6. The analysis of Mariner 9 radio occultation data by P. M. Woiceshyn, [*Icarus* **22**, 325 (1974)] indicates that north of 75°N the average surface pressure is 0.4 mbar greater than the martian average. A topographic map of the same region by D. Dzurisin and K. R. Blasius, [*J. Geophys. Res.* **80**, 3286 (1975)] indicates that the surface of the residual cap is on the average about 4 km higher than the unfrosted areas.
7. The Mariner 9 infrared radiometer and infrared interferometer-spectrometer did not have adequate spatial resolution to demonstrate that the frost areas of the residual north polar cap were not near 150 K. The global dust storm that occurred during the Mariner 9 mission caused considerable opacity in the atmosphere over the residual south polar cap, preventing a definite determination of the residual frost temperature.
8. The IRTM experiment is described in H. H. Kieffer, G. Neugebauer, G. Münch, S. C. Chase, Jr., E. D. Miner, *Icarus* **16**, 47 (1972); H. H. Kieffer, S. C. Chase, Jr., E. D. Miner, F. D. Palluconi, G. Münch, G. Neugebauer, T. Z. Martin, *Science* **193**, 780 (1976).
9. A buried solid CO_2 cap, which is sealed off from the atmosphere and has survived from some other climatic period, cannot be ruled out by these (and most other) observations. Although this has been suggested (*4*), a detailed theoretical treatment of its possible stability remains to be developed.
10. C. B. Farmer, D. W. Davies, D. D. La Porte, *Science* **194**, 1339 (1976).
11. On 30 September 1976, the inclination of the Viking 2 orbiter was increased to 75°. The improved viewing of the polar region by all three orbiter instruments should allow resolution of many detailed questions about these intriguing areas.
12. W. R. Ward [*J. Geophys. Res.* **79**, 3375 (1974)] has made a detailed analysis of the variation of the martian orbit and spin axis direction. The shortest period appreciably influencing the polar climate is the 175,000-year precession of the equinoxes.

13. J. Bennett has made major contributions to processing IRTM data. The assistance of P. Christensen, B. Jakosky, and A. Peterfreund, officially but totally inadequately described as data aides, is gratefully acknowledged. The imaging observations were provided by the Viking Orbiter Imaging Team, led by M. H. Carr. Financial support was provided by the NASA Viking Project Office.

18 October 1976

Soil and Surface Temperatures at the Viking Landing Sites

Abstract. *The annual temperature range for the martian surface at the Viking lander sites is computed on the basis of thermal parameters derived from observations made with the infrared thermal mappers. The Viking lander 1 (VL1) site has small annual variations in temperature, whereas the Viking lander 2 (VL2) site has large annual changes. With the Viking lander images used to estimate the rock component of the thermal emission, the daily temperature behavior of the soil alone is computed over the range of depths accessible to the lander; when the VL1 and VL2 sites were sampled, the daily temperature ranges at the top of the soil were 183 to 263 K and 183 to 268 K, respectively. The diurnal variation decreases with depth with an exponential scale of about 5 centimeters. The maximum temperature of the soil sampled from beneath rocks at the VL2 site is calculated to be 230 K. These temperature calculations should provide a reference for study of the active chemistry reported for the martian soil.*

The surface temperatures at the Viking landing sites have been measured at several times during the martian day by the infrared thermal mappers (IRTM) on the Viking orbiters (*1*). These measurements make possible a calculation of the daily temperature variation at depth in the soil and a prediction of the annual behavior of temperatures at the landing sites. This temperature information is directly applicable to a study of the peculiar chemistry reported for the martian soil and the possibility of biologic activity therein (*2*). In this work, "soil" is pragmatically defined as material too fine-grained to have its population accurately determined from Viking lander imaging, that is, less than a few centimeters (*3*). The term "surface" implies all exposed material, including blocks and possible bedrock.

The local times and viewing geometries available are governed by the spacecraft orbits. Thus far, high-resolution (8 km in diameter) observations have been possible only in the afternoon, when temperatures are not strongly dependent on thermal inertia. Observations shortly before dawn, which are the most useful for the determination of thermal inertia, have been possible only at very low resolution (about 200 km) for the Viking lander 1 (VL1) site and not at all for the Viking lander 2 (VL2) site. The temperature measurements at high resolution for both sites are reasonably uniform over the larger regions viewed at other local times; these results indicate that the thermal properties derived on the basis of low-resolution observations are probably representative of the 8-km area around each site and suggest that the landing sites are thermally uniform at a scale down to at least half this size. The landing areas were selected to be as bland as possible at the orbiter imaging resolution of 0.1 km (*4*) and to have no thermal anomalies; lander imaging reveals that at least the VL2 site is relatively monotonous at this scale (*5*).

On the basis of the initial assumption that the surface is homogeneous within the area viewed at each site, the observed temperatures were fitted by a one-dimensional thermal model, which accounts for the daily and seasonal changes of insolation and a weak interaction with the atmosphere (*6, 7*). The physical properties affecting the model surface temperature are the albedo A, for which the values measured by the IRTM were used, the emissivity which was set equal to unity (*8*), and the thermal inertia $I = (k\rho C)^{1/2}$, where k is the thermal conductivity, ρ is the density, and C is the specific heat of the surface.

