not be practical to drill holes deeper than about 20,000 feet to reach the hot rock. (This is, of course, an arbitrary and undoubtedly a temporary limitation.)

Finally, it has been assumed that waste heat from the power plant would be dissipated to the atmosphere by forced-draft, air-cooled heat-exchangers. These are more expensive than wet cooling towers, but save a great deal of water and avoid thermal pollution of lakes and streams. (The only pollution from this contained power system would be a rising plume of warm air, which, it is believed, would have no significant environmental effect).

On this basis, preliminary cost estimates have been made for a typical 100 MW-electrical steam power plant, in the western United States. Typically, to provide the necessary thermal energy from the geothermal source, this would require 2 pairs of 15,000-ft. holes into rock at about 570° F. The plant cost, including development of the underground circulation system, is estimated to be \$186 per kilowatt of generating capacity, and the generating cost is estimated to be 4.7 mills per kilowatt hours at the busbar. Even if these estimates are low by a factor of two, which is unlikely, such a system would be competitive with nuclear or fuel-fired plants.

In the eastern United States, accessible rock temperatures are in general significantly lower than in the West. However, there are large regions in the East in which rock temperatures above 340° F can be reached at depths less than 20,000 feet. Accordingly, cost estimates have been made for a typical case in which 5 pairs of 18,000-ft. holes would be required to supply energy in the form of water at 340° F to a 100 MW-electrical isobutane-cycle power plant. Because of the high cost of drilling 10 deep holes, plant cost in this case is high--estimated to be \$316/kW, which is higher than that of a coal-fired plant and approaching that of a nuclear power station. However, because the fuel cost is essentially just the cost of amortizing the underground system, the generating cost is estimated to be only 8.0 mills/kWh. If these estimates are in error by 50%, it still appears that this type of geothermal energy development may be competitive even in large sections of the eastern United States.

VI. PROPOSED EXPERIMENTS

The engineering and economic aspects of the development of dry-rock geothermal-energy systems appear to be sufficiently favorable to justify a field experiment, intended to demonstrate the creation and operation of such a system, and to investigate its problems and economics. Such an experiment has been proposed to the U. S. Atomic Energy Commission, and exploration for a suitable site for it has been in progress for several months.

On the basis of geological information so far collected and heat-flow measurements made in a series of holes drilled for that purpose, it now appears that an area in the Jemez Mountains--about 2 to 5 miles west of the Valles Caldera, and about 30 miles west of Los Alamos Scientific Laboratory--is particularly suitable for a field experiment. Here the geology is relatively uncomplicated, the depth to the basement granite is only about 2500 ft., and the geothermal gradient is about 6 to 10 times normal. An exploratory hole in this area has recently been drilled and cased to 2430 ft. depth, to examine heat-flow lithology, hydrology, and drilling problems. It is intended to extend this hole a few hundred feet into the granite, with continuous coring, to investigate the character and probably competence of the granite, to measure temperatures and heat-flow in it, and to permit preliminary hydraulic-fracturing and pressurization experiments. If the basement rock is found to be capable of containing a pressurized system, then a specific site will be selected for development of an experimental underground circulation system.

Preliminary heat-flow measurements indicate that in this area a rock temperature of about 500 to 600° F can be expected at a depth of only 7500 ft.--which is not unusual in regions of geologically recent vulcanism. It is proposed to create, at approximately this depth, a circulation loop of the general type sketched in Fig. 2 but with a relatively small hydraulic fracture--perhaps 1500 ft. in radius--and with the extracted heat wasted to the atmosphere by an air-cooled heat-exchanger.

Simply creating such a system and establishing convective circulation in it will represent an important feasibility demonstration. Operating the loop for approximately 10 months should--with relatively small initial heat-transfer surface--indicate whether the system simply decays, or whether instead it perpetuates itself by thermal-stress cracking. Continued circulation for another 2 or 3 years will then permit detailed studies of the thermal, chemical, and mechanical behavior of the system, and of its economics. Problems are, of course, expected to develop in such areas as fluid loss through the natural void system in the rock, and plugging of circulation channels by mineral deposition. However, it is believed that there are straightforward engineering solutions to such problems.

