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STATUS OF THE MAGMA ENERGY PROJECT

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ABSTRACT

The current magma energy project is assessing the engineering feasibility of extracting thermal energy directly from crustal magma bodies. The estimated size of the U. S. resource (50,000 to 500,000 quads) suggests a considerable potential impact on future power generation. In a previous seven-year study, we concluded that there are no insurmountable barriers that would invalidate the magma energy concept. Several concepts for drilling, energy extraction, and materials survivability were successfully demonstrated in Kilauea Iki lava lake, Hawaii. The present program is addressing the engineering design problems associated with accessing magma bodies and extracting thermal energy for power generation. The normal stages for development of a geothermal resource are being investigated: exploration, drilling and completions, production, and surface power plant design. Current status of the engineering program and future plans are described.

INTRODUCTION

Magma intruded into the crust is the heat source for geothermal reservoirs. Magma also represents an energy resource itself that is both much larger and of higher quality than the geothermal resource. Smith and Shaw (1,2) estimate this resource within the upper 10 km of the crust in the U. S. to be 50,000 to 500,000 quads - larger than the current estimate for U. S. fossil resources.

In 1975 the Magma Energy Research Project was initiated by ERDA (now DOE) to investigate the scientific feasibility of extracting energy directly from deeply buried magma sources. The project addressed five task areas: source location and definition, source tapping, magma characterization, material compatibility, and energy extraction. Work on these topics proceeded for seven years and culminated in a demonstration of many of the magma energy concepts in the molten zone of Kilauea Iki lava lake (3). The conclusion reached after this seven year study was that energy extraction from active magma bodies is indeed scientifically feasible and two different scientific review panels agreed with this conclusion (4).

In 1984, the Magma Energy Extraction Program became part of the Department of Energy's Geothermal Program. The objective of this follow-on program is to assess the engineering feasibility of the magma energy concept and to provide the data base needed for industry to evaluate economic feasibility. We are working to answer the question: Is magma generated power practical from an engineering point of view? The project was organized to address five areas: (1) overall system concept, (2) geophysics/site selection, (3) drilling, (4) energy extraction, and (5) magma characterization and materials compatibility. We have the ultimate objective of drilling into an active crustal magma body, emplacing energy extraction hardware, and conducting a long-term energy extraction experiment.

System Studies

Two system analyses have been completed. The first was carried out by Well Production Testing (5) and included well and casing design, surface plant design, and energy extraction analysis. Major results from this investigation are: (1) a 6 km well drilled and completed into magma at Long Valley caldera was estimated to cost $16 M, (2) plant capital costs were estimated to be $1.45M per MW of installed electrical capacity, and (3) energy extraction rates of 20 MWe were predicted for the base case open heat exchanger system.

The second study was a combined Sandia/WPT evaluation of the economics of magma power generation (6). Economic calculations determined the price that would need to be charged for electricity in order to balance the costs of power generation

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and provide a real rate of return of 10% (before taxes but above inflation). A typical result is shown in Figure 1 where energy extraction rate and well depth were used as variable parameters. Well maintenance costs, surface plant capital costs, and plant operating and maintenance costs were included as were realistic plant lifetime and operating factor. Magma based electricity prices required are in the neighborhood of 80 to 100 mils per kilowatt hour. These prices are higher than current prices for fossil fuels and hydrothermal resources, but below current prices for new nuclear plants. Based on the uncertainties associated with well costs and energy extraction rates, the conclusion at this point is that magma appears to be in the same "economic ballpark" with other energy resources. The analysis identified well cost, well productivity, and well lifetime as the parameters most critical to the economics of magma power generation.

Geophysics/Site Selection

Early in the current program, twenty-one potential magma sites were evaluated in terms of suitability for conducting a long-term energy extraction experiment (7, 8, 9). This resulted in the selection of two primary sites: Long Valley caldera and the Coso Hot Springs area, both located in California. Existing geophysical data at these two sites were then evaluated in detail and additional surveys were conducted. Both of these sites provide reasonable magma targets, but Long Valley was selected as the primary site based primarily on the extensive geophysical, geological, and geochemical studies that had been completed in the area.

