THE MAGMA ENERGY PROGRAM

by
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Introduction

The concept of extracting energy directly from crustal magma source emerged as a possible energy alternative during the early 1970s. International recognition of this concept and wide scientific interest grew following two important workshops (Colp and Furumoto, 1974; Crop and others 1975). In FY 75, the Department of Energy initiated the Magma Energy Research Program and funding continued until FY 82 when scientific feasibility was demonstrated (Colp, 1982). The research program focused on key aspects of magma energy to determine if there are barrier s that invalidate the concept. Studies concluded that the magma energy concept could be implemented.

As a culmination of years of analyis and experiments, a drilling operation was successfully completed in Kilauea Iki lava lake, Hawaii. We succeeded in drilling through the hottest portion of a remaining melt zone in this lake where temperatures exceed 1,000°C. We obtained over 105 m of core from the melt and ran energy extraction experiments in magma (Hardee and others, 1981).

During FY84, the Geothermal Technology Division of DOE initiated the Magma Energy Extraction Program to investigate engineering feasibility. The primary goal of this program is to develop and demonstrate the technology needed to produce power from magma resources so that industry can evaluate economic viability (Dunn, 1988). In the United States, the major potential for magma energy is in the form of silicic melts that have accumulated in the crust at relatively shallow depths (Eichelberger and Dunn, 1990). The current engineering program is directed at utilization of this potential resource. We are developing specific technologies in energy extraction, material, drilling, and source definition so that wells can be drilled into large magma bodies and energy extracted for power production.

The current focus of the magma energy program is the drilling of a deep exploration well in Long Valley caldera (see Figure 1). The location of the well is on the resurgent dome, coincident with a large number of shallow (5 to 7 km depth) geophysical anomalies and near the point of maximum inflation (see discussion below). This well is targeted for the near- magmatic regime at a temperature of 500°C and is designed for a depth of 20,000 feet. Measurements obtained from the well will enable definition of magma at depth, an assessment of the significance of the observed geophysical anomalies, and investigation of the patterns and conditions of deep fluid circulation and heat transport below the caldera floor. Deep wellbore measurements will provide important new information about the hydrothermal system at Long Valley, and perhaps shed

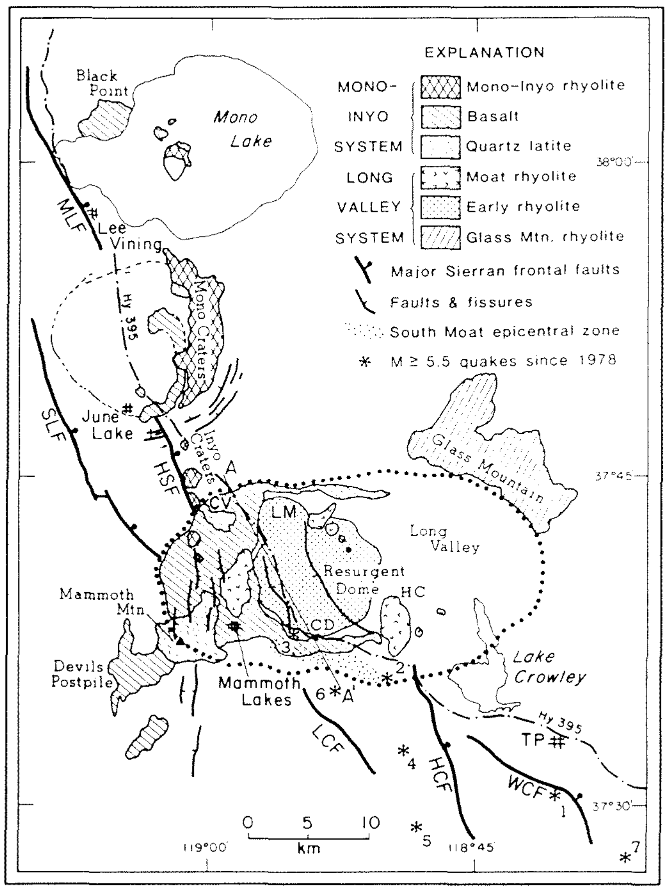

Figure 1
Regional geological and tectonic map of Long Valley caldera (after Hill and others, 1985a).

light on why a major hydrothermal resource has not been discovered.

Since this well will be the first deep well drilled into the margins of an active magma system, there is important scientific interest as well. Through signed agreements among the Department of Energy, the National Science Foundation, and the U.S. Geological Survey, the Magma Energy Exploratory Well has been designated part of the U.S. Continental Scientific Drilling Program. Scientific issues that can be addressed by the magma well were developed during a workshop held in Albuquerque during June 1988. The results are published in a science guide for the Long Valley caldera deep hole (Rundle and Eichelberger, 1989).

Project Objectives

The Long Valley well has a number of project objectives that address either source location and definition or engineering hardware development. The primary objective is confirmation of the existence of magma at drillable depths beneath the surface. This well will test the very foundation of the magma energy concept-- that huge quantities of partially molten magma reside in the crust at relatively shallow depth. Because of its size and recent activity, Long Valley caldera is one of the best locations in the U.S. to test this hypothesis.

An additional objective is the testing and calibration of surface geophysical methods for magma location and definition. Numerous surveys have been completed in Long Valley with conflicting results (Rundle and Hill, 1988). Most geophysical measurements detect anomalies beneath the caldera but intepretations do not agree. The deep well will provide hard evidence of structure beneath the resurgent dome and wellbore measurements of density, elelctrical conductivity, and seismic velocity will greatly improve the accuracy of geophysical data analysis. Furthermore, wellbore geophysical measurements will provide a means to infer structured and properties at depths greater than those penetrated by the well.

Energy extraction from an active magma body presents a number of formidable engineering challenges. Several new drilling technology ideas, such as insulated drillpipe, will be tested and evaluated in the less severe environment of the exploratory well. Likewise, materials selected through laboratory experiments for magma compatibility will be tested in the actual near-magma environment.

The magma program is organized to address engineering feasibility by investigating four primary areas: 1) geophysics, 2) drilling, 3) energy extraction, and 4) geochemistry. The following sections summarize work completed in these areas and point out the needs for future studies.

Geophysics

Long Valley caldera has been the site of intensive geophysical and geological investigations for the past 15 years. (See Rundle and Hill, 1988). These investigations assumed much greater importance beginning in 1980 due to the major earthquake sequences, ground deformation, and renewed hydrothermal activity which began at that time. Figure 1 is a map of the Long Valley -- Mono Craters -- Mono Lake region showing the principal physiographic and geologic features.

During 25-27 May 1980, four earthquakes of magnitude greater than 6 occurred within and to the immediate south of Long Valley. Uplift of as much as .25 meter, centered on the old resurgent dome of the caldera (Figures 1 & 2), was subsequently measured by extensive leveling observations, and has been inferred to have accompanied the earthquake sequence.

