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The Utilization of Magma Energy A Project Summary

John L. Colp, Harold M. Stoller

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THE UTILIZATION OF MAGMA ENERGY -
A PROJECT SUMMARY

John L. Colp
Harold M. Stoller
Geo Energy Technology Department 4730
Sandia Laboratories
Albuquerque, NM 87185

ABSTRACT

The scientific feasibility of extracting energy from magma bodies is the objective of this project. The high temperature ($\sim 1000^{\circ}\text{C}$) and estimated large resource ($\sim 10^4$ quads) within 10 km of the surface in the US provides the incentive for this work. The areal extent of a near-surface molten lava body has been defined with geophysical sensing systems. Improved knowledge of the in situ physical properties of buried molten rock is required to assess the thickness of magma bodies. Drilling into molten lava is a complex operation and requires further technological development. Experimental studies of rock deformation at near-magma temperatures and pressures show that boreholes can be made to stay open. Computational analyses of magmatic gas samples provide a satisfactory definition of the gas content of in situ magmas. Material compatibility experiments show that Ni- and Co-based alloys can survive and operate in the magma environment. Thermal heat exchangers can survive in molten rock and allow significant rates of heat transfer to an internal fluid.

Presented at the Second Circum-Pacific Energy and Mineral Resources Conference, Honolulu, HI, July 31 - August 4, 1978 (SAND78-0190C).

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THE UTILIZATION OF MAGMA ENERGY - A PROJECT SUMMARY

Introduction

The nation's geothermal energy resources exist in a variety of forms; dry steam, hot water, geopressured water, hot/dry rock, thermal gradients in the earth's crust, and magma. The objective of the Magma Energy Research Project now underway at Sandia Laboratories is to investigate the scientific feasibility of extracting energy directly from deeply buried circulating magma sources.

With temperatures on the order of 1000°C, buried magma sources represent great amounts of clean, high-quality energy. The United States Geological Survey in Circular 726 estimates the energy contained in molten and partially molten magma within 10 km of the ground surface in the US at 5×10^4 quads.¹ Total energy consumption in the US in 1976 equaled 75 quads. Thus, the estimated energy in the US magma resource is equal to approximately 700 times its annual total energy consumption.

Any program devoted to tapping the energy of a buried magma source is considered as long term and high risk because of the technological problems to be solved and the many unknowns to be resolved. The program at Sandia, under funding by the Division of Basic Energy Sciences of the Department of Energy, is emphasizing the investigation of basic scientific and engineering questions of energy extraction from magma. It is not structured toward early on-line power production.

To provide additional scientific guidance to the program, Sandia Laboratories has formed a Magma Energy Research Advisory Panel; the members of the panel are selected for their expertise in relevant fields (Table 1).

Table 1

Magma Energy Research Advisory Panel

<u>Task</u>	<u>Current Efforts</u>
Volcanology/Geophysics	Prof. Robert Decker Dartmouth College Hanover, NH
Volcanology/Geophysics	Dr. Gordon Eaton US Geological Survey Hawaiian Volcano Observatory
Magma Petrology	Dr. James Moore US Geological Survey Menlo Park, CA
Tectonophysics/Rock Deformation	Prof. Melvin Friedman Texas A&M University College Station, TX
Geophysics/Seismic	Dr. Peter Ward US Geological Survey Menlo Park, CA
Geophysics/Electrical	Prof. John Hermance Brown University Providence, RI
Material Compatibility	Prof. Roger Staehle Ohio State University Columbus, OH

As an adjunct to the Magma Energy Research Project and in recognition of the small body of knowledge which existed on magma, Sandia, in cooperation with the US Geological Survey, conducted a Magma Workshop in March 1975 to address two objectives:

- To assess the present knowledge of the occurrence of magma bodies, the chemical and physical properties of in situ magma, and the methods of exploration for magma;
- To recommend the most critically needed research and development in these areas.

Approximately 30 selected participants were present at this workshop. The major recommendations of the workshop constitute the basis around which the Magma Energy Research Program has been organized.²

Project Organization

The Sandia Magma Energy Research Project has been divided into four discrete program tasks for the period of initial study, as shown in Table 2.

