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MAGMA ENERGY RESEARCH, 79-1

SEMIANNUAL REPORT FOR OCTOBER 1, 1978 - MARCH 31, 1979

MASTER

EDITED BY:
R. K. TRAEGER, J. L. COLP, AND R. R. NEEL

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JULY 1979

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ABSTRACT

The objective of the Magma Energy Research Project is to determine the scientific feasibility of extracting energy from magma bodies. Project activities are divided into five individual tasks representing all aspects of the concept. In the past six months, the following was accomplished.

Task 1. Research Location and Definition:

Results from previous geophysical measurements in Kilauea Iki lava lake suggested but could not confirm the presence of a low viscosity, molten rock lens. Recent drilling and thermal studies in the lava lake suggest that the lake is in the last stage of solidification with no low viscosity lens but a plastic, multi-phase region of crystals (mainly olivine) in melt with intermittent, thin (1-4 cm?) veins of very fluid molten rock. Models were developed to predict the thermal behavior of the lava lake geothermal system and to estimate the solidification state of the multi-phase lens. Data analysis is currently in process.

Task 2. Source Tapping:

Strengths of dry andesite, basalt, granodiorite and obsidian were determined to 1050°C at confining pressures of 0 and 50 MPa. Initial analysis of the data suggests that a 10 km deep, 1000°C hole will not fail under short time loading.

Jet-augmented coring bit and jet-augmented drag bit drilling concepts successfully penetrated into the viscous multi-phase zone in the lava lake where conventional drilling had failed.

Task 3. Magma Characterization:

Construction of the 800cc, 1500°C, 4 kbar test facility was completed and the system successfully tested at maximum temperature and pressure.

Gas Analyses:

Thermodynamic calculations have been developed to eliminate errors incorporated in volcanic gas analyses. Approximately 100 gas analyses have been corrected allowing scientific interpretation of the data.

Task 4. Material Compatibility:

Stability diagrams were developed for 15 pure metals and the metals plus some simple alloys were evaluated in low pressure, simulated magma environments. Preliminary results suggest iron, cobalt and molybdenum containing chromium show little degradation.

Task 5. Energy Extraction:

A limited experiment performed in a cased hole in the lava lake gave energy extraction rates on the order of 11 kW/m^2; approximately twice that expected from conduction alone. The high rates are believed due to convection set up by residual drilling water which suggest use of convection enhancing fluids may be a means of extracting energy from magma chamber margins.

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INTRODUCTION

The objective of the Magma Energy Research Program is to define the scientific feasibility of extracting energy from magma bodies. Activities to accomplish the objective are divided into five tasks:

Task 1. Resource Location and Identification

Task 2. Source Tapping

Task 3. Magma Characterization

Task 4. Materials Compatibility

Task 5. Energy Extraction

Status of the project has been reviewed[1,2] in previous reports. This report summarizes the program activities of the last six months according to the individual tasks.

Major emphasis of the program in the last period was on field experimentation with the U.S.G.S. in geoscience and technological studies at the Kilauea Iki lava lake. Other major efforts included installation of the magma simulation facility, and magma-metal compatibility studies. The Magma Energy Advisory Panel also met during this time period. Efforts and results are summarized in this document with individual, complete reports being prepared where appropriate.

RESULTS AND DISCUSSION

Activities and results are summarized for each of the tasks. Names of individuals responsible for each of the areas are included and the individuals should be contacted for further information. Detailed data and analyses will be included in topical reports when appropriate.

Task 1. Resource Location and Definition (J. L. Colp)

Kilauea Iki lava lake provides a unique microcosm of a geothermal system. Geophysical measurements were performed at Kilauea Iki in 1976 to evaluate techniques over a known molten rock body. Although the measurements did define the upper frozen crust regions and the edge of the lake, they could not quantify the nature or extent of the liquid zone. Analysis of the data by Hermance[3] resulted in the estimation of a physical model of the lake shown in Figure 1. A set of experiments was defined for the 1979 effort to penetrate into the molten zone and obtain data to help interpret the 1976 results. The set of experiments planned is given in Table 1, with notes on status of experimental results; location of the boreholes is shown in Figure 2.

Core Studies: Only preliminary analyses are available at the present time. Cores obtained generally exhibited:

0-53m competent, fractured rock
53-56m competent rocks with 1-4cm veins of melt
> 56m plastic, multi-phase material with about 40% olivine crystals and 60% glass (liquid in situ) at ∿ 62m (79-1)

The plastic nature of the core was exhibited (Figure 3) by the corrugated external surface of the core (as if it has been extruded) and by several hundred percent core recovery when the melt extruded up the core barrel during drilling. Petrographic analysis on a limited number of thin sections of cores from 79-5 (through the completely frozen lens), 79-1 (deepest in the center of the lake) and 79-2 (through the now-frozen region of alternate melt-solid layers encountered in the 1976 drilling) are being done by Sandia in conjunction with Dr. Helz at the U.S.G.S.

Thermal Studies (H. C. Hardee): Validity of temperature measurements in uncased holes was evaluated by measuring temperatures before and after casing the deepened drillhole K.I. 75-1. In the upper two-phase hydrothermal zone, uncased hole temperatures were found to be higher than rock formation temperatures. In the lower conduction-dominant zone uncased hole temperatures measured represent rock formation temperature. Rock formation temperatures were observed to be influenced (depressed) by drilling fluids for periods from 4-8 weeks after drilling stopped. Temperature profiles in the hole through the frozen margin (79-5) and in the center, deepest hole (79-1) are shown in Figure 4.

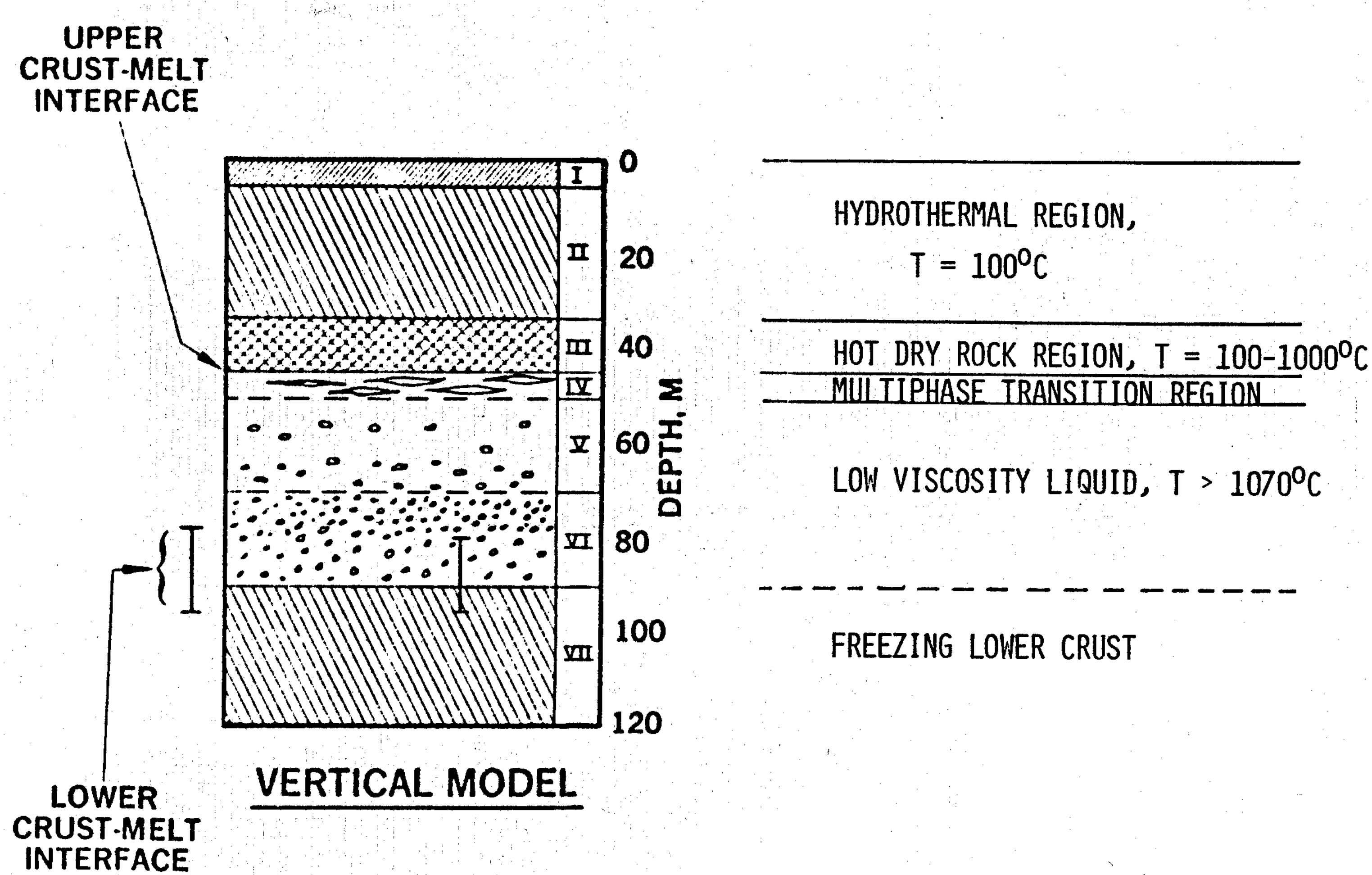


FIGURE 1. VERTICAL MODEL OF KILAUEA IKI LAVA LAKE (REF. 3)

Table 1. Geoscience Experiments - Kilauea Iki 1979

Experiment	Scientist	Purpose	Status
Cores & Analysis	USGS/Sandia	Characterize structure and history.	400m original core. 33m redrilled glass. One core (100 m) through frozen lake (79-5). Limited petrographic USGS/Sandia analysis in process.
Temperature Profiles	Hardee	Model geothermal system.	State of molten body verified. Model for liquid rock-hydrothermal region developed.
Rainfall Effect on Temperature	Hardee	Define rainfall effects on level of hydrothermal region.	Rain and night-day effects resulted in isothermal region fluctuation of 1-2m.
Crust	Hardee	Measure upper crust permeability.	Average 0.3 Darcy measurement agrees with heat transfer rate calculations.
Long Term Creep	Ryan/ U. of Hawaii	Measure in situ creep strength of hot (>900^{o}C) formation.	Experiment in process in K.I. 79-6.
Molten Rock Resistivity	Dobecki	Measure in situ resistivity of molten rock.	No test; unable to penetrate into molten rock.
Mise-a-la-masse Electrical Survey	Zablocki/ USGS	Define molten lens areal extent.	Raw data look good. Analysis in process.
Drilling	Neel	Penetrate into liquid lense.	Encountered regions of liquid veins interspersed in high viscosity, multiphase mixture below 52m.

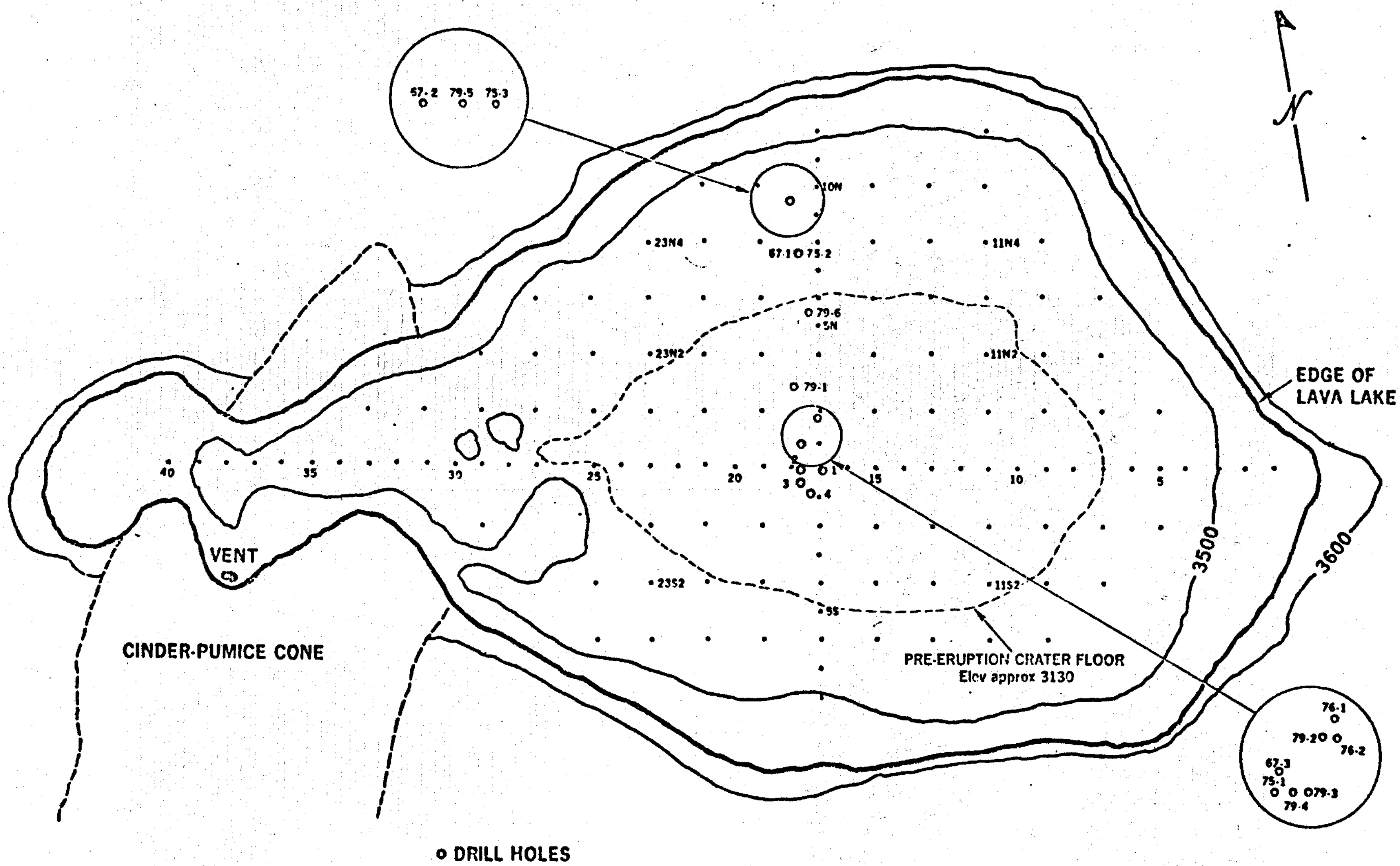


FIGURE 2. KILAUEA IKI LAVA LAKE BOREHOLE LOCATIONS.

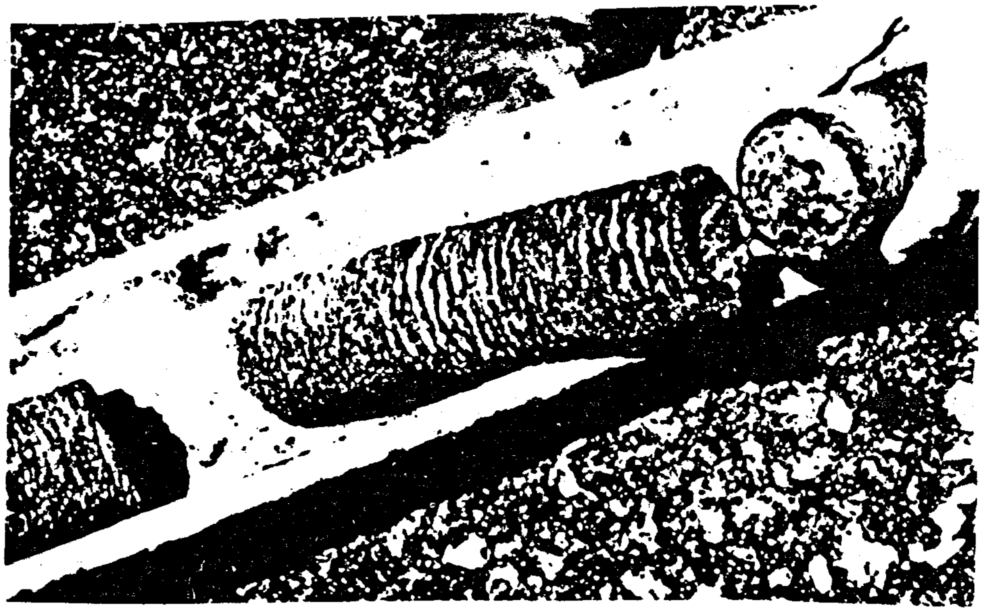


FIGURE 3. CORE FROM BOREHOLE K.I. 79-1 (~ 60 M DEPTH) SHOWING CORRUGATED EXTERNAL SURFACE.