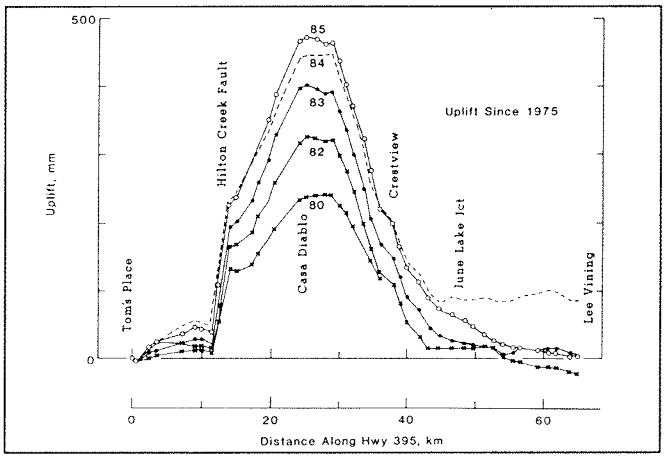

Figure 2

Leveling data along Highway 395 through Long Valley caldera (after Savage and others, 1987).

Since 1980, considerable seismic activity has been occurring, albeit at a variable pace. The south moat swarm which began on 6 January 1983, had two events with magnitudes in excess of 5. Subsequent events included the 23 November 1984 Round Valley earthquake of magnitude 5.8, and the 20 July 1986, Chalfant earthquake sequence, which included three events of magnitude 6 or greater. While these two earthquake sequenced were located to the south and east of the caldera, respectively, seismicity within the caldera has also been a continuing feature of the regional activity (Figure 3).

Uplift observed by leveling along Highway 395 has grown to a peak value of at least half a meter (Figure 2), and extensive surveys covering the entire caldera demonstrate that it remains centered on the resurgent dome. Most recently, two- color geodolite surveys spanning the last 6 years indicate that horizontal straining has increased by a factor of 5 since September 1989,

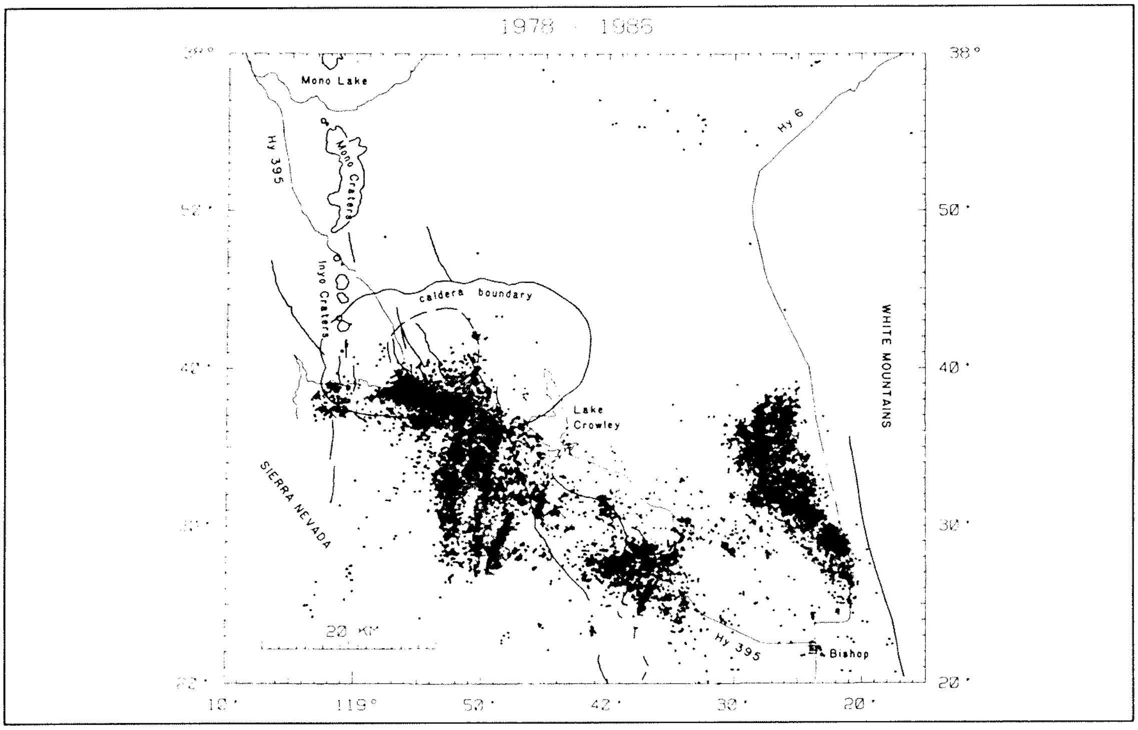

Figure 3
Map of Long Valley regional seismicity from 1978 through 1986 (from Rundle and Hill, 1988).

centered over the southern margin of the resurgent dome (D.P. Hill, personal communication, 1990). These higher rates are typical of those observed 6 years ago, when the seismic activity within the caldera was considerably more intense. For comparison, a rate of 5 ppm/yr is a factor of 30-50 higher than rates typified by the San Andreas fault system in southern California. Associated seismic activity has also begun to spread in a gradual northward migration under the resurgent dome.

As a result of the frequent tectonic and renewed volcanic activity, an extensive series of geophysical and geological activities were planned in conjunction with the U.S. Geological Survey's Volcanic Hazards Program and the U.S. Department of Energy's Continental Scientific Drilling Program and Magma Energy Programs. Work began in 1982, with a comprehensive seismic refraction experiment throughout the Long Valley — Mono Craters region, gravity surveys, heat flow measurements, greatly increased passive seismic observations through densification of existing networks, electromagnetic, hydrothermal and a variety of geochemical and geologic surface investigations (Rundle and Hill, 1988).

Seismic refraction experiments were completed during the summers of 1982 and 1983, and results were supplemented by deployments of arrays of seismometers during the frequently occurring earthquake swarms, such as that of January 1983. Sources for the active experiment were a series of 1-ton shots distributed throughout the caldera and along a major east-west profile intersecting the Mono Craters to the north. Average depth of ray penetration in the active experiments was typically about 4-5 km; thus the refraction studies have principally contributed to defining the structure of the uppermost part of the crust (Hill and others, 1985b).