Rundle et al. (10), combined the seismic data at Long Valley to form a preliminary composite view of the magma chamber underlying the caldera (See Figure 2). The inferred chamber was large, with dimensions on the order of the caldera diameter (20 km). Two cupolas were identified, extending toward the surface, at drilling depths of 5 and 7 km. A later overlay of published geophysical data (11) is reproduced in Figure 3. Two distinct anomalous regions associated with the inferred magma cupolas are clearly identified. Estimates of depth to the shallowest cupola in the southern resurgent dome area range from 4 to 7 km. Elbring and Rundle (12) obtained more detailed definition of the southern cupola by recording local earthquake events with a three-component seismometer emplaced in the bottom of a 900 m deep well. Their estimate of depth to the top of the anomaly is 3.7 km.

Recently Lawrence Berkeley Laboratory held a symposium on the Long Valley caldera that brought together current data and models for the caldera. Results from geology, geohydrology, geochemistry, seismology, potential field and electromagnetics studies were presented. New data continue to show anomalies in the basement beneath the resurgent dome. In addition, the first evidence of an anomalous region beneath Mammoth Mountain has emerged. New data also support location of the highest temperature hydrothermal system in the western portion of the caldera to the west of the resurgent dome.

Future magma energy support for geophysics in Long Valley will be for downhole measurements in the Long Valley exploratory well which will be spudded during 1988. Downhole measurements will avoid the attenuation and structural complications introduced by caldera fill and provide higher resolution data. Plans are to drill the well in three phases with downhole geophysical measurements conducted between each phase. These measurements may, in fact, lead to early termination of the drilling if a suitable magma target is not confirmed.

Drilling

Conceptually, deep crustal magma bodies can be drilled with the same technology used to core Kilauea Iki lava lake in 1981. The differences that must be considered are that a deep magma body will have an overlying high temperature hydrothermal system of considerable extent and the deep body will be at much higher pressure and contain dissolved gases. The temperature problem has been addressed first by designing an insulated drill string to control drilling fluid temperatures (13). Drilling fluid temperature affects the properties and degradation of additives, the strength and corrosion rate of tubulars, bit cooling, and borehole stability. The advantage of using an insulated drill string can be seen in Figure 4 where fluid temperatures were calculated for drilling 1 km into a magma body whose roof is located at a depth of 5 km. An idealized temperature profile for Long Valley caldera was used that matches the heat flow data and shallow temperature logs. The calculations assume a 0.31 m wellbore, 0.13 m drillpipe, and a water flow rate of 22 kg/s. Fluid temperatures reached in the conventional drillpipe without insulation are clearly unacceptable. The addition of a .0095 m insulation shell to the drillpipe has a large effect and reduces temperatures to acceptable levels throughout the 6 km well. Pipe insulation also affects temperature distribution in the solidified magma region surrounding the hole. An example of this effect can be seen in Figure 5 which gives the radial temperature distribution when drilling reaches the 6 km depth. Since rock strength is a strong function of temperature, the benefits of cooler drilling fluid may be crucial to hole stability.

While general wellbore stability problems were considered in the early research project by Friedman (14), problems associated with creep were not fully evaluated. Two problems are of concern. The first is creep of the surrounding hot rock that could cause the wellbore to squeeze in behind the bit during drilling. The second involves reheating of the surrounding rock and creep closure of the well after circulation is lost. Both situations were analyzed using a finite element rock mechanics code (13). The results are generally encouraging. Displacement of the wellbore wall during drilling is predicted to be only a few millimeters and, therefore, is not expected to be a problem. One result that addresses the second problem is shown in Figure 6. Displacements are shown as a function of time after a break in circulation which is assumed to occur exactly when the depth of 6 km is reached. The figure shows that at least one day is available to regain circulation before significant displacement takes place. As circulation time is increased at a particular depth horizon, borehole stability time after loss of circulation also increases.

Energy Extraction

The current engineering project is investigating energy extraction from silicic magma systems which are most representative of magma bodies expected at western U. S. sites. Unlike basaltic bodies, the more viscous rhyolites will probably require direct contact fluid circulation to achieve economic energy extraction rates. Figure 7 shows a conceptual representation of a single well open heat exchanger system. The well is cased into the plastic transition zone and a concentric inner injection tube extends into the magma. The region surrounding the injection tube is cooled, solidified, and thermally fractured by circulation of the heat transfer fluid. Extent of the fractured zone is controlled by the rate of energy extraction. Beyond the fractured region, is a transition zone which behaves as a plastic solid and does not support fracturing. Cooling in the magma zone induces large scale natural convection that enhances heat transfer to the solidified region.

