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MAGMA-TAP - THE ULTIMATE GEOTHERMAL ENERGY PROGRAM*

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Abstract

An engineering research program is in progress at Sandia Laboratories investigating the feasibility of extracting energy directly from deeply buried circulating magma sources. With temperatures of the order of 1000°C these sources represent great amounts of high quality energy. A fully closed heat exchanger system inserted directly into the source would allow extraction of this energy with minimal environmental impact. Major problem areas being studied include source location and configuration, in situ magma characteristics, material compatibilities, tapping methods, and energy extraction equipment.

*This report was presented at the Circum-Pacific Energy and Mineral Resources Conference at Honolulu, Hawaii, August, 1974.

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MAGMA-TAP - THE ULTIMATE GEOTHERMAL ENERGY PROGRAM

Introduction

The objective of the Direct Magma Tap Research Program now under way at Sandia Laboratories is to investigate the feasibility of extracting energy directly from deeply buried circulating magma sources. With temperatures of the order of 1000°C, these buried sources represent great amounts of high-quality energy. Plan outlines call for a program whereby a fully closed heat exchanger system is inserted directly into such a magma source to allow the heat energy to be brought to the surface with minimal environmental impact. The conversion of this heat energy to a usable form, such as electricity, at the surface could utilize reasonably conventional techniques (Figure 1). To determine whether such plans are even remotely possible to achieve, whether thay are feasible to achieve, and whether they are economical if achieved, are the objectives of the Sandia program.

To outline plans for such a program is easy; to accomplish such a program would be difficult. Nevertheless, if the energy reposing in molten rock sources beneath the surface of the earth could be tapped, the prize would be well worth the effort.

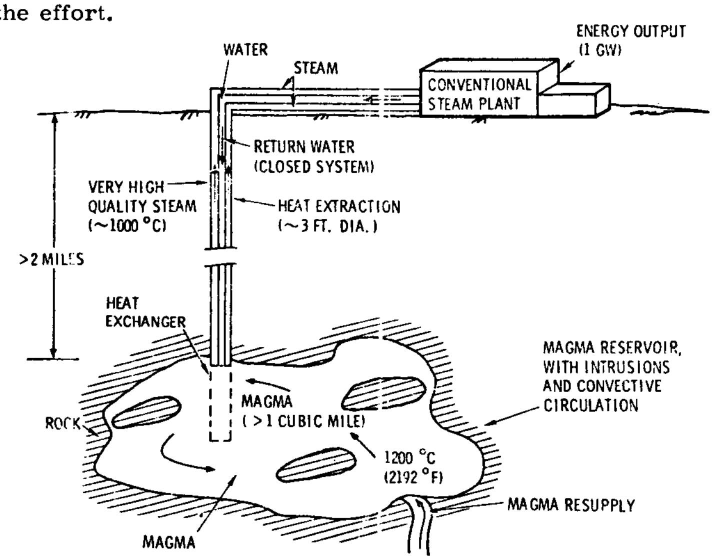


Figure 1. Generalized drawing of the magma tap concept

A program of this magnitude must be approached in an orderly, methodical manner if it is to achieve any degree of success. The problems associated with such a research program must be well defined and must be approached in a manner that will permit their evaluation as the program proceeds. The program must be organized in such a way that, if at any time in its progress it becomes apparent that a real physical law precludes the possibility of a successful completion, the regret costs of the entire program can be minimized. Any program devoted to tapping the energy of a buried magma source is bound to be long-term. Because the program at Sandia is recognized to be that, it is not being directed toward any nearby deadline for power production. Steps in the program are being taken cautiously until the initial obstacles have been shown to be surmountable.

It is unlikely that any single installation will possess the expertise for a program comprising such diverse fields. Sandia Laboratories recognizes this fact and has formed a Magma Tap Advisory Panel (Table I) consisting of persons from installations throughout the United States selected for their expertise in particular relevant fields. Their purpose is to provide advice on directions in which the Sandia program should proceed, and each panel member is to provide advice in his specialty to those persons at Sandia responsible for that part of the program.

TABLE I

Magma Tap Advisory Panel

Volcanology/Geophysics	Prof. Robert Decker Dartmouth College Hanover, N. H.
Magma Petrology	Dr. Dallas Peck U. S. Geological Survey Washington, D. C.
Tectonophysics/Rock Deformation	Prof. Melvin Friedman Texas A&M University College Station, Texas
Geophysics/Seismic	Dr. Peter Ward U. S. Geological Survey Menlo Park, California
Geophysics/Electrical	Prof. John Hermance Brown University Providence, R. I.
Material Compatibility	Prof. Roger Staehle Ohio State University Columbus, Ohio
Heat Transfer/Source	Prof. William E. Brigham Stanford University Stanford, California

It has become obvious that three areas involved in this program currently require a comprehensive analysis: (1) studies of the composition of in situ magma, (2) techniques for locating and configuring subsurface magma sources, and (3) processes of drilling into molten rock sources. Sandia proposes a series of workshops to address these problems, to assess the current state of knowledge, to decide what additional knowledge is needed, and to suggest directions for future research. These workshops will consist of a very small number of selected participants who are believed to be able to contribute to a meaningful analysis in each of the areas of interest.

