SAND79-2205

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Printed December 1979

MAGMA ENERGY RESEARCH PROJECT -
FY 1979 ANNUAL PROGRESS REPORT

by

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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.

Task 1 -- Resource Location and Definition: Results from previous (FY 76) geophysical measurements in Kilauea Iki lava lake suggested but could not confirm the presence of a low viscosity, molten rock lens. FY 1979 drilling and thermal studies in the lava lake show that the lake is in a late stage of solidification, with no low-viscosity lens, but rather 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. Continued temperature profile measurements in a drillhole through the solid edge of the lake show that 90 days are required for the effect of drilling water to be dissipated. The boiling departure point in the upper solid crust was observed to shift downward more than 2 meters during a period of several days of heavy rainfall. The apparent permeability of the upper crust showed variations from 0.09 Darcies to 0.3 Darcies, apparently due to fracturing.

Petrographic studies of the Kilauea Iki cores indicate the presence of disequilibrium mineral assemblages presumably reflecting high chill rates; that in situ crystallization as well as crystal settling plays a role in the observed differentiation; that the overall chemical changes that have occurred cannot be accounted for by olivine settling alone -- multiphase crystallization is required; and that preliminary mass balance calculations are consistent with the inference of 35 to 40% liquid phase remaining in the melt-crystal suspension lens.

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. The three crystalline rocks were essentially brittle

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throughout the P-T ranges investigated until partial melting occurred. Boreholes filled with a fluid having a density equal to that of water are stable to depths of 5 km for basalt and greater than 10 km for granodiorite at temperatures in the range of 900-1000°C. Open boreholes cooled to 400°C are in both materials to depths of 10 km.

Conventional wire line core bits using water as the coolant successfully penetrated ~10 m of the melt-crystal suspension lens at a temperature greater than 1052°C. The water jet-augmented core and drag bits successfully penetrated glassy flow-back material where conventional drilling had failed.

Task 3 -- Magma Characterization: The Magma Simulation Facility (800 cc, 1500°C, 4 kbar) was completed, brought on-line, and proven reliable and repeatable. Ten phase equilibria and gas melt equilibria experimental runs were completed. Development of a falling sphere viscometer is underway.

Restoration computations of all known high temperature volcanic gas analyses from tholeiitic and alkaline lavas are now completed. Results are being reported.

Task 4 -- Material Compatibility: Stability diagrams were developed for 15 pure metals. The pure metals, plus a number of alloys, were evaluated in low pressure, simulated magma environments. Preliminary results suggest iron, cobalt and molybdenum containing chromium show little degradation. The chromium content of both ferritic and austenitic stainless steels is the most important factor in providing corrosion resistance. Type 310 is by far the most corrosion-resistant alloy of any of the commercial stainless steels.

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/m², approximately twice that expected from conduction alone. The high rates are believed due to convection set up by residual drilling water, which suggests that use of convection-enhancing fluids may be a means of extracting energy from magma chamber margins.

The effect of weak convection in magma adjacent to a heat exchanger has been examined and found to result in energy extraction rates of around 7 kW/m² of heat exchanger surface area. Based on these calculations, a preliminary economic estimate suggests a conventional type magma/electric power plant is feasible.

TABLE OF CONTENTS

	<u>Page</u>
I Introduction	7
II Task I - Resource Location and Definition	8
Lava Lake Drilling Program	8
III Task II - Source Tapping	41
Borehole Stability.....	41
IV Task III - Magma Characterization	56
Thermodynamic Analyses	56
Kilauea Iki Gas Analyses	62
Magma Simulation Facility	63
V Task IV - Materials Compatibility	71
Pure Metals	73
Alloys	74
Preliminary Conclusions	82
VI Task V - Energy Extraction	87
Lava Lake Experiment	87
Effect of Weak Convection of Heat Extraction Rate	88
VII Summary	89
VIII Recent Publications	90
IX References	92

LIST OF FIGURES

<u>Fig. No.</u>		<u>Page</u>
II-1	Vertical Model of Kilauea Iki Lava Lake	8
II-2	Kilauea Iki Lava Lake Borehole Locations	10
II-3	Zoning of Ground Mass Olivine in a Crystal from 58.8 m Depth, KI 79-2	18
II-4	Graph of Calculated Weight Percentages of Liquids with Derived Glass Compositions	24
II-5	Expansivity of Four Core Samples of Solidified Ooze (Glass) from Borehole KI 79-6 (Redrill)	27
II-6	Effect of a Bottom-Sealed Casing on the Temperature Profile of Borehole KI 75-1	28
II-7	Borehole Temperature Profile, KI 79-5 (18N900')	29
II-8	KI 79-5 Maximum Borehole Temperature	30
II-9	KI 79-5 Maximum Borehole Temperature Over Time	31
II-10	Past Records of Temperature Profiles in Kilauea Iki Boreholes	33
II-11	Temperature Profiles of Kilauea Iki Boreholes, Showing Curvature Reversal	34
II-12	Depth to First Melt Indication	36
II-13	Temperature Profile for KI 75-1 on July 22, 1975	38
III-1	Assessment of Borehole Stability for the Mount Hood Andesite	44
III-2	Assessment of Borehole Stability for the Cuberio Basalt	45
III-3	Assessment of Borehole Stability for the Charcoal Grandiorite	46
III-4	Drill Response -- Conventional Bit in Solidified Glassy Flowback	51
III-5	Drill Response -- Conventional and Jet-Augmented Bits in Plastic Zone	52
III-6	Thermocouple Probe Weight	54
III-7	Thermocouple Slip-Ring Assembly	54
III-8	Casing Break Locator	55
IV-1	Representative O ₂ Fugacities at Collection Temperatures for Restored Volcanic Gas Analyses	57
IV-2	Representative S ₂ Fugacities at Collection Temperatures for Restored Volcanic Gas Analyses	59
IV-3	Total Sulfur vs O ₂ Fugacity for the Restored Volcanic Gas Analyses Normalized to the Quartz-Magnetite- Fayalite O ₂ Buffer	60
IV-4	Atomic H/C vs Atomic S/C for the Restored Volcanic Gas Analyses	61
IV-5	Schematic Layout of Magma Simulation Facility	64

<u>Fig. No.</u>		<u>Page</u>
IV-6	Magma Simulation Facility	65
IV-7	10/90 Lead Borate Viscosity Plots	66
IV-8	Viscosity Test Cell Configuration	67
IV-9	Falling Sphere Viscomenter Schematic	68
V-1	Iron-Sulphur-Oxygen Stability Diagram	72
V-2	Ferritic Stainless Steels Corroded 96 Hours	75
V-3	Ferritic Stainless Steels Corroded 400 Hours	76
V-4	High-Purity Fe-Cr Alloys Corroded 96 Hours	77
V-5	High-Purity Fe-24Cr Corroded 400 Hours	79
V-6	Austentic Stainless Steels Corroded 96 Hours	80+81
V-7	High-Purity Ni-Cr Alloys Corroded 24 Hours	83
V-8	High-Purity Ni-30Cr Corroded 400 Hours	84
V-9	High-Purity Co-27Cr	85

LIST OF TABLES

<u>Table No.</u>		<u>Page</u>
II-1	FY 79 Lava Lake Drilling Program Experiments	9
II-2	Sandia/USGS FY79 Kilauea Iki Lava Lake Core Recovery Summary. All Cores HQ, 6.35 cm Diam.	11
II-3	Data Collected on Kilauea Iki Samples Obtained from 1979 Drilling	12
II-4	Kilauea Iki Samples to be Analyzed in FY80.	14
II-5	Glass Compositions from Kilauea Iki Samples	16
II-6	Olivine Compositions from Kilauea Iki Samples	17
II-7	Plagioclase Compositions in Kilauea Iki Samples	20
II-8	Pyroxene Compositions in Kilauea Iki Samples	21
II-9	Initial Magma and Mineral Compositions for Least-Squares Mass Balance Calculations	23
II-10	Weight Percentage Results of Mass Balance Calculations for S7	23
II-11	Volume Percentage Results of Mass Balance Calculations for S7	25
II-12	Variations in Depth to Boiling Departure Point in Borehole KI 76-1.	32
II-13	Permeability of Kilauea Iki Basalt.	35
III-1	Lava Lake Drilling Concepts.	47
IV-1	Restored Volcanic Gas Analyses	58
IV-2	Gas Analyses from KI 79-3.	63
IV-3	Summary of Phase Relation and Volatile Solubility Samples Tested.	69
VI-1	Energy Extraction, 1979 Kilauea Iki.	87
VI-2	Comparison of Magma and Electric Power Costs.	88

MAGMA ENERGY RESEARCH PROJECT - FY 1979 ANNUAL PROGRESS REPORT

I. Introduction

The objective of the Magma Energy Research Project 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 in previous reports (Colp et al, 1976; Colp and Traeger, 1979). This report summarizes the program activities of FY79 according to the individual tasks.

Major emphasis of the program in the last year was on field experimentation with the United States Geological Survey (USGS) 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 period. Efforts and results are summarized in this document. Individual, complete reports provide detail where appropriate.

Activities and results are summarized for each of the tasks. Names of individuals responsible for each of the areas are noted; these individuals should be contacted for further information. Detailed data and analyses included in published topical reports will be referenced rather than duplicated in this report.

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

Lava Lake Drilling Program

Kilauea Iki lava lake provides a unique microcosm of a total geothermal system. It has been and continues to be used in that context by the Magma Energy Research Project. Based on the recommendations of the Magma Workshop (Colp et al, 1975), geophysical measurements were performed at Kilauea Iki in 1976 to evaluate techniques over a known molten rock body (Colp and Traeger, 1979). Although the measurements did define the upper frozen crust regions and the edge of the liquid lens, the nature or thickness of the liquid lens could not be quantified. Analysis of the data by Hermance et al (1979) resulted in the development of a physical model of a vertical section of the lake (Figure II-1).

In mid-1978 a set of experiments was defined for the 1979 Lava Lake Drilling Program, whose objective was to penetrate into the molten lens and obtain data to help interpret the 1976 geophysical measurements. The set of experiments planned is given in Table II-1, together with brief notes on the status of the results. Two topical reports (Neel et al, 1979; Colp, 1979) describe the experiments and preliminary results in more detail. The balance of this section will summarize the present status of the analysis of the results of these experiments. Figure II-2 shows the location of the drill holes in Kilauea Iki where the experiments were performed.

Figure II-1. Vertical Model of Kilauea Iki Lava Lake

Table II-1 FY 79 Lava Lake Drilling Program

<u>Experiment</u>	<u>Scientist</u>	<u>Purpose</u>	<u>Status</u>
Cores & Analysis	USGS/Sandia	Characterize structure and history	391 m original core. 19 m redrilled glass. One core (100 m) through frozen lake (79-5). Initial petrographic analysis in process. (Sandia/USGS)
Temperature Profiles	Hardee	Model geo-thermal system	State of molten body verified. Model for liquid rock-hydro-thermal region developed.
Rainfall Effect on Temperature	Hardee	Define rain-fall effects on level of hydrothermal region	Rain and night-day effects resulted in isothermal region fluctuation of 1-2 m.
Upper Crust Permeability	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°C) formation	Downhole equipment appears to have failed.
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 lens	Encountered regions of liquid veins interspersed in high viscosity, multiphase mixture below 52 m. Two of three new drilling concepts showed success.

Figure II-2. Kilauea Iki Lava Lake Borehole Locations

Core Recovery - Approximately 410 m of HQ core (6.35 cm dia.) was recovered, logged, photographed, and stored at the USGS Hawaiian Volcano Observatory (HVO). Table II-2 shows the hole location, drilling dates, core depth interval, and total length of the cores recovered. The recovered core was split, and detailed visual petrographic observations and logs were made by R. T. Helz and T. Wright, USGS National center. Half of the split cores have been shipped to the Smithsonian Institution for curatorship. Procurement of samples for further study can be arranged through Dr. Helz.