Table 2

Major Tasks of Magma Energy Research Project

<u>Task</u>	<u>Current Efforts</u>
1. Source Location and Definition	Cooperation with USGS and Universities on magma-source surveys and sensing-methods development. Lava Lake sensing experiment. Lava Lake drilling program.
2. Source Tapping	Texas A&M University borehole stability study.
3. Magma Characterization and Materials Compatibility	Magma geochemistry studies. Material compatibility studies at high pressure and high temperature. Field studies with University of Hawaii. Design/fabrication of magma simulation facility.
4. Energy Extraction	Molten lava/single-tube boiler experiment. Long tube heat-exchanger experiment. Design of Lava Lake energy-extraction experiment. Magma fluid mechanics, heat-transfer, and geochemistry calculations. Flowing lava heat-transfer measurements. Fuels from magma laboratory experiments.

Source Location and Definition

It is imperative that the existence of a magma source, its depth, areal extent, and general form (whether in a finite pool or in a honeycomb of crevices filled with molten material) be known with the greatest degree of certainty before proceeding with plans for source tapping.

A few studies have been conducted to locate and identify a buried magma source; most of the existing remote sensing methods have been used-- seismic, microseismic, resistivity, gravity, magnetic, magnetotelluric, infrared, and thermal.³ The USGS has examined areas under Yellowstone National Park; Long Valley, CA; Kilauea Volcano, HI; Geysers/Clear Lake, CA; and other locations in the western US.

Discussions at the Magma Workshop indicated that insufficient knowledge exists about the precise location and physical configuration of magma sources. The major recommendation for future work on the search for and evaluation of magma chambers at the Workshop was

"The primary need in search and evaluation at the present time is to test the various geophysical techniques on known molten-rock bodies so that the effectiveness of the different techniques for finding magma can be determined."²

Sensing Studies

Following the above recommendation, Sandia conducted a Molten Lava Sensing Experiment, begun in March 1976. The still-molten lense in Kilauea Iki Lava Lake (a prehistoric pit crater located in the Hawaii Volcanoes National Park that was partially filled with lava during a 1959 eruption) was selected as the experiment site. The objective of the experiment was to define the areal extent, the depth, and the thickness of the molten lense using a variety of geophysical sensing methods.

The experiment was divided into three parts, as shown in Table 3.

Table 3
Lava Lake Sensing Experiment

<u>Method</u>	<u>Conducted By</u>	<u>Date</u>	<u>Principal Investigator</u>
Active and Passive Seismics ⁴	Sandia/HVO/MIT	March 1976	K. Aki
Resistivity and Active Electro-magnetic ^{5,6}	Sandia/HVO/USGS Denver	April 1976	F. Frischknecht
Audio Magnetotelluric ⁷	Sandia/HVO/Univ. of Texas	May 1976	F. Bostick

Two supplemental sensing experiments were run by Sandia Laboratories following the completion of the three originally planned experiments. One was a fine-mesh grid passive seismic survey of the northeast quadrant of the lava lake.⁸ The other was an active seismic survey using downhole sensors and explosive sources.

The results from the various systems used were in fairly general agreement on the definition of the areal extent of the molten lense. However, the evaluation of the depth and thickness of the molten lense was very unclear from the results of both the mechanical and electrical geophysical sensing systems. This lack of clarity probably results from not having accurate values of physical properties (such as acoustic velocity, electrical resistivity, etc) of the molten rock.

Professor John F. Hermance, Brown University, has made a critical assessment of the sensing experiments conducted on Kilauea Iki lava lake.⁹ Figure 1 shows a horizontal and vertical model of the lava lake resulting from a preliminary analysis of the experimental results taken from this report.

Figure 1. Models of Kilauea Iki Lava Lake from Preliminary Analysis of Sensing Experiment Results

For an interpretation of the respective sensing systems used in the experiment, it is necessary to get exact data on the dimensions (areal, depth, and thickness) of the molten lense. These data must be obtained by means of drilling at the lava lake experiment site.

Drilling Program

In late summer of 1976, two holes were drilled by Sandia with the cooperation of the Hawaiian Volcano Observatory. Conventional rotary drilling technology was utilized with diamond core bits and with water as the drilling fluid. Each of the holes was drilled through the overlying crust to the molten rock interface at a depth of 45.4 m (149 ft). One hole penetrated the molten rock to a depth of 76.2 cm (30 in.) until it encountered an unsuspected solid obstruction. The second drilling operation was terminated when rising lava cooled and solidified in the drill bit and prevented water circulation. Thus, conventional technology was not successful in characterizing the depth of the molten lake.