The Sandia Direct Magma Tap Program has been divided into five discrete program facets for this period of initial study: source location, magma properties, material compatibilities, energy extraction, and source tapping. Each of these facets is discussed in detail with some background on the current state of the knowledge, what programs are currently in process, and what programs are proposed for the near future.

Source Location

General

Critically important to the Direct Magma Tap Program is developing the ability to locate and identify a source of molten rock in the subsurface. It is imperative that the existence of a magma source, its depth, its areal extent, and its 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 drilling. Little is known at this time about the precise location and the physical configuration of magma sources. What knowledge exists is based almost entirely on intuitive evidence from areas near active volcanos and eroded structures of ancient volcanos. In the past, the acquisition of such information was of interest only to volcanologists concerned mainly with the internal structures of volcanos.

Although many methods have been developed for the remote subsurface sensing of various geologic structures for a variety of purposes, until very recently none of these have been directed intentionally toward locating molten magma sources.

Current Programs

Because of the increased interest in seeking supplemental energy sources, some programs have been proposed for locating and identifying a subsurface magma source, with most of the existing remote subsurface sensing methods--seismic, microseismic, resistivity, gravity, magnetic, magnetotelluric, infrared, thermal--being considered for use.

Of the programs proposed, the office of the U. S. Geological Survey, (USGS) Menlo Park, California, is considering the one of greatest magnitude. The USGS plans to conduct its search for a molten magma source on the Island of Hawaii, in the Yellowstone National Park area, in the geyser area in Northern California, and in the San Francisco Peaks area near Flagstaff (Ward, 1974). This agency currently has work under way at some of these locations and plans to have programs going at all of them in the near future.

The Hawaii Institute of Geophysics at the University of Hawaii is proposing a program to perform subsurface sensing surveys of magma sources in the Kilauea Volcano rift zone near Puna, Hawaii. The Colorado School of Mines is proposing a similar program in the Kilauea summit area (Furumoto, 1974). The University of Alaska proposes magma surveys on Augustine Volcano in Cook Inlet, Alaska (Kienle, 1974).

As part of the initial effort in Sandia's Direct Magma Tap Program, a study was initiated to evaluate possible methods for locating and identifying magma sources. A survey of the literature published on the subject revealed that although there had been much previous work in the field of subsurface instrumental sensing, very little effort had been directed toward the search for molten rock. Only one instance of recognition of a molten region was found in the Free World literature and very few references to Russian work related to this subject were noted.

A preliminary survey was performed of possible locations of magma sources in Western United States. The guidelines used for selecting the locations were simple: (1) knowledge of a volcanic eruption in historic times, (2) knowledge of a volcanic material flow less than 10,000 years ago, and (3) surface evidence of a very great thermal anomaly in the subsurface. The locations selected (Figures 2, 3, and 4) are not all the possible magma locations in these areas and, certainly, the inclusion of a location in these figures should not be taken as an indication that the location is being considered for future magma tap exploration. Actually, many locations shown are currently believed to be unsuitable for exploration consideration.

The University of Hawaii Geothermal Program was using the method of electrical dipole resistivity measurements to locate possible hot brine sources on the Island of Hawaii. According to participants in the program, a major problem in using this method was the difficulty in implanting electrodes in the lava with adequately low contact resistance. Sandia suggested an experimental effort to implant the electrodes by using air-dropped earth penetrators as the electrode and, in December 1973, 29 terradynamic electrodes were implanted (Figure 5) (Brandvold, 1974). It appears that good electrical contact (100 to 200 ohms) was achieved in all sites except for about six where there were relatively new lava flows with no soil cover or vegetation. Electrical contact using penetrators appears to be better than that obtained for electrodes placed by other methods.

Proposed Programs

The major thrust of Sandia's effort in source location and identification for the next year will be close cooperation with other agencies which either are addressing or are proposing to address this problem with subsurface sensing programs. The program under way at the U. S. Geological Survey is foremost in this area and Sandia will work closely with their geothermal group. Sandia will also closely monitor the progress of the programs of the aforementioned universities.