Table II-2
Sandia/USGS FY 79 Kilauea Iki Lava Lake Core Recovery Summary
All Cores HQ, 6.35 cm Diameter

<u>Hole Number</u>	<u>Drilling Dates</u>	<u>Core Interval Depth (m)</u>	<u>Total Length (m)</u>
KI 75-1 Reentry	12/8-11/78	40.2-52.7	12.5
KI 79-1	12/13-21/78	0-61.9	61.9
KI 79-1 Redrill	1/25-27/79	50.6-54.3	3.7
KI 79-2	12/28/78-1/5/79	0-50.6	2.8
KI 79-2 Redrill	1/5/79	46.9-50.0	3.1
KI 79-3	1/8-10/79	0-52.7	52.7
KI 79-3 Redrill	1/11/79	48.8-51.8	3.0
KI 79-4	1/12-16/79	0-52.4	52.4
KI 79-5	1/30-2/9/79	0-100.9	100.9
KI 79-6	2/10-14/79	0-57.9	57.9
KI 79-6 Redrill	2/14/79	48.5-57-3	8.8
			<u>410.3</u>

Core Analysis (W. C. Luth, T. M. Gerlach, E. J. Graeber, and R. P. Warner*): Kilauea Iki Samples - Preliminary chemical, mineralogical, and modal data were obtained on a suite of 11 samples obtained during the 1978-79 Kilauea Iki Lava Lake Drilling Program. These data were sought to determine their value in assessing the amount, distribution, extent, and properties (by inference) of the high temperature silicate liquid remaining in the lava lake. The samples and the extent of the currently available data on them are listed in Table II-3. The samples from KI 79-2 were located immediately (within 1 m) adjacent to the bottom of KI 76-2 hole and are believed to have been affected by the water employed in the 1976 drilling (See Figure II-1 for KI drill hole locations).

*University of New Mexico, Albuquerque, NM.

Table II-3 Data Collected on Kilauea Iki Samples Obtained from 1979 Drilling

Sample	Depth (m) Hole	42.9 79-2	43.7 79-2	43.9 79-2	44.3 79-2	44.9 79-2	50.6 79-1	53.0 79-1	55.2 79-1	57.6 79-1	59.7 79-1	60.4* 79-1	52.1 79-3
Data													
Modal		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N
Chemical													
Olivine (PC)		4**	0	11	10	15	14	6	9	3	0	11	0
Olivine (GM)		4	0	0	0	0	9	7	9	7	8	12	0
Plagioclase		10	16	14	10	11	9	6	9	11	14	9	0
Clinopyroxene													
Ca Rich		7	7	5	10	8	2	3	0	0	0	7	0
Ca Poor		3	0	3	6	2	1	0	0	0	0	0	0
Glass		5	3	0	1	5	0	6	4	5	0	11	26

* Reported Previously

** Number of Individual Analyses

Y Analyses completed

N No Analyses

The data referred to in Table II-3 and presented in Tables II-5, II-6, II-7, and II-8 include both modal (volume percentages of the phases) and chemical information. The chemical data, obtained by means of the CAMECA electron microprobe at Sandia Laboratories, are preliminary information at this time and are insufficient to fully answer the questions outlined above for the following reasons: (1) We do not believe that the hematite (Fe_2O_3) standard used in the electron microprobe analysis is an appropriate quantitative standard for FeO in glass, olivine, and pyroxene. A more adequate standard (fayalitic olivine) has been obtained from R. Gooley, LASL G-6, to be used in future analyses. (2) Chemical variation in the pyroxenes augite, pigeonite, and hypersthene (Table II-8) was found to be quite extensive. It will be necessary to assess in detail both variability within grains and between grains in a sample before the analytical results can be fully used. (3) These data were obtained using the reflected light stage for the electron microprobe, and thus we cannot be certain that all edge-effects have been avoided. (4) Finally, these data must be considered preliminary and tentative in terms of the number of samples studied.

We have recently obtained additional samples, through the courtesy of R. Helz, USGS Reston, which comprise a representative suite for consideration of the reservoir assessment of Kilauea Iki lava lake. Additional analyses indicated in Table II-4 are planned and will take advantage of the transmitted light capability of the microprobe. To ensure maximum compatibility of data obtained in our studies with those developed by the USGS in their long-term and continuing studies of Hawaiian volcanism, our future analyses will involve the suite of basaltic glass standards used by R. Helz in her analytical work within the next two quarters on both old and new samples indicated in Table II-4. Samples from KI 79-5 represent a complete section through the solidified lava lake near its margin.

It is possible to draw certain preliminary conclusions from the data in spite of the limitations discussed above. In summary, it does seem possible to use the microprobe analyses of phases in the samples to model the lava lake in a petrologic context and, ultimately, to utilize these data to complete a reservoir assessment of the amount, composition, and extent of silicate liquid remaining in the lava lake. It also seems possible to place limits on the distribution of crystals and liquid, though a unique solution does not appear likely. If these data are coupled with geophysical data, then it will be possible to tighten the bounds on the distribution of liquid within the lava lake.

Table II-4 Kilauea Iki Samples to be Analyzed in FY 80

Depth (feet)	20.0	40.0	60.0	80.0	100.0	120.0	133.7	140.9	141.6	143.2
(m)	6.1	12.2	18.3	24.4	30.5	36.6	40.8	42.9	43.2	43.6
Hole	79-2	79-2	79-2	79-2	79-2	79-2	79-2	79-2	79-2	79-2
Depth (feet)	144.0	144.8	145.4	146.1	146.8	147.2	148.6	152.0	158.1	160.0
(m)	43.9	44.1	44.2	44.5	44.7	44.9	45.3	46.3	48.2	48.8
Hole	79-2	79-2	79-2	79-2	79-2	79-2	79-2	79-2	79-2	79-1
Depth (feet)	162.0	165.7	166.1	170.2	173.9	177.0	181.2	185.3	189.0	193.0
(m)	49.4	50.5	50.6	51.9	53.0	53.9	55.2	56.5	57.6	58.8
Hole	79-2	79-2	79-1	79-1	79-1	79-1	79-1	79-1	79-1	79-1
Depth (feet)	196.0	198.0	202.0	170.9	27.3	49.7	74.7	100.0	125.5	151.0
(m)	59.7	60.4	61.6	52.1	8.3	15.1	22.8	30.5	38.2	46.0
Hole	79-1	79-1	79-1	79-3	79-5	79-5	79-5	79-5	79-5	79-5
Depth (feet)	159.0	170.0	180.0	190.2	199.7	211.2	Additional deeper samples from DH 79-5 may be studied.			
(m)	48.5	51.8	54.9	58.0	60.8	64.4				
Hole	79-5	79-5	79-5	79-5	79-5	79-5				

DH 79-5 was predicted to encounter pre-1959 basement at approximately 67 m. This interface was actually observed at approximately 94 m.

In addition, it now seems reasonably clear that before beginning further drilling activities, plans should be made for obtaining real-time chemical data on the glasses encountered during drilling. The modal percentage glass and the glass analyses for samples from 53 m to 62 m in KI 79-1 (Table II-5) suggest the possibility that drilling in this hole penetrated a 10 m zone of crystals and liquid before drilling ceased.

The glass analyzed in samples from KI 79-2 in the interval from 42.9 to 44.9 m is granitic in composition, and present in amounts of 3-8 volume percent (Table II-5). The glass analyzed in samples from KI 79-1 at depths greater than 53 m is basaltic in composition (Table II-5) and is present in amounts of 20-40 volume percent. These results are consistent with a hypothesis involving quenching of the domain encountered by KI 79-2 at 42.5 to 44.5 m by drilling water injected during the 1976 drilling, followed by devitrification of the original basaltic glass to form a residual granitic glass, additional plagioclase, and pyroxene. The variability in composition of the granitic glass may be due to gas phase transport of alkalis controlled by local textural features. Considerable uncertainty in interpretation exists because of the sparseness of samples and lack of adequate chemical data for the sample from KI 79-1 at 50.6 m. We were unable to analyze the glass in KI 79-1 at 50.6 m, which is particularly unfortunate in that it is present at the level of 8 volume percent, similar to samples from KI 79-2 at shallower depths.

Phenocrystic olivine was observed in nearly all samples (Table II-6). In the samples from KI 79-2 over the 42.9 to 44.9 m interval, the olivine phenocrysts are less abundant, more iron-rich, and more variable in composition than olivine phenocrysts found in the deeper samples of KI 79-1. Ground mass olivine in amounts of 1 to 3.4 volume percent was observed in all samples examined in both drill holes; however, analyses were not obtained for the lower four samples in KI 79-2. At depths greater than 53 m, the ground mass and phenocrystic olivine are identical in composition within the limits of analytical precision and variability within a sample. Zoning of ground mass olivine was specifically examined in one small (0.5 mm) crystal from the sample at a depth of 58.8 m in KI 79-2. The results, shown in Figure II-3, illustrate continuous zoning from Fe_{85} (core) to Fe_{79} (rim) in terms of molecular percent. Examination of the olivine, reflected in standard deviation of MgO and FeO values, is quite high in samples from depths of less than 50.6 m. Additional data are required to assess the extent to which this variability may be attributed to inter-grain differences and to

Table II-5 Glass Compositions from Kilauea Iki Samples

Depth (m)	Hole	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	MnO	NiO	Cr ₂ O ₃	P ₂ O ₅	Total	Analytic Total	N	Modal % Glass (Vol.)
42.9	79-2	72.40 σ1.01	.58 .22	14.06 .97	1.47 .28	0.21 .07	1.44 .14	4.82 .56	4.62 .44	.02 .02	.02 .03	.01 .02	.35 .22	100.00	98.84 .54	5	8.6
43.6	79-2	73.08 σ4.82	.17 .10	15.50 3.31	.86 .51	.02 .02	1.09 .28	5.11 1.96	4.06 .26	.03 .03	.03 .03	.01 .02	.03 .03	99.99	98.97 .37	3	7.9
44.3	79-2	76.74	.80	12.40	1.11	.02	.59	4.05	4.29	0	0	0	0	100.00	98.76	1	3.5
44.9	79-2	74.41 σ1.49	.87 .19	13.90 .87	1.75 .18	.21 .08	.46 .16	3.62 .30	5.59 .16	.01 .01	.01 .03	.03 .03	.13 .05	99.99	99.20 .66	5	4.8
53.0	79-1	55.80 σ .79	3.62 .05	13.05 .10	10.26 .18	3.75 .06	6.93 .07	3.76 .09	1.69 .05	.15 .01	0 0	.01 .02	.98 .05	100.00	98.17 .47	6	21.8
55.2	79-1	52.48 σ .61	4.77 .27	12.65 .24	11.22 .35	5.07 .41	8.81 .38	3.03 .13	.99 .15	.22 .06	.06 .02	.02 .03	.67 .06	99.99	98.54 .31	4	29.7
57.6	79-1	51.91 σ .24	3.75 .12	13.47 .69	11.27 .50	5.55 .23	9.64 .23	2.88 .03	.79 .03	.17 .02	.01 .02	.02 .03	.54 .03	100.00	98.37 .80	5	37.2
61.6	79-1	51.98 σ .42	3.54 .06	13.47 .18	10.66 .22	6.21 .16	10.23 .13	2.95 .06	.75 .03	.16 .10	.03 .02	.02 .03	ND	100.00	98.90		ND
52.1	79-3	52.45 σ .46	4.27 .17	13.15 .25	11.80 .40	4.45 .28	8.49 .28	3.39 .10	1.08 .07	.12 .07	.04 .03	.02 .03	.73 .05	99.99	99.96	26	ND