Science will not be forgotten in this experiment. A long list has been developed of parallel and follow-on programs that should be undertaken, and of systems modifications and alternative operating modes that should be tried. However, the principal objective of the first major experiment will be a very practical one: to demonstrate a new, nonpolluting, geothermal energy system which might be producing commercial power within about 10 years, and within about 20 years could contribute significantly to the energy and pollution problems of the world.

APPENDIX A

The Energy Content of a Mass of Rock.

A mass of rock in the form of a cylinder 15 miles in diameter and 1 mile high is cooled by 250 °F. The thermal energy removed, assuming a heat capacity of 0.19 BTU/lb, and a density of 168 lbs/ft³, is given by (volume of rock in cubic ft.) X 0.19 X 168 = 2.07×10^{17} BTU. World energy consumption in 1972* = 2×10^{17} BTU.

*Extrapolated from table 12 of United Nations Statistical Yearbook, 1969.

APPENDIX B

Comparison of Energy Transport from Reservoir in the Form of Water or Steam.

I. STEAM CYCLE

Superheated steam from a reservoir at a temperature of 640 °F and a depth of 9842 feet flows to the surface through a pipe of inside d (inches), arriving as dry saturated steam at pressure P. From saturated steam tables we may find the entropy at pressure P. Since the flow is isentropic, we may find the pressure corresponding to the same entropy at the reservoir temperature in tables of superheated steam. From the pressure and entropy, the specific volume $\bar{V}$ may be found by interpolation. The empirical Babcock formula for steam flow¹² is:

$$\delta P \text{ (psi)} = 0.47 W^2 L \bar{V} (d+3.6)/d^6 \quad (1)$$

where L is length in feet and w is flow rate in pounds/sec. Fig. B-1 shows the results of calculations using (1) under the assumptions and conditions given in Table B-1. The length L was divided into 10 equal increments and $\bar{V}$ was recalculated for each increment. To calculate the flow rate for 100 megawatts (94826 BTU/sec), the difference in enthalpy between saturated steam at the surface pressure P and the same steam after it has been isentropically expanded to a temperature of 150 °F is calculated, and the result divided into 94826 BTU/sec. It is seen that a 12 inch pipe is not quite large enough to transport 100 megawatts under the assumed conditions, but that a 13 inch pipe will do so.

Reservoir Temperature:	640° F	
Reservoir Depth:	9842 feet	
Turbine Outlet Temperature:	150° F	
Assumed Surface Pressure (Dry saturated steam):	<u>1000 psi</u>	<u>800 psi</u>
Entropy (BTU per Lb per °F):	1.3897	1.4153
Enthalphy:	1191.8	1198.6
Enthalpy after isentropic expansion to 150° F:	834.1	849.8

(Cont.)

Available Energy (BTU/lb):	357.7	348.8
Flow (Pounds per sec):	265.1	271.8
Initial Specific Volume $\bar{V}$:	.3232	.3767

Table B-1. Boundary conditions and assumptions for steam pressure drop calculations. Results are plotted in Fig. B-1.

II. WATER CYCLE

Water at the reservoir temperature of 640° F flows to the surface through a 12 inch pipe. After passing through a heat exchanger, the water flows down a similar pipe at a temperature of 150° F. The pressure difference at the bottom of the hot and cold water pipes is 1400 psi, as may be seen from Fig. 5. Part of this will appear as pressure drop across the heat exchanger and across the reservoir. We may assume that 1000 psi is available to overcome the impedance of the pipe, pumping if necessary. The viscosity of water at 640° F is about 1/12 of that at 60° F, as may be seen from Fig. 3. At 150° F, viscosity is approximately 1/2 of that at 60° F. We may take this into account, within the accuracy of this water/steam flow comparison by considering the impedance of only one of the pipes and assuming that the water is at 60° F. Hazen and William's formula¹² for the flow of water in a smooth pipe of length L (feet), diameter d (inches), and a pressure difference $P_1 - P_2$ (psi) is

$$Q \text{ (lbs/sec)} = 8.59 d^{2.63} [(P_1 - P_2)/L]^{0.54}. \quad (2)$$

If we assume that $L = 9842$, $P_1 - P_2 = 1000$ psi and $d = 12$ inches, then $Q = 1721$ pounds/sec. The enthalpy difference between 640° F water and 150° F water is 560.7 BTU/lb, so the available energy is 964,982 BTU/sec or 1000 megawatts, vs. the 100 in the case of steam.