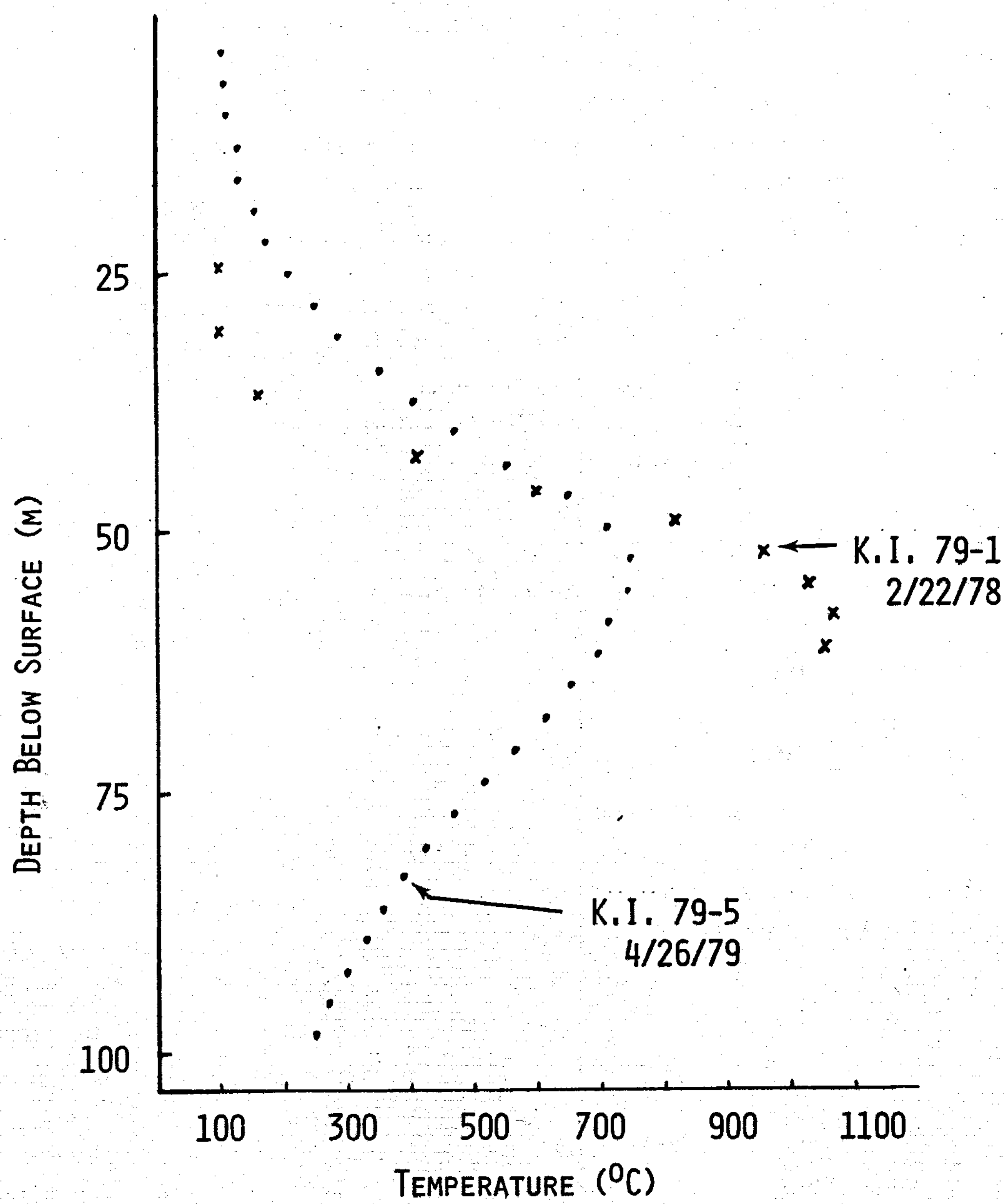


FIGURE 4. Temperature Profiles in Boreholes K.I. 79-1 and K.I. 79-5.

Analysis of the curvature of thermal profiles in the hot, dry rock region can give information on the solidification state of the molten material. When the molten region presents a semi-infinite, isothermal, solidifying source, the temperature-depth thermal profile has a definite curvature; that curvature can be defined in terms of a parameter β. As the molten material ceases to be isothermal, β changes. This change is evidenced in Figure 5 showing the thermal profile change with time for 75-1 and the reversed curvature noted in 79-1. The data suggest that the lake is in its last stage of freezing.

The overall geothermal system can be modeled based on temperature measurements. The model suggests an upper hydrothermal region that increased in thickness as cooling proceeds. The subsequent hot, dry rock region moves downward at essentially constant thickness (12m for this lava lake). Permeability of the upper crust controls circulation in the hydrothermal region and thus the rate of heat removal from the molten zone. The in situ permeability was estimated from a layered isothermal-hot-rock-hydrothermal model and the measured thermal profiles to be 0.30 Darcys, which agrees with the average in situ permeability measurement of 0.32 Darcys.

Task 2. Source Tapping (R. R. Neel)

Conventional drilling technology and that currently being developed by the Division of Geothermal Energy in the U.S. Department of Energy[4] is expected to provide the majority of any 5-10 km drilling effort required to tap a magma chamber. However, drilling through the hot (> 700°C), corrosive (H_2S), high pressure environment will require extensive drilling and completion development. Such a development is not compatible with the intent nor budget of the Magma Energy Research Project and the effort has been oriented to defining the borehole stability. This study is being done at the Center for Tectonophysics, Texas A&M University by Dr. M. Friedman.

Drilling activities in the lava lake support the geoscience experiments and are not designed for magma tap development. Nevertheless, the lava lake provides a geothermal model system with liquid rock over 1000°C under low pressure (150-200 psi) and experiences in the lava lake will provide a basis for any future deep drilling development. Thus, the lava lake drilling results are included in this section.

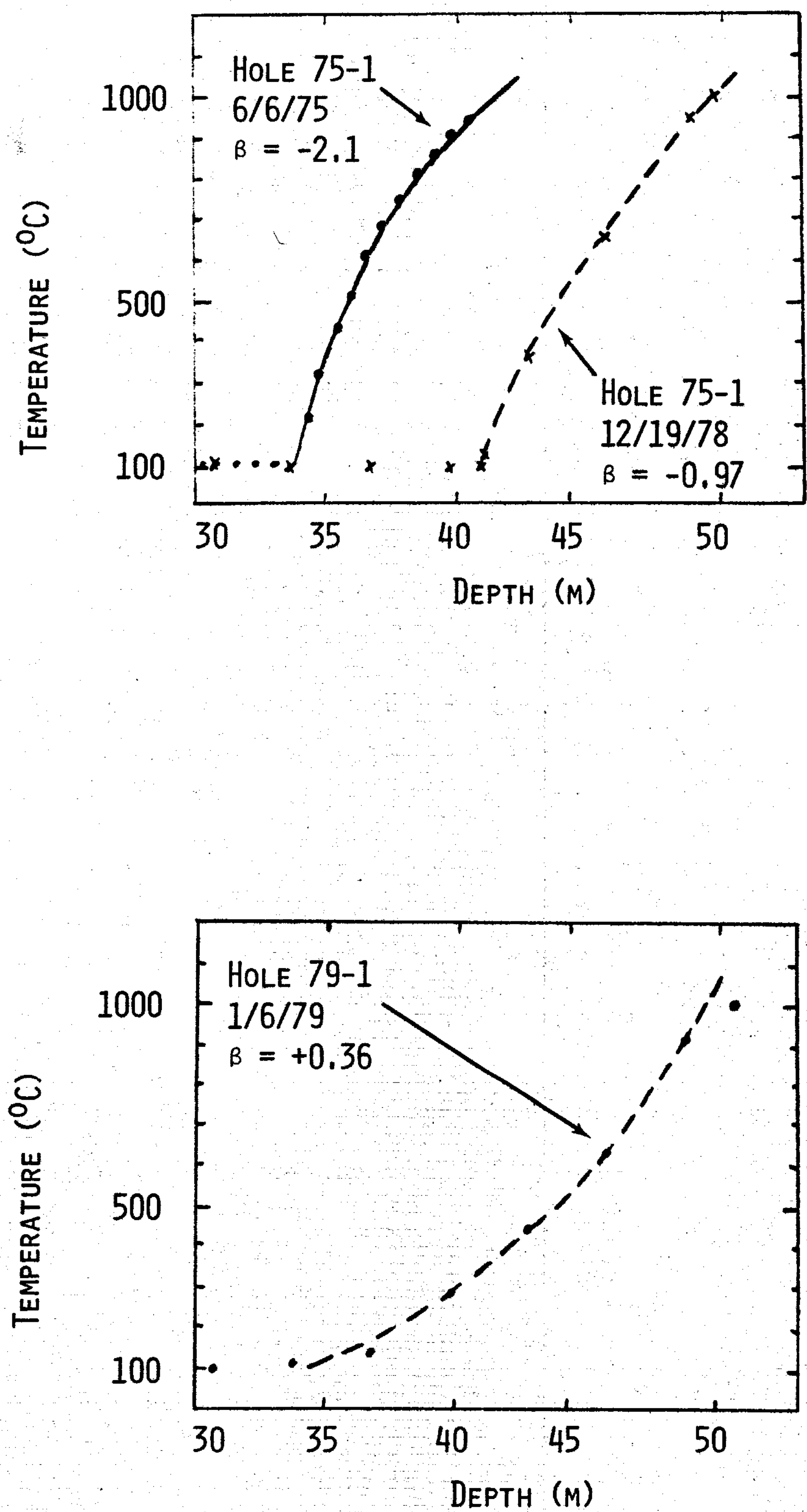


FIGURE 5. Temperature Profile Change with Time

Borehole Stability (Dr. M. Friedman[5]):

The failure strengths, strains at failure, and associated deformation mechanisms of room-dry andesite, basalt, granodiorite, and obsidian are determined at temperatures to partial melting ($\sim$ 1050°C), at confining pressures of 0 and 50 MPa, and a strain rate of 10^{-4}/s. The strength reductions of the crystalline rocks are more or less linear until they steepen suddenly with approach to melting. When that occurs, strengths vanish and deformations become quasiviscous. The obsidian is stronger than the crystalline rocks to 600°C where glass softening begins and strength goes to zero at 800°C. All rocks are brittle throughout the entire temperature range until melting or softening occurs. Shortenings at failure are 3 percent or less. The crystalline rocks tend to deform primarily by precursive microscopic extension fracturing and its coalescence into macroscopic faults. The abundance of load-induced fractures remains about constant, but thermal cracking increases with increasing temperature. Results from tests at 25°C on specimens that previously had been heated to 900-1000°C clearly show that the weakening of unconfined specimens, however, probably is due to an inherent temperature effect on the load-induced fracturing process. Comparisons of instantaneous failure-strengths with stresses likely to occur at the walls of boreholes show that a hole as deep at 10 km in impermeable crystalline rock is not likely to fail under short-time loading even at 1000°C, unless the maximum in situ horizontal stress is $\geq$ vertical stress and the hole is open (i.e., borehole pressure is zero).

Lava Lake Drilling Concepts (R. R. Neel):

Table 2 summarizes the drilling techniques designed for penetrating into the low viscosity melt of the lava lake. In addition to the techniques, the drill rig was instrumented to provide real time records of torque, bit load, penetration and rotation speed. Results are reviewed below.

Drilling methods devised to penetrate into molten rock during the FY 79 Lava Lake Drilling Program were the Insulated Drill String (IDS) system and water jet-augmented drilling systems. The IDS was designed to withstand the molten rock environment through the use of high temperature materials, insulation and internal structural components cooled with a minimum of air and water.

Table 2. Lava Lake Drilling Concepts

Techniques	Designer(s)	Concept	Results in FY 79
Insulated Drill String	Colp, Larson, Striker	Bit and external surface of drill rod operate at formation temperatures	Laboratory thermal and hot rock drilling tests satisfactory. Not used in Lava Lake.
Jet-augmented Core Bit	Dunn, Ortega	Water jets around the core bit penetrate into the liquid freezing a rigid porous or fractured medium ahead of the cutting edges.	Successfully penetrated 5-6 m through alternating liquid veins and multiphase regions in lava lake. No core obtained; generated fine chips.
Jet-augmented Drag Bit	Dunn, Ortega	Water jet from center of drag bit penetrates into the liquid freezing a rigid porous or fractured medium ahead of the cutting edges.	Successfully penetrated 5-6m through alternating liquid veins and multiphase regions in lava lake. Cutting removal is a problem.
Penetrometer	Colp	Push a pointed cylinder thru hot (plastic?) rock into liquid	Unsuccessful in lava lake; believe rock temperature too low to allow creep.

The jet-augmented drilling operations were based on the concept of injecting a high-velocity jet of water forward into the molten rock to freeze it sufficiently to allow drilling at an acceptable rate with conventional drilling equipment. Another method investigated for penetrating the molten rock consisted of a high strength linear penetrator designed to be pushed into the molten rock zone.

Insulated Drill String Development - IDS (D. W. Larson)

The drilling experiments conducted in 1976 at the Kilauea Iki Lava Lake indicated that nonconventional drilling techniques and hardware would be needed to drill into a body of molten rock under lithostatic pressure. The IDS was conceived as a result of the drilling experience of 1976 where a layer of liquid rock about 60 cm in thickness was penetrated with conventional drilling equipment. The liquid froze initially on the relatively cool drill rod and bit preventing rotation or linear motion. After the system was permitted to attain the temperature of the surrounding liquid, the drill rod and bit were free to rotate and raise. Thus a drill string whose bit and outer surface of the drill rod could survive and perform while at molten rock temperature (> 1070°C) but having an inner torque tube that could be insulated and cooled to a temperature of a few hundred degrees centigrade was developed. The resultant hardware was not tested in the 1979 Lava Lake Drilling Program since no large volume of low viscosity, molten rock was located in the lava lake. However, laboratory testing of critical components of the IDS were conducted and the IDS is available for future drilling efforts.

Concept: The basic constituents of the insulated drill string (IDS) concept are (1) a special drag bit that can operate at molten rock temperatures (> 1100°C), (2) a dual concentric insulated drill rod with the cooled inner rod carrying torque to the drill bit and the outer rod operating at or near molten rock temperatures, and (3) a "lava seal" at the bottom of the cased hole (above the molten rock) to prevent the geo-pressurized lava from flowing up the well-bore. A thick-walled sub is provided between the drill bit and the insulated drill pipe to locate sensors for measurement of the in situ magma conditions. The magma temperature, lithostatic pressure, thermal diffusivity, and potential energy extraction rates were to be determined from this instrumentation section. Schematic drawings of the IDS insulation lava seal, and overall assembly are shown in Figures 6, 7, and 8.

Design Analyses and Tests: A number of analyses and tests were conducted to determine the feasibility and the details of the IDS conceptual design.

The drill bit selected was a conventional 3-wing drag bit cast from Mar-M 509. Structural analyses of the bit (by S. N. Burchett) indicated that at 1100°C the bit could successfully handle the torque capability of the available drill rig. Titanium carbide in an Inconel matrix was selected for the cutting inserts of the drill bit. These inserts are attached to the drill bit using a high-temperature brazing (diffusion bonding) process. A "hot" drilling test of the bit, i.e., drilling into hot solidified basalt at 1050°C, demonstrated satisfactory bit operation and survival.