Table II-6 Olivine Compositions from Kilauea Iki Samples

Depth (m)	Hole	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	MnO	NiO	Cr ₂ O ₃	P ₂ O ₅	Total	Analytic Total	N	Modal % Olivine
42.9	79-2	38.35	.02	.02	23.27	37.62	.25	.01	0	.29	.16	.01	.01	100.01	101.41	4	5.5
PC		σ .34	.03	.03	2.62	2.10	.02	.02	0	.06	.08	.01	.02		.29		
42.9	79-2	36.35	.02	.01	33.82	28.95	.21	0	0	.43	.16	0	.05	100.02	101.40	4	2.2
GM		σ .24	.02	.02	2.64	1.21	.03	0	0	.03	.04	0	.03		.29		
43.9	79-2	38.15	.02	0	24.75	36.32	.15	0	.01	.34	.22	.01	.02	99.99	102.03	11	5.5
PC		σ .84	.02	0	3.14	2.59	.02	0	.01	.06	.03	.01	.02		.60		
44.3	79-2	38.10	.02	.01	23.73	37.24	.27	.01	0	.33	.25	.03	.02	100.01	101.21	10	16.7
PC		σ .32	.02	.01	1.69	1.57	.02	.01	0	.04	.03	.02	.02		.61		
44.9	79-2	38.29	.02	.01	22.47	38.41	.24	0	0	.32	.19	.05	.01	100.01	101.26	15	8.6
PC		σ .55	.02	.02	2.30	1.86	.03	0	0	.04	.07	.04	.02		.55		
50.6	79-2	38.44	.02	.01	20.93	39.75	.13	0	0	.29	.31	.12	.01	100.01	100.23	14	25.9
PC		σ .75	.02	.01	4.60	3.24	.03	0	0	.08	.07	.06	.03		.60		
50.6	79-2	38.17	.05	.04	23.24	37.58	.25	.01	.01	.34	.18	.01	.03	100.01	99.73	9	2.4
GM		σ .81	.01	.01	2.94	2.46	.02	.01	.01	.07	.05	.02	.05		.74		
53.0	79-1	38.81	0	.04	20.51	39.80	.25	.02	0	.29	.24	.02	.02	100.00	101.03	6	20.0
PC		σ .36	0	.02	1.57	1.39	.01	.02	0	.03	.05	.03	.02		.48		
53.0	79-1	38.30	.05	.01	23.80	37.00	.24	.01	0	.29	.23	.02	.05	100.00	100.55	7	2.3
GM		σ .50	.02	.01	1.67	1.89	.02	.01	0	.05	.03	.03	.05		1.08		
55.2	79-1	38.78	.05	.01	19.17	41.10	.28	.01	0	.26	.30	.03	.03	100.01	101.25	9	38.4
PC		σ .17	.01	.01	.40	.61	.01	.01	0	.01	.03	.02	.02		.72		
55.2	79-1	38.53	.06	0	19.66	40.95	.16	0	0	.33	.30	0	.03	100.02	101.51	9	1.8
GM		σ .40	.02	0	.52	.53	.01	0	0	.03	.02	0	.02		.49		
57.6	79-1	39.66	0	.01	19.12	40.44	.23	0	0	.26	.26	.02	0	100.00	99.24	3	23.6
PC		σ .30	0	.01	.30	.76	.01	0	0	.03	.03	.02	0		.23		
57.6	79-1	40.00	.04	.02	18.61	40.41	.26	0	0	.25	.26	.13	.01	99.99	98.90	7	3.4
GM		σ .21	.02	.02	.67	.75	.01	0	0	.03	.04	.19	.02		.59		
59.7	79-1	39.51	0	.03	18.31	41.33	.29	0	0	.30	.12	.08	.02	99.99	99.77	8	3.1
GM		σ .37	0	.02	.36	.52	.02	0	0	.04	.09	.02	.02		.63		
61.6	79-1	39.18	0	.04	17.98	41.89	.32	.02	0	.28	.26	.05	ND	100.01	100.84	7	ND
GM		σ .65	0	.02	.46	.67	.01	.01	0	.01	.05	.03			1.33		
61.6	79-1	39.28	.02	.04	17.87	41.94	.28	.01	0	.27	.28	.02	ND	100.01	101.26	11	ND
PC		σ .36	.02	.02	.13	.66	.01	.01	0	.09	.06	.02

Figure II-3. Zoning of Ground Mass Olivine in a Crystal from 58.8 m Depth, KI 79-2

intra-grain (i.e., zoning) differences. In general, the ground mass olivine at the shallower depths appears to be significantly more iron-rich than at depth. In addition, the disparity in composition of ground mass and phenocrystic olivine decreases with depth.

Plagioclase is a ubiquitous ground mass phase, characteristically present in amounts exceeding 40 volume percent in the shallower samples of KI 79-2 and in amounts of less than 30 volume percent in the deeper samples of 79-1. There is a general decrease in abundance with increase in depth in the samples from KI 79-1. Variability in composition of plagioclase is significantly greater in the shallower samples. There is no marked change in plagioclase composition with depth in samples from depths greater than 53 m in KI 79-1. Because of the obvious zoning exhibited by plagioclase in transmitted light, additional data are required to assess intra-grain and inter-grain variability. Plagioclase ground mass data are presented in Table II-7.

Augitic and pigeonitic clinopyroxenes and orthopyroxene are present as abundant ground mass phases. Total pyroxene exceeds 27 volume percent in the shallower samples but is typically present in lesser amounts for the deeper samples from KI 79-1. The sub-calcic pyroxene found in one analysis at a depth of 50.6 m (KI 79-1) is an orthopyroxene, while in the shallower samples of KI 79-2 all analyses were of pigeonite. Augitic pyroxene (Table II-8) varies considerably in composition; however, mean values of Ca/Mg and Mg/Fe tend to be higher in the deeper samples and somewhat less variable.

Oxide phases such as magnetite, ilmenite, and chrome spinel were frequently encountered and analyzed but no specific study has been conducted.

Mass Balance Calculations - We have implemented a computer code that solves least-squares mass balance equations for tracing compositions of derivative liquids as mineral phases are crystallized from initial magma compositions. The calculations can be made by selecting data in any desired order from our current set of microprobe analyses for glasses and minerals from KI 79-1, KI 79-2, and KI 79-3. The code is employed in an interactive mode so that magmatic differentiation models can be evaluated rapidly, and the feedback of results from one calculation can be used immediately to guide the next calculation.

The results thus far obtained have several interesting petrologic implications, but conclusions are preliminary in nature because of the limited and potentially inaccurate analytical data currently available. Future microprobe investigations will remove these limitations and allow us to utilize the code for a reservoir assessment of the amount, composition,

Table II-7 Plagioclase Compositions in Kilauea Iki Samples

Depth (m)	Hole	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	MnO	NiO	Cr ₂ O ₃	P ₂ O ₅	Total	Analytic Total	N	Modal %
42.4	79-2	53.16	.10	28.79	.91	.07	12.29	4.30	.25	.01	.05	.02	.05	100.00	99.70	10	43.8
		σ 2.12	.03	1.44	.11	.01	1.79	.97	.10	.01	.04	.02	.06		.46		
43.6	79-2	53.30	.07	28.76	.73	.17	12.24	4.24	.19	.02	.02	.02	.24	100.00	99.29	16	48.8
		σ 1.10	.02	.75	.07	.03	.88	.46	.04	.02	.03	.02	.03		.61		
43.9	79-2	51.66	.09	29.96	.95	.06	13.25	3.48	.17	.10	.07	.01	.02	99.99	99.67	14	44.1
		σ 1.98	.05	1.14	.09	.02	1.41	.78	.06	.03	.02	.02	.02		.70		
44.3	79-2	52.19	.04	30.13	.72	.04	12.85	3.74	.21	0	.02	.01	.04	99.99	98.85	10	37.9
		σ 1.86	.02	1.40	.07	.02	1.51	.78	.16	0	.02	.02	.02		.53		
44.9	79-2	52.94	.12	29.09	.91	.07	12.51	4.02	.25	0	.01	.04	.03	99.99	99.41	11	41.0
		σ 2.90	.02	1.83	.15	.03	2.29	1.22	.15	0	.02	.05	.03		.66		
50.6	79-1	54.13	.13	28.06	.95	.19	11.23	4.66	.36	.02	0	.01	.24	99.98	98.71	9	28.8
		σ 2.03	.09	1.73	.25	.28	1.41	.82	.17	.03	0	.02	.04		.70		
53.0	79-1	50.61	.02	30.41	.75	.11	14.61	3.15	.11	.01	.02	.01	.18	99.99	99.18	6	26.3
		σ 1.37	.03	1.05	.08	.02	1.03	.58	.03	.02	.03	.02	.03		.56		
55.2	79-1	50.09	.16	30.28	.94	.20	15.00	2.91	.10	.05	.02	.01	.23	99.99	98.90	9	13.1
		σ .94	.08	.77	.16	.07	.67	.37	.02	.03	.02	.02	.04		.73		
57.6	79-1	49.92	.10	31.05	.85	.19	14.89	2.68	.07	.01	0	.01	.23	100.00	99.82	11	16.3
		σ .61	.10	.58	.26	.11	.33	.13	.02	.02	0	.02	.04		.49		
59.7	79-1	49.23	.12	31.10	.87	.27	15.48	2.52	.09	.01	0	.02	.29	100.00	99.69	14	13.6
		σ .51	.14	.86	.38	.17	.45	.19	.02	.02	0	.02	.03		.62		
61.6	79-1	49.40	.09	31.17	.89	.23	15.42	2.63	.09	.03	.04	.03	ND	100.00	100.55	9	ND
		σ .49	.08	.32	.16	.08	.20	.13	.02	.02	.07	.03			.72		

intra-grain (i.e., zoning) differences. In general, the ground mass olivine at the shallower depths appears to be significantly more iron-rich than at depth. In addition, the disparity in composition of ground mass and phenocrystic olivine decreases with depth.

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Depth (m)	Hole	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	MnO	NiO	Cr ₂ O ₃	P ₂ O ₅	Total	Analytic Total	N	Modal %
42.4	79-2	53.16	.10	28.79	.91	.07	12.29	4.30	.25	.01	.05	.02	.05	100.00	99.70	10	43.8
		σ 2.12	.03	1.44	.11	.01	1.79	.97	.10	.01	.04	.02	.06		.46		
43.6	79-2	53.30	.07	28.76	.73	.17	12.24	4.24	.19	.02	.02	.02	.24	100.00	99.29	16	48.8
		σ 1.10	.02	.75	.07	.03	.88	.46	.04	.02	.03	.02	.03		.61		
43.9	79-2	51.66	.09	29.96	.95	.06	13.25	3.48	.17	.10	.07	.01	.02	99.99	99.67	14	44.1
		σ 1.98	.05	1.14	.09	.02	1.41	.78	.06	.03	.02	.02	.02		.70		
44.3	79-2	52.19	.04	30.13	.72	.04	12.85	3.74	.21	0	.02	.01	.04	99.99	98.85	10	37.9
		σ 1.86	.02	1.40	.07	.02	1.51	.78	.16	0	.02	.02	.02		.53		
44.9	79-2	52.94	.12	29.09	.91	.07	12.51	4.02	.25	0	.01	.04	.03	99.99	99.41	11	41.0
		σ 2.90	.02	1.83	.15	.03	2.29	1.22	.15	0	.02	.05	.03		.66		
50.6	79-1	54.13	.13	28.06	.95	.19	11.23	4.66	.36	.02	0	.01	.24	99.98	98.71	9	28.8
		σ 2.03	.09	1.73	.25	.28	1.41	.82	.17	.03	0	.02	.04		.70		
53.0	79-1	50.61	.02	30.41	.75	.11	14.61	3.15	.11	.01	.02	.01	.18	99.99	99.18	6	26.3
		σ 1.37	.03	1.05	.08	.02	1.03	.58	.03	.02	.03	.02	.03		.56		
55.2	79-1	50.09	.16	30.28	.94	.20	15.00	2.91	.10	.05	.02	.01	.23	99.99	98.90	9	13.1
		σ .94	.08	.77	.16	.07	.67	.37	.02	.03	.02	.02	.04		.73		
57.6	79-1	49.92	.10	31.05	.85	.19	14.89	2.68	.07	.01	0	.01	.23	100.00	99.82	11	16.3
		σ .61	.10	.58	.26	.11	.33	.13	.02	.02	0	.02	.04		.49		
59.7	79-1	49.23	.12	31.10	.87	.27	15.48	2.52	.09	.01	0	.02	.29	100.00	99.69	14	13.6
		σ .51	.14	.86	.38	.17	.45	.19	.02	.02	0	.02	.03		.62		
61.6	79-1	49.40	.09	31.17	.89	.23	15.42	2.63	.09	.03	.04	.03	ND	100.00	100.55	9	ND
		σ .49	.08	.32	.16	.08	.20	.13	.02	.02	.07	.03			.72		