In areas where Sandia has relevant and unique capabilities of value a more active contribution will be made. For example, regarding the thermal survey program proposed by the University of Alaska for implementation on Augustine Volcano, Sandia feels that the earth penetrator technology developed over the past several years may be directly applied. A study is under way to design a remotely implanted earth penetrator that will be thermal-sensor instrumented at various locations along the penetrator body. At various time intervals after implantation of the penetrator the thermal gradient will be measured and telemetered to a receiving station for recording. The penetrator will be air delivered into virtually inaccessible areas. By using a grid of such penetrators, a three-dimensional plot of thermal gradients near a suspected geothermal source can be determined.

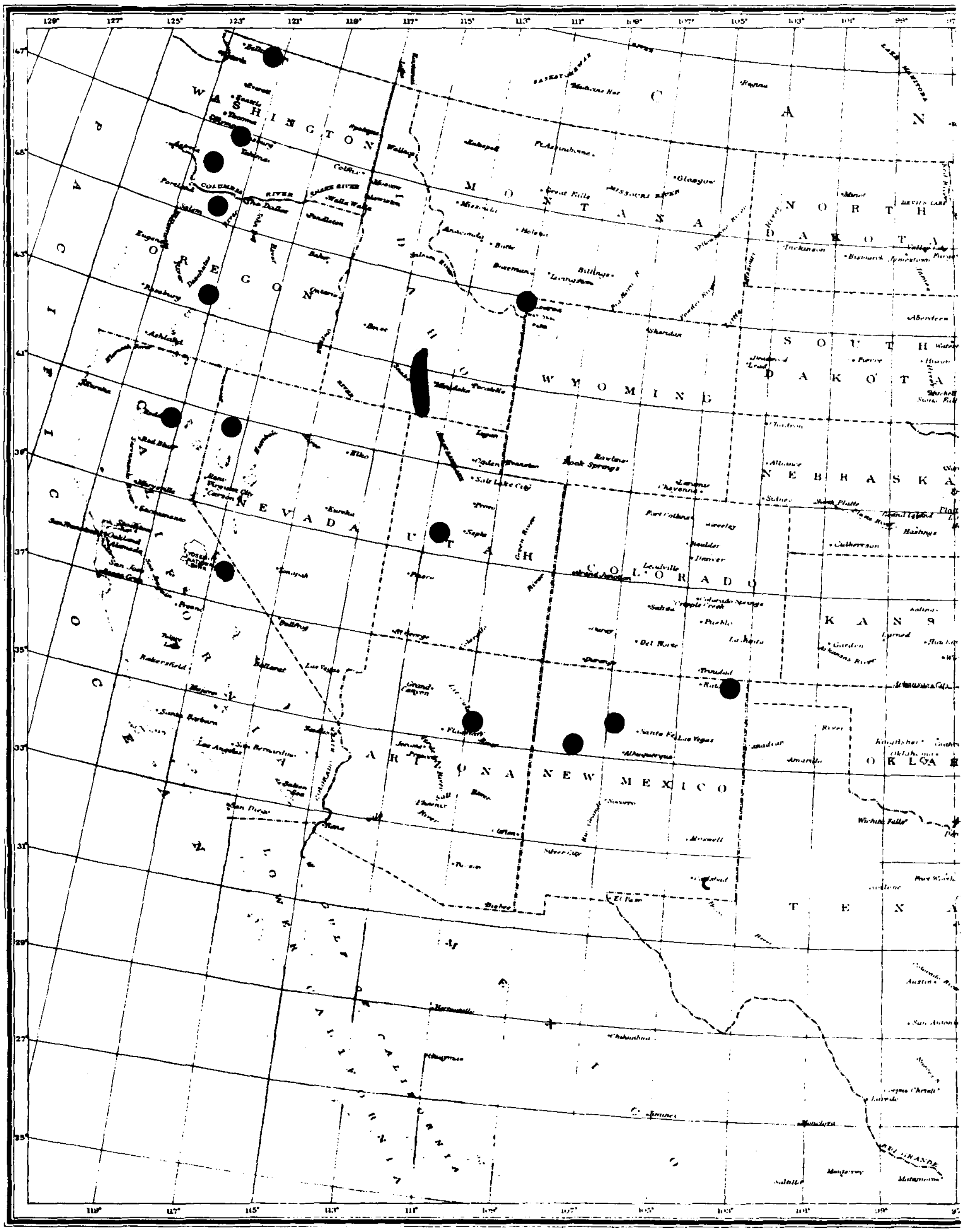


Figure 2. Possible locations of magma sources in the western conterminous United States