Several insulation and cooling techniques were investigated to maintain the inner, torque-carrying drill rod to reach the 300-1100°C temperatures of the surrounding environment. The IDS design that was successfully tested in the Sandia radiant heat facility consisted of an outer pipe of RA-330 stainless steel (4.0 inch schedule 40), and an inner pipe of the same material (2.5 inch schedule 80). The 0.5 inch wide annular space between the pipes was filled with two alternate layers of Kaowool (Babcock and Wilcox trademark) and 0.001 inch nickel foil (serving as a radiation barrier) wrapped tightly around the inner pipe and held in place with a final wrap of 0.002 inch stainless steel shim stock and Nichrome wire (Figure 6). The inner pipe was cooled by an air/water mixture which was sprayed onto the inner wall of the inner pipe from 0.020 inch diameter nozzles creating a thin film of water on the pipe wall. This configuration resulted in heat transfer rates to the cooling fluid of approximately 7 kw/m^2 with the outside surface at 1100°C and the inner pipe temperature at 100°C (must be maintained below 300°C for structural integrity). A photograph of the test section showing the condition of the insulation layers and the inner pipe, following the radiant heat test is shown in Figure 9.

Air/water flow rates were determined to (1) adequately cool the inner torque rod during drilling, (2) overcome the lithostatic pressure and thus prevent plugging of the exit nozzles from the bit, and (3) remove drilling chips from the bottom of the hole. Air flow of 0.077 lbm/sec and water flow of 0.5 lbm/sec (3.76 gal/min) were required for torque rod cooling. Water pressure 30 psi above the drill stem internal pressure was required to attain the appropriate flow.

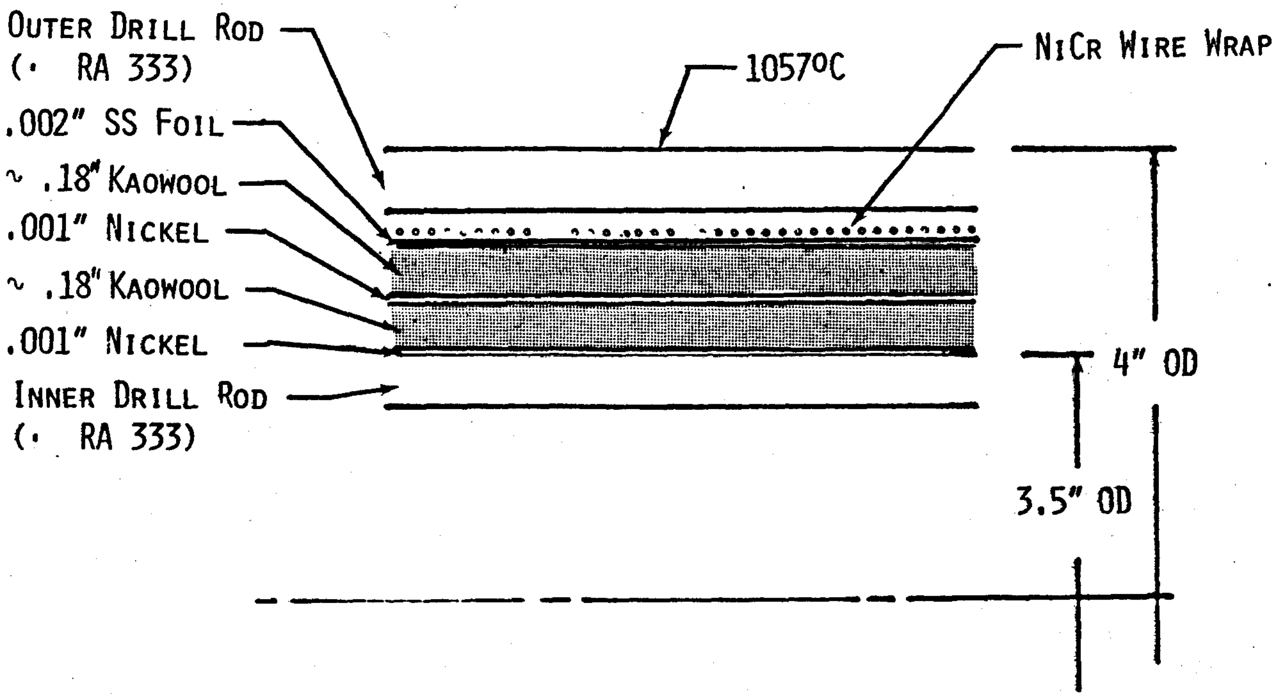


FIGURE 6. INSULATION SECTION INSULATED DRILL STRING

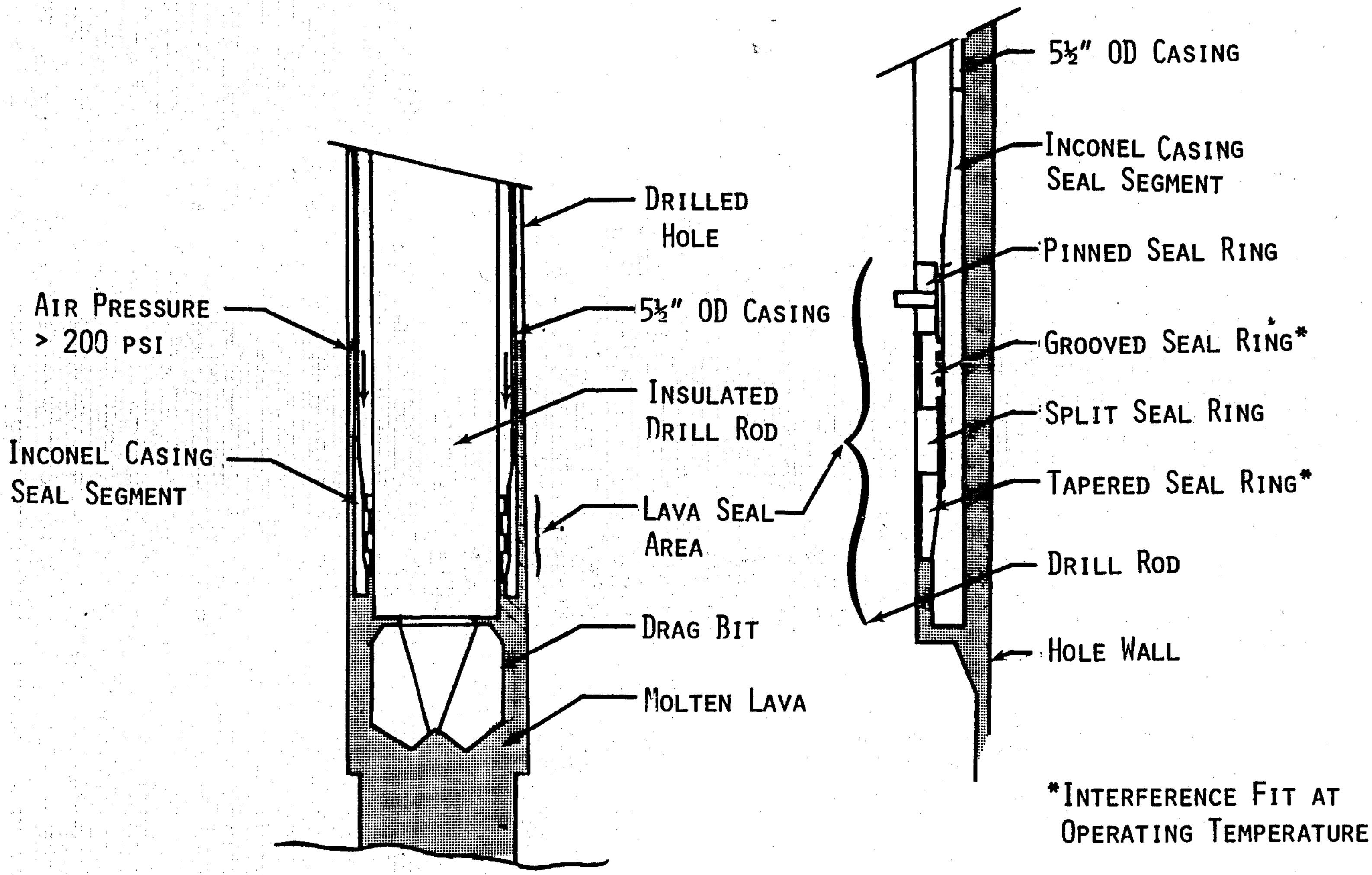


FIGURE 7. IDS Lava Seal Schematic

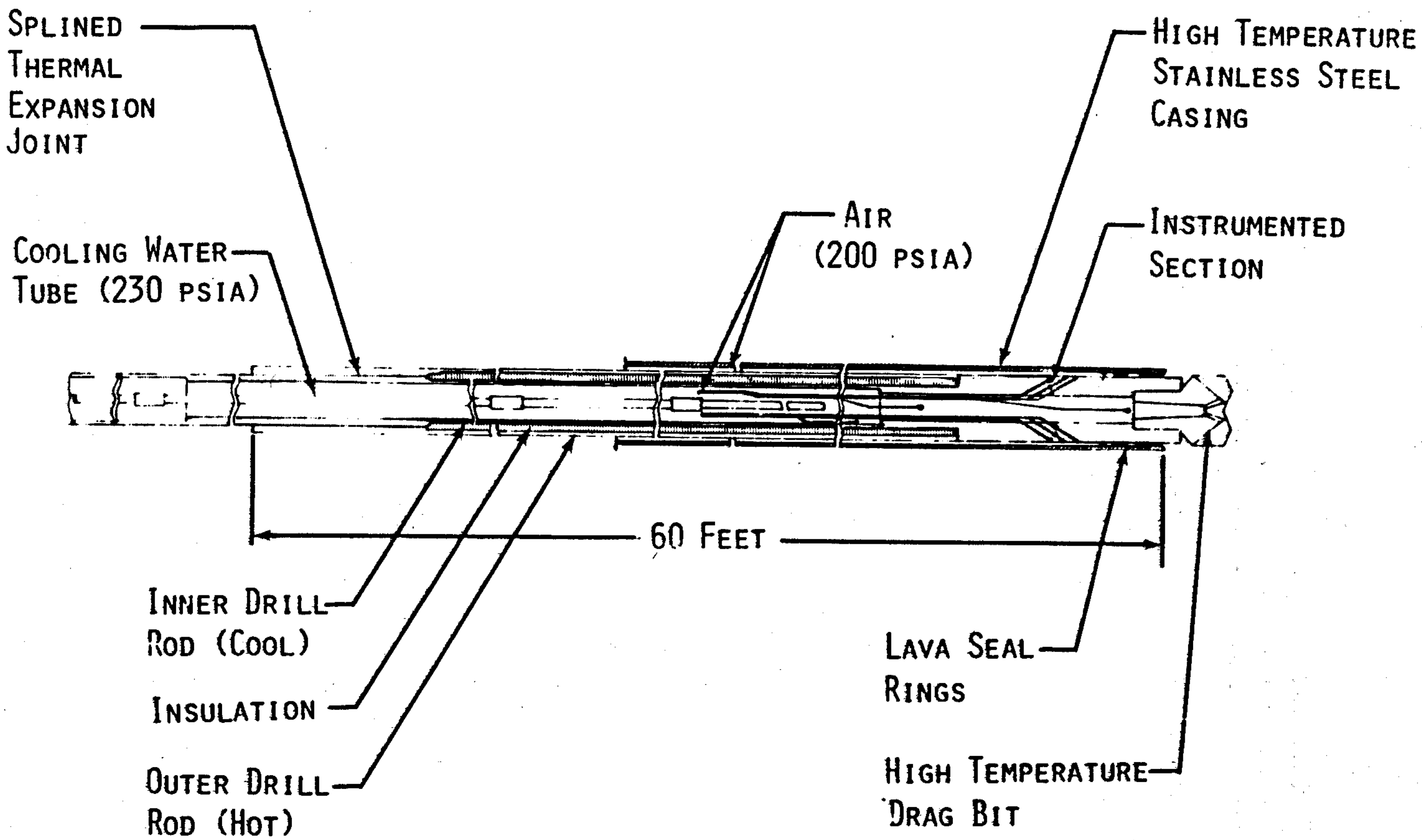


FIGURE 8. INSULATED DRILL STRING SCHEMATIC

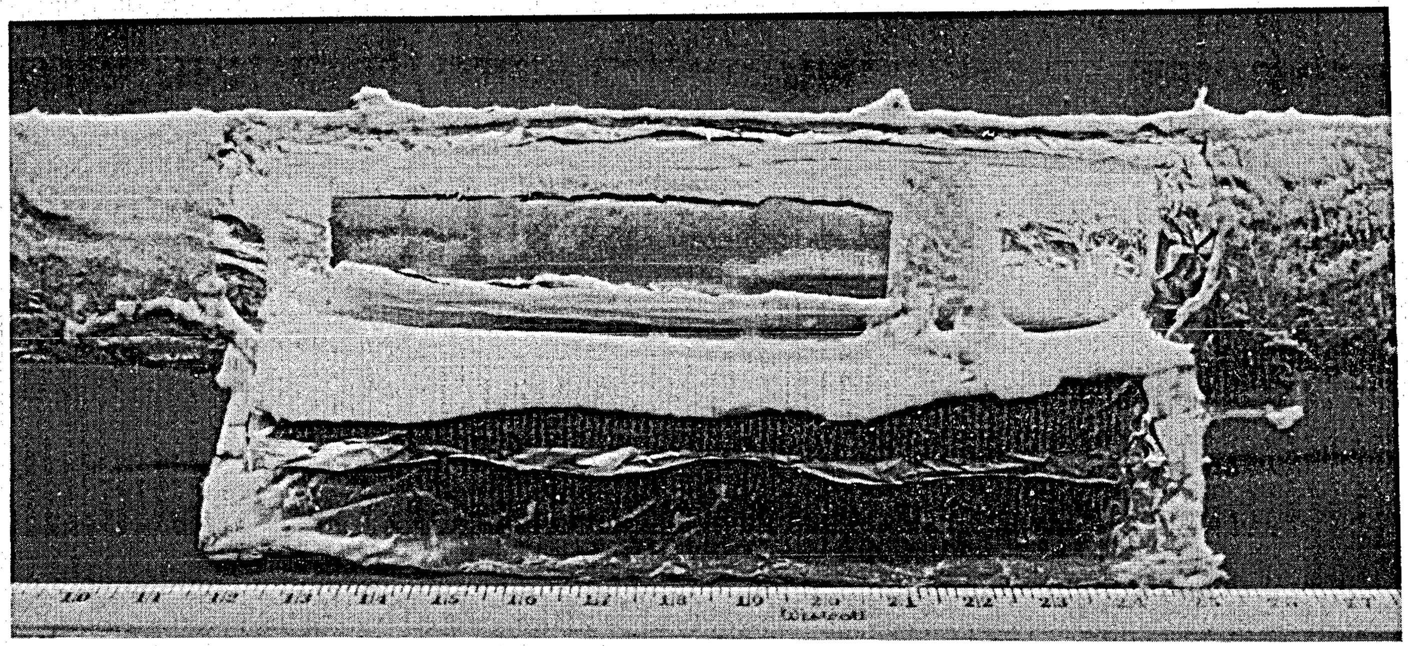


FIGURE 9. DRILL STRING INSULATION ASSEMBLY FOLLOWING 1100°C RADIANT HEAT TEST.

Nine 0.88" diameter exit nozzles restricted the flow through the drill string and enabled internal drill stem pressure (210 psi) to be held above the expected lithostatic back pressure. A coolant exit velocity of about 446 ft/sec was expected to be adequate for chip removal at the face of the bit.

The lava seal (Figure 7) was designed to prevent molten rock from flowing into and up the well bore. One set of rings fits snugly against the casing wall and a second set of rings is split and sized to fit tightly against the drill stem as it rotates. These rings are pressed against each other at the bottom of the casing by holding the upper ring in place with a frangible pin forcing the lower ring against a taper in the casing wall during insertion. The space above the ring was to be pressurized by air to above lithostatic pressure so that when drilling into molten rock, the lithostatic pressure on the molten rock cannot cause the rings to move up the wellbore. Since lithostatic back-pressure may be as high as 210 psia in Kilauea Iki lava lake, high pressure (2000 psi) gas bottles and air compressors were planned to provide a minimum of 210 psia above the seal rings while drilling through the solid/liquid interface.