Table II-8 Pyroxene Compositions in Kilauea Iki Samples

Ca-Poor Pyroxenes

Depth (m)	Hole	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	MnO	NiO	Cr ₂ O ₃	P ₂ O ₅	Total	Analytic Total	N	Modal % Total Pyroxene
42.9	79-2	53.23	.59	.87	17.93	22.58	4.26	.07	.01	.41	.01	.01	.03	100.00	99.62	3	33.0
		σ .48	.15	.21	.46	.47	.97	.02	.02	.04	.01	.02	.04		.70		
43.9	79-2	53.63	.63	.83	17.12	22.50	4.62	0	0	.53	.15	0	0	100.01	99.97	3	34.5
		σ .31	.04	.12	.35	.78	.78	0	0	.02	.03	0	0		.35		
44.3	79-2	53.67	.55	.77	17.91	22.49	3.99	.07	0	.43	.08	.04	.01	100.01	100.29	6	32.2
		σ .59	.10	.13	1.61	1.21	.49	.03	0	.06	.07	.05	.02		.35		
44.9	79-2	53.15	.52	.78	19.32	21.29	4.32	0	.01	.41	.13	.06	.01	100.00	101.12	2	35.6
		σ .47	.18	.29	1.82	1.26	1.10	0	.01	.05	.08	.01	.01		.41		
50.6	79-1	58.82	.82	1.19	15.48	25.88	2.34	.03	.01	.35	0	0	.08	100.00	98.84	1	27.9

Ca-Rich Pyroxenes

42.9	79-2	51.73	1.12	1.98	9.76	16.04	18.55	.31	.02	.22	.02	.11	.14	100.00	99.24	7	33.0
		σ .53	.14	.26	1.65	.49	.80	.01	.01	.06	.03	.20	.10		.56		
43.6	79-2	51.66	1.18	2.14	9.23	16.63	18.15	.17	0	.25	.05	.16	.37	99.99	99.56	7	27.3
		σ .82	.26	.36	2.18	.82	1.22	.02	0	.07	.01	.14	.03		.45		
43.9	79-2	52.66	1.05	2.34	7.92	16.14	18.79	.19	.01	.27	.17	.42	.06	100.02	99.48	5	34.5
		σ .34	.11	.41	1.38	.28	.80	.02	.01	.06	.06	.37	.01		.12		
44.3	79-2	52.08	1.06	2.15	9.35	15.98	18.39	.31	.02	.26	.06	.27	.07	100.00	99.91	10	32.2
		σ .58	.15	.45	2.67	.60	1.74	.05	.06	.08	.04	.32	.05		.48		
44.9	79-2	52.11	1.01	2.57	7.13	16.42	19.69	.15	0	.15	.10	.63	.03	99.99	99.79	8	35.6
		σ .49	.12	.31	1.01	.25	.77	.03	0	.05	.04	.35	.02		.69		
50.6	79-1	51.57	.99	2.57	7.03	16.09	20.17	.31	.02	.19	.05	.60	.41	100.00	99.37	2	27.9
		σ .21	.04	.01	.01	.42	.13	.01	.02	.03	.07	.02	.05		.37		
53.0	79-1	50.77	1.09	3.03	6.73	16.37	20.32	.31	.02	.14	.08	.86	.26	99.99	98.75	3	26.4
		σ .24	.12	.78	.15	.39	.16	.03	.01	.06	.03	.40	.06		.71		
61.6	79-1	51.93	.96	2.81	6.14	16.49	20.35	.31	0	.16	.04	.81	ND	100.00	100.24	7	ND
		σ .54	.04	.17	.10	.36	.25	.05	0	.03	.04	.12			.54		

and extent of liquid remaining in the lava lake. It is already clear, however, that the derivation of glass compositions in KI 79-1 and KI 79-2 from any reasonable initial magma composition requires multiphase crystallization of olivine, pyroxene, plagioclase, and ilmenite; even the basaltic glasses of the deeper samples from KI 79-1 are incompatible with a simple petrologic model, such as predominant crystallization of olivine. Furthermore, models for the derivation of the glass compositions in samples from these drill holes must incorporate changes in the compositions of olivine, plagioclase, and possibly clinopyroxene during crystallization.

Several mass balance calculations have been made to evaluate hypotheses for the derivation of glass compositions in KI 79-1 and KI 79-2 from various assumed initial magma compositions obtained from analyses published by Murata and Richter (1966) for Kilauea Iki lavas. The results summarized in Tables II-10 and II-11 are for a parent magma with the composition of S7 (Murata and Richter, 1966). A good case can be made for derivation of the glass compositions from a parent magma with a composition like that of S7 if mass balance constraints alone are considered. The analysis of S7 is reproduced in Table II-9, along with representative mineral compositions used in the calculations. The mineral compositions were obtained from microprobe analyses summarized in Tables II-6, II-7, and II-8. Note that we have attempted to include the effects of composition changes for olivine and plagioclase during crystallization by using integrated analyses for early (OL-E, PLG-E) and late (OL-L, PLG-L) phases. The glass compositions used in the calculations are given in Table II-5. The results for the unweighted mass balance calculations are tabulated in Table II-10 as weight percentages of the phases that must be subtracted from S7 to derive the glass compositions at various depths in KI 79-1 and KI 79-2. The calculated weight percentages of liquids with the derived glass compositions are also included in Table II-10. The data in Table II-10 are summarized graphically in Figure II-4.

The weight percentage data in Table II-10 have been converted to volume percentage data in Table II-11 in order to compare the results from the mass balance calculations with petrographic modal data. This conversion required density data for the phases involved. Densities for the minerals were estimated from linear combinations of end-member densities weighted according to the end-member molar proportions present in the respective phases. Glass densities were estimated from the glass compositions and the partial molar volume data of

Table II-9 Initial Magma and Mineral Compositions for
Least-Squares Mass Balance Calculations

	<u>SiO₂</u>	<u>TiO₂</u>	<u>Al₂O₃</u>	<u>FeO</u>	<u>MgO</u>	<u>CaO</u>	<u>Na₂O</u>	<u>K₂O</u>	<u>MnO</u>	<u>Total</u>
S7	48.46	2.28	11.62	11.59	13.74	9.73	1.95	0.45	0.18	100.00
OL-E	39.31	0.00	0.04	17.99	42.03	0.32	0.02	0.00	0.28	99.99
OL-L	36.43	0.02	0.01	33.89	29.01	0.21	0.00	0.00	0.43	100.00
PLG-E	49.74	0.07	31.65	0.73	0.24	15.00	2.48	0.07	0.01	99.99
PLG-L	54.87	0.09	28.10	0.74	0.13	10.99	4.81	0.23	0.03	99.99
CPX	52.36	1.00	2.80	6.98	16.42	19.96	0.30	0.01	0.17	100.00
IL	0.11	47.31	0.16	48.49	3.38	0.05	0.00	0.05	0.44	99.99

Table II-10 Weight Percentage Results of Mass Balance Calculations for S7

Glass Sample Depth (m)	Hole	---Wt.% Crystalline Phases Subtracted---						Wt.% Derived Liquid	$\sum r^2$
		<u>OL-E</u>	<u>OL-L</u>	<u>PLG-E</u>	<u>PLG-L</u>	<u>CPX</u>	<u>IL</u>		
42.9	79-2	10.14	16.14	6.37	27.36	27.98	4.08	7.93	0.0003
43.7	79-2	10.01	16.19	7.18	25.86	28.33	4.16	8.27	0.0034
44.3	79-2	10.16	16.24	4.82	30.32	27.92	4.12	6.42	0.0137
44.9	79-2	10.03	16.17	2.96	32.30	28.25	4.06	6.23	0.0008
53.0	79-1	13.69	10.96	12.23	14.48	23.20	2.52	22.92	0.0004
55.2	79-1	14.58	9.55	10.68	12.01	18.51	1.10	33.57	0.0127
57.6	79-1	16.39	6.31	9.44	9.37	16.28	1.24	40.97	0.0129
59.7	79-1	15.65	7.13	6.60	14.38	19.06	1.59	35.59	0.0038
61.5	79-1	16.66	5.31	12.77	0.84	11.67	0.69	52.06	0.0238

Figure II-4. Graph of Calculated Weight Percentages of Liquids with Derived Glass Compositions.

Table II-11 Volume Percentage Results of Mass Balance Calculations for S7

Glass Sample Depth (m)	Hole	Vol. % Crystalline Phases Subtracted						Vol. % Derived Liquid
		OL-E	OL-L	PLG-E	PLG-L	CPX	IL	
42.9	79-2	8.94 (7.9)*	13.35	7.09 (45.0)	30.93	27.28 (33.9)	2.65 (3.8)	9.76 (8.8)
43.7	79-2	8.32 (1.9)	13.46	8.04 (50.7)	29.39	27.77 (28.4)	2.72 (6.4)	10.31 (8.2)
44.3	79-2	8.94 (18.4)	13.42	5.38 (39.6)	34.29	27.23 (33.6)	2.68 (3.9)	8.06 (3.7)
44.9	79-2	8.86 (10.6)	13.36	3.29 (43.6)	36.56	27.55 (37.9)	2.65 (2.8)	7.73 (5.1)
53.0	79-1	12.02 (22.7)	9.02	13.56 (26.8)	16.28	22.52 (26.9)	1.63 (1.4)	24.97 (22.2)
55.2	79-1	12.74 (40.85)	7.83	11.77 (13.31)	13.43	17.86 (15.6)	0.69 (0.1)	35.68 (30.2)
57.6	79-1	14.32 (27.5)	5.16	10.43 (13.9)	10.49	15.74 (17.6)	0.78 (0.2)	43.06 (35.9)
59.7	79-1	13.72 (29.5)	5.86	7.31 (13.9)	16.16	18.46 (20.4)	1.03 (0.1)	37.46 (36.0)
61.6	79-1	14.51 (nd)	4.33	14.06 (nd)	0.93	11.23 (nd)	0.45 (nd)	54.59 (nd)

*Numbers in parentheses give petrographic modes after corrections for holes in thin sections.

nd: no data

Bottinga and Weill (1970). The glass density calculations were made over the temperature range 1200° to 600°C. The calculated volume percentages were not significantly affected by the temperature dependence of the glass density estimates. The results presented in Table II-11 utilize glass density estimates at 600°C. A graphic presentation of the data in Table 9 gives phase fields nearly identical in size and shape to those obtained in Figure II-4 from weight percentage data. Modal abundances are included in Table II-11 for comparison with the calculated volume percentage results.

The observed and calculated modal abundances for pyroxene show reasonably good agreement. Calculated modal abundances for total olivine tend to be much larger than observed abundances at shallower depths but less than observed abundances at greater depths. Conversely, calculated total plagioclase modes are much smaller than observed abundances at shallower depths and somewhat larger than observed abundances at greater depths. The calculated modes for ilmenite are less than the observed modes in the shallower samples and greater than the observed modes for deeper samples. There are several possible petrologic explanations for these differences, but at present we are not certain that the assumed initial magma composition is the only reasonable choice; neither are we convinced that our current analytical data are sufficiently adequate in quantity and quality to justify detailed mass balance calculations. Further microprobe investigations should remove these uncertainties.

Core Expansivity (E. J. Graeber) - Differential dilatometer measurements of the expansivity of four core samples of the solidified ooze recovered during the redrilling of borehole KI 79-6 were made at depths of 48.5 m (159 ft), 51.2 m (168 ft), 57 m (187 ft), and 57.9 m (190 ft). The results are shown in Figure II-5.

The 48.5 m and 57.9 m samples appear similar and have an average coefficient of expansion (from 20°C to 500°C) of 65×10^{-7} in/in/°C, an average glass transition point at 630°C, and an average dilatometric softening point of 670°C. Samples from 168 ft and 187 ft depths have an average coefficient of expansion of 75×10^{-7} in/in/°C.