Initially, a simplified mathematical model of the open and closed energy extraction systems was developed (15) to address basic engineering questions. We found that energy can be brought efficiently from the magma to the surface using concentric pipes with counterflowing heat transfer fluid. Calculations show that the proper flow path is cold fluid down the annulus with hot fluid returning to the surface through the central core. Insulation of the core results in both higher wellhead temperatures and cooler fluid in the annulus. Insulation thickness of only .0064 m produces adequate wellhead temperatures and is sufficient to ensure a net heat gain from the overlying formation rather than a heat loss. The calculations also confirm that for a fixed magma heat transfer coefficient there is a flow rate that maximizes electric power production. Single well extraction rates of about 25 MWe were predicted with the simple model using an ideal cycle for thermal energy conversion.

Recently, a numerical code named MAGMAXT was developed to more accurately model the energy extraction process (16). Two-phase compressible fluids are treated to fully evaluate flashing problems in the return pipe. By specification of the injection pressure and mass flow rate, the flow state throughout the circulation path is computed in an iterative marching procedure. The open heat exchanger is assumed to be a permeable annulus whose outer diameter can vary with depth according to the rate of heat transfer. Figure 8 gives temperature results for a high flow rate of 10 kg/s. In this calculation, water was used as the heat transfer fluid and well geometry was based on the WPT well design for Long Valley (5). At this flow rate heat transfer occurs within the counterflowing fluids and in the magma zone between states C and D. The pressure-enthalpy diagram for this set of conditions is shown in Figure 9. As in the simplified model, optimum flow rates exist that maximize the rate of electric power generation. This can be seen in Figure 10 where an ideal Carnot cycle is assumed for the conversion of thermal to electric energy. Three curves are shown: (1) a closed heat exchanger without fluid/rock direct contact, (2) an open heat exchanger (case 1) with conservative estimates of fluid/rock heat transfer in the solidified zone, and (3) an open heat exchanger (case 2) with higher heat transfer characteristics to account for developing flow in the annulus and buoyancy effects not included in case 1. The Case 1 estimate of about 30 MWe per well must be reduced to account for more realistic power conversion cycles. We are currently working with the University of Utah to confirm our numerical energy extraction calculations, evaluate the effects of buoyancy assisted porous media flows, and develop realistic power conversion cycles. Early results that include the influence of developing flow and use Rankine cycles for power conversion predict energy extraction rates in excess of 30 MWe per well (17).

Several additional conclusions were reached based on simulation of the energy extraction process with MAGMAXT. Heat transfer to the fluid in the solidified magma zone occurs essentially isobarically but with substantial volumetric expansion. The resulting density imbalance between the injection and return flow paths is sufficient to allow the well to flow as an open thermosyphon without pumping. In all cases analyzed, flashing to two-phase flow in the return line does not occur. Thus two-phase choking problems commonly encountered in geothermal wells are avoided. As expected, the extent of the solidified magma region was found to vary with depth. However, large variations in diameter only occur for low flow rates. For optimum conditions, the average diameter is approximately 10 to 20 m.

The open heat exchanger concept depends on fracturing of the solidified magma region. Theoretical models that describe fracturing of this region due to thermal stresses have been developed (17, 18). The analyses predict vertical and horizontal fractures even for large over-burden pressure. A series of experiments was carried out to verify the analytical models and to examine the qualitative features of initiation and propagation of thermal stress fractures in a solidifying melt (18). Simulant glass cylinders were axially cored, heated, and then suddenly cooled along their inner boundary. Extensive fracturing occurred as shown in Figure 11 and fracture distribution was in general agreement with theoretical predictions. Melt solidification experiments were conducted using simulant glass in an induction furnace with a central cooling tube passing through the melt. The outer melt zone was maintained at 1273 K while water was circulated through the cooling tube giving an inner temperature of about 423 K. This experiment produced a solidified zone with a large number of horizontal and vertical fractures. In the actual open heat exchanger, secondary fracturing processes, not yet evaluated, are expected to play a significant role in the formation of the fractured region. Fluid flow in the primary fractures will have two effects: (1) creation of secondary thermal fracturing normal to the primary fractures, and (2) hydraulic extension of the fracture due to pressure buildup. Future experiments are designed to evaluate these processes.