APPENDIX C

Void Generated Per Million BTU of Heat Energy Withdrawn from Rock.

If the specific heat of rock is c [BTU/(lb °F)], its density is ρ (lb/ft³), and its volume coefficient of expansion, B (per °F), then withdrawal of $Q \times 10^6$ BTU of heat energy from a volume V gives a temperature drop $\delta T = Q \times 10^6 / (\rho c V)$. This change of temperature causes a thermal contraction $\delta V/V = B \delta T = 10^6 B Q / (\rho c V)$, so

$$\delta V = 10^6 B Q / (\rho c). \quad (1)$$

Typical values of the constants ^{5,13} are:

$$B = 13.8 \times 10^{-6},$$

$$c = 0.19,$$

$$\rho = 168.$$

Inserting these values in (1), we have

$$\delta V/Q = 0.43. \quad (2)$$

If 100 MW of power is withdrawn for 24 hours, $Q = 8191$, and the void is 3541 ft³, requiring 26,559 gallons of make-up water.

APPENDIX D

The Temperature at Which Thermal Fracture Occurs, vs. Depth.

Consider a mass of rock in which the temperature gradient, directed downward, is G . At a depth h (ft.), the temperature before the rock is cooled is T ($^{\circ}\text{F}$) = $Gh + T_s$, (1) where T_s is the surface temperature, averaged over the entire year.

From hydraulic fracturing experience, we note that fracture occurs at some multiple of hydraulic pressure, say at $b \times 0.433 h$. An average value of b is about 1.5 (Ref. 14). Since we assume that at least full hydrostatic pressure is acting, an additional tension, arising from thermal contraction, equal to $(b - 1) \times 0.433 h$, is required to induce cracking. Let the thermal expansion coefficient be a (per $^{\circ}\text{F}$), and Young's modulus, E .

We consider a process in which the shrinkage, $\delta L/L = a(T_0 - T)$ (T_0 = temperature to which the rock has been cooled) is followed by a stretching to bring the rock back to its original length, which requires a tension = $E|\delta L/L| = Ea(T - T_0)$. (2)

We equate this to the extra tension required for cracking, using (1) for h , and arrive at

$$T_0 = [1 - (b-1) \times 0.433/(GEa)] T + (b - 1) \times 0.433/(GEa) \times T_s \quad (3)$$

Some typical rock values¹³ are:

$$E = 8 \times 10^6 \text{ psi},$$

$$a = 4.6 \times 10^{-6}$$

$$G = 0.1 \text{ } ^{\circ}\text{F/ft},$$

$$T_s = 40 \text{ } ^{\circ}\text{F},$$

$$b = 1.5.$$

Inserting these in (3), we have

$$T_0 = 0.94T + 2.35, \text{ or } T_0 = 0.94 T. \quad (4)$$

In this example, cooling by only 36 $^{\circ}\text{F}$ would crack 600 $^{\circ}\text{F}$ rock. The coefficient of T in (4) is designated K in the machine calculations⁷. It becomes smaller if the thermal gradient is low, as rock of temperature T will lie at greater depths.

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Fig. 1 Circulation loop with concentric pipes.

Fig. 2 Circulation loop with separate pipes.

Fig. 3 Viscosity of water and steam vs. temperature.

Fig. 4 Turbine/pump for use in concentric circulation loop.

Fig. 5 Pressure difference between hot and cold water vs. depth.

0 YEARS

3 YEARS

30 YEARS

41 YEARS

Fig. 6 Contours of equal porosity from computer calculation.

Fig. 7 Power vs. time at constant circulation rate.

Fig. B-1 Results of Steam Flow Calculations.