The sample from the drill bit that was plugged with fluid glass during the 1976 drilling had a coefficient of expansion (from 20°C to 500°C) of 67×10^{-7} in/in/°C, a glass transition point at 615°C, and a dilatometric softening point of 670°C (Colp and Traeger, 1979). The 1976 material has been described as coming from a fluid diabasic segregation vein (Helz, 1979). The KI 79-6 material examined probably originates from a similar vein.

Figure II-5. Expansivity of Four Core Samples of Solidified Ooze (Glass) From Borehole KI 79-6 (Redrill) at Depths Noted.

Thermal Studies

Temperature Profiles - Temperature profile measurements in drill hole KI 75-1, before and after casing of the hole, have shown that the casing has no noticeable effect on temperature measurements in the lower conduction zone of the crust (Figure II-6). In the upper two-phase zone of recently drilled holes, however, the temperature measurements in uncased holes are not representative of the true crust temperature. In this instance, the thermocouple in the hole is significantly affected by the flow of superheated steam originating from water used during the drilling operation. True crust temperatures in the two-phase zone can be obtained by installing a casing or by waiting a couple of months until all the perturbations created by the drilling water are dissipated.

Figure II-6. Effect of a Bottom-Sealed Casing on the Temperature Profile of Borehole KI 75-1.

A series of five temperature profiles of borehole KI 79-5 has been made since this borehole was completed (Figure II-7). This borehole is the first one that has been drilled through the total depth of the lava lake since the lake's formation. Figure II-8 shows an enlargement of the location and values of the maximum temperature observed. The effect of the drilling coolant used on the borehole temperatures can be seen on this figure. The depth at which the temperature maximum is located has consistently decreased, and the value of the maximum temperature has increased, as the effect of the drilling coolant has dissipated. Figure II-9 illustrates that a period of ~ 90 days must pass before borehole temperature stabilizes.

Figure II-7. Borehole Temperature Profile, KI 79-5 (18N900').

Figure II-8. KI 79-5 Maximum Borehole Temperature.

Additional borehole temperature profiles measured during this 1979 operation are shown in Colp (1979).

Rainfall Effect on Temperature (H. C. Hardee) - A sharp discontinuity in the slope of the temperature profiles occurs at the boundary between the two-phase zone and the conduction zone where the temperature departs from the boiling point. The depth to this boiling departure point was measured over a period of several days. Daily variations of as much as 0.5 m were recorded. This point shifted downward over 2 m, during a period of heavy rainfall over several days (Table II-12).

The crust of Kilauea Iki lava lake at present consists of an upper porous two-phase convection zone 41 m thick and a lower conduction zone 12 m thick extending to the melt. The crust has been solidifying at a near constant rate of 6.7×10^{-8} m/s for the past twelve years. The thickness of the lower conduction zone has been relatively constant during this period (Figure II-10). Temperature profiles in the lower conduction zone have a curvature that can be explained in terms of a moving solidification-front conduction solution. Recent temperature profiles in Figure II-11 show the reversal of curvature predicted when solidification has ceased.

For further information, discussion and analyses, see the topical report by Hardee (1979).

Figure II-9. KI 79-5 Maximum Borehole Temperature Over Time.

Table II-12 Variations in Depth to Boiling
Departure Point in Borehole KI 76-1

<u>Depth to Boiling Departure Point</u>	<u>Time</u>	
37.5 m	12/11/78	1:17 p.m.
37.5 m	12/12/78	9:27 p.m.
38.7 m	12/12/78	2:18 p.m.
38.1 m	12/13/78	8:39 a.m.
39.6+m (bottom of hole)	12/19/78	10:51 a.m.
39.6 m	12/19/78	11:30 a.m.

Depth of two-phase circulation zone increased 2 m during week of heavy rainfall (≈ 1 in./day).

Upper Crust Permeability (H. C. Hardee) - The apparent permeability of solidified lava in the upper crust of Kilauea Iki lava lake was measured at several depths during December 1978. The drill hole used (designated KI 79-1) was located near the center of the lake.

Permeability was determined by injecting water into the formation at a constant flow rate while measuring downhole pressure rise as a function of time. A balloon packer was used to isolate the region of water injection. Measurements were taken at 15.2, 34.7, and 39.0 m. Inspection of the KI 79-1 core for regions of fracture indicated the following: (1) solid rock with no fracturing in the vicinity of 15.2 m; (2) a fracture zone running directly through the region of water injection at 34.7 m; and (3) a fracture present approximately 1 m above the region of water injection at 39.0 m.

Preliminary analysis of the water injection data indicates an apparent permeability of approximately 0.12 Darcy at 15.2 m and a somewhat lower value of 0.09 Darcy at 39.0 m. Near the fractured zone at 34.7 m, apparent permeability was initially about 0.3 Darcy. Additional fracturing by the injected water then increased permeability to approximately 0.8 Darcy (Table II-13).

Figure II-10. Past Records of Temperature Profiles in Kilauea Iki Boreholes.

Figure II-11. Temperature Profiles of Kilauea Iki Boreholes Showing Curvature Reversal.

Table II-13 Permeability of Kilauea Iki Basalt

Depth (M)	Permeability (Darcy)	Measurement Location	Comments
15.2	0.12	in-situ	*No apparent fractures
34.7	0.29	in-situ	*Fracture running through region of water injection *Initial measurement
34.7	0.85	in-situ	*Measurement after additional fracturing caused by water injection
39.0	0.092	in-situ	*Fracture present about 1 m above region of water injection
37.8	0.005	Laboratory	*No fractures *Both water and air flow measurement techniques used

We are not aware of other in-situ permeability measurements in solidified lava. However, comparison can be made with laboratory measurements of permeability using core taken from the Kilauea Iki lava lake. Dunn measured the permeability of a 6.35 cm diam. x 11.4 cm core sample taken from drill hole 76-2 at a depth of 37.8 m. Both water and air flow measurement techniques were used. These data show an average permeability of .005 Darcy, much lower than the in-situ values. Thus, it appears that fracturing plays an important role in the in-situ transport of water.

Thermal Model of Kilauea Iki (H. C. Hardee) - Using techniques developed by Hardee (1979), it was evident that a one-dimensional thermal model of the lava lake could be constructed using only known thermal/fluid properties of lava and water and the recently-measured in-situ permeability of the upper solidified crust. It was suggested that such a model would be valuable in understanding the petrology of the lake.

A preliminary thermal model has been constructed. The model predicts the current thickness of the upper crust, the current solidification rate, and the temperature curvature factor. Figure II-12 shows a comparison of predicted and measured depth to melt as a function

Figure II-12. Depth to First Melt Indication.

of time. Figure II-13 shows a comparison for predicted and measured downhole temperatures for a particular time and borehole.

The comparison of predicted and measured data is surprisingly good for a simple, one-dimensional thermal model. A more refined or detailed numerical calculation might improve the model, except that the current accuracy is already better than our knowledge of physical properties, particularly permeability. Although we assumed a reasonable value for permeability, in fact it is probably not known to within a factor of three or four, and probably varies within a factor of two or three depending on the location measured. Further, there is no way to recover permeability information from the past. We therefore question whether a more refined thermal model is justified.

Long Term Creep Study

The right circular cylindrical creep penetrator (4.45 cm dia.) was placed on the surface of the ooze-back in borehole KI 79-1 at a depth of 54.3 m (178 ft 2 in.) in February 1979. Just prior to insertion, the temperature at this location was measured at 974°C. Insertion of the penetrator proceeded as planned, with the NW-size casing extension rod (used to load the penetrator and extend it to the surface) being filled with water as it was lowered. As the penetrator encountered the ooze-back surface and its weight plus that of the water-filled NW casing (approximately 950 k total) was released, it was closely observed for any measurable penetration. There was none.

Four to five minutes after the penetrator/extension rod assembly was installed, a violent expulsion of water contained in the casing occurred. The casing was refilled with water and a similar expulsion occurred after about the same length of time. It was decided to leave the downhole assembly empty. This reduced the weight on the penetrator contact surface to about 680 k.

Dr. M. Ryan (Hawaii Institute of Geophysics) installed and connected the experimental measuring and recording apparatus (a modified tide gage/recorder) he had furnished. Continued examination of the data record for a period of 94 days indicated no measurable movement of the projecting extension rod.

The observed results of this experiment as planned and performed indicate no creep of the penetrator into the hot ooze at the bottom of the borehole. However, measurements of the depth and temperature of the bottom of the NW casing (extension rod) measured inside it in July 1979 indicate a temperature of 938°C and a depth of 51.7 m.

Figure II-13. Temperature Profile for KI 75-1 on July 25, 1975.

Since there is a discrepancy in depths measured before and after the experiment, interpretation of results is not meaningful.

Molten Rock Resistivity (T. L. Dobecki)

The melt resistivity experiment was attempted on January 11, 1979, in borehole KI 79-3, located near previously-drilled KI 75-1. Melt was encountered in KI 79-3 at a depth of 51.8 m. Subsequent soundings showed a melt flowback of some 18 ft. This plug was redrilled to a depth of 50.9 m, at which depth no flowback occurred. At this point, the penetrator-resistivity probe was lowered to the bottom of the hole. The borehole was producing steam, but this did not complicate the assembly and lowering of the probe. The lowering operation required approximately 1.5 hours.

Upon reaching hole bottom, temperature measurements were attempted; however, both thermocouples read open. These may have been severed in the process of eliminating a short between two electrodes the day before. All resistivity leads and electronics were connected and turned on. Full rig push was begun at 1550 hours. Input voltage of 22.5 volts was sufficient to set up a current of $\pm$ 680-730 mamp, implying low contact resistance even though the probe had not passed through rock. It is felt that the probe was not centralized, and the observed conduction path was through the sidewall against which the measuring section of the probe was pushed. In any case, a conducting path with finite resistance existed; the electrodes were not shorted, nor were they open as would be expected.

The full rig push was maintained for approximately 15 minutes. In this time, the probe had not advanced. It was decided that successful penetration could not be achieved under the given set of circumstances. Options were limited: (1) retrieve the probe and wiring intact, and try again in the next boring (drilled to a few inches above melt); (2) abandon the resistivity probe but attempt penetration with the 1-3/4" penetrator in the next hole; or (3) abandon all resistivity and penetration experiments and proceed to advanced drilling experiments. After discussion, the last course was chosen. The resistivity probe was recovered, at the expense of the 90 m of lead wires which had to be cut as pipe sections were removed. Upon probe recovery, we observed the following: (1) A small, hairline crack had formed in the transite block. However, the block was whole and functional. (2) The transite resistance had dropped from infinite to approximately 200 K ohms. (3) The electrodes were shorted -- this due to cut lead wires lying in a water-filled pipe.

In all, the probe had survived both the temperature and the applied static load.

The observed lowered resistance of the transite is felt to have been caused by absorption of water in the steam section of the borehole. It was also felt that any absorbed steam on the trip in would be driven off by the elevated temperatures at the bottom of the hole.

It was concluded that due to substantial strength in chilled ooze, insignificant penetration could be obtained using full rig push. Although penetration was not realized, apparent resistivity measures of 2.3 to 2.6 ohm-m were obtained, perhaps implying contact of electrodes with the sidewall. It is interesting to note that 2.3 ohm-m is the value of melt resistivity used by earlier experimenters (Smith et al, 1977). The probe was recovered intact and useable. Further analysis of full current/potential waveforms from tape recorded data, as well as complete dissection and evaluation of the probe, may provide insight as to what was being measured at hole bottom. The failure of this experiment, then, was in its inability to gain penetration and, of less importance, to measure temperature. The resistivity system proved functional both downhole (probe) and uphole (instrumentation).

Mise-a-la-masse Electrical Survey (C. V. Zablocki, USGS)

The stainless steel casing installed in borehole KI 75-1 as part of a previous experiment was used as the lava lake electrode. A low-frequency current transmitter (5 to 20 Hz) was used to energize the casing electrode and some distance grounded electrode placed outside the lava lake.