Another heat transfer process of importance to sustained energy extraction is magma convection within the chamber. The magnitude of the convective heat flux available at the outer surface of the heat exchanger essentially depends on two phenomena: one, the vigor with which fresh, hot magma is transported to the plastic region by chamber convection, and two, the efficiency of convection and diffusion in the boundary layer next to the heat exchanger. A typical chamber may have representative length scales on the order of 5 km with magma temperatures ranging from 923 to 1173 K. The representative chamber Rayleigh number may be on the order of 10^{16} which is far greater than the critical Rayleigh number below which one could expect steady, laminar convection. The physics of turbulent natural convection in such enclosure are not well understood. The problem is further complicated by large variations in the magma viscosity. The physics of the boundary layer interaction at the cooled heat exchanger walls are equally complex and poorly understood.

In order to better understand the fundamental mechanisms of the chamber and boundary layer convection, and ultimately, to improve our engineering estimates of the heat flux available at the exchanger, we have begun a laboratory study in which we simulate the most important mechanisms in a scaled experiment. The apparatus consists of a clear, plexiglas enclosure with a typical dimension of 0.5 m. The simulant working fluid is corn syrup. Figure 12 shows a typical result recently obtained with two-dimensional strip heating at the bottom surface and isothermal cooling at the top surface with insulated side surfaces. The time exposure shows the flow field where Prandtl numbers vary by a factor of 5. (Variations up to 1000 can be achieved.) Velocity, temperature, and heat flux will be measured throughout the test section. This experimental data will be compared with numerical simulations to develop a computational procedure for obtaining magma chamber convective heat transfer rates.

Geochemistry/Materials

While the previous geochemistry/materials effort of the research project dealt completely with basaltic systems, the current effort is focused on rhyolitic systems typical of Long Valley. Sulfidation, a major problem in basaltic magmas, is not induced by rhyolitic magma. Here, the main corrosion problem for most alloys is oxidation. Four specific problem areas are being investigated: (1) characterization of rhyolitic magma typical of Long Valley, (2) materials compatibility in this magma, (3) vesiculation hazards of drilling into a volatile-rich rhyolitic magma, and (4) solution transport in the fractured open heat exchanger.

Mineral compositions and volatile concentrations have been determined for crustal magma bodies in the Long Valley and Coso locations. Extensive testing of metals in the expected volatile rich magmatic environment at 1123 K and 200 MPa lead to the conclusion that nickel based superalloys have very good chemical resistance and strength in this environment (19). Reaction rates between alloys and silicates are significantly reduced at normal heat exchanger operating conditions of 773 K and 50 MPa.

An experimental facility was recently completed to measure silicate dissolution rates and solution composition in open direct contact heat exchangers. The potential for loss of permeability due to precipitation of secondary minerals will also be evaluated. The importance of several different mechanisms on reaction rates will be assessed. This includes temperature which has a large and measureable effect, solution composition, defect concentration, and hydrodynamic effects.

LONG VALLEY EXPLORATORY WELL

A deep exploratory well is planned for Long Valley caldera. The well will be drilled in the southern portion of the resurgent dome near the peak of recent uplift within the caldera (roughly 0.5 m uplift since 1979). The primary objective of the well is to determine the nature of identified geophysical anomalies at 4 to 7 km depth that have been interpreted as magma. Surface geophysical measurements have reached a point of diminishing return and new information from depth is needed to more accurately characterize anomalous regions beneath the dome. A deep hole at this location will also provide data to test the accepted hypothesis that a long lived magma body has existed beneath the caldera for a time period of about one million years. If high temperature near magmatic conditions are reached, the well can be used to test newly developed drilling technology, evaluate engineering materials, and confirm heat transfer calculations. The well is planned in three stages. The first stage will penetrate caldera fill and enter basement where casing will be set to a depth of 2.1 to 2.4 km. The second stage will extend the hole to a depth of about 4.3 km where casing would again be set. The final stage will reach a total depth of 5.5 km. Between each drilling phase, the well will be open for downhole geophysical measurements. Critical programmatic experiments include: temperature and heat flow measurements, fluid and gas sampling, in situ stress measurements, physical and chemical analysis of limited core samples, permeability measurements, and passive and active seismic observations. The data from these measurements will be evaluated to determine if the drilling should proceed into the next phase.