Data from passive studies have been more successfully used in constructing models for regions of the caldera deeper than 5 km, but the results continue to be controversial. One of the first of these experiments was a shear wave shadowing study (Sanders, 1984), in which earthquakes occurring within the Sierra Nevada Mountains to the south of the caldera were recorded on the University of Nevada seismic network with stations located to the west, north, and east. Results from these observations indicated that the heatwave energy appeared to be systematically removed from the wave trains for raypaths penetrating the central part of the clder at depths below 5-6 km. These results may imply the existence of a partially molten body of rock at depths in excess of 5 km beneath the central and south central part of the old resurgent dome. Other kinds of observations (summarized in Rundle and Hill, 1988), including P-wave tomography and teleseismic wave reflection measurements, have contributed to the general picture of a substantial geophysical anomaly at Long Valley. This anomaly, inferred to be magmas, lies beneath the central resurgent dome, at depths possibly as shallow as 5-6 km. The peak of the recent uplift as defined by both leveling and gravity observations is roughly coincident with the site chosen for deep drilling. Estimates for the volume of the anomaly range from a few tens of km^3 on the low side to a thousand km^3 or so at the upper end.

Drilling

Technology used to drill into molten lava a Kilauea Iki can be applied to deeper drilling into silicic magma bodies. A major problem posed by deep drilling is that the drill string serves as a heat exchanger and drilling fluids are heated to an unacceptable level. Drilling fluid temperature influences almost all aspects of drilling, especially fluid selection, tubular selection, bit cooling and hole stability. Our current work in drilling technology addresses this problem area and has resulted in the concept of insulated drillpipe (IDP). IDP is essential for maintaining reasonable drilling fluid temperatures when magma is penetrated. Although the Long Valley exploratory well will stop short of magma, the performance of IDP can be effectively evaluated during deep drilling.

Many fluids are unsuitable for use at high temperatures either because a property (such as viscosity) changes reversibly to an unusable state, or because the fluid and its additives are permanently degraded by the heat. Casing and drillpipe can be significantly affected by high temperature for at least two reasons. Strengths of the various steels not only drop as they get hotter but sometimes also have a time-dependent strength loss. Also, corrosion will be a severe problem in a magma well since chemical reaction rates are accelerated at high temperature.

Regardless of the type of bit used for drilling, lower temperatures will improve bit life. Roller cone bits have longer-lived hearings, seals and lubricants; drag bits will have better diamond (natural or synthetic) life at lower temperatures. This becomes increasingly important as depth increases.

As the hole approaches magma, the wellbore wells become more plastic, reducing the wellbore stability. When the magma is actually penetrated, there will be no wellbore at all if the fluid circulation does not keep the rock chilled into solidity. The radius of the solidified rock around the wellbore in the magma chamber depends on the temperature of the fluid and the length of time that it has been circulated. Stability is especially crucial when the wellbore has recently entered magma.

Thermal analyses of drilling into magma show that even deep within the molten body, drilling fluid and tubular temperatures can be maintained below 230°C by circulating the fluids through insulated drillpipe (Finger, 1986). Figure 4 shows the inward creep in the wellbore wall calculated as a function of time after fluid circulation is lost; the longer collapse time at the shallower depth reflects the longer exposure time to relatively cool drilling fluid.

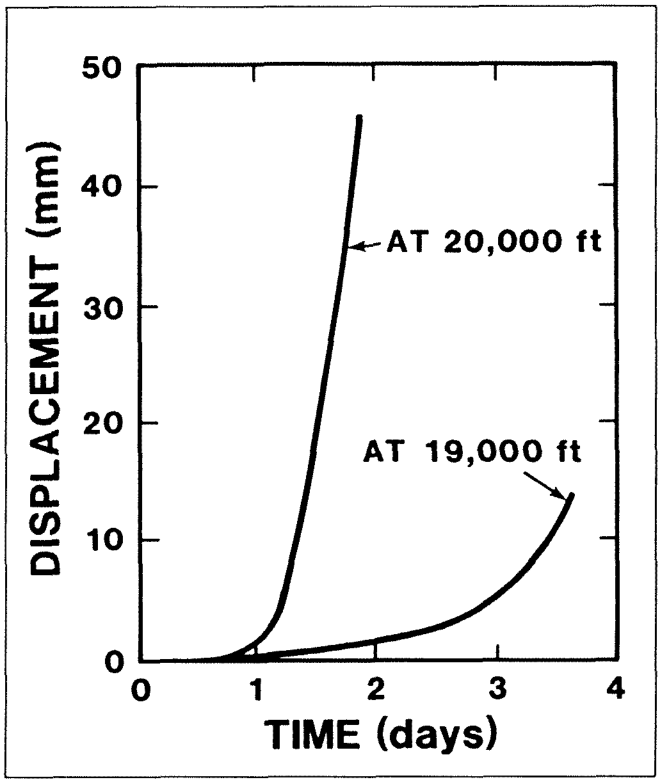

Figure 4
Theoretical displacement of wellbore wall after stopping circulation in a magma well with an initial magma temperature of 900°C.

Preliminary designs for insulated drillpipe have been analyzed for thermal and mechanical performance. Construction of the pipe body (between the tool joints) is relativiely straight-forward, with technology similar to the double-wall insulated tubing used for steam injection in enhanced oil recovery. The quality of the insulation in the pipe body is not even very important, since a thermal conductivity equal to or lower than that of Teflon is adequate. The major structural and thermal challenge comes at the tool joints, where the design must be rugged enough to handle the extra loads imposed by the heavier drillpipe and must have enough insulation to reserve the advantages of the IDP principle. Proposed designs for the tool joints incorporate ceramic liners at the inside diameter of the joints; although design concepts exist, they will require considerable analysis and prototype development.

Energy Extraction

The rate at which energy can be extracted from a magma well is a major factor in evaluating its economic viability. Determining such rates, however, is complex because of uncertainties in the nature and properties of in situ magma bodies and the complexity of potential heat-exchange processes within the magma. Our approach has been to perform fundamental engineering analyses in conjunction with phenomenological experiments so that we can develop conceptual models of the magma heat exchanger to obtain estimates of potential rates of energy extraction.

Figure 5 shows our current conceptual representation of a single well during steady operation in a direct-contact heat exchanger mode. The solidified magma surrounding the borehole is fractured by thermal stresses or can be hydraulically fractured by pressure build-up. Energy is extracted by calculating a working fluid from the surface through the mass of fractured magma.

In order for the direct-contact heat exchanger to work effectively, the solidified magma surrounding the injection tube must be sufficiently fractured to provide a large heat transfer area. Initial thermal stress fracturing experiments were performed using a high-silica content aluminosilicate glass as a magma simulant. The test samples were upright cylinders fitted with a stainless steel tube so that water could be injected into the center bore of the preheated cylinders. Extensive fracturing of the specimen occurred within seconds after cooling was initiated (Figure 6a). The fractures were typically centimeters apart, in general agreement with theoretical predictions (Wemple and Longscope, 1986).