The low frequency current transmitted into the casing electrode in borehole KI 75-1 causes the melt lens in the lake to appear as an electrode. The current leaving this melt "electrode" encounters the bounding high resistivity zone and results in a large voltage gradient at the lake surface. The potential distribution was mapped on the surface with a band-pass high impedance volt meter. Because of the present limitation of analytical interpretive techniques to simple and restrictive models, the USGS made physical tank model studies to aid in the interpretations.

The experimental measurements were made successfully as planned. The initial examination of the data acquired showed it to be coherent. Computer modeling studies to analyze the experimental data are underway. A final report on this experiment will be prepared by C. J. Zablocki, USGS.

III. Task 2 -- Source Tapping (J. L. Colp)

The development of technology to enter deeply buried (< 10 km) magma chambers has not been considered as part of the Magma Energy Research Project. Such a development is not compatible with the intent or the budget of the Project. However, the magnitude of such a technological development was considered and discussed in the Magma/Hydrothermal Drilling and Instrumentation Workshop (Varnado and Colp, 1978), as part of a proposed Continental Scientific Drilling Program (National Academy of Science, 1979).

The Magma Energy Research Project has addressed the physical characteristics of a hole drilled through the roof rocks overlying a magma source. The main concerns are whether those rocks fail in a brittle fashion under in-situ temperature and pressure so that they can be drilled by conventional methods, and if the borehole will stay open after drilling to allow the insertion of energy extraction equipment. A continuing laboratory research contract with the Center of Tectonophysics, Texas A&M University, to investigate these concerns has been underway since 1974. Friedman et al (1979) presented a summary of past work on this contract. Work during this reporting period is summarized below.

Borehole Stability (M. Friedman)

Energy extraction from magma requires drillable rocks (brittle behavior) and stable boreholes at relatively shallow depths (< 10 km) at temperatures of the order of 1000°C . Complete assessment of this problem requires a knowledge of (a) instantaneous failure strengths, and strains at failure and associated deformation mechanisms of representative wet and dry rocks at temperatures to partial melting ($> 1050^{\circ}\text{C}$), low to modest confining pressures, and strain rate of $10^{-4}/\text{sec}$; (b) time-dependent rock strength at the same T and P; and (c) temperature profiles and borehole stresses (both purely mechanical and thermo-elastic) for a cooled borehole in hot rock intersected by a fracture transmitting hot fluids to the wellbore.

Work to date has dealt primarily with (a) above. Room dry specimens of Mount Hood Andesite, Charcoal Granodiorite, Cuerbio Basalt, and the Newberry Rhyolite Obsidian have been deformed at temperatures to partial melting and at confining pressures of 0, 50, and 100 MPa. An investigation of time-dependent flow of the obsidian was completed because it had been proposed that boreholes might be "cased" with a natural glass (obsidian) lining to enhance stability. The initial concentration of

effort on the instantaneous failure of room dry rock was justified because corresponding strengths are maximum ones, and "dry-out" zones may in fact exist above buried magma chambers. Moreover, drilling deals with the instantaneous failure of rocks.

Specifically, during the 1978-1979 contract year Texas A&M University published the paper Friedman et al (1979), gave oral presentations of this work at the SANDIA/DOE Workshop on Advanced Geothermal Drilling and Completion Systems, New Orleans, January 9-11, 1979, at the 20th U. S. Symposium on Rock Mechanics, Austin, June 4-6, and at the Hawaii Symposium on Intraplate and Submarine Volcanism, Hilo, August. Most recently it has essentially completed the room-dry tests on the andesite, basalt, and granodiorite at 100 MPa.

Work to date (Friedman et al, 1979) leads to the following conclusions:

1. The three crystalline rocks are essentially brittle throughout the T and P range explored until partial melting occurs. Shortenings at failure are less than three percent, and fracture is by far the dominant mechanism of deformation. This means that the rocks will remain drillable, even by conventional methods, up to partial melting.

2. The failure strength of the crystalline rocks decrease gradually with increasing temperature to about 900°C, and then more rapidly as partial melting is approached at >1000°C. The strengthening effect of confining pressure largely vanishes above 900°C. The obsidian is even stronger than the crystalline rocks at temperatures below 600°C, above which, however, the glass softens and its strength vanishes at 800°C.

3. Borehole stability is assessed by plotting the compressive strength (maximum differential stress at failure) against mean stress $[(\sigma_1 + \sigma_2 + \sigma_3)/3]$ and by comparing these data with the comparable stresses likely to occur at the borehole wall for a given depth and set of assumptions. This criterion for stability is based on the assumptions that (1) the borehole will fail in shear when the differential stress at the borehole wall reaches the ultimate compressive strength, and (2) that a reasonably linear relationship between ultimate compressive strength and mean stress holds. Data for the three confining pressures suggest the latter is valid (see data points for temperatures $\geq 575^\circ\text{C}$, Figures III-1, III-2, and III-3). Examination of Figures III-1, III-2, and III-3 show that:

1. Open holes in all three rock types at 900 to 1000°C are apt to be unstable at depths as shallow as about 2 km for the andesite and basalt and 3 km for the granodiorite (compare lines linking data points with borehole stresses marked by solid line and associated depth scale).

2. Filled holes, on the other hand, will be stable to greater depths, 5 and > 10 km for the basalt and granodiorite, respectively, and probably also for the andesite if the data point at 3 km depth can be neglected.

3. Since strength decreases with increasing temperature, both filled and open boreholes can be stabilized by cooling. It would appear that if borehole temperatures are kept < 400°C, even open holes in the basalt and granodiorite would be stable to 10 km and those in the andesite to about 5 km.

Our predictions of borehole stability are optimistic because we have not yet accounted for time-effects, water weakening, or the frictional sliding strengths of fractures that might intersect the borehole. Assessment of these effects is the next objective of our research. However, predictions must remain qualitative until sophisticated numerical methods can be applied to the problem.

Drilling Activities

Drilling activities conducted in Kilauea Iki were primarily in support of the geoscience experiments described above. They were not designed for technological development of magma access methods. Nevertheless, the lava lake provides a model magma/geothermal system with liquid rock at temperatures above 1050°C under low geostatic (150-200 psi) pressures, and experience gained in the lava lake can provide a basis for any future deep drilling development undertaken.

A total of six new (KI 79-1 through 79-6) holes were drilled into the lava lake, and two old holes (KI 75-1 and KI 76-2) were re-entered and extended in depth (Figure II-2). One hole (KI 79-5) was drilled in the frozen margin of the lake and cored to the pre-1959 crater surface. As noted earlier, a total of 410 meters of HQ core (6.35 cm dia.) were recovered for scientific study.

Four novel drilling concepts were developed for penetrating into the expected low viscosity molten lens of the lava lake. Three of these concepts were tested during the 1979 program. Table II-1 summarizes these concepts and the results. The drill rig used was instrumented to provide real time records of torque, bit load, penetration, and rotation speed when using the novel systems as well as when using the conventional

Figure III-1. Assessment of borehole stability for the Mount Hood Andesite. Differential stress versus mean pressure at wall of an open hole (solid line and depth scale) and a "water" - filled hole (dashed line and depth scale) in impermeable rock. Superposed are ultimate compressive strength versus mean stress data. Each data point is the average of two or more tests at a given confining pressure and temperature.

Figure III-2. Assessment of Borehole Stability for the Cuervo Basalt

Figure III-3. Assessment of Borehole Stability for the Charcoal Grandiorite

Table III-1 Lava Lake Drilling Concepts

<u>Techniques</u>	<u>Designer(s)</u>	<u>Concept</u>	<u>Results in FY 79</u>
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 multi-phase regions in lava lake. No core obtained; generated fine chips.
Jet-augmented Drag Bit	Dunn, Ortega	Water jet from center of drag bit penetrates the liquid, freezing a rigid porous or fractured medium ahead of the cutting edges.	Successfully penetrated 5-6 m through alternating liquid veins and multi-phase regions in lava lake. Cutting removal is a problem.
Penetrometer	Colp	Push a pointed cylinder through hot (plastic?) rock into liquid.	Unsuccessful in lava lake; believe rock temperature too low to allow creep entry.

drilling equipment. The drilling concepts and results will be described briefly in the following pages. For additional details and analysis of results, see the topical report by Neel et al (1979).

Insulated Drill String Development (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 insulated drill string (IDS) was conceived as a result of the drilling experience in 1976, when 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 reached the temperature of the

surrounding liquid, the drill rod and bit were free to rotate and rise. Thus a drill string whose bit and outer drill rod surface could survive and perform while at molten rock temperature ($\sim 1070^{\circ}\text{C}$), but with an inner torque tube that could be insulated and cooled to a temperature of a few hundred degrees C, 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.

The basic constituents of the concept are (1) a special drag bit that can operate at molten rock temperatures ($\sim 1100^{\circ}\text{C}$), (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 wellbore. 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.

Water Jet-Augmented Drilling Systems (J. C. Dunn) - 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.

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} liters per 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 port. 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°C (2000°F) rock to about 204°C (400°F), if the drill advance rate was held at around 1.25 cm/min.

The water jet-augmented drilling systems were designed to operate in boreholes 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.

Linear Penetrator - The linear penetrator experiment was an attempt to thrust an appropriately shaped probe thorough 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.

Drilling Activity Results (R. R. Neel) - Kilauea Iki drilling encountered four rock regimes: (1) rigid, competent crust; (2) liquid, 1 to 4 cm thick 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 formation temperatures of > 1052°C in the initial drilling of KI 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 the bit re-entered 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, multiphase and resolidified glassy zones. However, continuous coolant flow was required. When the bit was retracted and water shut off for addition of drill rod, 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 overlaid by melt overlaid by a rigid material, encountered in 1976 and for which the IDS system was designed, did not exist at the time of this drilling. 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 KI 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 III-4 shows records of drill torque made while a conventional core bit drilled in solidified glassy borehole flowback. Figure III-5 shows records of drill torque made while conventional and water jet-augmented bits drilled in plastic rock.

Future Experiment Equipment (R. P. Striker) - Following the completion of the drilling activities in Kilauea Iki lava lake in mid-February, a number of studies of equipment that would be useful in future experiments were initiated. These studies and their results are described below.

Core catchers - A number of commercial manufacturers of coring equipment were visited to obtain information on available core catchers to recover fragmented cores. This requirement exists because of the experience in the operation of the jet-augmented core bit when no solid core was recovered. It was found that designs of core catchers to alleviate this problem were available.

Temperature measuring equipment - Two 400-ft lengths of thermocouple wire with a 310 stainless steel sheath (instead of the previously-used Inconel) were obtained. Use of one of these to measure Kilauea Iki borehole temperature profiles in July demonstrated that the SS310 sheath did not deteriorate as rapidly in the downhole environment as the Inconel sheath had done.

Figure III-4. 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 III-5. Drill Response - Conventional and Jet-Augmented Bits in Plastic Zone

A new thermal probe weight (Figure III-6) having less mass near the thermocouple end and a more positive Swagelok fitting to anchor it to the thermocouple cable was designed and fabricated. This probe was also used successfully in the July operation.

A commercially available length measurer was added to the thermocouple cable wheel to more accurately measure the probe depth during downhole measurements. This unit was used in July and was found to provide downhole measurements that were repeatable within 0.625 cm in a total depth of > 90 m.

A new thermocouple wheel assembly incorporating the length measurer described above and a commercial thermocouple slip ring assembly in its hub was designed and fabricated. The slip ring will eliminate the need to unplug the temperature measuring instrumentation during each lowering of the probe. It will also permit continuous reading of the downhole temperature profile if desired. This equipment, shown in Figure III-7, has been assembled and laboratory tested. It is available for the next field operation.

Creep test break locator - As described earlier, measurements made in July indicate that the lower end of the casing in the Long Term Creep Study set up on the lava lake in February appears to be moving downward even though the top of the casing has not moved. This implies that the casing has broken at some location downhole and that the creep penetrator is proceeding as planned. To determine if this is the situation, a special device to move down the casing and indicate the presence and location of the postulated break has been designed and fabricated. Figure III-8 shows a sketch of this device. It has been assembled, laboratory tested, and is ready for the next field operation.