If the well is drilled to total depth it will be the world's deepest observation port into an active caldera. Thus, there would exist the opportunity for numerous scientific add-on experiments that could lead to a better understanding of the evolution and dynamics of magmatic systems. If an active magma target is confirmed, the project will proceed to a final phase where the magma body will be drilled and the long term heat extraction experiment carried out.

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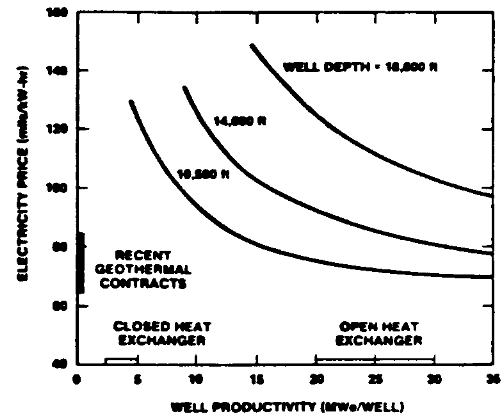

Figure 1. Effect of well depth and productivity on magma energy costs.

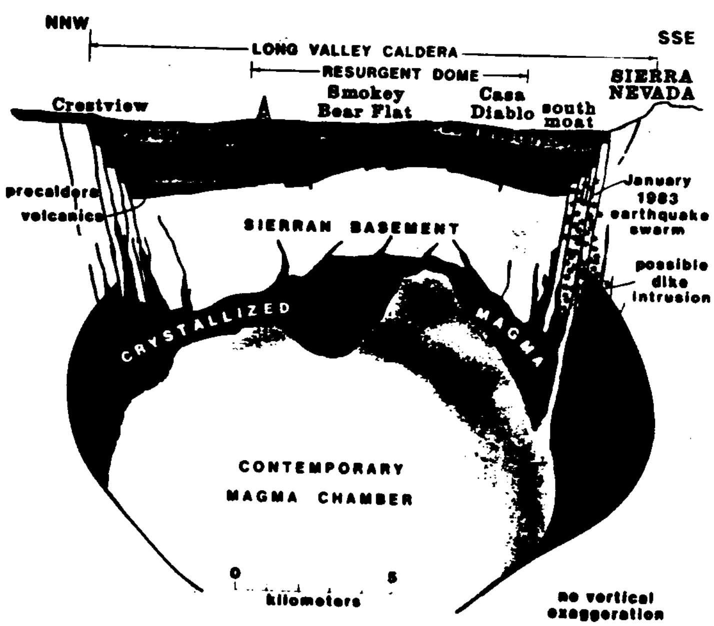

Figure 2. Cross section of Long Valley caldera, California, showing the underlying magma chamber as inferred from geophysical measurements.

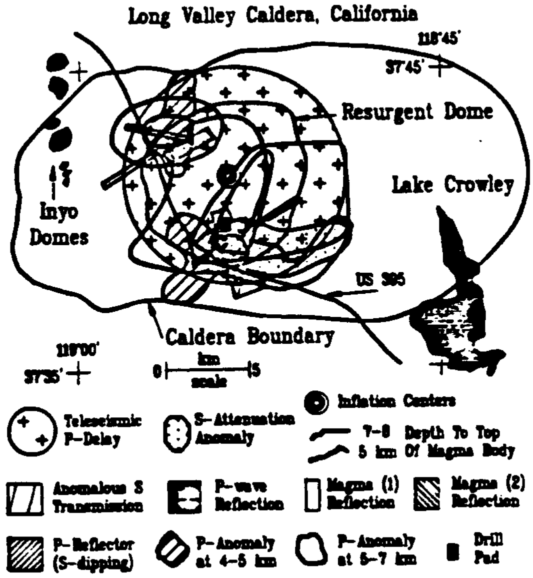

Figure 3. Geophysical anomalies in Long Valley caldera.