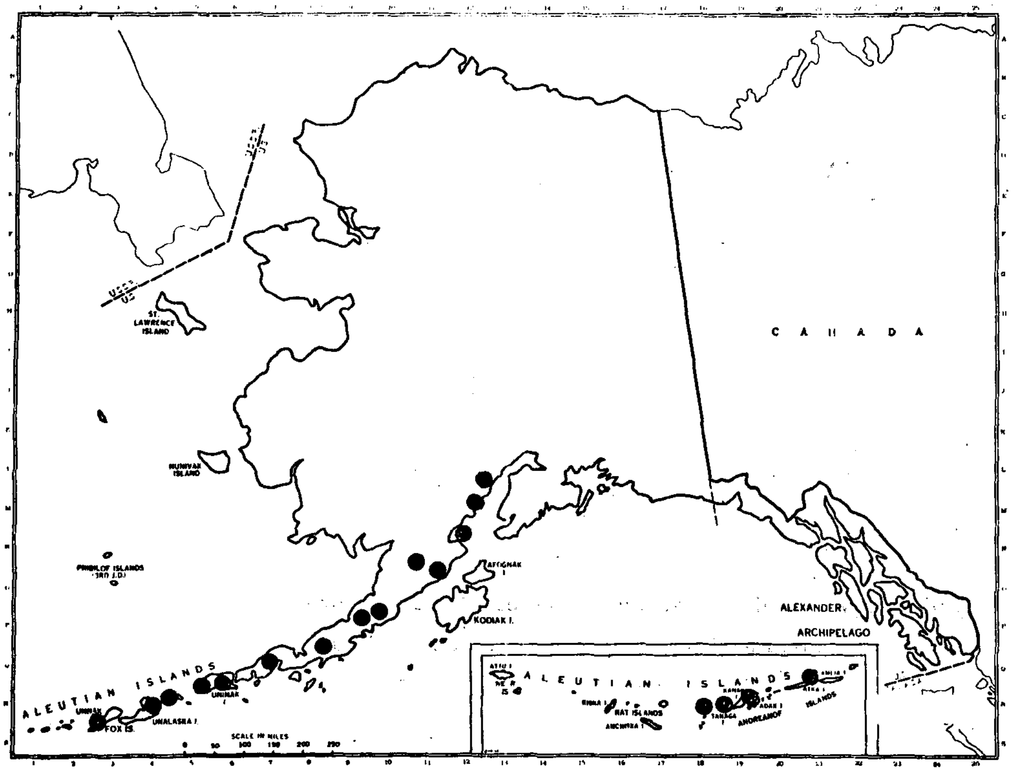


Figure 3. Possible locations of magma sources in Alaska

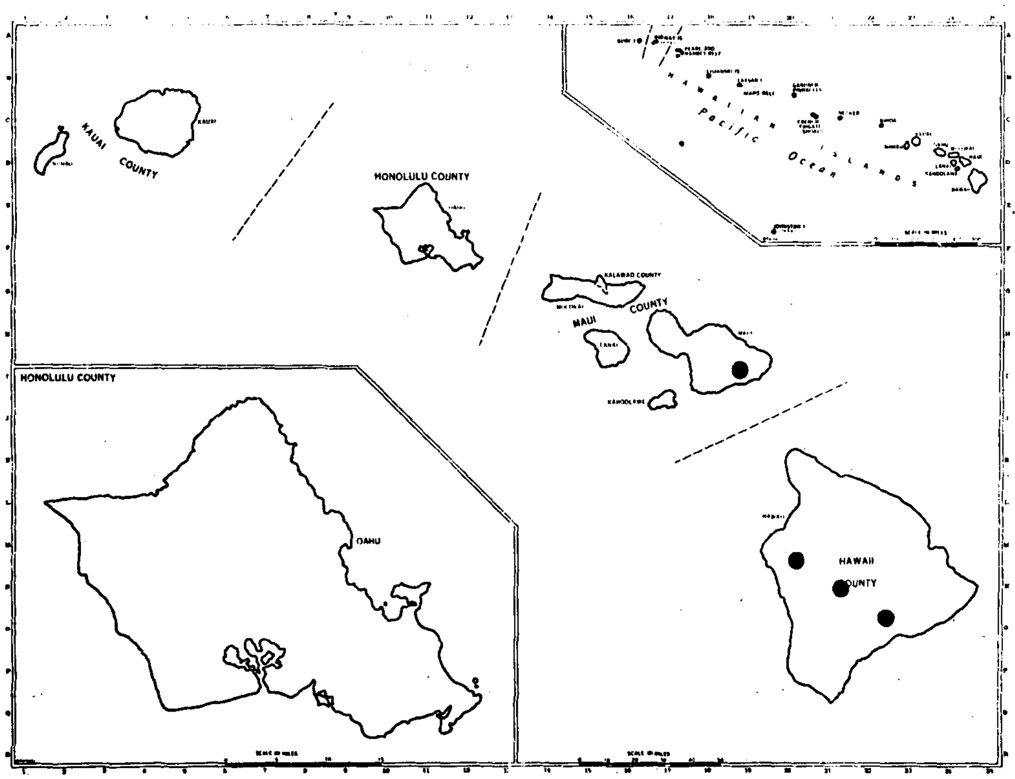


Figure 4. Possible locations of magma sources in Hawaii

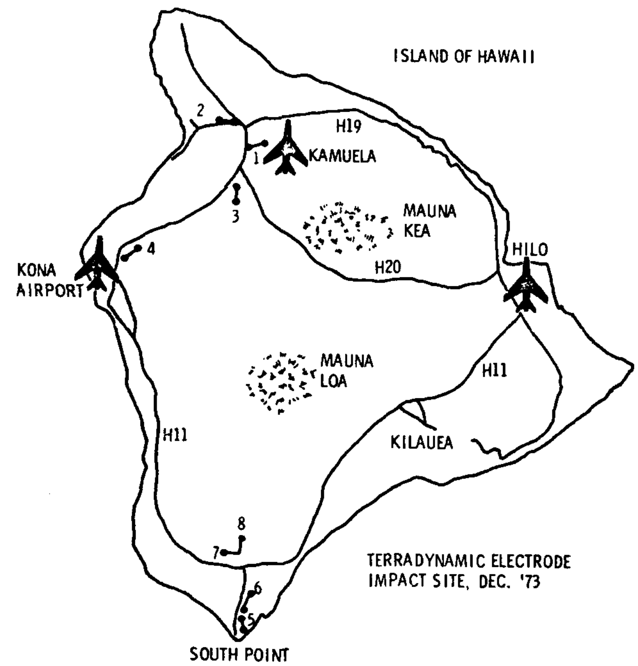


Figure 5. Map showing the location of terradynamic electrode impact sites on the island of Hawaii

One of the (aforementioned) proposed workshops will be devoted to magma source location and configuration. The objectives will be (1) to determine the current methods and systems suitable for locating magma sources in the earth surface and for determining their subsurface configuration, (2) to discuss the validity of previous results, (3) to assess the requirements for additional knowledge, and (4) to suggest directions in which future studies should proceed. The participants in this workshop will be (carefully) selected from those people who are believed to be able to contribute to the discussion of such a subject. It is expected that as a result of this workshop, which will be held sometime in March 1975, the direction in which the Magma Tap Program should proceed will become clearer.

Magma Properties

General

Magma is known to be a high-temperature, highly corrosive environment. Much definitive information must be learned about the character of this environment (i.e., the in situ properties) and its effects on engineering materials before heat-exchanger equipment is inserted into it for long periods of time.

Previous studies of the character and properties of magma have been performed by petrologists and geochemists to determine its age, source, content, methods of formation, etc. Most of this work has been accomplished on samples obtained from past (ancient to recent) lava flows.

To our knowledge there are no current or planned programs to study the in situ properties of magma as it relates to the compatibility of engineering materials with the magma environment.