A Lava Lake Drilling Program was instituted following the drilling of the two 1976 holes. The objective of the program is to design and develop a system capable of drilling through solid obstructions while the drill stem is surrounded by 1070°C molten rock. It should be emphasized that this drilling design study is aimed specifically at the conditions represented by Kilauea Iki. While perhaps a necessary first step in developing technology to drill into deep magma sources, the engineering effort devoted to this activity is only a small portion of that which will be required to achieve true magma source tapping.

The selected system for the 1978 drilling experiment uses a drag drill bit made of a high-temperature-resistant material so that it can drill uncooled at molten-rock temperature while being driven by an insulated drill stem. The outer part of the insulated drill stem remains at a temperature near that of the molten rock to minimize the amount of rock that is chilled onto the drill stem exterior. The inner pipe is air/water mist-cooled to permit it to carry the torque required to drive the bit.

Source Tapping

Reaching the source to insert an energy-extraction device is vital to the utilization of magma energy. However, the Sandia Magma Energy Research Project, as presently funded, is not intended to be directly involved in developing deep-drilling methods in the high-temperature magma environment, but with tapping methods for the purpose of energy extraction.

As drilling approaches the magma source, it is obvious that the temperatures of the rocks above it are going to increase, causing the rocks to approach a plastic state. Two basic questions must be answered:

- Will a hole through such a hot plastic material stay open?
- Are there methods for keeping it open so that energy extraction equipment can be inserted through it into the magma source?

To answer these questions, Sandia Laboratories is involved in a continuing research program with the Center for Tectonophysics at Texas A&M University to investigate the physical properties of four rocks--Mt. Hood andesite, charcoal granodiorite, Newberry rhyolite, and tholeiite basalt--under dynamic stress conditions at pressures up to 5 kbar and at temperatures of approximately 1000°C.

Preliminary results from this study¹⁰ indicate that:

1. The failure strength of both the andesite and the granodiorite decrease with increasing temperatures to 1000°C. At 1000°C, the strength of the granodiorite (35 MPa) is less than that of the andesite (78 MPa).
2. Both rocks are essentially brittle throughout the temperature range explored until partial melting occurs.
3. Because the deformations of both rocks are essentially cataclastic at all temperatures, the borehole will probably fail in compression when differential stress reaches the ultimate strength.

Table 4 shows the expected maximum depth of a stable borehole for a variety of conditions.

Magma Property and Material Compatibility

Magma Property Studies

Much definitive information must be obtained about the character (that is, the in situ properties) of the highly corrosive, high-temperature environment of magma and its effects on engineering materials before equipment for energy extraction is inserted into it for long times. Three specific rock types--Hawaiian tholeiite, Mt. Hood andesite and Newberry rhyolite obsidian--were chosen as standards for magma/material-compatibility laboratory tests. The choice for magma simulants was based on, first, a realistic chemistry anticipated to be encountered in the field and second, rocks that are well characterized with respect to chemical and physical properties.

Table 4

Maximum Depth (km) of a Stable Borehole

Conditions		σ_h/σ_v	25°C	400°C	700°C	1000°C
Andesite	Dry	Open hole	2.0	2	2	1
			1.0	6	4	3
			0.5	>10	>10	>10
		Filled hole	2.0	4	3	2
			1.0	>10	>10	>10
			0.5	>10	>10	>10
	Saturated	Open hole	2.0	2	2	1
			1.0	9	7	5
			0.5	>10	>10	>10
		Filled hole	2.0	5	4	3
			1.0	>10	>10	>10
			0.5	*	*	*
Granodiorite	Dry	Open hole	2.0	6	3	1
			1.0	>10	>10	2
			0.5	>10	>10	>10
		Filled hole	2.0	>10	>10	6
			1.0	>10	>10	>10
			0.5	>10	>10	>10
	Saturated	Open hole	2.0	6	3	1
			1.0	>10	>10	2
			0.5	>10	>10	>10
		Filled hole	2.0	>10	>10	>10
			1.0	>10	>10	>10
			0.5	*	*	*

*Tangential stress is tensile.

Recent and continuing magma characterization studies include

- Thermodynamic modeling of magmatic gases at high and low pressures for different magma types to predict in situ compositions.
- Experimental measurement of the heat flux in freshly-erupted lava at a recent Kilauea eruption.
- Computer modeling of magma-fluid dynamics and heat-transfer mechanisms.
- Collection and analysis of magmatic gases from recent Kilauea eruptions.