Figure III-6. Thermocouple Probe Weight

Figure III-7. Thermocouple Slip-Ring Assembly

Figure III-8. Casing Break Locator

IV. Task 3 -- Magma Characterization

Definition of chemical and physical properties of magma is necessary 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 (1) to predict in situ compositions using analyses of gases from volcanic eruptions and (2) to measure properties of simulated systems at in-situ conditions.

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.

At the start of this year we had data on approximately 100 volcanic gas analyses of collections taken at high temperatures ($> 950^{\circ}\text{C}$) 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 comprised 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 .

Figure IV-1. Representative O₂ fugacities at collection temperatures for restored volcanic gas analyses: + (Surtsey 1964, 1965, 1967); O (Erta Ale lava lake 1971, 1973, 1974); □ (Ardoukoba 1978); ◇ (Kilauea 1918, 1919; X (Mount Etna 1970); Δ (Nyiragongo 1959). The dotted line shows the O₂ fugacity of a volcanic gas during cooling from 1150°C at 1 bar total pressure. NNO and QMF refer to the nickel-nickel oxide and quartz-magnetite-fayalite O₂ buffers, respectively (Heubner and Sato, 1970; Wones and Gilbert, 1969).

Procedures have been developed for correcting the reported analyses for several of the imposed modifications noted above. The restored analyses (Table IV-1) 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 or organohalogens (e.g. CH_3Cl), suggest contamination by pyrolysis of organic materials.

The restoration of all known high temperature volcanic gas analyses from tholeiitic and alkaline lavas is now complete. The data base of restored analyses has been increased to 150 samples. The most recent additions to the data base continue to show chemical characteristics and trends outlined in the Semiannual Report (Traeger, Colp and Neel, 1979) and summarized here in Figures IV-1, IV-2, IV-3, and IV-4.

Table IV-1 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	1.0
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		.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	.0	.1
NYIRANGONGO (1959)	44 56	1.3-2.2	49 36	2.2	2- 1	.6-.4	1.7-2.5

Figure IV-2. Representative S₂ fugacities at collection temperatures for restored volcanic gas analyses: Δ (Surtsey 1964, 1965, 1967); $\square$ (Erta Ale lava lake 1971, 1973, 1974); $\circ$ (Ardoukoba 1978); $+$ (Kilauea 1918, 1919); $\diamond$ (Mount Etna 1970); $\times$ (Nyiragongo 1959).

The most important finding is that the variability of gas compositions, over time and space, results principally from the low solubility of CO₂ in silicate melts (compared to H₂O and S solubilities) and from the control of S solubility by melt O₂ fugacity. Figure IV-3 shows the positive correlation of total sulfur content for the restored analyses with relative O₂ fugacity. In order to allow for the variable temperatures of the gases, the O₂ fugacities in Figure IV-3 are normalized to those of the quartz-magnetite-fayolite buffer (Figure IV-1). The predominance of a CO₂ degassing trend in the restored analyses is illustrated by the CO₂ control lines in Figure IV-4. A paper summarizing generalizations from the restored analyses is in preparation.

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.

Figure IV-4. Atomic H/C vs atomic S/C for the restored volcanic gas analyses: Δ (Surtsey 1964, 1965, 1967, all restored data); $\square$ (Erta Ale 1971, 1973, 1974, means of restored data); $\circ$ (Ardoukoba 1978, all restored data); (Kilauea 1918, 1919, all restored data); $+$ (Kilauea 1965, "Best" samples of Finlayson et al., 1968); $\diamond$ (Mount Etna 1970, all restored data for fumaroles 1 and 2); ∇ (Nyiragongo 1959, points show range in H/C and S/C for restored analyses). Dashed lines are control lines showing increase in H/C and S/C resulting from removal of CO_2 from Surtsey sample 13, from the mean of the 1971-1973 Erta Ale lava lake gases, and from Kilauea sample J-8.

- (3) Long-term variations (months to 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 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 oxidized lavas (e.g., Etna) containing 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.

Kilauea Iki Gas Analysis (E. J. Graeber)

On April 25, 1979, three gas samples were collected from Kilauea Iki borehole 79-3 in order to ascertain what gas species caused the severe corrosion observed on the stainless steel casing in nearby borehole KI 75-1. The three gas samples have been analyzed and the results summarized in Table IV-2.

From mass spectrometry data, all the samples contained in addition (in the low ppm range): butane, 2-propanone, an organic of mass 67 and 68, and an aromatic of molecular weight 92 (possibly toluene). No sulfur species were detected in any of the three samples. From these data it appears likely that the copious quantities of oil used in the coring operations have contributed to downhole hydrogen production via hydrocarbon distillation.

Table IV-2 Gas Analyses from KI 79-3

	Sample Number		
	1	2	3
Collection Depth (ft)	159.8	150	145
Collection Temperature (°C)	921	635	510
Bottle Pressure (torr)	27.09	36.33	26.45
H ₂	ND	0.56	5.94
N ₂	14.24	53.95	13.79
O ₂	3.58	13.05	1.41
Ar	ND	0.46	0.12
CO ₂	4.16	1.32	13.22
H ₂ O	78.02	30.66	65.53

ND (< 0.06%)

Magma Simulation Facility (R. P. Wemple)

The Magma Workshop (Colp et al, 1975) recommended that extensive laboratory studies be started to (1) measure the effects of pressurized volatile atmospheres on the physical properties of molten rocks, and (2) examine selected aspects of the chemical equilibria between silicate melts and a gas phase. Following this recommendation, and with continuing advice of the Magma Energy Research Advisory Panel, it was decided to design and build a Magma Simulation Facility at Sandia Laboratories. A schematic drawing of the Facility is shown in Figure IV-5. The pressure vessel is capable of operation at 4 kbar pressure and is pressurized with argon by a Harwood DA-4 two-stage compressor. The furnace within the pressure vessel, built by Autoclave Engineers, is capable of heating a hot zone 10.16 cm diam. by 10.16 cm tall to 1600°C. Additional details on the Facility are given in Colp (1979). Figure IV-6 shows a picture of the facility installed within the blast cell (Building 9938).

The pressure vessel and furnace system has been brought online and has proven to be reliable and repeatable. Ten test runs have been made with the facility and only minor problems have been discovered in the monitoring control and protective interlock systems. The large (10.16 cm diam. x 10.16 cm tall) hot zone of the furnace permits experiments to be performed that in the past were limited by hot zone size.

Figure IV-5. Schematic Layout of Magma Simulation Facility

Figure IV-6. Magma Simulation Facility

The test items used in the initial runs have been a series of sealed Pt or Ag-PD capsules containing various basalt, andesite and rhyolite powders combined with varying proportions of water and/or sulfur. Analysis of these specimens for phase relations and volatile solubility is not complete at this time. Table IV-3 summarizes these initial experiments.

A high temperature, high pressure falling sphere viscometer has been developed and bench tested to 1200°C at atmospheric pressure. Lead borate glass samples have been used to test this real-time device, and the viscosity values obtained compare favorably with data from another viscometer developed at Sandia and documented by Gilbert (1977). The test data are shown in Figure IV-7 for qualitative comparison purposes only. The viscometer hardware is now ready for installation into the vessel/furnace assembly. Initial testing in the furnace will be with a series of NBS glass standards to obtain calibration of the viscometer. After calibration, the viscosity of several pure lavas and doped lavas will be examined over a range of pressures and temperatures. Figure IV-8 shows the viscometer test cell and Figure IV-9 is a schematic representation of the viscometer system.

Figure IV-7. 10/90 Lead Borate Viscosity Plots

Figure IV-8. Viscosity Test Cell Configuration

Figure IV-9. Falling Sphere Viscometer Schematic

Table IV-3 Summary of Phase Relation and Volatile Solubility
Samples Tested

	Rock Type	Capsule Material	W* or WO** H ₂ O	Test P (k bar)	Test T °C	Comments	
5-9-79	basalt	Ag-Pd	WO	1	1100	Welded Closure	
	basalt	"	W	"	"	"	"
	basalt	Pt	WO	"	"	"	"
	basalt	"	W	"	"	"	"
	andesite	"	WO	"	"	"	"
	andesite	"	W	"	"	"	"
	rhyobite	"	WO	"	"	"	"
	rhyobite	"	W	"	"	"	"
6-27-79	basalt	Ag-Pd	W	1	1150	"	"
	basalt	"	WO	"	"	"	"
	andesite	"	W	"	"	"	"
	andesite	"	WO	"	"	"	"
	basalt	"	W	"	"	Crimped closure	
	basalt	"	WO	"	"	"	"
7-26-79	basalt	Pt	WO	3	1150	"	"
	rhyolite	"	"	"	"	"	"
	andesite	"	"	"	"	"	"
	basalt	"	"	"	"	Crimped closure trace of S added	
	rhyolite	"	"	"	"	"	"
	andesite	"	"	"	"	"	"
	basalt	Ag-Pd	"	"	"	"	"
	basalt	Pt	"	"	"	Crimped closure trace of S added	

*With water

**Without water

Further improvements to the facility include the transfer of pressurization, heating, and data acquisition functions to the HP 1000 computer system. Software for all of these functions must still be developed.

Electrical conductivity experiments will be attempted after the initial viscosity experiments. Techniques and test cell configurations for these measurements have not been established.

Other geoscience experiments proposed for the facility include the study of rhyolite/basalt/andesite interface reactions at various pressures and temperatures, and additional studies relating to volatiles in molten rock. These volatiles will eventually include highly reactive gases, but techniques for injecting the gases are still being discussed.

V. 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 IV) 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, Nb, Ta, Zr, V, Ti, Re, Pt, Rh, and Pd. 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 iron-oxygen-sulfur system at 1150°C and 1 bar is given in Figure V-1. The range of O_2 fugacities and S_2 fugacities expressed by dashed lines in Figure V-1 corresponds to the range of these fugacities in the restored volcanic gas analyses (Table IV-1). The implication of these thermodynamic studies for most of the metal-gas systems are similar to those in Figure V-1, 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, tholeiitic 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.

Figure V-1. Iron-Sulfur-Oxygen Stability Diagram

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 IV#B, V#B, and VII#B.

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 and are summarized below. A topical report (Douglass and Healey, 1979) has been prepared and issued describing this work.

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 detailed analysis of each metal has been made and is discussed in the topical report (Douglass and Healey, 1979). 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.

*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.

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), and some ferritic stainless steels (410, 430, and 446), plus some hybrid alloys (310-6Mo, Ni-30Cr-4Al, Ni-30Cr-4Ti, and Ni-30Cr-9Mo).

The work is incomplete, but some of the observations and a preliminary analysis of trends are given in this summary.

Ferritic Stainless Steels - Three grades of 400 series stainless steels, types 410, 430, and 446 containing 12, 16, and 26% chromium, respectively, were exposed for periods of 24, 96, and 400 hours. All three alloys formed an external scale of Cr_2O_3 during the 96-hour test. In each case the outer portion of the oxide had reacted with iron oxide in the molten lava to form a spinel of the type FeCr_2O_4 . Cross sections of the 96-hour samples are shown in Figure V-2. Type 410 stainless steel exhibited extensive internal oxidation with a trace of chromium-manganese sulfide formation in the substrate. Type 430 internally oxidized to a very limited extent, and type 446 formed only an external scale of Cr_2O_3 . The effect of increasing chromium was to markedly reduce internal reaction due to the formation of a protective layer of Cr_2O_3 . The oxide was partially detached and convoluted on all three alloys.

An increase in reaction time to 400 hours caused some notable changes in corrosion behavior, as noted in Figure V-3. The same external scale was present, but all three alloys had internally sulfidized to form chromium-manganese sulfide (the globular gray phase), the extent of internal sulfidation decreasing with increasing chromium content. Type 446 also internally oxidized (primarily in the grain boundaries), although the amount of internal oxidation was considerably less than in the lower chromium alloys. The internal oxides were generally either chromium oxide or silicon dioxide. In some cases aluminum was detected. Both silicon and manganese are present in stainless steels (about 1% each), and aluminum was probably picked up from the melt.