Sandia plans to direct a sizable portion of its initial research effort toward a solution to this problem. The Material Science group at Sandia Laboratories has had extensive experience in material compatibility studies and in the development of materials to survive in extreme environments. This recognized expertise will be brought to bear on the problem.

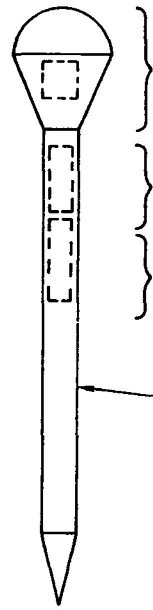
Current Programs

The small amount of information now known about the in situ properties of magma has been obtained largely from submarine pillow lava samples and from bombs that have been propelled from great depths and quickly cooled, thus sealing in the contained gases. As a start toward obtaining actual in situ magma properties, Sandia has designed and built an instrumented penetrator capable of measuring properties of in situ magma during volcanic eruption before the lava cools or is exposed to air (Figure 6). Two penetrators of this type were built to measure deceleration and temperature. The temperature-measuring instrumentation consists of two radiometers mounted along the sides of the penetrator and two thermocouples mounted on the nose of the penetrator. Each penetrator weighs 200 pounds and is designed to be air dropped into a volcano. The penetrator is parachute retarded to control the impact velocity and the trajectory angle. Sandia intends to drop these devices into sources of erupting magma, allow them to penetrate through the molten material, and telemeter out data on the thermal gradient of the material. It is expected that in this environment the instrumentation and the data transmission equipment will have a life of about 30 seconds. This will provide adequate time to get several feet of thermal gradient measurements. These penetrators are now ready for application whenever the opportunity comes to insert them into an erupting magma source.