The instrumentation (test) section consists of an RA-333 stainless steel cylinder with a 4.5-inch outside diameter and a 1.75-inch inside diameter. Two sets of 3 thermocouples were inserted to measure the radial temperature gradient through the cylinder. In addition, the free-stream coolant flow temperature and the inside wall temperature of the insulated section were to be measured. Table 3 shows the predicted external surface temperature of the test section, the radial temperature gradient, and the resulting heat flux for the instrumentation section.

Water Jet-augmented Drilling Systems

High velocity water jet-augmented drilling systems were conceived as a means of freezing the molten rock ahead of the drill bit at a rate consistent with reasonable drilling rates. The jet-augmented drilling systems consisted of conventional drag and core bits modified so that high velocity water jets could be generated by the pressurized water system. A cased hole was pressurized with air to suppress the upward surge of the molten lava.

Table 3. Thermal Response of I.D.S. Instrumentation Section

Minutes	External Surface Temp. (^oC)	Temp. Gradient (^oC)	Heat Flux (kw/m^2)
0	600	300	-
11	506	178	59
22	470	141	46
33	425	126	41
4	402	110	36
65	380	91	30
87	367	84	28
109	358	80	26
218	326	63	21
436	380	53	17

Note: This response of the instrumentation section is predicted to result when inserted into 1100^oC molten rock, with an initial test section temperature of 300^oC.

The jet-augmented drag bit was a conventional three-winged drag bit 7 cm in diameter with standard tungsten carbide inserts as cutting edges. The central nozzle, normally used to wash cuttings away from the cutting surfaces, was replaced by a converging-diverging nozzle designed to provide a coherent water jet delivering approximately 3.6×10^{-2} l/minute with a velocity of about 26 m/sec ahead of the bit. A pressure drop of about 3.5×10^5 Pa (50 psi) across the nozzle and an estimated lithostatic pressure of about 1.4 MPa (200 psi) resulted in a pressure of 1.8 MPa (250 psi) at the bit or 1.2 MPa (170 psi) at the surface supplied by the water pressure system.

A second jet-augmented bit was formed by modifying the water ports of a face discharge NW-size diamond core bit to produce high velocity coherent jets at each ports. The water pressures, velocities and flow rates were similar to those produced by the jet-augmented drag bit. The cooling capacity of the water flowing from both bits was sufficient to cool 1093^oC (2000^oF) rock to about 204^oC (400^oF), if the drill advance rate was held at around 1.25 cm/min.

The water jet-augmented drilling systems were designed to operate in bore holes which were cased to a depth as near the liquid level as possible. The bottom of the casing was then sealed by allowing the molten rock to flow up into the borehole around the bottom of the casing. Air pressure was applied to the annulus around the drill rod inside the casing to preclude further flow of the liquid rock up the hole around the drill rod. Figure 10 is a schematic drawing of the jet-augmented drilling systems.

Linear Penetrator

The linear penetrator experiment was an attempt to thrust an appropriately shaped probe through the last interval of mechanically stable rock into the underlying plastic and liquid rock. This experiment was coupled to an experiment to measure the in situ electrical resistivity of the molten rock by incorporating four high temperature electrical contacts into the forward end of the penetrator. The penetrator experiment is described schematically in Figure 11.

Drill Rig Instrumentation

The drill rig and the various drilling systems were instrumented to measure response of the drilling techniques to the changing media. The drill functions recorded were turning torque, bit load, advance rate, and turning rate. Coolant (both air and water) flow rates and pressures were recorded during all jet-augmented drilling operations.

Results from Lava Lake Drilling Program

A total of six new (K.I. 79-1 through 79-6) holes were drilled into the lava lake and two old holes (K.I. 75-1 and K.I. 76-2) were re-entered and extended in depth (Figure 2). One hole (K.I. 79-5) was drilled in the frozen margin of the lake and cored to the pre-1959 crater surface.

Kilauea Iki drilling encountered four regimes: 1 - rigid, competent crust; 2 - liquid, 1-4 cm veins in competent rock; 3 - a viscous solid-liquid mixture; and 4 - glass formed by freezing of melt re-entering a borehole after removal of the drill string. Conventional wire line core drills, using water as the drilling fluid and drill coolant, successfully penetrated through the crust and vein regions to

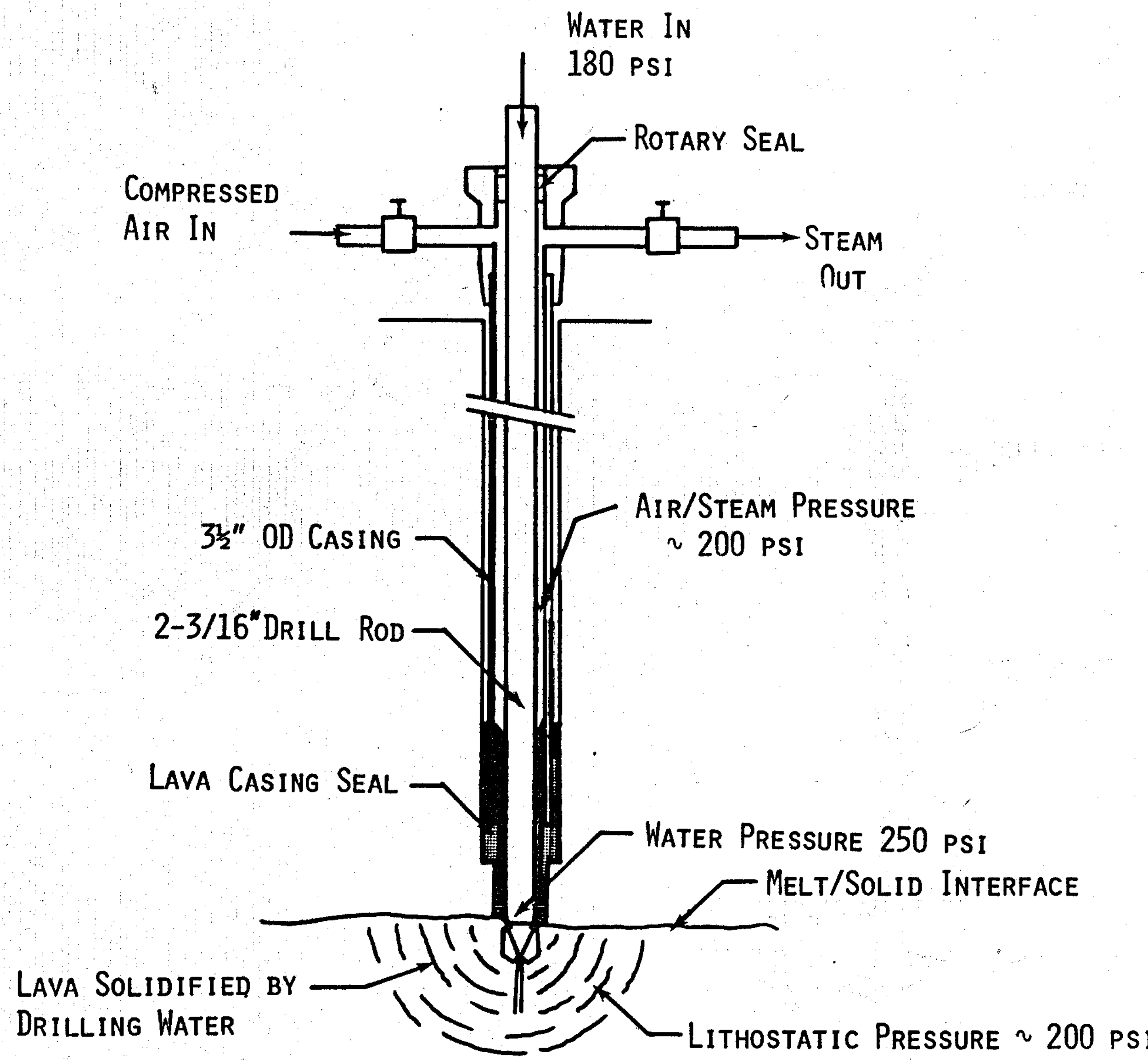


FIGURE 10. WATER JET-AUGMENTED DRILLING SYSTEM

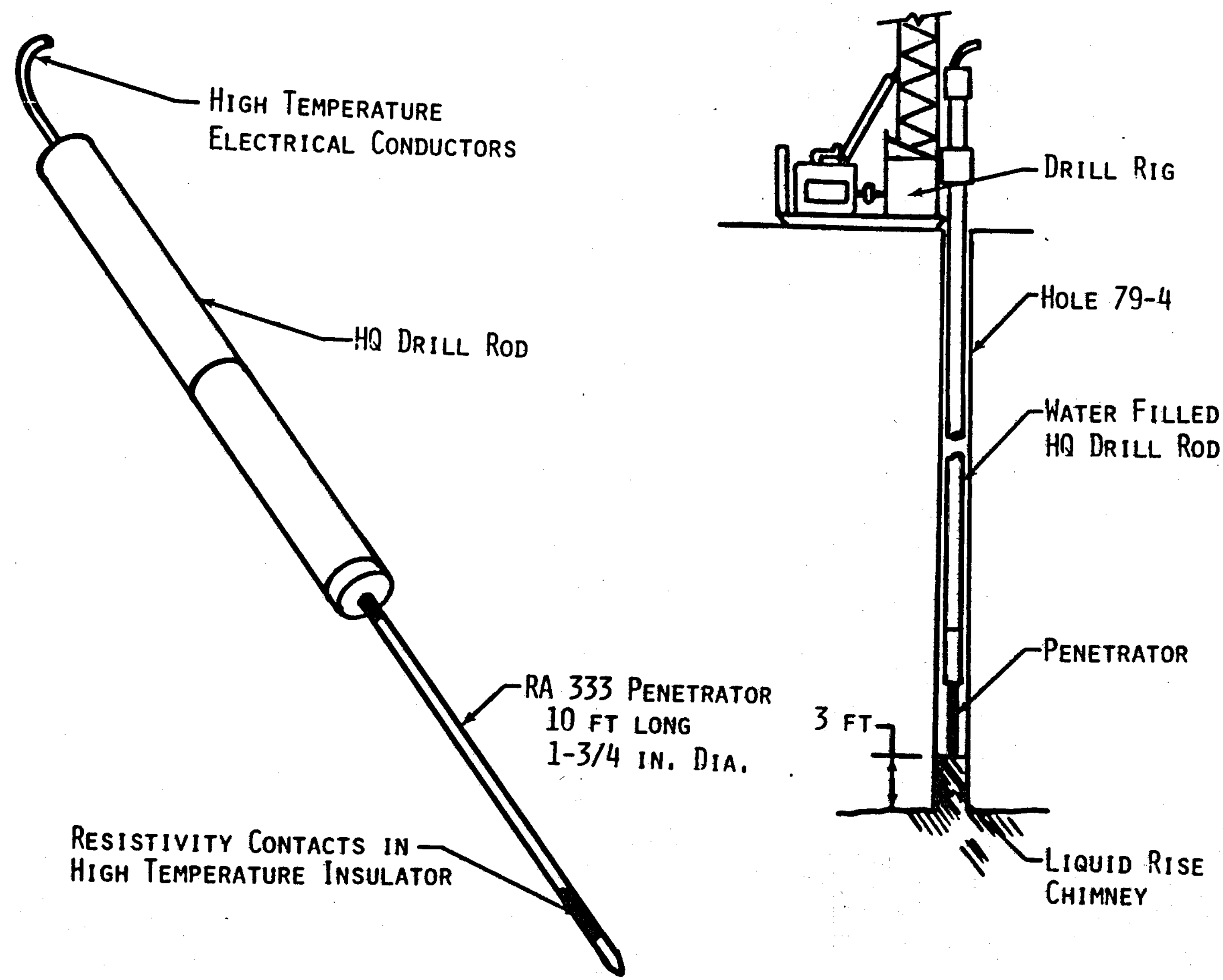


FIGURE 11. LIQUID PENETRATOR WITH RESISTIVITY CONTACTS

formation temperatures of > 1052°C in the initial drilling of K.I. 79-1. In other instances, conventional drilling failed in the multi-phase region (temperatures of 950-1000°C) when the liquid would freeze in the face of the bit, shutting off coolant flow, and also failed when re-entering glassy plugs. When temperatures reached about 800°C during re-entry, the viscosity of the flow-back material was sufficiently low to plug the conventional bit.

Both the jet-augmented core and the jet-augmented drag bits successfully penetrated through the liquid veins, multi-phase and resolidified glassy zones. However, continuous coolant flow was required. When the bit was retracted and water shut off for addition of drill string, the melt would refill the hole, freeze, and negate the previous penetration. The jet-augmented core bit produced fine chips instead of a continuous, solid core and the chips were not recoverable with the drilling equipment available at the lava lake. Techniques are available for maintaining coolant flow during the addition of drill string and for the recovery of core as sand or chips. These techniques are being investigated for future drilling studies.

Conventional and jet-augmented drilling operations confirmed that the sequence of solid upper crust underlaid by melt underlaid by a rigid material encountered in 1976 and for which the IDS system was designed did not exist at the time of this drilling. Therefore, the IDS concept was not tested in the field. However, considerable laboratory simulation testing confirmed the design of the insulation system and satisfactory IDS bit strength was indicated by hot and cold rock drilling tests in the laboratory.

A downward force of 10,000 lbs was not adequate to push the penetrator through a plug of solidified glassy rock in the bottom of the K.I. 79-3 borehole. However, recent results from high temperature rock mechanics studies and evaluation of cores suggest that the penetrator concept could succeed in an appropriate temperature regime.

Drilling parameters were measured as a function of time for the conventional and special drilling systems and techniques in the upper, middle, and lower crust as well as in the hot, dry zone, in high temperature plastic rock, and in regions of alternating thin layers of liquid and solid rock. Figure 12 shows records of drill torque while drilling with a conventional core bit in solidified glassy borehole flowback. Figure 13 shows records of drill torque while drilling with conventional and water jet-augmented bits in plastic rock.