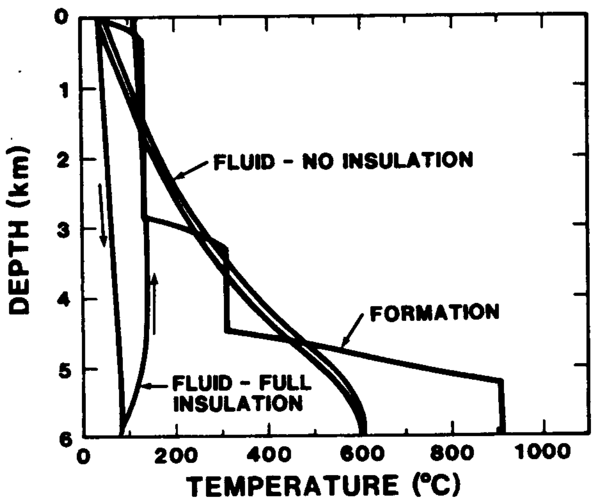

Figure 4. Fluid and formation temperatures in a magma well in Long Valley.

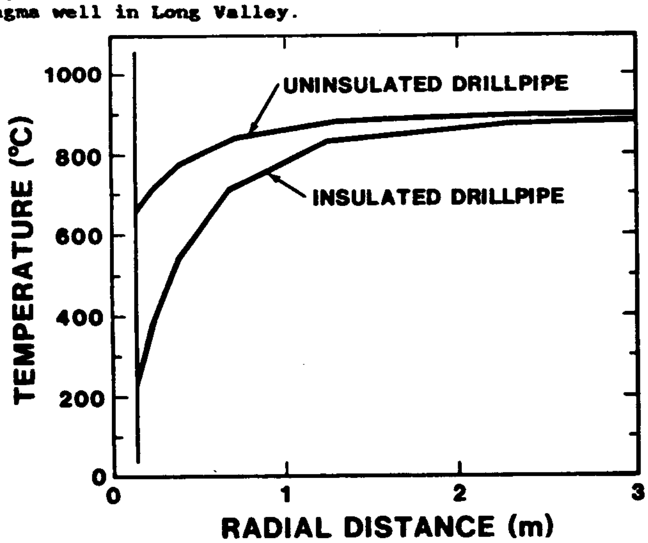

Figure 5. Bottom hole formation temperatures after drilling to 6 km in Long Valley

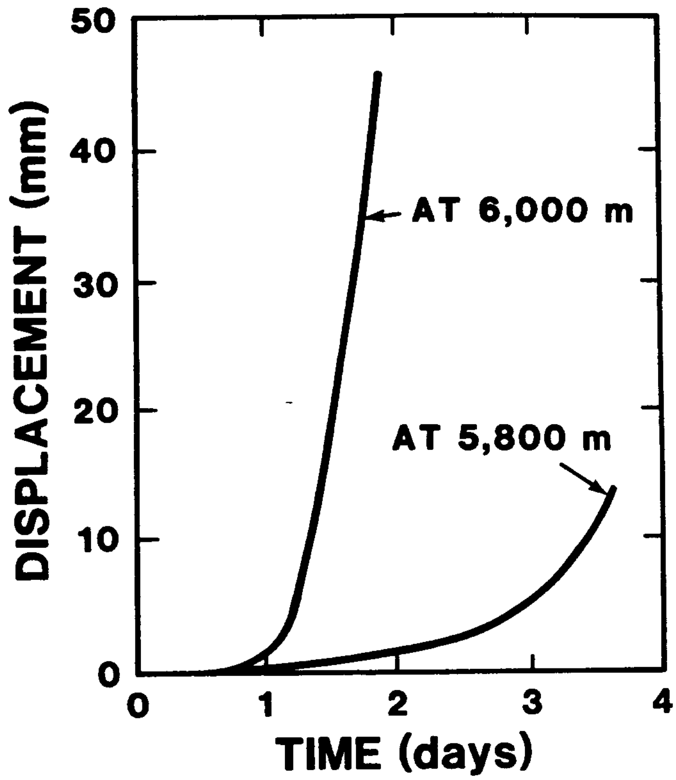

Figure 6. Wellbore displacement after circulation is stopped.

