Notice to Contributors

Efforts at *Science* to reduce a backlog of accepted reports in order to attain faster publication* have been successful. The acceptance rate for reports, which was reduced to about 10 percent over the summer, is now being increased. We are now able to publish reports within 2 months after acceptance on average.

*See notice in *Science*, 15 July, p. 259.

# Reports

## Heat Transfer Measurements of the 1983 Kilauea Lava Flow

Abstract. *Convective heat flow measurements of a basaltic lava flow were made during the 1983 eruption of Kilauea volcano in Hawaii. Eight field measurements of induced natural convection were made, giving heat flux values that ranged from 1.78 to 8.09 kilowatts per square meter at lava temperatures of 1088 and 1128 degrees Celsius, respectively. These field measurements of convective heat flux at subliquidus temperatures agree with previous laboratory measurements in furnace-melted samples of molten lava, and are useful for predicting heat transfer in magma bodies and for estimating heat extraction rates for magma energy.*

The 1983 eruption of Kilauea volcano in Hawaii occurred along the volcano's east rift zone. This eruption began on 2 January 1983, and over a period of 2 weeks there were a number of eruptive episodes producing several lava flows. Additional lava flows occurred during eruptions in February. The active lava flows offered an opportunity to run field verification measurements of induced convective heat flow in basaltic lava. Convective heat flow in lava and magma has been studied (*1*, *2*) because of its importance to energy extraction from molten magma (*3*–*5*) and because of its relation to tectonic processes (*6*).

Many laboratory measurements of convective heat transfer in basaltic melts have been made at temperatures ranging from superliquidus down to near the solidus (*1*, *2*). These measurements were performed on furnace-melted samples of lava. The lava remelts were thoroughly degassed in the remelting process. Volatile components that are present in magma at depth lower the viscosity of the magma and improve convection heat transfer (*7*). Freshly erupted lava that still retains some volatile components should exhibit this same effect. Before the 1983 Kilauea eruption there was only one field measurement of convective heat transfer in freshly erupted basalt. This measurement was made in the 1977 Kilauea eruption, and it indicated a steady convective heat flux of 5 to 10 $kW/m^2$ in a region of combined natural and forced convective flow (*8*).

The convective heat flow measurements were made with a transient convection probe. This probe consists of a titanium-zirconium-molybdenum (TZM) rod with an internal thermocouple. TZM metal is used because of its high thermal conductivity and high melting point. In operation, the probe is inserted into molten lava with a long, stainless steel rod. The transient temperature response, recorded on a battery-powered recorder, is related to the amount of convection induced in the molten lava adjacent to the probe. Assuming that convective heat transfer is induced when the cool probe is inserted into molten lava, the expected temperature response of the probe is given by

$$\frac{T - T_\infty}{T_0 - T_\infty} = \exp\left(\frac{-2h\tau}{c\rho R}\right) \qquad (1)$$

where $T$ is the temperature of the probe as a function of time, $\tau$, when the probe is inserted into lava of ambient temperature $T_\infty$, $T_0$ is the effective solidification temperature of the lava, $h$ is the convective heat transfer coefficient for the lava, and $c$, $\rho$, and $R$ are the specific heat capacity, density, and radius of the probe, respectively (*9*).

To simplify data reduction and eliminate phase change effects due to a crust of solidified lava on the probe and subsequent remelting of the crust as the probe heats up, only data above 1050°C ($T_0$ = 1050°C) are used in determining the convective heat transfer rate. The validity of this approach has been verified by laboratory comparisons with steady-state convection probes in molten basalt (*2*).

The heat transfer field measurements for the 1983 Kilauea eruption were made in lava flows that occurred during January and February 1983. Five measurements were made in lava flow that occurred during the 18th eruptive phase on the morning of 15 January. Lava fountaining began at 0333 and continued until 0855 on that morning, producing a lava flow in the vicinity of Puu Kahaualea. The heat transfer measurements were made in the edge of the lava flow at the base of Puu Kahaualea between 1100 and 1300, or 2 to 4 hours after the end of the 18th eruptive phase. Temperatures in this flow were still high (1088° to 1128°C) when the heat transfer measurements were taken. The lava consisted of approximately 90 percent (by volume) liquid, 6 percent plagioclase, 3 percent clinopyroxene, and 1 percent olivine (*10*).