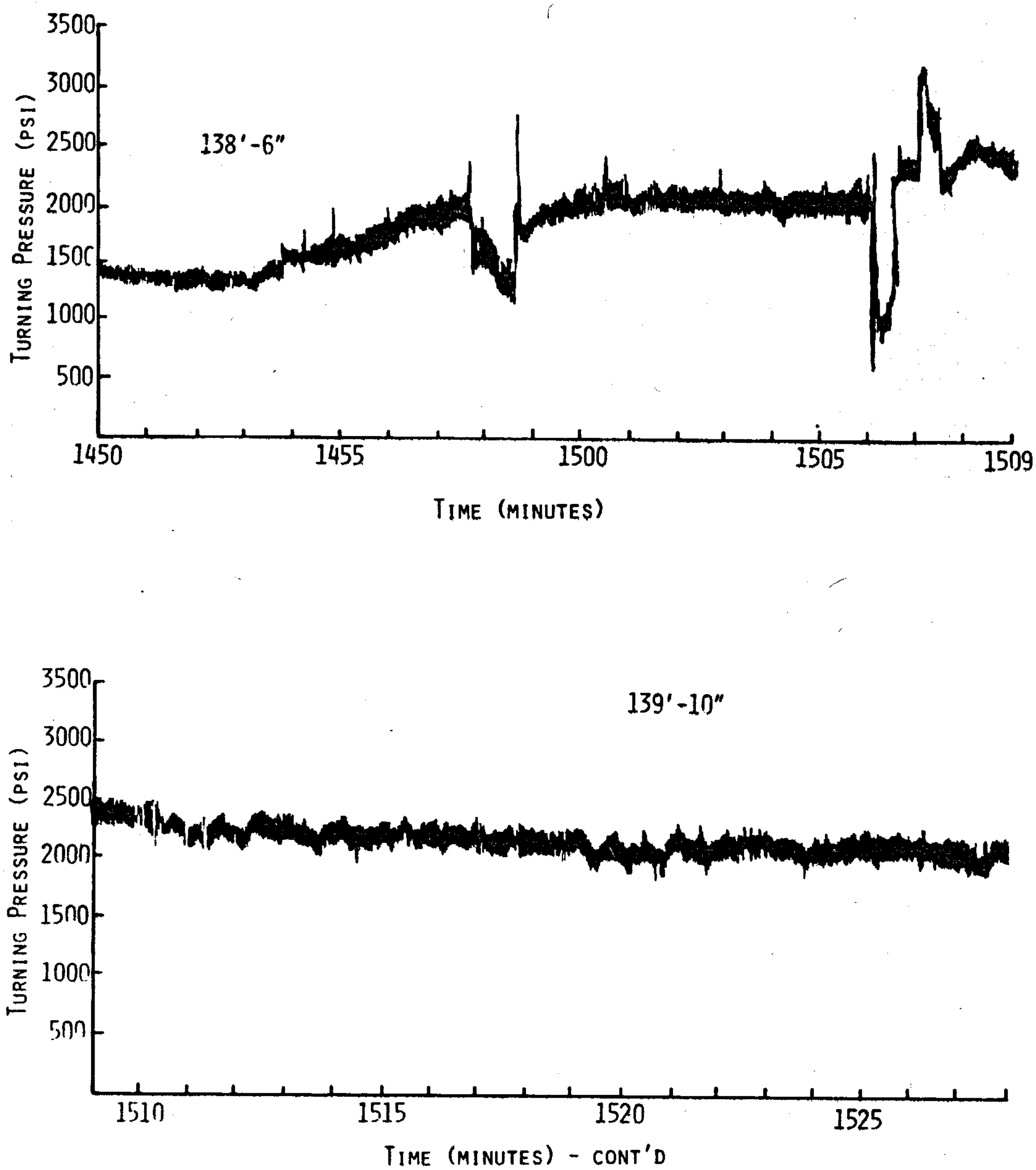
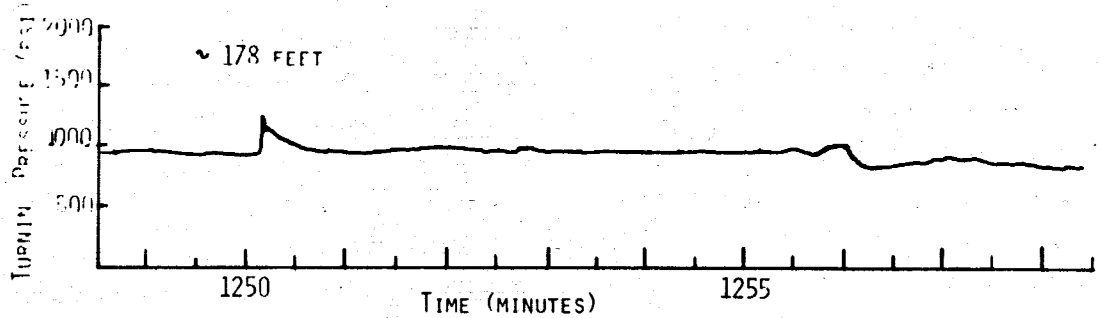
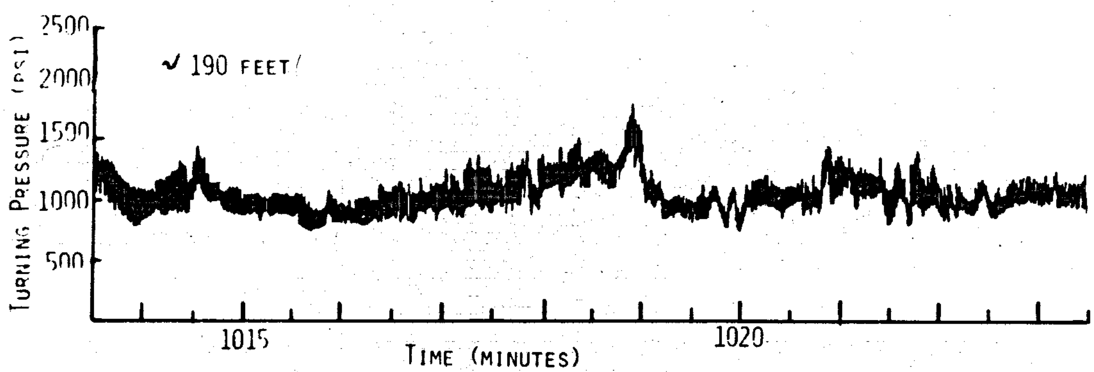


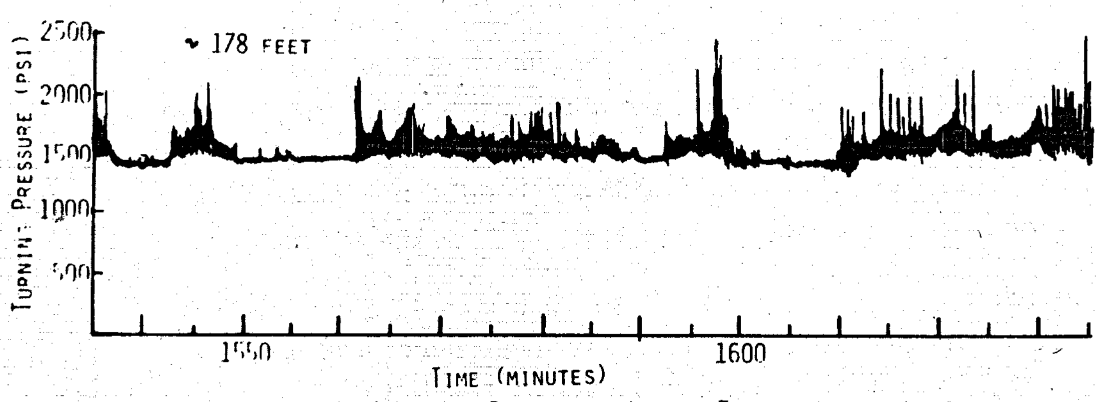
FIGURE 12. DRILL RESPONSE - CONVENTIONAL BIT IN SOLIDIFIED GLASSY FLOWBACK



DRILLING IN PLASTIC ZONE OF HOLE 79-1
WITH CONVENTIONAL BIT



DRILLING IN PLASTIC ZONE OF HOLE 79-1
WITH JET CORE BIT



DRILLING IN PLASTIC OR LIQUID FINGERS OF
HOLE 79-4 WITH JET DRAG BIT

FIGURE 13. DRILL RESPONSE - CONVENTIONAL AND JET-AUGMENTED BITS IN PLASTIC ZONE

Task 3. Magma Characterization

Definition of chemical and physical properties of magma is needed to interpret results from geophysical sensing techniques, to estimate energy extraction mechanism and rates, and to evaluate materials compatibility. Since fugative gases significantly affect properties, studies must be made on materials simulating in-depth compositions. Consequently, efforts of this program are to predict in situ compositions using analyses of gases from volcanic eruptions and measuring properties of simulated systems.

Thermodynamic Analyses (T. Gerlach)

It is well known that volatiles have a strong effect on several magma properties that require characterization in magma energy research: crystallization temperatures, viscosity, density, electrical resistivity, etc. In order to examine these properties in the presence of realistic volatile phases, an investigation has been made of high temperature volcanic gas analyses reported in the literature.

There are approximately 100 volcanic gas analyses of collections taken at high temperatures (> 950°C) in source regions of tholeiitic and alkaline mafic lavas (Hawaii, 1918-19; Nyiragongo, 1959; Surtsey, 1964-67; Etna, 1970; Erta Ale, 1971-74). These "high quality" volcanic gas samples exhibit erratic chemical characteristics. Atmospheric contamination has long been recognized as an obvious cause of much of the observed variability; however, substantial compositional variation remains even after the analyses have been corrected for air contamination. This feature has compromised attempts by volcanologists to relate the collections in terms of temporal, spatial and petrologic parameters.

Detailed computerized studies of the "high quality" gas samples have led to an identification of several sources of modification in addition to atmospheric contamination. These include: addition of meteoric H_2O; condensation and re-evaporation of S and H_2O in lead-in tubes; reactions between the erupted gases and metal sampling equipment; oxidation of minor species (S_2, H_2S, H_2, CO); incomplete chemical analyses; and analytical errors in H_2O determinations. Reduced gases tend to result when samples are collected in metal sample bottles (e.g., Etna, 1970). Samples taken with evacuated glass tubes have frequently become oxidized (e.g., Erta Ale, 1971). The least modified samples are those taken in glass sample bottles connected to metal lead-in tubes (Surtsey, 1964-67 and Erta Ale, 1974). Most techniques have provided little or no direct information on HCl, HF, H_2S, S_2 and COS.

Procedures have been developed for correcting the reported analyses for several of the imposed modifications noted above. The restored analyses (Table 4) are believed to be representative of the erupted gases. The principal species in all the restored analyses are H_2O, CO_2 and SO_2. Minor species include H_2, CO, H_2S, S_2 and HCl; the latter three are rarely observed directly, but are usually inferred from condensate analyses and thermodynamic calculations. Minor amounts of N_2 and A are also present. Trace species, which repeatedly occur in the restored compositions, but which are rarely reported in the analyses, are COS, SO, S_2O and HS. Trace amounts of CH_4 can be present in high temperature volcanic gases, but high concentrations, as well as the presence of higher hydrocarbons and organohalogens (e.g., CH_3Cl), suggests contamination by pyrolysis of organic materials.

The restored analyses provide a basis for several interesting observations and inferences:

(1) Volcanic gases are erupted in a state closely approaching chemical equilibrium.

(2) After removal of imposed modifications, apparent short-term variations (minutes-hours) virtually disappear, implying that meaningful data can be obtained over relatively short periods of observation.

(3) Long-term variations (months-years) are apparent in some series of collections after the scatter imposed by secondary variations is removed. Evidence of long-term variations consists mainly of decreasing CO_2 content with time--a trend compatible with the lower solubility of CO_2 relative to H_2O and S in silicate melts.

(4) The restored analyses of gases collected from lavas in regions of crustal spreading (e.g., Surtsey and Erta Ale) are characterized by high H_2O contents (70-90 mole %). Those from alkaline lavas (e.g., Etna and Nyiragongo) are characterized by lower

Table 4

Restored Volcanic Gas Analyses

VOLCANO	H_2O	H_2	CO_2	CO	SO_2	S_2	H_2S
ERTA ALE (1971)	70.	1.6	17.8	.8	9.	.5	1.
ERTA ALE (1973)	71.	2.1	19.4	1.2	4.9	.3	.8
ERTA ALE (1974)	77.	1.6	11.7	.5	7.4	.3	.9
SURTSEY (1964)	82.	2.8	9.8	.7	3.2	.1	.7
SURTSEY (1965)	88.	2.3	6.4	.4	2.4	.05	.3
SURTSEY (1967)	91.-92	1-4-1.8	1.-3.	.7	2.8-3.7	.02	.12
MOUNT ETNA (1970)							
1	47.	.5	23.	.5	29.	.3	.2
2	48.	.5	20.	.4	30.	.3	.2
3	49.	.5	34.	.7	15.	.1	.1
NYIRANGONGO (1959)	44.-56.	1.3-2.2	49.-36.	2.2	2.-1.	.6-.4	1.7-2.5

H_2O (45-50 mole %) and relatively high CO_2 (25-50 mole %). These observations are consistent with recent experimental evidence on the effects of volatile compositions on the chemistry of partial melts formed under mantle conditions.

(5) The total sulfur content (SO_2, S_2, H_2S) of volcanic gases appears to be in part a function of the O_2 partial pressure of the outgassing lava. Relatively reduced lavas (e.g., Surtsey and Nyiragongo) produce gases with low total sulfur (1-3 mole %). More oxidized lavas (e.g., Etna) contain up to 30 mole % total sulfur. The direct relationship between O_2 partial pressure and sulfur outgassing of lavas has a simple thermodynamic explanation and can be shown to be pressure dependent. These observations may have considerable bearing on the atmospheric and climatologic effects of volcanic outgassing.

Magma Simulation Facility (P. J. Modreski)

A facility layout is shown in Figure 14 and a photo of the installed system is shown in Figure 15. The installation and load-testing of all pressure lines plus local and remote isolation valves between the Harwood pressure intensifier and the Autoclave pressure vessel has been completed. The pressure transducers, signal conditioners, and digital displays have been calibrated. The system has been pressurized several times to intermediate pressures and once to a maximum of 4.1×10^8 Pa (4.06 kbar) to evaluate intensifier performance, pressurizing rates, and the ability of the system to maintain pressure. Acoustic emission equipment was used to monitor the vessel during pressurization; it revealed the vessel to be extremely quiet. A 15 kW (50,000 Btu/hr) water to air heat exchanger was received and installed for closed loop cooling of the vessel during furnace operation. A 50:50 ethylene glycol-water solution is used as coolant, at a maximum flow rate of 10 l/min at 5.2×10^5 Pa (75 psi).

The 1600°C molybdenum furnace, built by Autoclave Engineers, was received, installed in the vessel, and tested by Autoclave and Sandia personnel. The furnace was successfully tested at pressures from 3.4×10 to 2.8×10^8 Pa and at temperatures from 1000°C to 1600°C. Temperature uniformity at all temperatures and pressures was within