A laboratory study of the gas evolution and vaporization of magma and lava at high temperatures and pressures is under way (Meyer, 1974). As a result of Sandia's experience with the high-temperature vaporization of materials, a multiphased program is being conducted to characterize the volatization and vaporization of solid and molten magmas and lavas. The program conists of the following:

1. Characterize noncondensable volatile gases as a function of origin of the magma and as a function of the hydrostatic pressure at the time or place of the original solidification of the sample.
2. Study of high-temperature vaporization properties of molten magma/lava with quantitative measurements of vapor pressures and heats of vaporization of the vaporizing species.
3. Experiment with pulsed-laser-induced and high-temperature, high-pressure vaporization of solid lava to determine the relative abundances of vapor species.
4. Design a technique to measure gases in high-pressure equilibrium with magma or under conditions of high hydrostatic pressure at moderately high temperatures (1000K, 2000K).

Figure 6. Schematic drawing of the Sandia magma penetrometer for measuring in situ properties of molten rocks in lava lakes



Also under way is another laboratory study of electrochemical methods to measure oxygen activities, to increase the efficiency of energy extraction, and to protect materials used in a magma tap application (Haaland, 1974). The three selected areas of proposed research follow:

1. Develop and use a solid electrolyte oxygen probe cable of making in situ oxygen activity measurements in magma, using the Sandia penetrator technology. The resulting measurements will be the first in situ oxygen determinations of magma.

2. Develop a fuel cell which uses the reduced iron present in magma as the fuel and/or direct oxidation of magma to increase the amount and efficiency of energy withdrawal.

3. Investigate use of electrochemical methods for materials protection in magma. The electrochemical protection research must be conducted in conjunction with detailed material compatibility tests. Once all corrosive reactions are determined, various cathodic and anodic protection schemes can be proposed and tested.

Proposed Programs

Another of the aforementioned workshops will be held to address the current state of knowledge on magma material characteristics. The objectives of this workshop are (1) to determine the state of knowledge concerning the material characteristics (physical, thermal, electrical, chemical, minerological) of representative types of magmas, particularly in the in situ state; (2) to discuss the validity of the results constituting this state of knowledge; (3) to assess the requirements for additional knowledge to the present state; and (4) to suggest directions in which future studies should proceed.

Participants in this workshop will be selected from those workers in the field who are known to be able to contribute to the objectives. It is currently planned to hold this meeting in mid-January 1975. From the results of this workshop, the future directions of the program to study magma characteristics can be determined.

Material Compatibilities

General

The ability to build a heat-transfer device that can be inserted directly into a magma source is critical to the success of the planned Direct Magma Tap Program. The materials developed for building a heat exchanger must retain their physical and structural properties sufficiently to allow the heat exchanger to perform for many years if the installation is to have an economic value.

Little is known about the compatibilities of engineering materials in this environment. What is known has resulted chiefly from empirical applications of materials by workers in the field. Samples of molten magma have been obtained from lava eruptions in metal pots. Observations have been made of the performance of some types of materials plunged into lava lakes through holes drilled in their surfaces. To our knowledge no laboratory analyses have been performed of the mechanisms involved in the degradation of engineering materials in the magma environment.

Current Programs

The problem of developing materials compatible with a magma environment does not appear insurmountable since there are analogies between the composition of magma and that of slags encountered in metallurigical processing (Sallach, 1974). Existing materials which may meet the requirements are the heat-resistant metal alloys and the refractory compounds. Combinations of these two classes of materials in the form of cermets, if commercially available, may also be worthwhile for this application.

Preliminary data on the interaction of various representative alloys with degassified molten basalt indicate that a good correlation may be made between reactivity and the free energies of formation of the various metal oxides. These data further indicate that the Ni- and Co-based alloys may have special qualities in regard to the magma environment.

The refractory compounds primarily, Al_2O_3, MgO, ZrO_2 have had extensive application in metal production processes at temperatures up to 1700°C and exhibit good resistance to the corrosive action of slag. Their application in the magma environment may be limited by their relatively poor tensile strengths.

Magma is largely composed of silicates of Ca and Mg, with lesser amounts of compounds of Fe, Al, Ti, Na, and K. Within the earth, magma also contains dissolved substances primarily H_2O, CO_2, and SO_2 which volatilize from the magma as the surface is approached. These latter substances are anticipated to have significant effects on the corrosiveness of the magma. A case in point is the accelerated hot-gas corrosion of gas turbines, termed hot corrosion, induced when superficial melts of Na_2SO_4 attack the protective metal oxide film.

The current program consists of a survey of high-temperature reactivity of metals with degassed molten basalt and will include refractory compounds and commercially available cermets. In these tests individual specimens will be immersed in degassed molten basalt at temperatures between 1100° and 1300°C in a low-pressure atmosphere of argon. The extent and composition of any reaction products will be determined by using metallographic procedures in conjunction with analyses by the electron microprobe. These results will permit the formulation of criteria for more sophisticated materials selection and testing in the future.