Another major eruptive phase began at 0145 on 25 February, with sustained fountaining at vent 1123 near Puu Kahaualea. The fountaining continued for a week and produced a river of lava flowing downrift. During the afternoon of 26 February three additional heat transfer measurements were made in the edge of the lava river near Kalalua 2.5 km downrift from the erupting vent. The temperature in the lava at this point was measured at 1119°C by a thermocouple inserted in the flow. Earlier in the afternoon the temperature in a flow near the fountaining vent was measured at 1118°C.

Table 1. Field measurements of convective heat transfer coefficients.

| $T_\infty$ (°C) | $r^2$ | $a$ | $b$ ($sec^{-1}$) | $h$ (kW/$m^2$-°C) | $q_0$ (kW/$m^2$) |
|---|---|---|---|---|---|
| 1088 | 0.998 | 0.879 | 0.00532 | 0.0469 | 1.78 |
| 1096 | 0.965 | 1.110 | 0.00812 | 0.0716 | 3.29 |
| 1117 | 0.988 | 0.909 | 0.00859 | 0.0757 | 5.07 |
| 1119 | 0.994 | 0.985 | 0.00944 | 0.0832 | 5.74 |
| 1119 | 0.987 | 0.925 | 0.01164 | 0.1025 | 7.07 |
| 1119 | 0.992 | 1.105 | 0.01207 | 0.1064 | 7.34 |
| 1122 | 0.986 | 0.887 | 0.01021 | 0.0900 | 6.48 |
| 1128 | 0.991 | 0.880 | 0.01177 | 0.1040 | 8.09 |

Eight successful sets of measurements were made with the transient convective probe at points in the flow where the lava temperature ($T_\infty$) ranged from 1088° to 1128°C. The temperature response of the probe ($T$) at temperatures above the reference value, 1050°C ($T_0$), was put into the dimensionless temperature form $(T - T_\infty)/(T_0 - T_\infty)$ and an exponential curve fit of the form

$$\frac{T - T_\infty}{T_0 - T_\infty} = a \exp(-b\tau) \quad (2)$$

was applied to the data to determine the values of the constants $a$ and $b$. By combining Eqs. 1 and 2, the convective heat transfer coefficient ($h$) was then determined from the value of $b$ by

$$h = b\,(c\rho R/2) \quad (3)$$

The results of the eight sets of field measurements are summarized in Table 1 in ascending values of ambient lava temperature. The parameter $r^2$ (coefficient of determination) in Table 1 is a measure of the correlation of the data with the expected exponential fit. A value of $r^2$ near unity indicates good correlation of the data with an exponential fit.

The convective heat flux at some boundary, such as the surface of a heat exchanger immersed in magma or at a boundary where magma contacts country rock, is (2)

$$q_0 = h\,(T_\infty - T_0) \quad (4)$$

This convective heat flux, also shown in Table 1, is easily determined once the convective heat transfer coefficient ($h$) is known. Figure 1 shows convective heat flux for basaltic lava. These data were obtained from theoretical calculations and laboratory measurements of furnace-melted samples of basalt (2). The recent field results given in Table 1 are also plotted in Fig. 1, and the agreement with the previous laboratory measurements and theoretical calculations is excellent.

Table 1 shows convective measurements in the 1983 eruptive flow at lava temperatures from 1088° to 1128°C. The ambient temperature was usually measured with a thermocouple inserted into the lava near the point where the convective heat transfer probe was inserted. In some cases the convective heat transfer probe was left in long enough for the probe to reach thermal equilibrium with the lava. The final temperature of the probe was then taken as the ambient temperature of the lava. In the latter method there was a risk of losing the convective heat transfer probe if it became frozen in the lava crust on the outer surface. By taking convective heat flux measurements at various points near the edge of the flow, it was possible to find regions where the lava was still at eruptive temperatures as well as cooler zones. We were thus able to make convective heat flux measurements over a range of subliquidus temperatures.

Even if magma or lava is not convecting on its own, convection will be induced when a cooler object, such as country rock or a heat exchanger, comes in contact with it. The presence of the cool, immersed object chills nearby magma or lava and the resulting density changes in the liquid produce convective motion. The convective heat flux values given in Table 1 and Fig. 1 are a measure of this type of induced convection.