In more recent tests using a low-temperature stimulant in glass test vessels, we were able to make direct observations of thermal stress fracturing during solidification. The material used was a terpene phenolic resin, which has a softening point at approximately 125° C. When cooled from an elevated temperature, the resin exhibits fracturing behavior qualitatively similar to glass. When cooled from 160 °C by a central probe, material solidified and fractured under thermal stress, forming a more or less regular, cellular fracture pattern (Figure 6b). Typically, the cells are polygons with four to six sides, quite similar to the fracture patterns found in solidified lava flows (Aydin and DeGraff, 1988). A close-up of the polygonal fracture pattern is shown in Figure 6c.

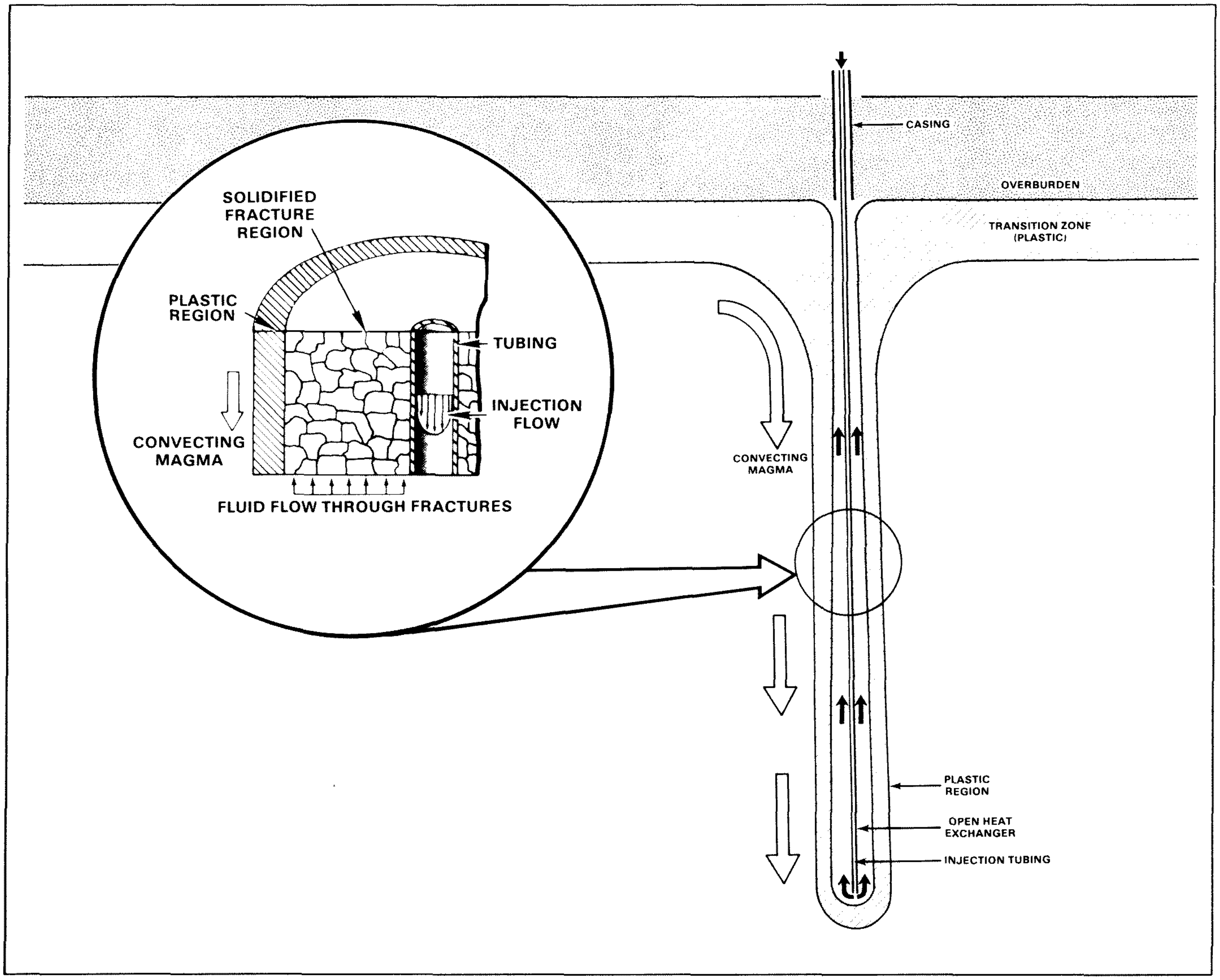

Figure 5
Current conceptual representation of a single well during steady operation of a direct-contact heat exchanger.

Figure 6a
Examples of thermal fracturing - (a) Typical thick-walled glass cylinder fractured by thermal stress.

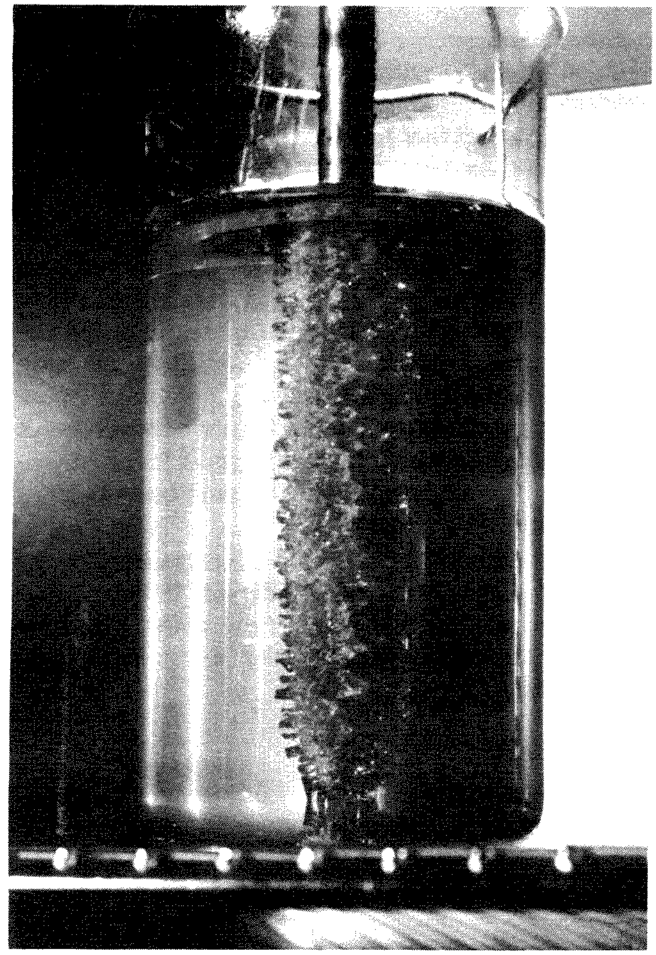

Figure 6b
Fracture pattern formed in a low-temperature simulant as solidification occurred around probe.