MAGMA SIMULATION FACILITY

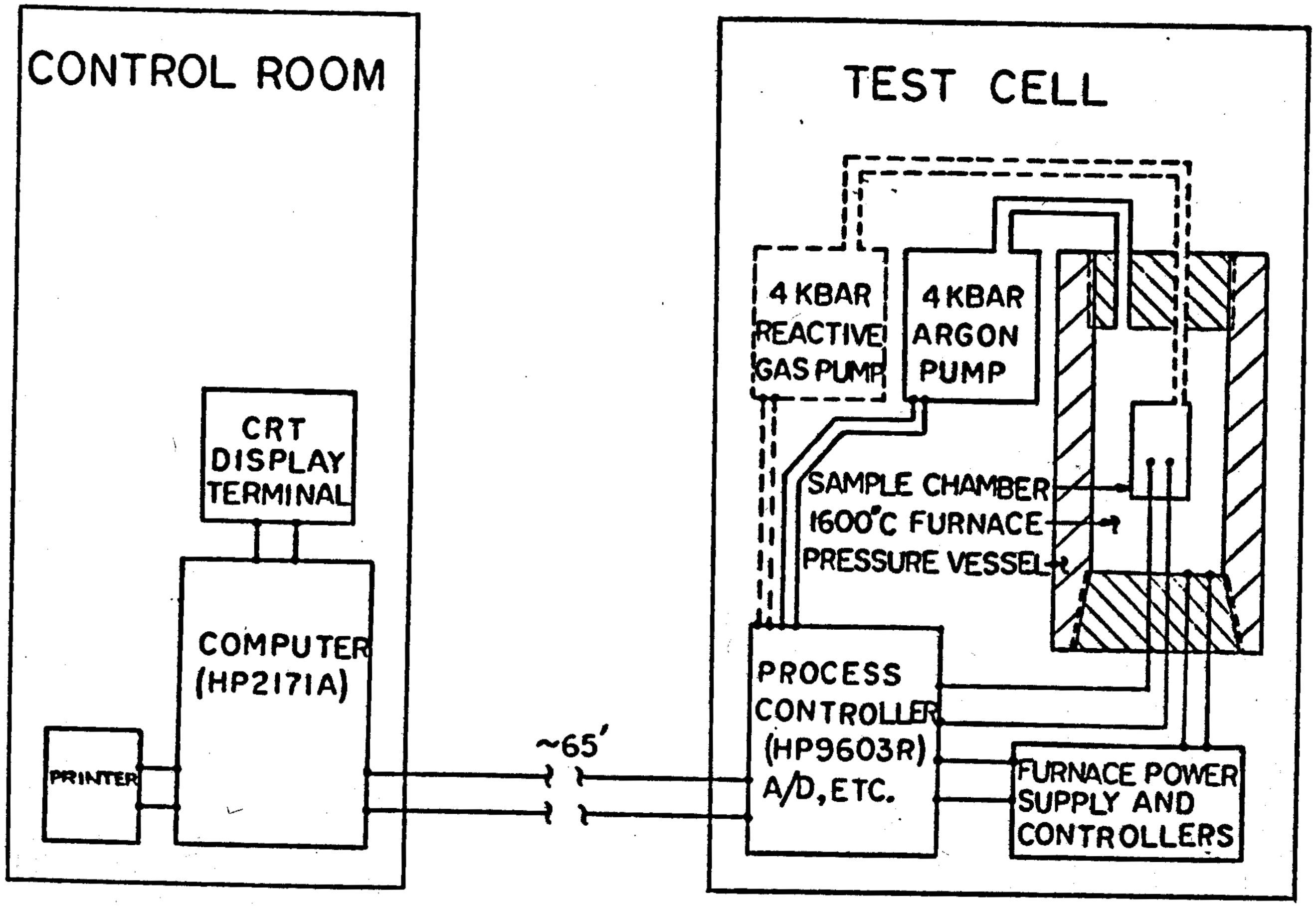


FIGURE 14. Schematic layout of Magma Simulation Facility

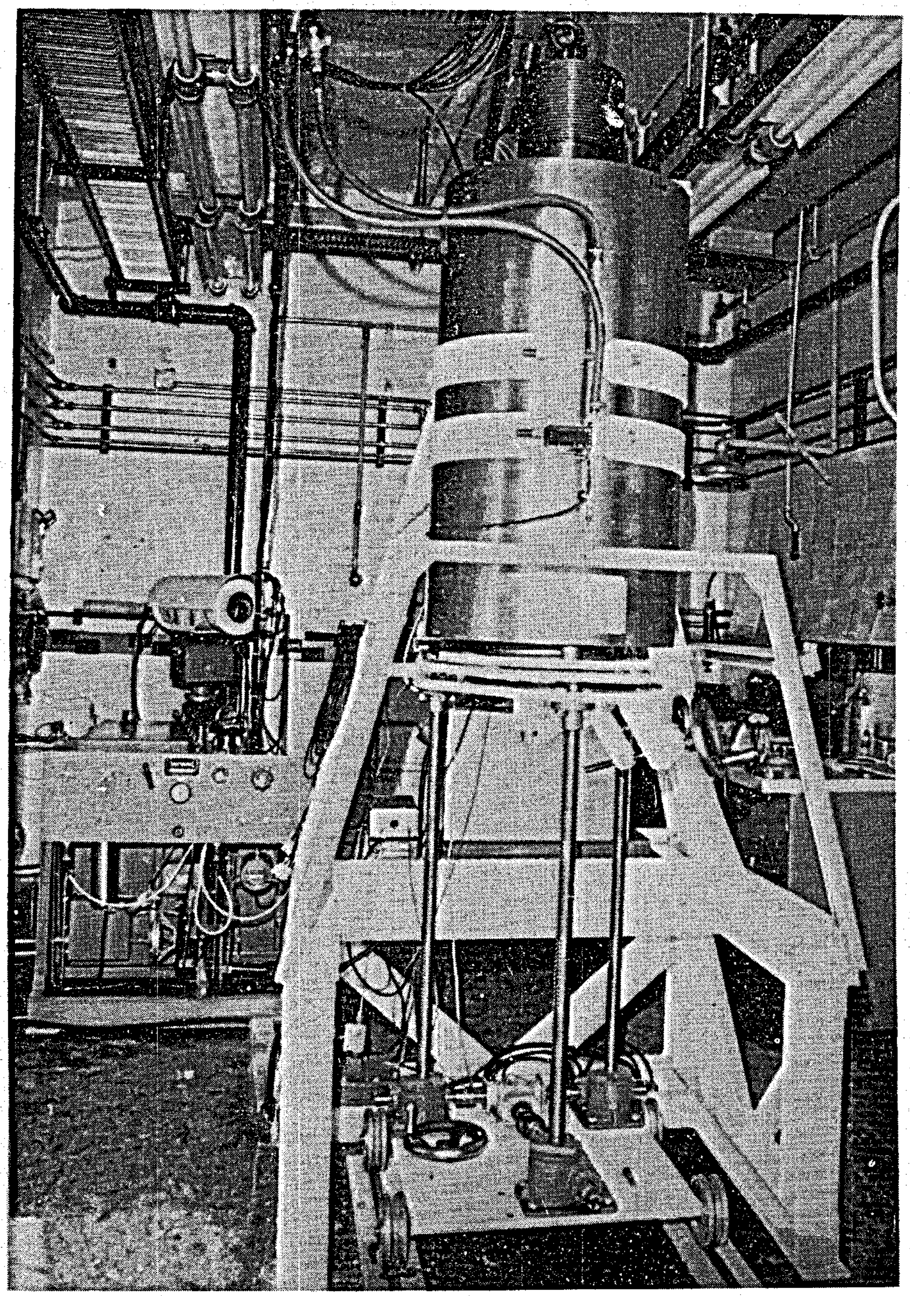


FIGURE 15. MAGMA SIMULATION FACILITY

5°C at all locations within the 10 cm x 10 cm specimen chamber, as measured by an array of seven Pt-6Rh/Pt-30Rh thermocouples. The thermocouple wire, extension wire, and digital readout device used were calibrated by the Sandia Primary Standards Department prior to the test.

Initial experiments in the vessel are being run in sealed noble metal tubes to obtain basic data on phase relations and water solubility in the basalt, andesite, and rhyolite lavas. A technique is being developed to measure viscosity of molten rocks within the 4 kbar apparatus using the falling-sphere method. In addition to the classical method of measuring the position of a dense falling sphere after the sample has been quenched following a known period of time at high temperature, a novel technique employing an electrical transformer circuit to provide an in situ measurement of the time at which a metallic sphere passes through successive coils of wire is being investigated. This method required the use of non-conductive ceramic crucibles as containers for the lava samples; trial apparatus employing this technique is now being evaluated at ambient pressure and high temperatures.

Task 4. Materials Compatibility (D. L. Douglass, T. M. Gerlach)

Materials incompatibility is a potential problem confronting engineering schemes to extract energy from magma bodies. Chemical incompatibility between magmatic volatiles and metals is of particular concern. The chemical characteristics of magmatic gases as inferred from existing volcanic gas collections are summarized in the Magma Characterization section of this report. The critical features of magmatic gases, from the point of view of metal incompatibility, are their O_2 and S_2 fugacities which are conducive to oxidation and sulfidation of most metals at magmatic temperatures.

The stability fields of solid and liquid metal sulfides and oxides have been calculated for metal-oxygen-sulfur systems at magmatic temperatures and one bar pressure for the metals Ni, Co, Mo, Fe, Cr, W, NG, Ta, Zr, V, Ti, Re, Pt, Rh, and PI. A computer code was developed to draw stability diagrams in terms of O_2 and S_2 fugacities for any metal-oxygen-sulfur system from standard state thermodynamic data at any temperature and pressure of interest. An example of the results for the Fe-oxygen-sulfur system at 1150°C and 1 bar is given in Figure 16. The range of O_2 fugacities and S_2 fugacities expressed by

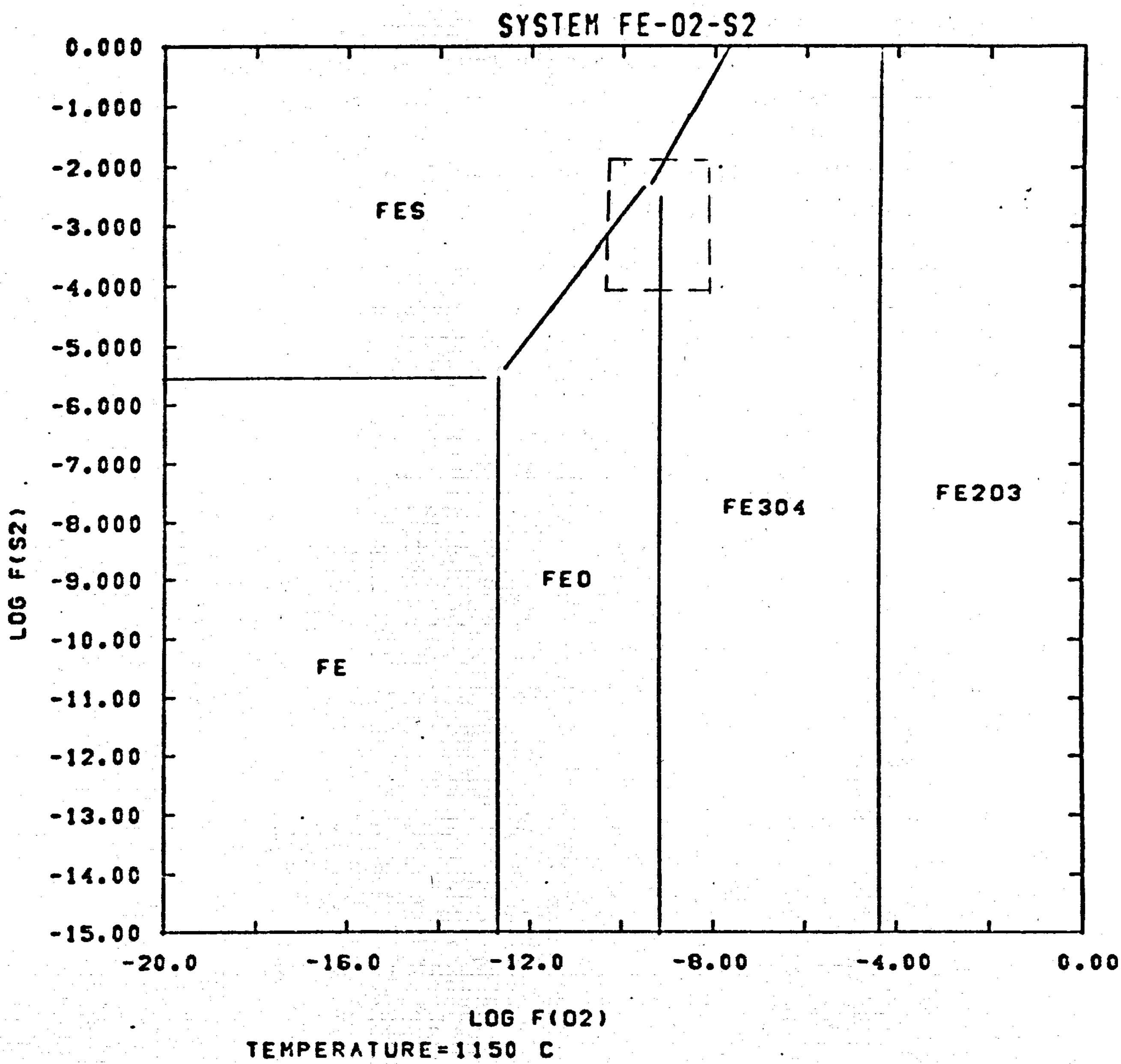


FIGURE 16. IRON-SULFUR-OXYGEN STABILITY DIAGRAM

dashed lines in Figure 16 corresponds to the range of these fugacities in the restored volcanic gas analyses (Table 4, Magma Characterization). The implication of these thermodynamic studies for most of the metal-gas systems are similar to those in Figure 16 and indicated that magmatic environments pose problems of metal oxidation and sulfidation. The only significant exception was Re.

To confirm the above expectations and to learn the details of magmatic gas-metal interactions, C-O-H-S laboratory gases having O_2 and S_2 fugacities characteristic of magmatic gases were synthesized for laboratory investigations at 1150°C and 1 bar.

The initial phase of the experimental program involved the study of fifteen pure metals in molten, tholeitic basalt (Kilauea - 1971) at 1150°C for 24 and 96 hours. A cover gas was used to simulate the gas dissolved in magma bodies, having an oxygen fugacity of 9.8×10^{-10} and a sulfur fugacity of 7.0×10^{-3}. The studies with pure metals were designed to determine the behavior of individual elements for interpretation of the behavior of alloys in later experiments. The second phase of the study concerned a number of alloys which were selected on the basis of results obtained on pure metals and on the presently existing generic families of alloys.

The pure metals were selected for various reasons; all the metals necessarily had high melting points. Iron, nickel, and cobalt are the base metals for stainless steels and superalloys. Some precious metals were studied because of their possible use of thermocouple elements, thermocouple sheaths, or electrical leads. Others were selected on the basis of their position in the periodic table, i.e., groups IVB, VB, and VIIB.

All samples were exposed for the desired time and subsequently prepared for metallography. Characterization of the corrosion behavior and reaction products was made by optical microscopy, scanning electron microscopy, dispersive X-ray energy analysis, and, in a few cases, by electron microprobe analysis. The studies of pure metals in molten lava are complete. A topical report is being prepared and will be issued in the near future. Studies of alloys are in progress and will be continuing.

Pure Metals:

A wide range of reactivity was observed; from virtually no attack to complete disintegration of the samples. In general, the type of attack can be classified into several categories, although in some cases, a given metal showed evidence of more than one type of attack, e.g., oxidation and sulfidation. The classifications are as follows:

A) "no" attack (Pt, Re)
B) slight oxidation (Cr, Mo)*
C) heavy oxidation (W, Ta, Nb)
D) sulfidation (Fe, Ni, Co, Pd, Rh)
E) reaction with lava constituents (V, Ti, Zr)

A macroscopic view of the corroded samples is shown in Figure 17 which portrays the gross effects. However, the low-magnification views mask the extent of the attack in some specific cases. Nickel, for example, appears to be slightly attacked in Figure 17, but a liquid sulfide-metal eutectic had completely penetrated the grain boundaries and extended across the entire sample thickness. The nature of the attack and the details may be seen in higher magnification micrographs of the cross sections in Figures 18-22, which correspond to the above classifications, A-E, respectively.

A detailed analysis of each metal has been made and is discussed in the topical report. The tentative conclusions regarding pure metals are as follows. Iron, nickel, and cobalt cannot be used without alloying due to extensive liquid sulfide formation and high reaction rates. Chromium appears to be the most beneficial addition. Molybdenum has a high degree of resistance to the environment as long as the oxygen fugacity remains low. Rhenium showed outstanding corrosion resistance but is prohibitively expensive. Platinum was the only precious metal tested which can survive the environment.

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* These metals form thin oxides initially but subsequently form sulfides in the substrate beneath the oxide films. The extent of sulfidation is minor compared to those metals classified in the "Sulfidation" category.

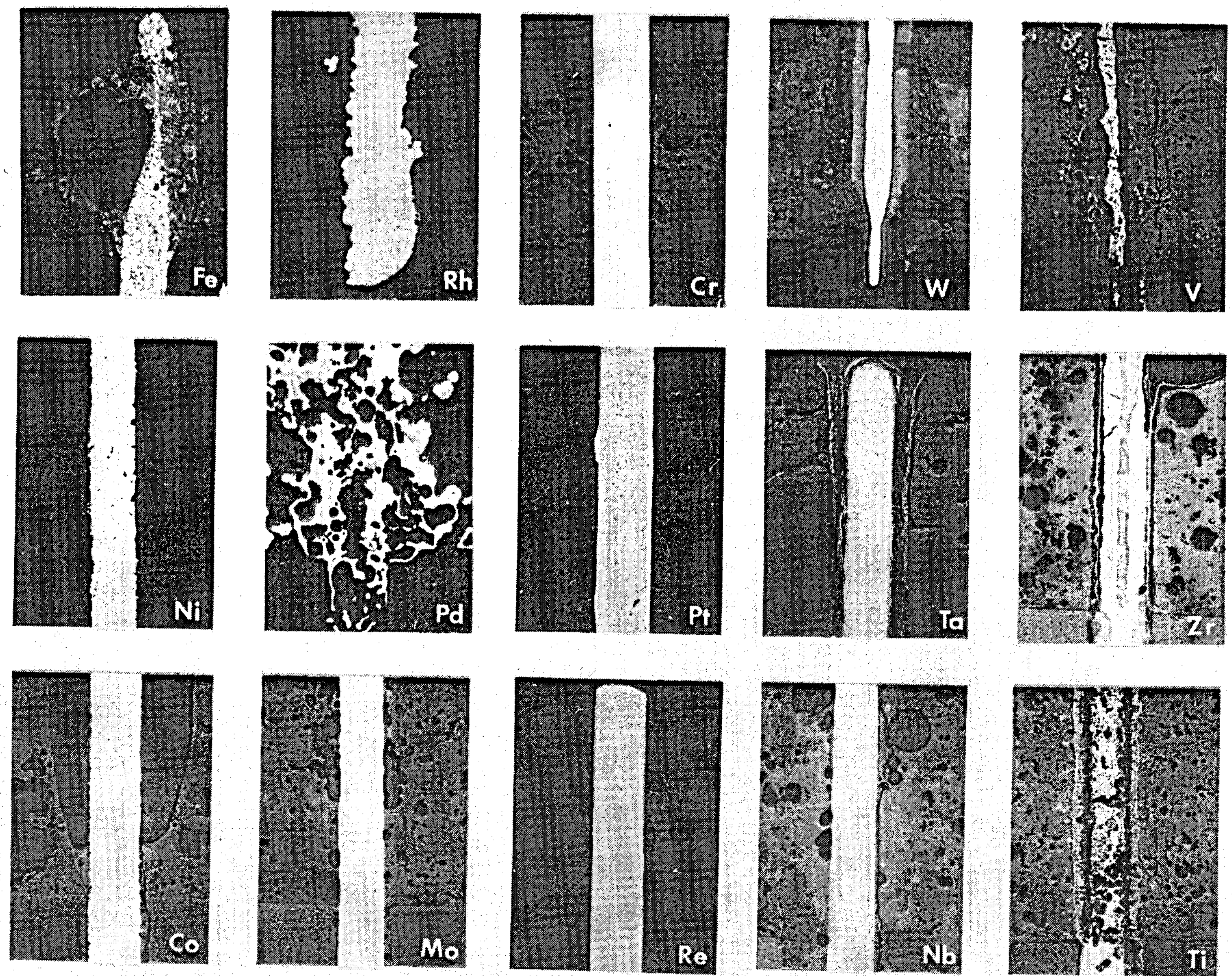

FIG. 17. MACROGRAPHS OF METALS EXPOSED FOR 24 HOURS AT 1150°C.