Chemical Characterizations -- Magma characterization, with respect to volatiles, is of concern in

Selection of engineering materials for magmatic environments.

Experimental determination of physical properties of magmas (density, viscosity, electrical resistivity, etc) that are sensitive to volatile components.

Design of open energy-extraction systems where volatile mass transfer is likely to occur as fluids are circulated through chilled magma.

Evaluation of a recent Sandia proposal that magma may be a potential source of fuels.

Accordingly, the recommendation of the 1975 Magma Workshop that characterization studies be made of complex magmatic volatile systems has been adopted.

A set of computer codes has been developed to calculate equilibrium distributions in multicomponent gas mixtures characteristic of magmatic volatiles over a wide range of specifiable conditions. The calculations can be carried out, treating the gas phase as an ideal or nonideal mixture. Nonideal properties are calculated from measured pressure-volume-temperature (P-V-T) data, if available, or from a corresponding state

version of the Redlich-Kwong equation. The equilibrium distributions can be calculated at a specific temperature and pressure for a full set of mass balance constraints, or one or more mass balance constraints can be replaced by fixed fugacities or activities.

As an example of the use of these magmatic volatile models,¹² a typical basaltic magmatic gas in a near surface environment is predicted to have a composition (mole %) of 77.1% H₂O, 1.6% H₂, 11.7% CO₂, 0.5% CO, 7.4% SO₂, 0.3% S₂, 0.9% H₂S, and 0.4% HCl. At greater depths (for example, under oceanic spreading centers), the models indicate basaltic magmatic gases become more CO₂-rich: 11.5% H₂O, 0.3% H₂, 80.0% CO₂, 4.6% CO, 1.3% SO₂, 0.7% S₂, 1.1% H₂S, 0.4% COS, and 0.1% HCl.

During the September 1977 Kilauea East Rift eruption, an opportunity was presented to measure the heat flux of freshly erupted lava within a few tens of meters from the erupting vent. Using portable, expendable experimental apparatus designed and built by Sandia, valid measurements of heat flux ranging from 10 to 200 kW/m² were made.¹³

Physical Characterizations -- A continuing series of modeling studies of various aspects of magma-fluid dynamics and heat-transfer mechanisms has been underway at Sandia for the last few years. One example of these studies is the recent determination of the solidification rate of the upper crust of a cooling lava lake. Based on data from Hawaiian lava lakes, it appears that the crust freezes in two zones: one, starting at the initiation of crust freezing when the heat-transfer mechanism is single-phase conduction, and continuing until the crust thickness reaches approximately 16 m (50-55 ft); and two, the overlaying of this zone by a zone in which the heat transfer is by two-phase conduction/convection. The first zone follows a square root of the time-cooling curve until formation of the second zone; then both zones begin to follow a linear time-cooling curve. Using this model, a Kilauea Iki lava lake crust thickness of 50.2 m (165 ft) has been predicted for December 1978, the time of the next proposed drilling.¹⁴

Material Compatibility Studies

In a magma energy-utilization application, engineering materials will be expected to perform in three different environments, ranging from near-surface to magma. The conditions and associated problems of these environments are shown in Table 5.

Table 5

Magma/Metal Environments

<u>Environment</u>	<u>Conditions</u>	<u>Problems</u>
Near Surface	Low temperature oxidizing H ₂ O rich gas	Oxidation corrosion
Hydrothermal Region	Moderate (150°-500°C) temperature oxidizing corrosive hydrothermal brines	Oxidation and brine corrosion
Magma	High (600°-1250°C) temperature reducing	Sulfidation corrosion
	High sulphur	Thermal strength degradation
		Metal dissolution

Metal samples have been exposed to fumarolic gases from various vents in Kilauea caldera, Hawaii, as part of a continuing study. In general, stainless steels are attacked fairly rapidly in the fumarole environment, while nickel-base alloys such as Inconel, Rene-41, and Hastelloy-C are resistant. Figure 2 describes the environment of some of these tests and shows the results of certain material exposures.

Initial laboratory tests on the interaction of various representative metal alloys with degassed molten Hawaiian tholeiite indicated that a good correlation could be made between reactivity and the free energies of formation of various metal oxides. These data further indicate that the Ni- and Co-based alloys may have special qualities in regard to survivability in the magma environment.¹⁵

Figure 2. Materials Compatibility in Magmatic Gases

Recent laboratory tests in molten basalt with the expected volatiles present have been performed. The test environment, degradation mechanisms observed, and before and after photos of some materials are shown in Figure 3. As noted, promising materials are Udimet 700, Inconel 718, and Hastelloy X.