As seen in Figure 5, the direct-contact heat exchanger is surrounded by convective molten magma. The rate of energy extraction ultimately depends on the convective heat transfer between the molten magma and the solidified magma comprising the direct-contact heat exchanger. One outstanding feature of convection in magma is the extremely large viscosity variation with temperature. This feature was examined by performing an enclosed convection experiment usiing corn syrup as a magma simulant (Chu and Hickox, 1988). The experiments covered top-to-bottom viscosity ratios ranging from 3 to 1,400. In addition to measuring the overall heat transfer between the heated strip and the top surface, velocity and temperature distributions were obtained. From the heat transfer data, we were able to derive a viscosity correction factor that can be applied to standard constant property heat transfer correlations. This result is important in that it allows use of the large body of literature dealing with constant property heat teansfer in convecting fluids.

The experiment was numerically simulated through the use of a state-of-the-art finite element computer program. Figure 7 shows typical isotherm pattern and a comparison between numerically and experimentally obtained streamline patterns. The flow is characterized by two counter-rotating cells driven by a plume rising from the heated stip. The agreement between prediction and experiment is very good over the entire range of ciscosiry variations. With this experiment, we established the capability to calculate convective transport in magma.

We also examined the heat transfer process in the direct- contact heat exchanger. The heat exchanger was modeled as an annulus filled with a porous material that was heated on the outside and cooled by a vertical flow of water through the porous bed. The use of a porous body to represent a fracture body is permissible since the fracture spacing (~1 cm) is much less than the overall dimension of the fractured body (~tens of meters). Both numerical modeling and experiments were performed. Again, good agreement was obtained when the numerical model was compared with the experiment.

A numerical code called MAGMAXT was developed to simulate the flow of compressible, homogeneous water/vapor within the well and heat exchanger, with heat transfer to and from the convecting magma and the overlying formation. Heat transfer between the injected water and the fractured body of magma comprising the direct-contact heat exchanger is modeled as flow through a porous annulus. MAGMAXT has been used to stimulate the energy extraction process in a reference well configuration with a total well depth of 6 km, of which the bottom 1 km is a heat exchanger in the molten magma. The heat flux between the convecting magma and the heat exchanger is calculated to be 1 kW/m^2, using the result of the magma convection study.

By specifying the injection pressure and mass flow rar, the flow state throughout the circlation path can be computed by MAGMAXT using an iterative marching procedure. Figure 8 shows the temperature of the circulating water at a flow rate of 40 kg/s (640 gal/min). Within the heat exchanger, the net temperature increase is 400°C. It should be noted that Figure 8 shows one of a family of calculations; under the most favorable assumptions, the net temperature rise can be as large as 500°C for this flow rate.

As the fluid is heated in the heat exchange region, its density decreases, resulting in a density imbalance between the injection and return flow paths. The flow loop, therefore, has the capacity for natural thermosyphoning.

Power Plants

The overall thermodynamic performance of a conceptual system to convert the thermal energy from a

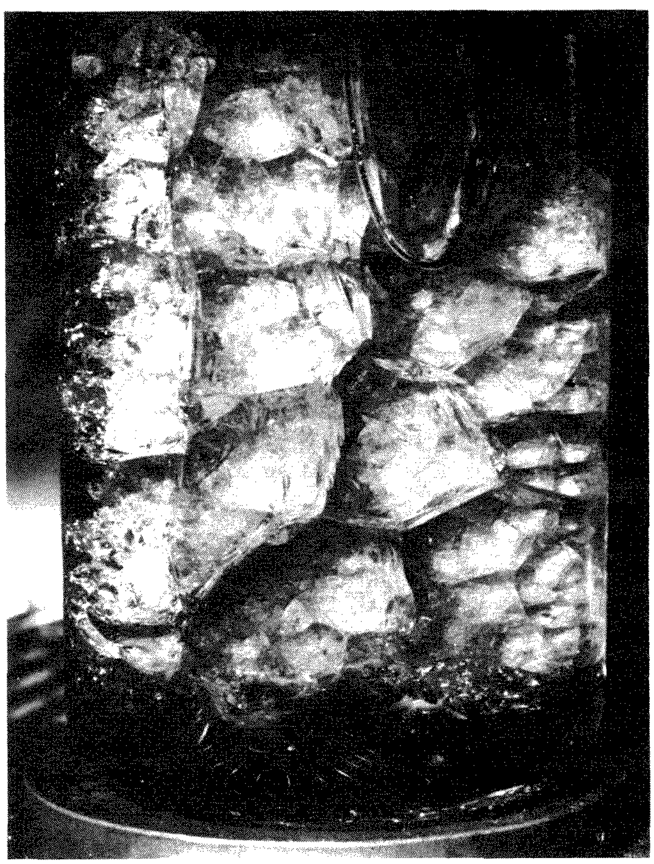

Figure 6c
Close-up of a polygonal fracture pattern.

magma well to electrical energy has been evaluated for a power plant utilizing a closed-loop Rankine cycle. In this cycle, a heat exchanger is used between water circulating through the well and the power plant working fluid. The closed-loop Rankine cycle is likely to be most practical in terms of corrosion and well control considerations because the well loop and the power loop are isolated from each other. Furthermore, in a closed-loop design, it is possible to exercise control over the cycle operating pressure for optimum performance.

The results of the closed-loop cycle analysis in terms of net power output as a function of well mass flow rate are shown in Figure 9. A shaded region rather than a single curve is presented, reflecting the uncertaintly in estimating the energy-extraction rate. Generally speaking, the net power output initially increases with mass flow rate because of increased energy extraction. However, the output temperature of the well decreases with flow rate, and the second law efficiency decreases. As a result, an optimal flow rate exists for maximum net energy extraction, which is on the order of 50 kg/s with a corresponding net power output and 25 to 45 MWe.

Optimization

At this point, two important areas remain to be examined. First, there is a remaining aspect of system optimization. Magma is a finite temperature resource, i.e., no matter how deep the well, the output temperature of the well is limited by the magma temperature. Furthermore, the incremental heat transfer between the injected water and the heat exchanger per well depth decreases more than linearly with well depth. Thus, as the well depth increases, a point of diminishing return is reached in terms of the gain in additional energy extraction and the cost of drilling. A parametric study of the net power output as a function of well depth and well configuration is needed to detemine optimum perfomance. Secondly, an integrated energy extraction expeiment is needed. Thus far, we have performed benchtop phenomenological experiments and the results have been used to construct the system model for energy extraction from silicic magma. However, a need still exists to perform an integrated expriment that involves the entire process from drilling to energy extraction. The integrated experiment should be sized to give results in the kilowatt range, bridging the gap between laboratory experiments (watts range) and the expected field experiment (megawatt range).