High-Purity Fe-Cr Alloys - Two Fe-Cr alloys containing 19 and 24% chromium, but without the residual silicon, manganese, and carbon associated with type 400 stainless steels, behaved differently from their less pure analogs. The high-purity alloys exhibited no internal oxidation in 96 hours (Figure V-4). A scale of Cr_2O_3 formed which was

Type 410 (12% Cr)

Type 430 (17% Cr)

Type 446 (26% Cr)

Figure V-2. Ferritic Stainless Steels Corroded 96 Hours

(a)

410 Stainless (12% Cr)

(b)

430 Stainless (17% Cr)

(c)

446 Stainless (26% Cr)

Figure V-3. Ferritic Stainless Steels Corroded 400 Hours

Fe-19Cr

Fe-24Cr

Figure V-4. High-Purity Fe-Cr Alloys Corroded 96 Hours

very similar to the scale on the 400 series stainless steels. However, there were areas over which the scale was not continuous due to reaction with the lava. Even though the scale was discontinuous, there was no evidence of either internal oxidation or internal sulfidation in those areas. It also appears that the scale on the Fe-24Cr alloy was thicker than that on the Fe-19Cr alloy, which is behavior contrary to that expected.

Exposure of the Fe-24Cr alloy for 400 hours caused a significant change in the nature of the Cr_2O_3 scale (Figure V-5). The Cr_2O_3 was highly convoluted and detached over most of the surface. The few areas which were attached to the substrate had a small amount of CrS acting as a "bonding agent" between the oxide and the substrate. Once again, no internal oxidation or internal sulfidation was observed. The Cr_2O_3 had also become very porous during the longer time period. A thin layer of relatively nonporous spinel existed on top of the Cr_2O_3 .

Austenitic Stainless Steels - The 300 series of austenitic steels are ternary Fe-Cr-Ni alloys, which showed a strong dependence of the corrosion resistance on the chromium and nickel contents (Figure V-6) for samples exposed for 96 hours. Types 304 (18Cr-8Ni), 316 (18Cr-12Ni-2Mo), and 309 (23Cr-13Ni) reacted extensively to form thick external scales, massive sulfide layers beneath the scales, internal oxidation and sulfidation. The external scales are Cr_2O_3 , the sulfide layer is CrS, the internal sulfides are chromium-manganese sulfide, and the internal oxides (dark phase) are probably a chromium-iron silicate.

An increase in the chromium and nickel contents to 25 and 20 %, respectively, in type 310 stainless steel resulted in the formation of a tightly adherent Cr_2O_3 layer (outer portion also converted to spinel) and the virtual elimination of internal sulfidation. A 310 stainless steel containing 6% Mo behaved similarly to the regular 310. A few internal particles of a titanium-chromium oxide existed in these alloys. The titanium had been added to the alloy (about 0.2%) as a deoxidizer in place of manganese.

Type 310 steels were high-purity ones, and thus the effect of silicon and manganese cannot be assessed at present. If these elements do not play a role at the higher alloy level present in 310, it appears that the combined amount of chromium and nickel are above a critical value to cause an abrupt transition in corrosion resistance.

50 μ

50 μ

Figure V-5. High-Purity Fe-24Cr Corroded 400 Hours

(a)

304 Stainless (18% Cr-8% Ni)

(b)

316 Stainless (18% Cr-12% Ni-2% Mo)

(c)

309 Stainless (23% Cr-13% Ni)

Figure V-6. Austenitic Stainless Steels Corroded 96 Hours

(d)

(e)

310 Stainless (25% Cr-20% Ni)

310 Stainless+Mo (25% Cr-20% Ni-6% Mo)

Figure V-6.

High-Purity Ni-Cr Alloys - Two levels of chromium, 23 and 30%, were studied. A considerable difference in behavior was noted for short times (24 hours), as shown in Figure V-7. The Ni-23Cr alloy formed a discontinuous, almost random array of reaction products on the surface with internal oxides. The bright areas are metallic particles of nickel contaminated with iron from the lava. The internal oxides are Cr_2O_3 .

The Ni-30Cr formed an adherent layer of Cr_2O_3 which was partially converted to FeCr_2O_4 on the exterior. A few fingers of Cr_2O_3 extended into the substrate, and a few isolated particles of Cr_2O_3 also had formed internally. The globules in the lava near the oxide scale are iron, and were the product of chromium reduction of FeO in the melt. It appears that a critical chromium level exists between 23 and 30%, the latter being sufficient to give good corrosion resistance.

However, at longer times (400 hours), the protective nature of the Cr_2O_3 layer on Ni-30Cr was lost (Figure V-8). The oxide had become detached and very porous (similar to the oxide on Fe-24Cr exposed for 400 hours). A sulfide layer formed between the oxide and substrate, and some internal sulfidation occurred. The presence of sulfides clearly indicates that the oxide scale had been penetrated by sulfur and that the reaction path had traversed the sulfide stability region.

High-Purity Co-27Cr Alloys - Cobalt-base alloys generally have better sulfidation resistance than nickel-base alloys. Earlier work on pure metals (Douglass and Healey, 1979) clearly showed that cobalt had greater corrosion resistance in the magma compatibility tests. A cobalt-chromium alloy was exposed for 24, 96, and 400 hours. An external scale of Cr_2O_3 formed (once again, the outer portion was converted to FeCr_2O_4) under which chromium sulfide formed (Figure V-9). The scale was mostly detached from the sample surface, even after 24 hours, and a notable convolution of the scale took place in 400 hours. The amount of sulfication increased with exposure time. A nearly continuous layer of chromium sulfide existed between the Cr_2O_3 scale and the substrate on the 400 hour sample.

Preliminary Conclusions

The chromium content of both ferritic and austenitic stainless steels is the most important factor in providing corrosion resistance. There appears to be a critical value in the vicinity of 23 to 25%, which, however, changes with time. Corrosion tests must be run for sufficient time to establish the true steady-state reaction products; the products forming at longer times, e.g., 400 hours, are more deleterious than those formed at shorter times.

Ni-23Cr

Ni-30Cr

Figure V-7. High-Purity Ni30Cr Corroded 400 Hours

Figure V-8. High-Purity Ni30Cr Corroded 400 Hours

Figure V-9. High-Purity Co-27Cr

The appears to be a difference in behavior between commercial ferritic stainless steels and high-purity Fe-Cr binary alloys. The difference is attributed to the presence of both silicon and manganese in the commercial alloys.

There may be a synergistic effect of chromium and nickel in the austenitic alloys in providing corrosion resistance. The role of silicon and manganese in type 310 stainless steel must be evaluated. Type 310 is by far the most corrosion-resistant alloy of any of the commercial stainless steels.

Although only preliminary data are available, it appears that molybdenum is a beneficial addition at the 6% level but not at the 2% level.

Iron-chromium alloys having sufficient chromium (24%) are more corrosion resistant than cobalt-chromium, which is more corrosion resistant than nickel-chromium.

VI. Task 5 -- Energy Extraction

Molten magma bodies offer a source of high quality, pollution free thermal energy. Evaluation of the scientific feasibility of energy extraction is the objective of this task of the Magma Energy Research Program.

A number of schemes for energy extraction have been considered; these include thermionics, thermoelectrics, steam generation for conversion to electricity, hydrogen production, and generation of synthesis gas (H_2 , CO , CH_4). The last three extraction schemes (steam, hydrogen and synthesis gas) were chosen for these scientific feasibility studies, since thermodynamics and surface processing technologies are well defined. The basic questions of energy extraction are then questions of heat and mass transfer rates in and from magma bodies. Definition of the properties of molten magmas (Task 3) is critical to understanding energy extraction limits. Efforts in the Energy Extraction Task have been aimed at limited studies on the dynamics of magma bodies, extraction rates from molten lavas, and preliminary studies on the internal dynamics of heat exchangers. Further information on past work can be found in Colp and Traeger (1979).

Lava Lake Experiment (J. C. 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. Water was pumped down a center pipe in the hole to about 53 meters depth, heated and returned up the injection pipecasing annulus to a calorimeter. Results are given in Table VI-1.

Table VI-1 Energy Extraction - 1979 Kilauea Iki

	Time (min.)	
	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)	12.0	11.0
Calculated Heat Transfer Flux (kw)		
Hydrothermal Region	16.0	14.0
Hot Rock Region	79.0	64.0
	95.0	158.0

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 suggest the possibility of enhancing heat transfer in magma chamber margins or in-situ formed exchangers by the injection of a fluid for convection enhancement.

Effect of Weak Convection on Heat Extraction Rate (H. C. Hardee)

Closed heat exchanger systems which depend only on conduction heat transfer through magma are known to be limited by heat extraction rates on the order of 1 kW/m^2 (Hardee, 1974). Weak levels of convection in the magma adjacent to the heat exchanger on the order of 1 to 2 kW/m^2 are reasonable and probable. Because of the cylindrical geometry of the heat exchanger and adjacent solidified magma crust, the weak convective heat transfer rate is amplified. The effective heat extraction rate at the heat exchanger surface is expected to be on the order of 7 kW/m^2 , and this improves the economics of magma energy extraction significantly. A simple analysis of the effect of weak convection on energy extraction has been performed. Table VI-2 from that analysis shows that at weak convection levels of 2 kW/m^2 , the energy extraction rate in terms of the surface area of the heat exchanger is around 7 kW/m^2 and is competitive with other energy forms.

Table VI-2 Comparison of Magma/Electric Power Costs

Magma	Heat Extraction Rate q_e	Cost/ kW_e Installed	
Conduction Only	1 kW/m^2	\$6800	Very conservative estimate
With Weak Convection			
$q_o = 0.5 \text{ kW/m}^2$	4.4 kW/m^2	\$2200	Probable Lower Limit
$q_o = 1.0 \text{ kW/m}^2$	5.5 kW/m^2	\$2000	
$q_o = 2.0 \text{ kW/m}^2$	7.3 kW/m^2	\$1500	Likely Range
$q_o = 3.5 \text{ kW/m}^2$	9.5 kW/m^2	\$1250	
$q_o = 4.5 \text{ kW/m}^2$	10.8 kW/m^2	\$1000	Probable Upper Limit
<u>By Comparison</u>			
Nuclear		\$2000	
Solar (Optimistic 1990 Prediction)		\$3000	
Solar Pilot Plant (Barstow, CA)		\$12000	(12 hr. daily operation)

Based on calculations above, the preliminary economic estimate suggests a conventional type magma/electric power plant is feasible.

Summary

A major effort in evaluating Kilauea Iki lava lake was completed with the following results:

- The lake is in a late stage of cooling, with no low viscosity liquid lava present, but has instead a melt/crystal suspension lens with 35 to 40% liquid phase.
- In-situ crystallization, as well as crystal settling, plays a role in the differentiation observed in the lava lake cores examined.
- A number of intermittent, thin (1-4 cm) veins of very fluid molten rock were encountered during drilling.
- Approximately 10 m of the melt/crystal suspension lens was successfully cored with conventional wire line coring equipment.
- Water jet-augmented drag and core bits successfully drilled glassy flowback material where conventional drilling had failed.
- Mathematical models of the cooling of the lava lake and the state of solidification of the multiphase lens were verified by thermal profile and permeability measurements.
- Heat transfer studies suggest that injection of fluids to enhance convection may be useful for extracting energy from magma chamber margins.

Laboratory tests of dry andesite, basalt, and granodiorite to temperatures of 1050°C and at confining pressures of 0 and 50 MPa showed that they failed in a brittle manner until partial melting occurred. Calculations based on measured strengths indicate that open boreholes in basalt and granodiorite are stable if cooled at 400°C or less.

Ten phase and gas/melt equilibria experiments were completed in the Magma Simulation Facility to temperatures of 1150°C and pressures of 3 kbar (30,000 psi).

Material compatibility tests of 15 pure metals and a number of metal alloys in a low pressure, simulated magma environment were completed.

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