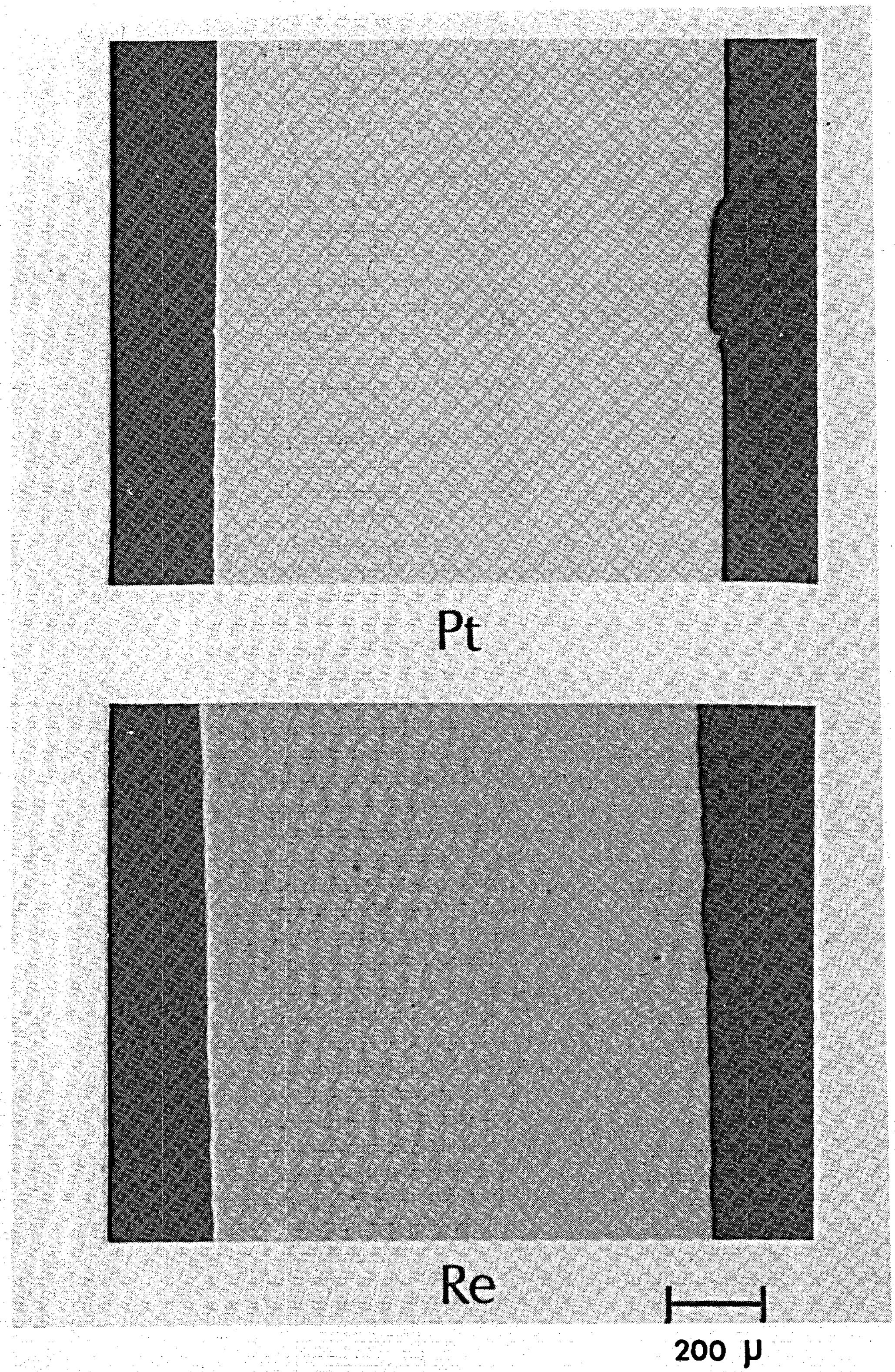

FIG. 18. MICROGRAPHS OF METALS EXHIBITING "NO" ATTACK IN 96 HOURS.

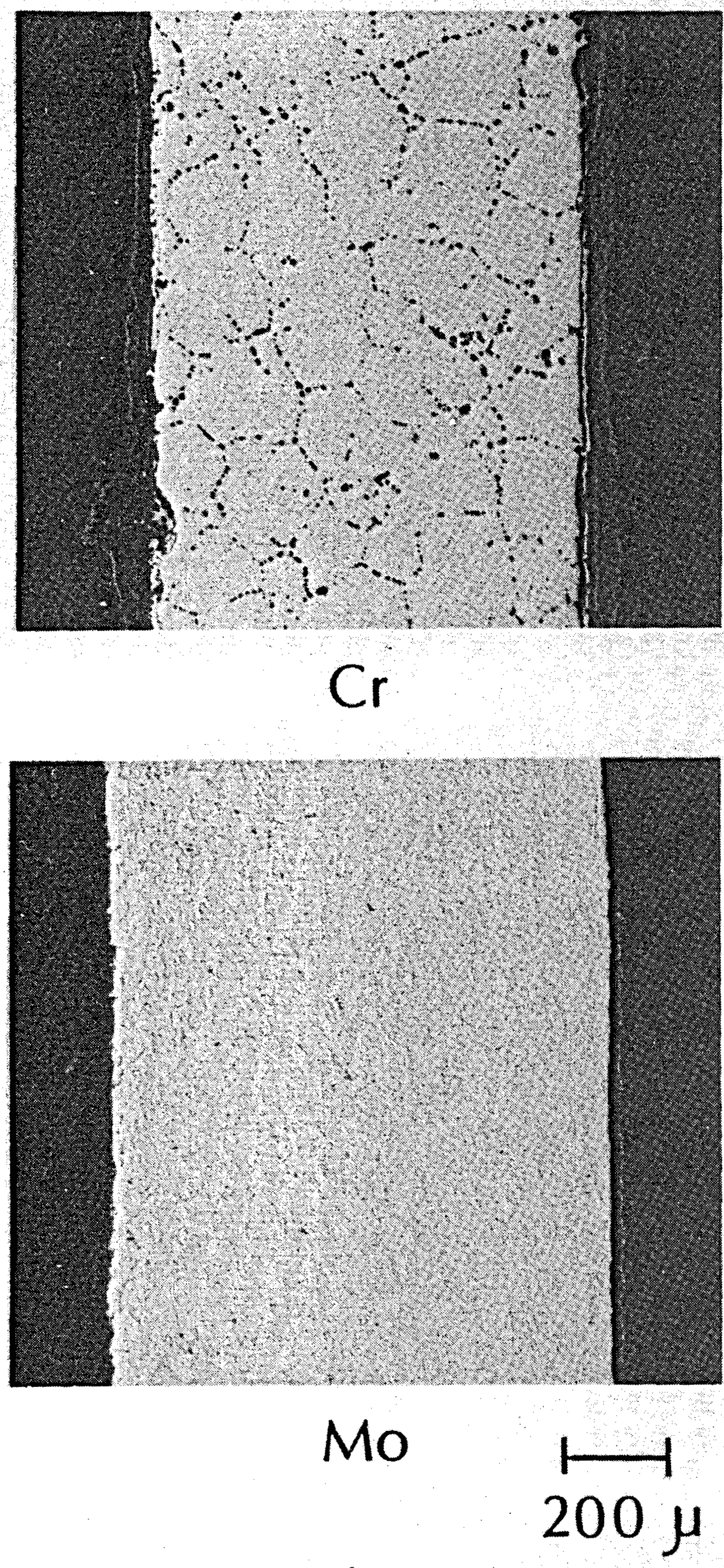

FIG. 19. MICROGRAPHS OF METALS SLIGHTLY OXIDIZED IN 96 HOURS.

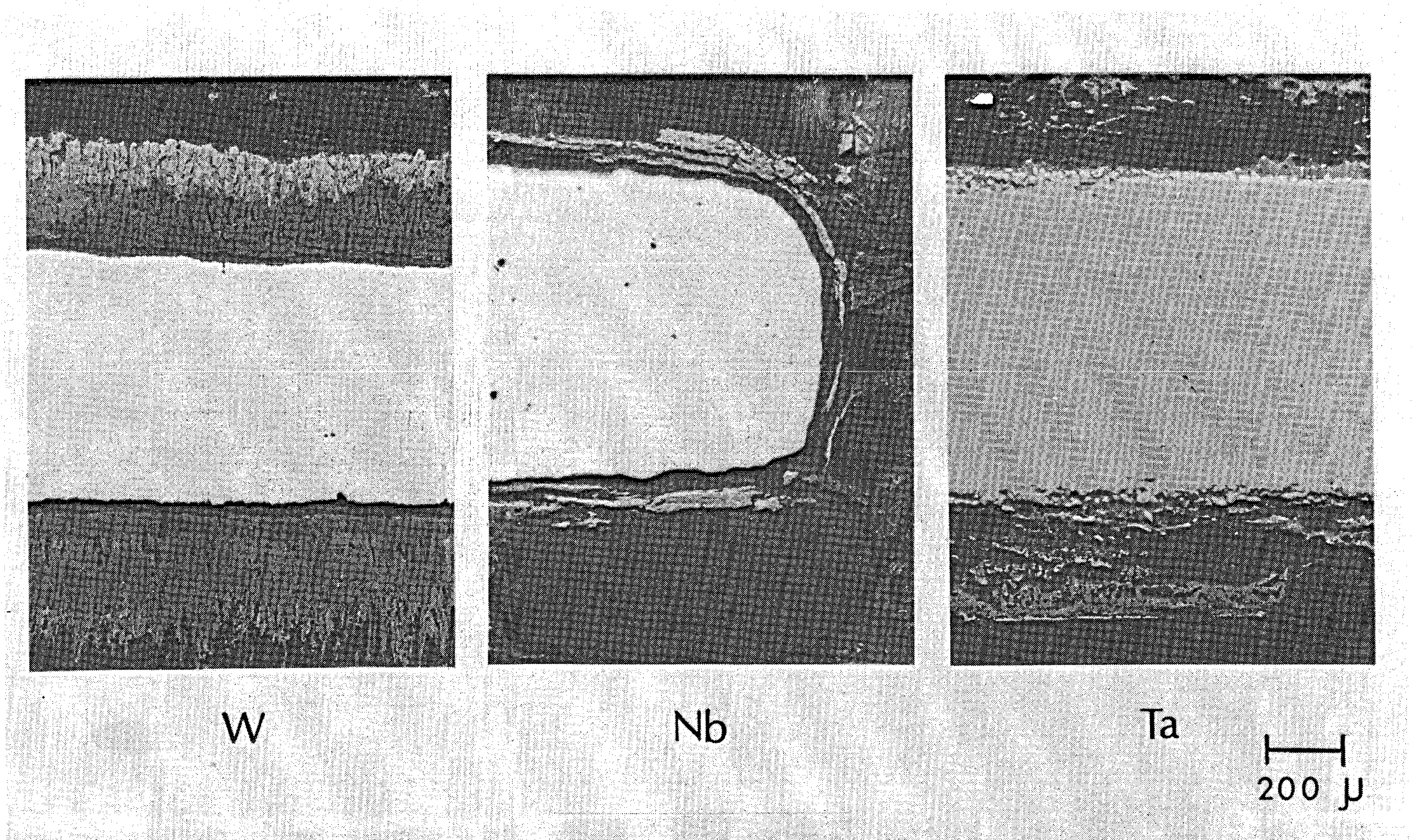

FIG. 20. MICROGRAPHS OF METALS HEAVILY OXIDIZED IN 24 HOURS.

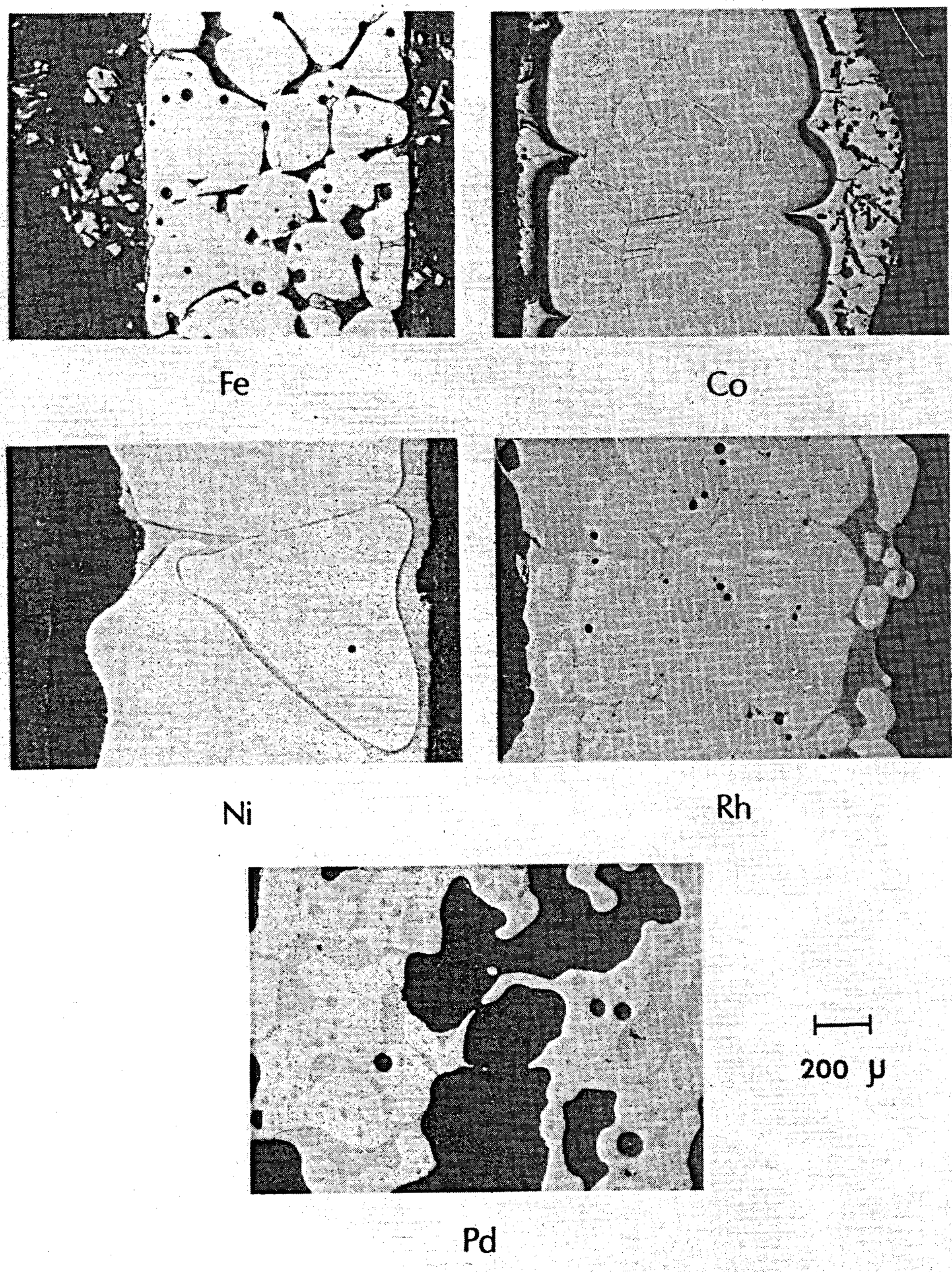

FIG. 21. MICROGRAPHS OF METALS HEAVILY SULFIDIZED IN 24 HOURS.