Geochemistry

Successful extraction of heat from a shallow magma body depends, in part, upon the results of ongoing geochemical and materials compatibility studies. This research involves chemical characterization of the Inyo magma, experimental evaluation of alloy compatibility

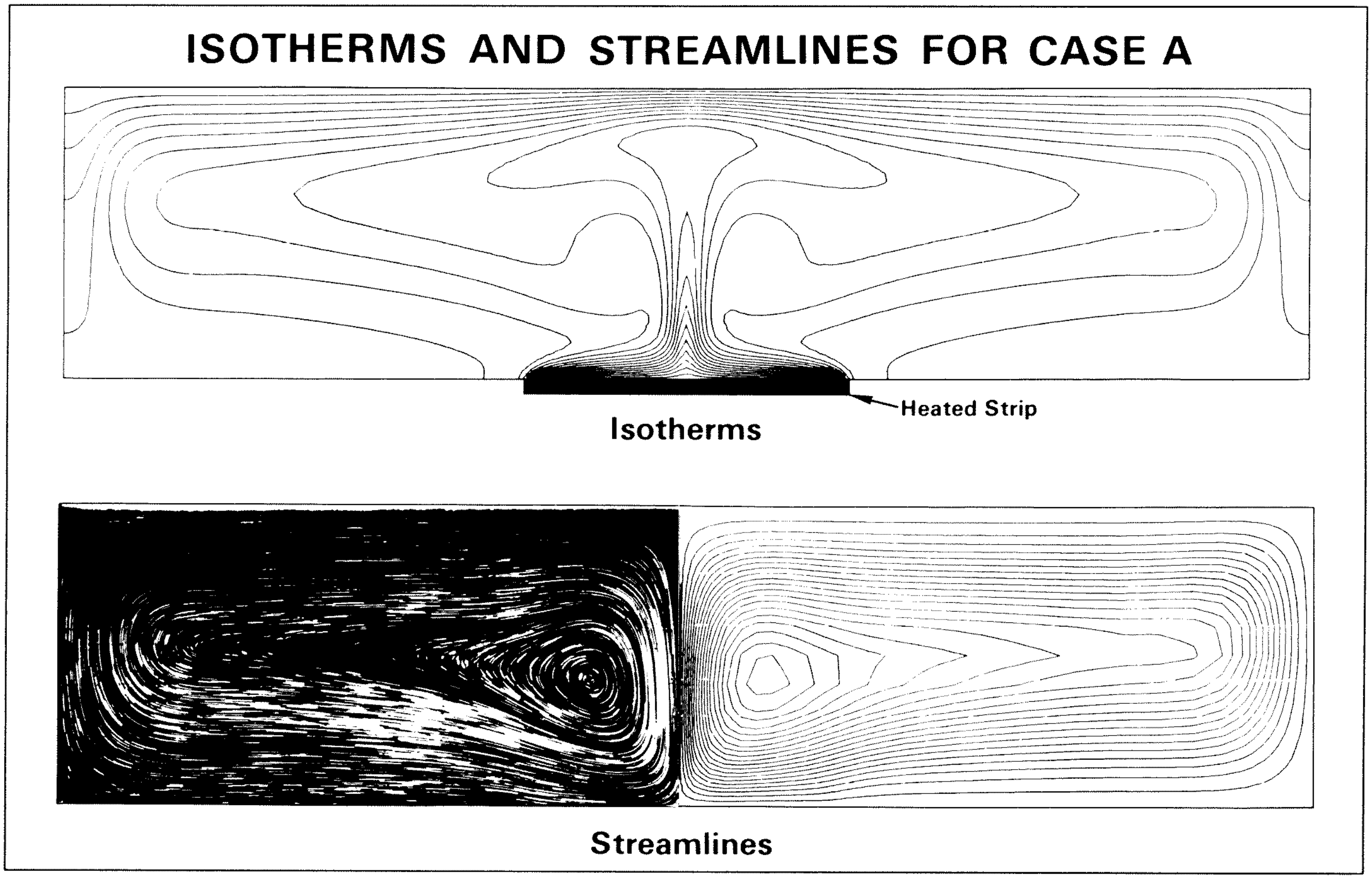

Figure 7
Typical isotherm pattern and comparison between numerically and experimentally obtained streamline patterns.

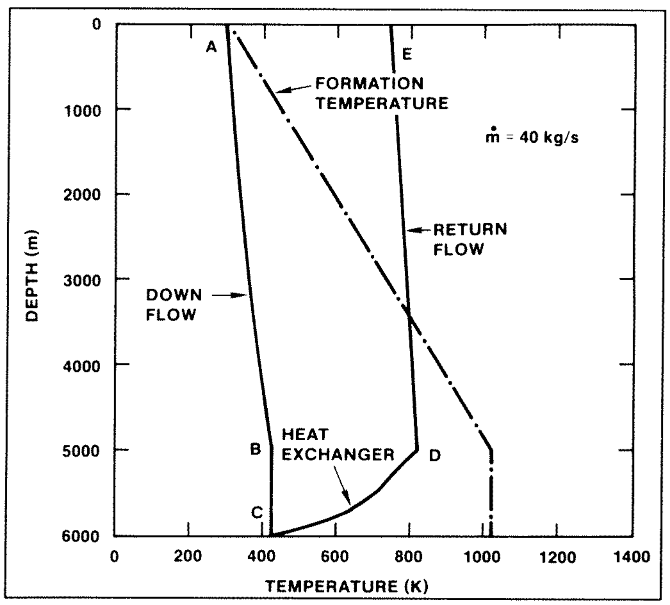

Figure 8
Calculated temperature of circulating water in a magma flow rate of 40 kg/s.

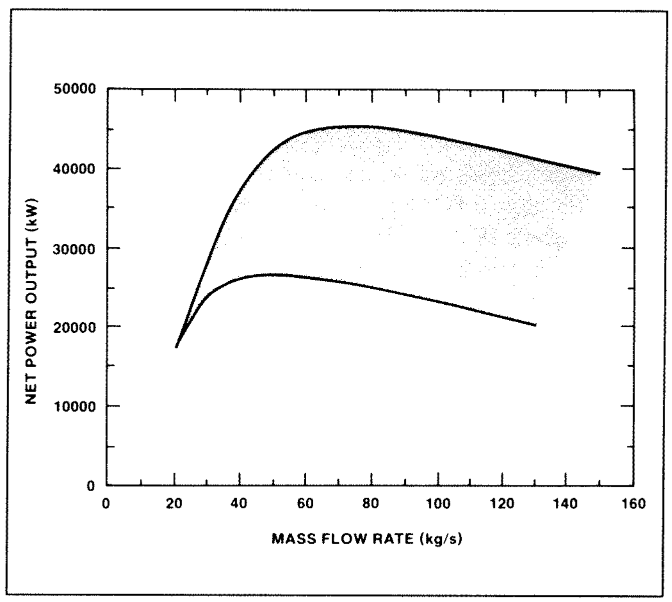

Figure 9
Net power output as a function of mass flow rate for a single magma well.