The Magma Simulation Facility (Figure 4), an experimental apparatus, is now being fabricated to study molten rock reactions and material compatibilities at pressures up to 4 kbar and temperatures up to 1600°C. The uniqueness of this facility is the size of its experimental chamber--11 cm (4-1/2 in) dia by 19 cm (7-1/2 in) high. Start-up operation is anticipated in 1979.

Figure 3. Materials Compatibility in Basaltic Lava

Figure 4. Magma Simulation Facility

Energy Extraction

The convection and heat-transfer processes operational in molten rock at extremely high geodynamic pressures must be understood before suitable energy-extraction methods can be devised and meaningful estimates of their efficiencies can be made.

Heat Extraction

A study of possible heat-extraction rates (per unit area of heat-exchanger surface) from a magma reservoir has been completed. Estimates of the heat-extraction rates ranged from a low of 1 kW/m² to a high of 175 kW/m², depending on the assumptions made about the character of the reservoir. The 1 kW/m² figure correspond to the rate expected from a conduction-dominated reservoir at the end of a 30-yr period. The higher figure of 175 kW/m² was typical of a magma reservoir with considerable convection; that is, circulation of the molten rock.

A small, single-tube boiler to study heat extraction from a molten-lava source has been tested in 0.2 m³ of Hawaiian tholeiite lava in an induction furnace (Figure 5). The two test runs showed that high heat-extraction rates (100 kW/m² to 300 kW/m²) could be obtained from a molten-heat source. Corrosion or failure of the heat exchanger due to corrosive thermal effects was not a problem, even though the temperature of the molten-lava core (1450° to 1650°C) was well in excess of the melt temperature of the heat exchanger. The test data verified previous assumptions in the heat-transfer calculations, particularly in the convection calculations and the calculations of the thermal transient during insertion. The test demonstrated that useful amounts of thermal energy in the form of high-quality steam can be extracted from a molten-lava heat source.

Figure 5. Molten Lava/Single-Tube Boiler Experiment

A Long-Tube Heat-Exchanger facility has been designed and constructed for evaluating heat-exchanger designs. This facility consists of a 20-m-long vertical electrically-heated furnace enclosing a single-tube boiler. The internal configuration of the boiler can be changed to incorporate a number of experimental setups. The facility is being used to study the basic dynamics of long single-tube vertical boiling. An initial shakedown run has been made; the performance of the experimental apparatus was generally satisfactory. Some expected instrumentation problems appeared and are being corrected. The insulation of the downcomer supply tube is being investigated for its effect on efficiency improvement. Additional operational tests are planned in 1979.¹⁶

The next logical step in the energy extraction studies is to move from the laboratory into longer-duration field experiments in molten rock. An energy extraction experiment inserted into a lava lake is planned. The objectives of this research experiment are to measure the dynamic mechanical and thermal changes on the buried molten-rock body resulting from

induced cooling (thermal-energy extraction), and the dynamic effects of the hostile environment of buried molten rock on the test (energy-extraction) equipment.

Fuels Generation

Thermodynamic calculations and experimental studies of the potential of magma and hot rock for the production of fuels (H_2 , CO, CH_4O) indicate that fluids containing one to three mole percent hydrogen are possible from the interaction of water with typical basaltic magma or hot rocks in the temperature range 1300° to 600°C. Fuel production can be enhanced by addition of organic matter to the injected aqueous fluid.

Summary

The status of the Magma Energy Research Program is such that an assessment of the scientific feasibility of energy extraction from magma cannot yet be made. However, encouraging progress has been made in several elements of the program. Specifically, these include:

1. The areal extent of a near-surface molten-rock body has been defined via geophysical sensing systems. Improved knowledge of in situ physical properties of magma are required to assess the thickness of magma bodies. The extension of these sensing systems to locate deep magma sources requires additional effort.
2. Experimental studies of rock deformation at near-magma pressures and temperatures show a possibility that a hole drilled in this region will or can be made to stay open.
3. Calculational analysis of magmatic gas samples have provided a satisfactory definition of the gas content of in situ magma. Material compatibility experiments have shown that Ni- and Co-based alloys can be expected to survive the magma environment.
4. Laboratory experiments and computational studies have shown that thermal-heat exchangers can survive while immersed in molten rock and accomplish significant rates of heat transfer to an internal fluid.

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