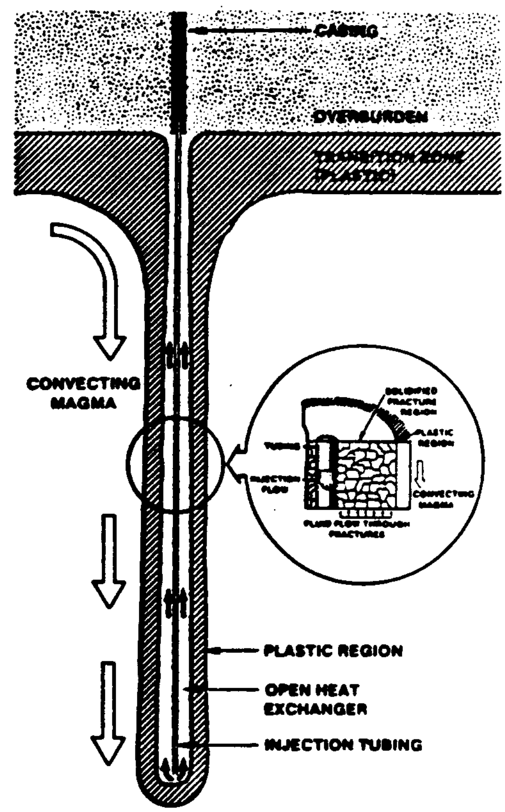

Figure 7. Conceptual representation of open heat exchanger with fluid flow through fractured, solidified magma.

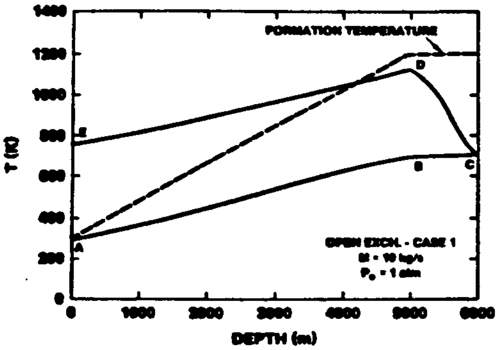

Figure 8. Fluid temperatures for circulation in an open heat exchanger.

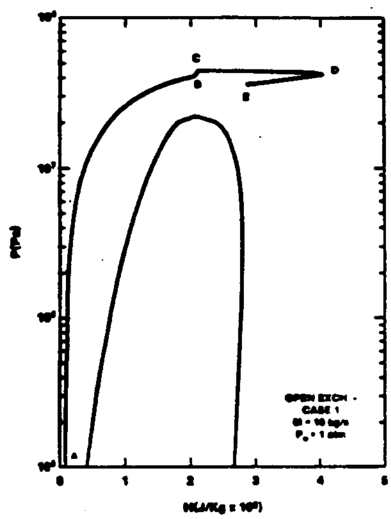

Figure 9. Pressure-enthalpy diagram for magma heat extraction.

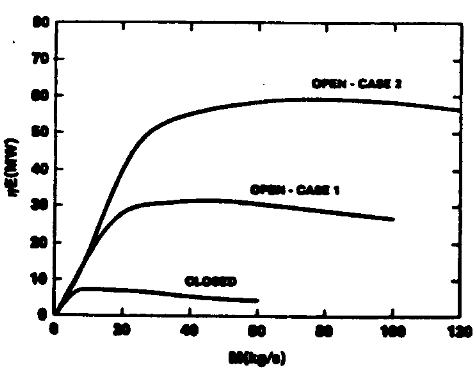

Figure 10. Energy extraction rate as a function of mass flow rate.

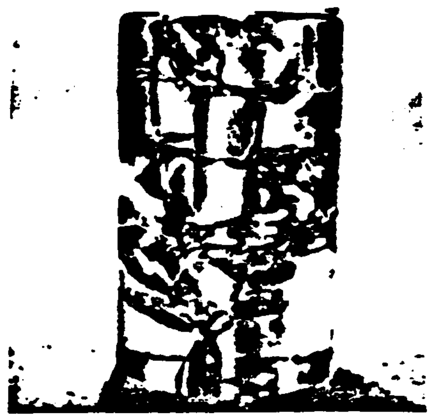

Figure 11. Thick walled glass cylinder thermally fractured at 200°C.

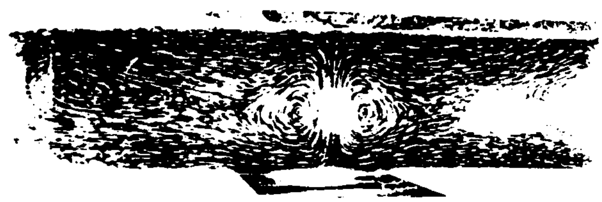

Figure 12. Magma convection simulation experiment with time exposure photograph showing fluid streamlines.

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