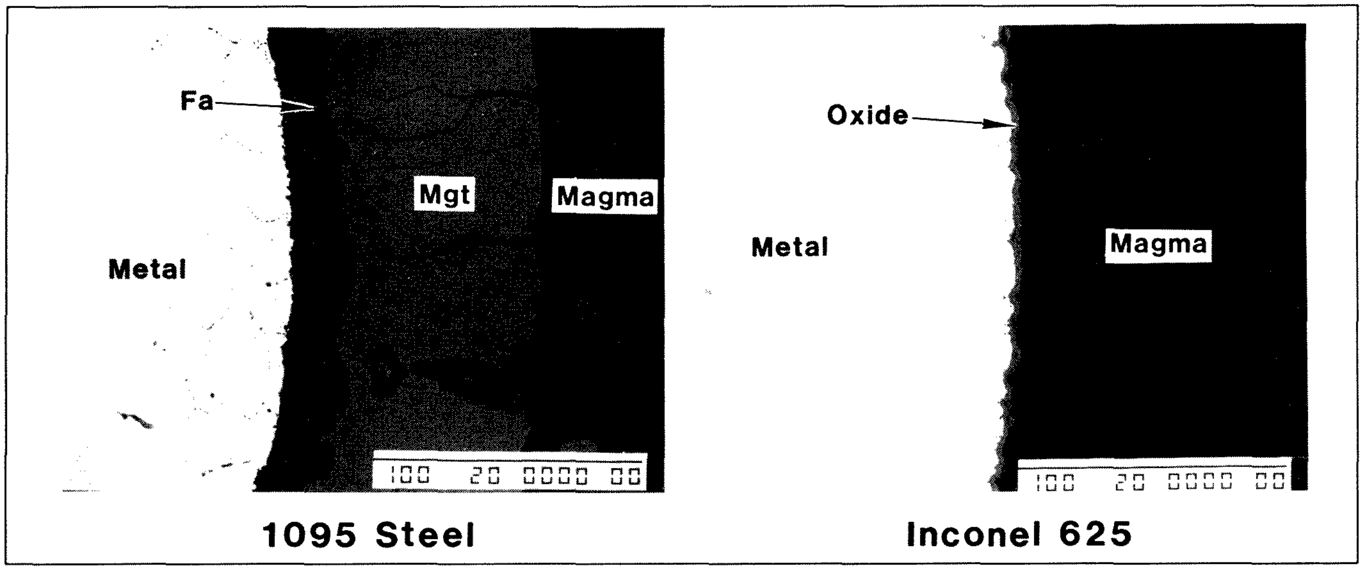

Figure 10
Comparison of the oxide rinds (fayalite, Fa and magnetite, Mgt) for 1095 carbon steel and Inconel 625 after reaction with a volatile-saturated rhyolite magma at 850°C and a 200 MPa for 7 days (scale bar is 100μm).

in magma and exsolved volatiles, and high temperature dissolution measurements of silicate minerals in hydrothermal fluids. The direction of geochemical research in support of this project is constrained by the geochemistry of the magmatic and hydrothermal environments as well as the response of engineering materials to those environments.

The Inyo magma is thought to be the rhyolitic in composition (Bailey, 1984) and contrasts dramatically with the basaltic magma encountered during drilling in Hawaii (Hardee and others, 1981), especially in regard to volatile components dissovled in the magma at high pressures (200 MPa; Table 1). The pre-eruptive volatile content of the Long Valley magma has been estimated from analyses of bulk glasses and glass inclusions from the Inyo Domes and the Long Valley caldera (Westrich and others, 1988) while those of basaltic magmas have been calculated from fumarolic gas analyses (Gerlach and Graeber, 1985). Rhyolitic magmas are known to be more oxidizing than basaltic magmas (Whitney, 1984), and probably have very low sulfur contents (Carroll and Rutherford, 1985). The compatibility of engineering materials in basalt buffered by C-0-H- S gas typical of a basaltic lava lake (1.0 MPa) has been investigated at magmatic temperatures (Douglass, 1983). These studies demonstrated the importance of magmatic volatile constituents, especially sulfur, to downhole corrorion problems in basaltic magma at low pressure.

The chemical nature of hydrothermal fluids that might be encountered during energy extraction is less clear. Presumably, the bulk of the magmatic fluids (water) will come from *in situ* degassing of the rhyolite magma, although some fluids could originate from an

Table 1
Composition of common rhyolites and basalts in magma chambers

Oxide (wt.%)	Rhyolite[a]	Basalt[b]
SiO_2	70.3 5	52.62
TiO_2	0.13	2.13
Al_2O_3	13.54	13.90
Fe_2O_3[c]	1.68	12.15
MgO	0.10	6.74
CaO	0.74	10.44
MnO	0.04	0.17
K_2O	5.02	0.43
Na_2O	4.11	2.41
P_2O_5	0.01	0.23
H_2O	4.00	0.27
F	0.050	0.035
Cl	0.120	0.009
S	<0.010	0.070
CO_2	<0.003	0.034
Total	99.00	101.64

a). Typical rhyolite from Inyo domes, CA with added magmatic volatiles (Westrich and others, 1988).
b). Typical basalt from Kilauea crater, HI with reservoir-equilibrated magmatic volatiles (Gerlach and Graeber, 1985).
c). Fe reported as Fe_2O_3.