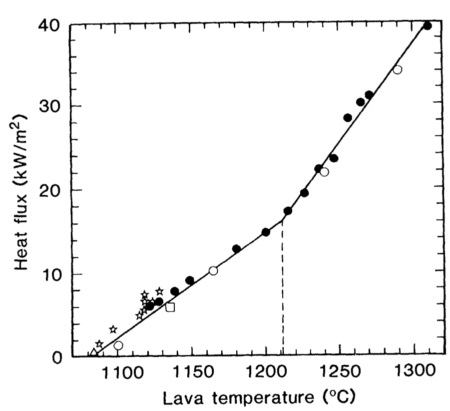


Fig. 1. Convection heat flux data for molten basalt in the 1983 Kilauea eruption, as determined by laboratory and field measurements. Symbols: (○) transient probe measurements; (●) steady-state probe measurements; (□) Acrivos solution, Hawaiian lava; (△) Acrivos solution, Mount Etna lava; and (☆) Kilauea eruption data.

The convective heat transfer coefficient ($h$) values listed in Table 1 tend to increase in magnitude as the ambient temperature of the lava ($T_\infty$) increases. The convective heat transfer coefficient is inversely proportional to a fractional power of lava viscosity (2). Since lava viscosity decreases rapidly with increasing temperature, particularly in the subliquidus temperature range, this causes the convective heat transfer coefficient to increase with temperature. Earlier laboratory measurements showed this same effect (2).

The convective heat flux data for this recent eruption fall slightly above the theoretical curve in Fig. 1. The lava at the 1983 eruption site was not totally degassed, while the lava used in the earlier laboratory measurements was thoroughly degassed by the furnace heating cycle. The presence of volatiles, particularly water, in freshly erupted lava lowers the viscosity, and this in turn increases convective heat flux values (7). Water-saturated basalt supports convective heat flux rates as much as 35 percent greater than in dry basalt (5). The convective heat flux values for the 1983 eruption are in excellent agreement with the previous laboratory measurements (Fig. 1), particularly in view of the volatiles present in the erupted lava.


H. C. HARDEE

*Geophysics Research Division 1541, Sandia National Laboratories, Albuquerque, New Mexico 87185*


### References and Notes


1. H. C. Hardee, *J. Volcanol. Geotherm. Res.* **10**, 175 (1981).
2. ______ and J. C. Dunn, *ibid.*, p. 195.
3. H. C. Hardee, *Geotherm. Resour. Counc. Bull.* **11**, 3 (1982).
4. ______, *Geophys. Lead. Edge Explor.* **2** (No. 3) 14 (1983).
5. J. L. Colp, *Sandia Natl. Lab. Rep. SAND82-2377* (1982).
6. H. C. Hardee, *Sandia Natl. Lab. Rep. SAND80-1671* (1980).
7. J. C. Dunn, C. R. Carrigan, R. P. Wemple, *Trans. Am. Geophys. Union* **62**, 1055 (1981).
8. H. C. Hardee, *J. Geophys. Res.* **184**, 7485 (1979).
9. P. J. Schneider, *Conduction Heat Transfer* (Addison-Wesley, Reading, Mass, 1957), pp. 230–231.
10. Electron microprobe analysis by W. C. Luth showed the liquid fraction of the lava to consist of the following (percent by weight): $SiO_2$ (51.03), $Al_2O_3$ (13.43), FeO (13.11), MgO (4.90), CaO (9.45), $Na_2O$ (2.63), $K_2O$ (0.79), $TiO_2$ (4.10), $Cr_2O_3$ (0.01), $P_2O_5$ (0.37), MnO (0.16), and NiO (0.02) (average of 30 analyses; mean analytic sum, 99.04 percent by weight).



11. This work, performed at Sandia National Laboratories, was sponsored by the Department of Energy under contract DE-AC04-76-DP00789. I thank the Hawaiian Volcano Observatory, particularly R. Decker and R. Okamura, for supporting our field operation during the 1983 Kilauea eruption. I also thank R. Striker, T. Gerlach, W. Luth, E. Graeber, and M. Caress for their help in making the measurements at the eruption site.

12 April 1983; revised 22 June 1983