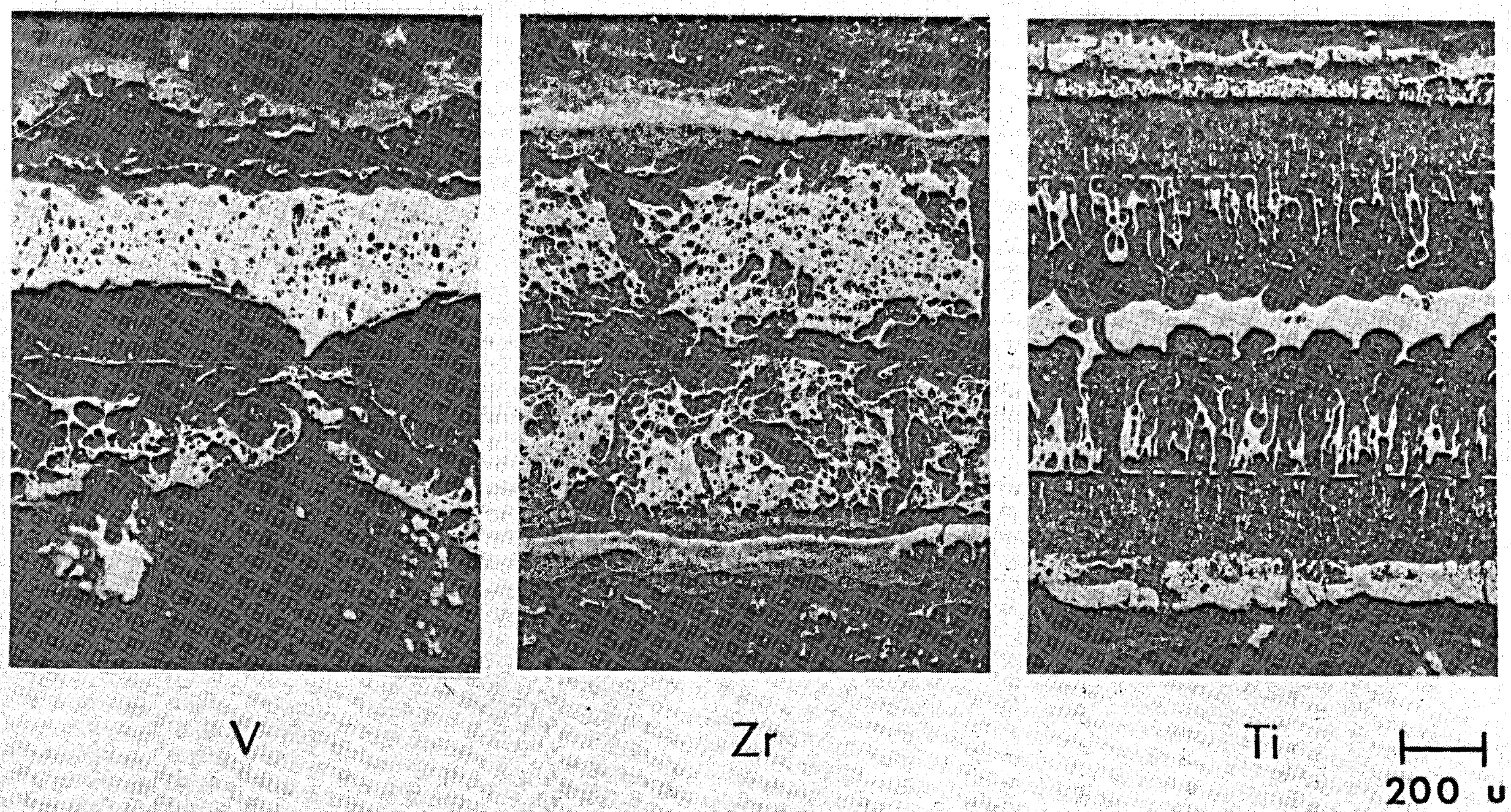

FIG. 22. MICROGRAPHS OF METALS SEVERELY REACTED WITH LAVA CONSTITUENTS IN 96 HOURS.

Alloys:

A number of alloys have been studied under the same conditions utilized for the pure metals. These included some high-purity binary alloys with chromium additions (Fe-19Cr, Fe-24Cr, Ni-23Cr, Ni-30Cr, and Co-27Cr), some austenitic stainless steels (304, 309, 310, and 316), some ferritic stainless steels (410, 430, 26-1, and 446) plus some hybrid alloys (310-6Mo, Ni-30Cr-4Al, Ni-30Cr-$Ti, and Ni-30Cr-9Mo).

The evaluation of the corroded samples is incomplete, but preliminary results indicate that iron, nickel, and cobalt containing appreciable amounts of chromium show relatively little attack and, in general, behave similarly to pure chromium. The austenitic stainless steels (300 series) generally appeared superior to nickel-base alloys, and the addition of chronium to any of the base metals suppressed liquid sulfide formation. The alloys in general formed adherent, thick scales of Cr_2O_3 with some subsurface attack (internal oxidation and internal sulfidation).

A preliminary conclusion is that many commercial alloys would be suitable for various components to be used in magma energy systems.

<u>Task 5. Energy Extraction</u> (J. Dunn)

In the 1979 lava lake study, an experiment was designed to evaluate heat transfer - cooling mechanisms by a heat extraction test in the low viscosity, liquid lens. The experiment was not performed since the low viscosity lens was not encountered. However, a limited heat transfer study was done in cased hole 79-4 (Figure 2). Water was pumped down a center pipe in the hole to about 53 meters depth, heated and returned up the injection pipe-casing annulus to a calorimeter. Results are given in Table 5.

Measured heat fluxes were twice that of calculated fluxes; calculations assumed conduction-only processes. The additional heat flux obtained is believed to be from porous convection induced by residual drilling water and steam outside the casing. The results suggests the possibility of enhancing heat transfer in magma chamber margins or in situ formed exchangers by the injection of a fluid for convection enhancement.

Table 5. Energy Extraction - 1979 Kilauea Iki

	Time (minutes)	
	45	90
Water Volume Flow Rate (GPM)	13.8	13.8
Measured Heat Transfer Rate (kw)	16.9	15.9
Measured Average Heat Flux (kw/m^2)	12	11
Calculated Heat Transfer Flux (kw)		
Hydrothermal Region	16	14
Hot Rock Region	79	64
Total	95	158

SUMMARY

A major effort in evaluating Kilauea Iki lava lake has been completed. Definitive conclusions cannot be drawn until analysis of data and samples are complete. However, results to date suggest:

1. Physical model based on FY 76 geophysical experiments is not correct in that a low viscosity, liquid lens of appreciable thickness does not exist. The FY 76 data should be re-evaluated with the inclusion of the final interpretation of Zablocki's 1979 Mise-a-la-masse data.

2. Mathematical models of the cooling of the lava lake and the state of solidification of the liquid lens were verified by thermal profile and permeability measurements.

3. New jet-augmented drilling concepts successfully penetrated the viscous, multi-phase molten rock region in some locations where conventional drilling failed.

4. Heat transfer studies in the lake suggest injection of fluids to enhance convection may be useful to extract energy from magma chamber margins.

Other activities resulted in the completion and successful testing of a 800 cc simulation facility for evaluating simulated magma properties at temperatures to 1500°C and pressures to 4 kbar.

In materials compatibility studies, thermodynamic stability diagrams were developed for 15 pure metals in basaltic magma systems and compatibility tests completed. Results are being used to define simple alloy systems which may be compatible with magmas and to identify other superalloy materials candidates.

FUTURE PLANS

On April 4-6, progress in the past year was reviewed for the Magma Energy Research Advisory Panel. Recommendations of the panel were to:

1. Continue characterization and materials studies as defined.

2. Complete description of the lava lake by:
   a. re-evaluating FY 76 data, including Zablocki's recent results;

   b. support the USGS in timely petrographic analyses of the 1979 cores;

   c. drill ∿ 6 holes through the frozen lake for core analyses and thermal profiles (this is to be a USGS/HVO effort with Sandia support);

   d. develop a drill design for penetrating the center of the lake to provide a core of the upper and lower crust; consider for drilling in FY 81.

These recommendations, plus other program needs, will be considered to develop a detailed program plan for the Magma Energy Research Project and to present that plan to the Advisory Panel on July 19.

Immediate plans include:

1. Initial petrographic analyses of FY 79 cores in conjunction with Helz of USGS/Reston.

2. Analyses and interpretation of Zablocki's Mise-a-la-masse data.

3. Re-evaluation of the FY 76 geophysics data.

4. Measurement of properties (electrical resistivity, acoustic velocity) of the multi-phase zone cores as a function of temperature.

5. Phase equilibria studies in the magma simulation facility.

6. Continued material compatibility studies in simulated magma.

7. Documentation of the geoscience and technological results from the FY 79 lava lake experiments.

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J. C. Dunn and H. C. Hardee, Measurement of In Situ Permeability in Kilauea Iki Lava Lake, Hawaii.

J. C. Dunn and P. C. Montoya, Water Jet Drilling into Liquid Lava.

H. C. Hardee and D. W. Larson, Thermal Techniques for Locating and Characterizing Buried Magma Bodies.

H. C. Hardee, Heat Extraction from Magma Bodies.

J. F. Hermance, D. W. Forsyth, and J. L. Colp, Summary of Geophysical Sensing Experiments on Kilauea Iki Lava Lake.

T. M. Gerlach, Volcanic Gases and Compatibility with Pure Metals.

D. L. Douglass, P. J. Modreski, and J. T. Healey, The Corrosion of Some Pure Metals in Basaltic Lava at 1150°C.

DISTRIBUTION:

Dr. Keiiti Aki
Massachusetts Institute of Technology
Dept. of Earth Science
54-526
Cambridge, MA 02139

Roy Austin
Project Leader - Geothermal Program
University of California
Lawrence Livermore Laboratory
P. O. Box 808
Livermore, CA 94550

Larry Ball
U.S. Dept. of Energy
Division of Geothermal Energy
Washington, DC 20545

Dr. Joseph Barnea, Special Fellow
United National Institute for Training and Research (UNITAR)
801 United Nations Plaza
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Dr. Milton Blander, Bldg. 205
Argonne National Laboratory
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Department of State
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Corvallis, OR

Prof. Francis X. Bostick
University of Texas
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Austin, TX 78712

Prof. William E. Brigham
Petroleum Engineering Dept.
Stanford University
Stanford, CA 94306

Dr. Robert Brownlee
G-DO, MS 570
Los Alamos Scientific Laboratory
Los Alamos, NM 87545

Dr. Ian S. Carmichael
University of California
Lawrence Berkeley Laboratory
Berkeley, CA 94720

Cliff Carwile, Chief
Advanced Technology Branch
Division of Geothermal Energy
U.S. Dept. of Energy
Washington, DC 20545

J. W. Salisbury
Hydrothermal Support Branch
Division of Geothermal Energy
U.S. Dept. of Energy
Washington, DC 20545

Robert Christiansen
U.S. Geological Survey
345 Middlefield Road
Menlo Park, CA 94025

Dr. Robert W. Decker
Scientist in Charge
U.S. Geological Survey
Hawaiian Volcano Observatory
Hawaii Volcanoes National Park
Hawaii 96718

Bennie G. DiBona, Director
Division of Geothermal Energy
U.S. Dept. of Energy
Washington, DC 20545

Dr. Myron Dorfman
Center for Energy Studies
University of Texas
Austin, TX 78712

Dr. Gordon Eaton, MS 911
U.S. Geological Survey
National Center
Reston, VA 22092

James Eckels
Westinghouse Electric Corp.
1801 K St. NW
Washington, DC 20006

Prof. Melvin Friedman
Center for Tectonophysics
Texas A&M University
College Station, TX 77843

Dr. Frank Frischknecht MS 964
U.S. Geological Survey
Box 25046
Denver Federal Center
Denver, CO 80225

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at Manoa
Hawaiian Institute of
Geophysics
Honolulu, HI 96722

John Griffith
Idaho Geothermal Program Mgr.
U.S. Dept. of Energy
Idaho Operations Office
550 2nd Street
Idaho Falls, ID 93401

Dr. Charles Helsley, Head
Hawaii Institute of Geophysics
University of Hawaii
Honolulu, HI 96822

Dr. Rosalind Tuthill Helz
MS 959
U.S. Geological Survey
Reston, VA 22092

Prof. John F. Hermance
Dept. of Geological Sciences
Brown University
Providence, RI 02912

Claude Herrick, CMB-8
Los Alamos Scientific Laboratory
Los Alamos, NM 87545

Dr. Charles E. Holley
CNC-2, MS 738
Los Alamos Scientific Laboratory
Los Alamos, NM 87545

Stephen Keruse
New Zealand - American
Association (Inc.)
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Auckland, New Zealand

Charles A. Kezar
Technical Consultant
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and Technologies
House Committee on Science
and Technology
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Washington, DC 20515

Dr. Juergen Kienle
University of Alaska
Geophysical Institute
Fairbanks, Alaska 99701

Dr. George A. Kolstad (10)
MS J-309
U.S. Dept. of Energy
Office of Basic Energy Science
Washington, DC 20545

Dr. A. William Laughlin
G-6, MS 978
Los Alamos Scientific Laboratory
Los Alamos, NM 87545

W. L. Marshall
Oak Ridge National Laboratory
P. O. Box X
Oak Ridge, TN 37830

Ian MacGregor
MS J-309
U.S. Dept. of Energy
Office of Basic Energy Science
Washington, DC 20545

Kenneth Mirk
Project Engineer
University of California
Lawrence Berkeley Laboratory
Berkeley, CA 94720

Dr. James G. Moore
U.S. Geological Survey
345 Middlefield Road
Menlo Park, CA 94025

D. K. Nowlin, Director
Special Programs Division
U.S. DOE/ALO
Albuquerque, NM 87185

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3801 B. West 44th Avenue
Anchorage, AK 99503

Dr. Dallas Peck
Chief Geologist
U.S. Geological Survey
MS 911
Reston, VA 22092

Dr. Don W. Peterson
U.S. Geological Survey
MS 26
345 Middlefield Road
Menlo Park, CA 94025

Dr. Robert E. Reicker
G-DOT, MS 26
Los Alamos Scientific Laboratory
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Hawaii Institute of Geophysics
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Morton C. Smith
G-DOT, MS 26
Los Alamos Scientific Laboratory
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MS 906
Reston, VA 22092

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U.S. Dept. of Energy
Division of Geothermal Energy
Washington, DC 20545

Dr. Peter Ward
U.S. Geological Survey
345 Middlefield Road
Menlo Park, CA 94025

Paul A. Witherspoon
Professor
University of California
Lawrence Berkeley Laboratory
Berkeley, CA 94720

Dr. Paul C. Yuen
Hawaii Geothermal Project
University of Hawaii
240 Holmes Hall
2540 Dole St.
Honolulu, HI 96822

Dr. Charles Zablocki MS 964
U.S. Geological Survey
Box 25046
Denver Federal Center
Denver, CO 80225

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