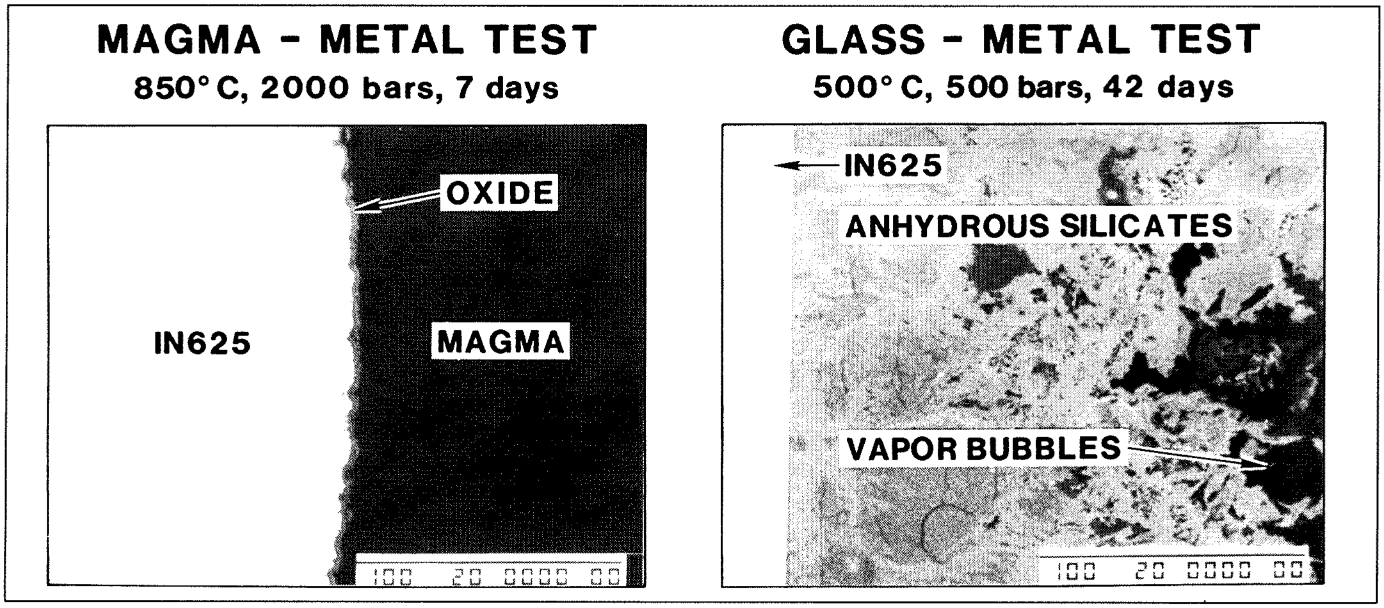

Figure 11

Comparison of Inconel 625 corrosion in a volatile-saturated rhyolite magma (850°C, 200 MPa, 7 days) and glass (500°C, 50 MPa, 42 days; scale bar is 100 μm).

underlying basaltic heat source. This degassing process can occur during drilling as the volatile-rich magma experiences isothermal decompression or, more likely, during heat extraction as the magma undergoes isobaric crystallization of anhydrous phases. Early exsolved magmatic fluids will be chlorine-rich, but the extract composition of the fluids in contact with the heat exchanger would depend upon the kinetics of magma degassing as well as upon the composition and flow rate of the heat reansfer fluid. As a further complication, these magmatic fluids could also be enriched in carbon dioxide if the contribution from an underlying basaltic magma were large.

It is crucial when choosing an alloy for construction of a downhole heat exchanger that it have sufficient mechanical and chemical durability in the magmatic and hydrothermal environments present during drilling and energy extraction. The mechanical strengths of most alloys are sufficient to support the weight of the heat exchanger in the rhyolite magma as long as downhole temperatures do not exceed normal operating temperatures (400-500°C). Loss of fluid circulation could lead to melting of the fractured chillrind surrounding the drillpipe/heat exchanger, where magmatic temperatures as high as 895-925°C could be reached. Only the superalloys have sufficient high temperature strengths to survive a loss-of-coolant accident.

The heat exchanger alloy alo should be corrosion resistant over its 20-year lifetime in a magmatic or hydrothermal environment. A series of magma-metal compatibility tests were conducted at 850°C and 150-200 MPa to evaluate the general corrosion resistance of several classes of potential drillpipe alloys, including carbon and stainless steels as well as Fe-, Ni-, and CO-base superalloys, after reaction with simulated, Long Valley magma (Westrich and Weirick, 1986). These compatibility tests, using rhyolite melts with restored magmatic volatiles, have demonstrated the oxidation, not sulfidation, will be the main corrosion process for drillpipe in the Long Valley magma. Oxidation of carbon steel was found to be unacceptably high in these tests. In contrast, Cr-bearing alloys simply oxidize to form a solid solution of Cr-. Mn-, and Fe- oxides adjacent to the metal, thereby inhibiting further reaction. Parabolic growth and metal penetration rates for Cr-bearing alloys are significantly reduced (by an order of magnitude) compared with those observed for carbon steel (Figure 10).

Of equal concern is the long-term corrosion resistance of the metal alloy to a hydrothermal environment during normal heat extraction. This may include interactions of the heat exchanger alloy with the chilled magma (volatile- bearing glass) or with hydrothermal fluids. Several glass-metal tests were run at anticipated operating conditions for a direct-contact heat exchange system (600°C and 50 MPa). Examination of the glass-metal interface indicates that resistance to corrosion was excellent for all alloy compositions. No metal oxidation was observed for Cr-bearing alloys in these tests even after run durations as long as 42 days (Figure 11).

Fluid-metal compatibility tests were completed to simulate an environment where heat exchanger material is directly exposed to a hydrothermal fluid at 500 °C and 500 MPa. Solutions added to fluid-metal tests span the range of fluids in contact with the heat exchanger from pumped-in water to exsolved magmatic volatiles. Just a few Fe-base superalloys exhibited any evidence of corrosion; the Ni-rich alloys were only slightly tarnished, even after 45 days in a simulated magmatic brine.

Completion of the Magma exploratory well in Long Valley caldera is critical to ongoing materials compatibility and geochemical research because of the unique downhole samples that could be collected. Chemical characterization of these samples, especially in regard to the sulfur content of the magma, and the pH and Cl content of hydrothermal fluids, will allow us to refine site-specific materials compatibility tests. While general corrosion rates for most Cr-bearing alloys in short-term compatibility tests at magmatic and hydrothermal conditions are low, other tests have shown that these alloys can experience severe pitting and stress corrosion cracking (SCC) in a hydrothermal brine (Cramer and Carter, 1980). Obviously, future compatibility studies will have to be longer in duration and quite specialized in order to address specific types of localized corrosion (pitting or crevace), as well as metallurgical and environmental effect (fatigue and stress corrosion cracking) upon heat exchanger alloys.

Conclusions

The concept that large bodies of silicic magma exist at shallow depths in the earth's crust is well supported by an abundance of geologic and geophysical data. Long Valley, one of the most impressive expressions of quaternary volcanism in the world, is an ideal site to conduct the first major drilling activity of the Magma Energy program. The technology under development in the Magma Energy program can, in principle, make the vast energy potential of these magma bodies available for the benefit of the nation. If we are successful in locating and eventually penetrating molten or semimolten magma within the caldera, an actual field demonstration of this technology will then be feasible. Continuation of this program will combine the uniquely valuable scientific insight into crustal magmatic processes with the potential for stimulating commercial development by defining the hydrothermal system and by demonstrating magma energy extraction.

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