A second series of tests is being performed on those materials exhibiting the most resistance to degassed molten basalt. In these tests, specimens in contact with the basalt will be placed in high-pressure high-temperature bombs together with varying amounts of H_2O, CO_2, and SO_2 (both individually and in combination) in order to quantify their effect on both the rate and mechanism of corrosion of the reaction and on product composition.

Proposed Programs

So little is known about material compatibilities to the magma environment that the future directions of the program are almost totally dependent upon the results achieved in the laboratory studies now under way. Also required before future directions can be determined are the results from the magma characterization studies. For these reasons it is almost impossible to predict the directions in which the material compatibility study program will proceed. It is fairly certain, however, that a part of the future program will involve insertion of material samples into natural lava lakes for extended periods and hopefully, into areas of erupting lavas.

Energy Extraction

General

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. No previous work along this line is known.

Sandia Laboratories possesses excellent calculational and experimental facilities for approaching a problem such as this. Currently under way is a study of the problem of radioactive waste disposal in deep rock cavities (Hardee, 1974; Hardee and Sullivan, 1974b) and the design of a heat sink pit (Hardee, 1973a) beneath a nuclear reactor to contain the molten core in event of a major reactor melt-down (Hardee and Sullivan, 1973). Both of these problems are concerned with the convection processes in molten rock. Both theoretical studies and laboratory experiments of this convection process are in progress, (Hardee and Sullivan, 1974 a), as well as a small-scale field experiment (Hardee and Sullivan, 1974 a). Much of what is being learned about convection in the radioactive waste disposal problem will be of importance in magma tap.

Current Programs

Results from preliminary long-term heat-extraction rates calculated for assumed magma fields show that rates could run from 1 to 26 kilowatts per square foot of tube area, depending on the assumptions used (Hardee 1973 b, c, d). These calculational studies are proceeding, and refinements in the assumptions are being made.

A small vane turbine developed by Dr. A. R. Shouman of New Mexico State University (recently on sabbatical at Sandia Laboratories) has been selected for the first model studies of a possible magma tap energy-extraction scheme. This turbine was selected not only because of its small size and availability, but also because it may offer certain advantages for geothermal sources in the future (i. e., higher efficiencies due to higher operating temperatures and satisfactory operation with low-quality steam).

A turbine generator unit has been assembled and tested in a Sandia Laboratories experiment. A long-tube boiler heat-exchanger device has been designed and built to be used in a model heat exchanger experiment. Facilities are available at Sandia to melt 100 pounds of basalt lava and maintain it in a molten state. The long-tube boiler heat-exchanger and turbine generator unit will be assembled for insertion into this pot of molten basalt (Figure 7). The primary purpose of this experiment is to study such phenomena as the temperature gradient across the magma and into the heat exchanger. This experiment should show that the temperature of the metal tube and the magma adjacent to it can be maintained low enough that corrosion of the tube is not a critical problem. In this experiment the thermal transient problem in the tube associated with start-up will also be examined. Being considered are design concepts of an improved, more efficient boiling heat exchanger compatible with the long tube shape required when heat-extraction pipes are placed in a magma source. Other heat-exchanger concepts such as a Brayton cycle in which a closed cycle with gas is used to extract heat from the magma will be considered. The extraction tube in the magma would use a recirculating gas as the cooling fluid in the heat exchanger. This hot gas would run conventional gas turbines (Brayton cycle) to generate electricity.

If further subsurface sensing methods studies determine that the configuration of magma sources is likely to resemble large liquid pools, it will be necessary to calculate convection rates both in the pool and adjacent to the heat-extraction pipes. This type of calculation will require the development of analytical and numerical techniques for handling convection problems. Some of this development work is already going on at Sandia in support of the reactor safety and waste management proposals.

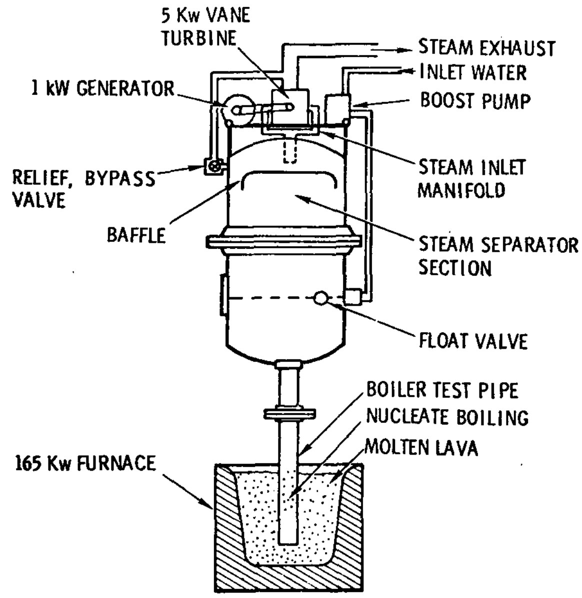


Figure 7. Schematic drawing of laboratory test apparatus for demonstrating the magma boiler tube concept

Proposed Programs

The next step in the energy-extraction studies, assuming success in the present laboratory heat-exchanger program, will be to begin design of a demonstration heat exchanger using materials that are determined to be compatible with the magma environment. The eventual objective of this effort will be to design a heat exchanger suitable for a research program pilot plant to be installed on an existing lava lake to demonstrate the utility of the magma tap method of extracting energy. The exact time that such a research pilot plant might be constructed depends entirely upon the success of all the different facets of the magma tap program and, of course, upon the availability of a suitable lava lake.

Source Tapping

General

A problem whose solution is vital to a magma tap is that of reaching the source and inserting the heat exchanger. As stated earlier, the magma tap program under consideration at Sandia Laboratoaies is regarded as one of extremely long range. It is recognized that in many locations magma sources will be at depths greater than 10 kilometers below the surface of the earth. It is also realized that conventional drilling technology at this time is limited to depths of about 30,000 feet, or 10 kilometers. Difficulty has been encountered in past attempts at deep drilling in areas suspected of being near magma sources because of the increasing temperature as the drill neared the possible magma source. The Sandia Magma Tap Program is not intended to be directly involved in developing deep-drilling methods in the high-temperature magma environment. Other organizations in this country are considering this problem and are initiating programs to solve it. The drilling subcommittee of the U. S. Geodynamics Committee currently recognizes the desirability of developing deep drilling techniques that may reach the magma environment (Newson, 1974a). The Los Alamos Scientific Laboratory has an on-going program to develop a rock melting drill that, if successful, would be an ideal means for tapping a magma source (Hanold, 1973).

Current Programs

Although not a part of the magma tap effort, Sandia has an on-going program in drilling research and development (Newsom, 1974 b). The objective of this program is to devise methods for improving the speed of drilling as well as the depth of drilling.. Methods being investigated under this program may be applicable to the magma tap problem. Close liaison is being maintained at Sandia Laboratories among persons working on the magma tap program and persons working on the drilling R&D program.

As drilling approaches the magma source, it is obvious that temperatures of the rocks above it are going to increase causing the rocks to approach a plastic state. A basic question must be answered: Will a hole through such a hot plastic material stay open, are there methods for keeping it open so that the heat exchanger equipment can be inserted through it into the magma source? Little is known about the physical properties of rocks at these elevated geostatic pressures and temperatures. To answer the question, Sandia Laboratories is involved in a research program with the Center for Tectonophysics at Texas A&M University to investigate the physical properties of rocks under dynamic stress conditions at pressures up to 5 kilobars and at temperatures of approximately 1000°C. This work is being performed under the direction of Dr. John Handin and Dr. Melvin Friedman from that Center (Handin, 1974).

Proposed Programs

Active participation in deep-drilling programs applicable to magma tapping being conducted by others may become feasible in the near future. Definite plans for such participation are dependent upon the results achieved in these other programs. At this time it is felt that immediate success in deep-drilling techniques is not a requirement for the Sandia Magma Tap Program to proceed in an orderly manner. It may be several years before this program has achieved enough success to warrant initiating any deep-drilling expeditions into magma sources. Much valuable information can be gained from conventionally drilled holes in existing lava lakes.

Conclusions

A survey report such as this does not necessarily result in a set of firm conclusions. However, some statements can be made on the expected outlook of this program and of the problems faced:

1. Tapping energy stored in molten rocks below the surface of the earth has been the dream of many for a long time. Geologists and laymen looking at the lava flowing from an active volcano have long wished that this energy could be harnessed. There is no doubt that these subsurface reserves of heat energy are enormous. However, no serious program has yet addressed the problems necessary to release this energy for man's use. That is the stated objective of the Direct Magma Tap Program now under way.

2. The problems associated with locating, identifying, and configuring the sources of this subsurface energy are recognized and are being faced. Programs are under way to evaluate these problems and to eventually overcome them.

3. The severity of the magma environment and its highly detrimental effects on materials placed in it are also well recognized. Although solutions are not now known, the programs in process lead persons knowledgeable in modern materials technologies to believe that the problems are not insurmountable.

4. Tapping a magma source with a drill has been achieved only in surface lava lakes. Although problems lie ahead before deep sources can be drilled, these are basically engineering problems that may be solved.

5. Extraction of heat energy from a magma source also faces problems that require engineering solutions. The current programs indicate that the desired objectives can be achieved.

In summary, the study of the ultimate geothermal energy system is being pursued in a serious, organized effort toward its achievement. Although problems are many, they are recognized and acknowledged. The program is being conducted in an orderly, methodical manner. The time scales are not optimistically short. Success is not certain, but the effort is under way.

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