The albedos measured with near verticle viewing are 0.26 and 0.225 for the VL1 and VL2 sites, respectively; although the apparent albedo is higher at large incidence angles, probably in large part due to haze in the atmosphere, these values were adopted as constant. The resulting thermal inertias are, respectively, 9 ± 0.5 and 8 ± 1.5; the unit of I is 10^{-3} cal cm^{-2} sec^{-1} K^{-1} throughout this work. The uncertainties are not formal but rather estimates based on the limited observation geometry available and the apparent atmospheric effects present throughout much of the northern hemisphere; the large uncertainty at the VL2 site results from the lack of predawn data. As was known during Viking site certification, both of these locations have thermal inertias higher than the martian average.

The flat-lying, homogeneous model used here does not explain completely the brightness temperatures at all the local times observed (*1*); however, it should approximate the physical temperature of the surface and subsurface to within about 5 K. Based on the properties derived above, the surface temperatures at the two sites for an entire martian year were computed. Because the model parameters are derived from remote observations, these temperatures (Fig. 1) represent an area-weighted average of the soil and rocks; they represent the environmental extremes at the Viking sites. The diurnal minimum probably models well the minimum for at least the first 2 m of the atmosphere; the diurnal maximum probably models well the peak temperature of a thinner atmospheric layer (*9*).

The predicted thermal behavior of the two sites is quite different. At midday, the temperature reaches a maximum near the autumn equinox (aerocentric longitude of the sun L_s = 180°) rather than at midsummer and has a secondary peak near the spring equinox (L_s = 0°). This large semiannual behavior results from the eccentricity of the orbit of Mars, tending to offset the effect of its polar tilt in the northern hemisphere (the effects add in the southern hemisphere). The VL1 site is near the latitude which experiences the smallest annual variation of temperature.

The VL2 site, in contrast, has well-defined seasons. The maximum temperatures occur in late summer, near the time of VL2 sampling activity, and decrease steadily until midwinter. In these computations CO_2 frosts, with a model albedo of 0.65, form at night during the winter but do not last through the day. A small increase in surface albedo, a decrease in thermal inertia, or a northward slope will cause frosts to last all day long. This model computation does not include latitudinal transport of heat by the atmosphere, which will tend to moderate the winter temperature, nor does it include possible reduction of insolation by the "polar hood," extensive winter clouds, which may reach this latitude. The midwinter temperatures at the VL2 site must be considered uncertain at present; the environmental temperature may fall well below that for which the Viking landers were designed.

To determine the thermal inertia of the soil, a correction must be made for the thermal radiation coming from the surface rocks. The best quantitative estimate is based on the lander imaging, which then requires the assumption that the lander scene is representative of the region out to about 4 km, the radius of the field of view of the IRTM. Both lander and orbiter imaging give the impression that this assumption is valid.

Analysis of high-resolution stereo images from VL1 and VL2 shows that 8.6 and 17 percent, respectively, of the surface area is covered by blocks 5 cm or larger (*10*). On the basis of a simple two-component model, if 8 percent of the area is represented by $I = 40$, appropriate for 20-cm and larger dense rocks and a fair approximation för 5-cm rocks, the observed surface inertia at the VL1 site requires that the 92 percent soil component have $I = 8 \pm 0.5$. At the VL2 site the rocks are largely vesicular (*5*) and probably have $I \approx 30$. Removing 17 percent of this component results in a soil I of 6.2 ± 1.5. This value agrees with $I = 6.5$, the value used to represent the martian surface average (*1*), to well within the uncertainty, and is used for detailed calculations.

Although the daily variation in the surface temperature depends on I, the scale with which this variation propagates downward depends on $(I/\rho C)$, the square root of the thermal diffusivity. A good estimate can be made for the product ρC. Particulate geologic materials typically have bulk densities near 1.7 g cm^{-3}. Soil bulk density estimates derived from Viking landing and sampling activity range from 1 to 1.8 g cm^{-3}, with most material being at the higher values (*11*); the average martian soil density is probably within 1.65 ± 0.15 g cm^{-3}. The specific heat of most common geologic materials is approximately $0.14 + 5.5 \times 10^{-4}(T-220)$ cal g^{-1} K^{-1} (where T is the absolute temperature) in the range of martian surface temperatures (*12*); the small temperature dependence has only a minor effect on the temperature distribution and is ignored. A nominal value of $\rho C = 0.24$ cal cm^{-3} K^{-1} is adopted here; the lander soils probably fall within 15 percent of this value. The use of this value results in thermal diurnal skin depths of 4.5 and 5.6 cm for $I = 6.5$ and 8, respectively; the corresponding thermal conductivities are 1.8×10^{-4} and 2.7×10^{-4} cal cm^{-1} sec^{-1} K^{-1}.

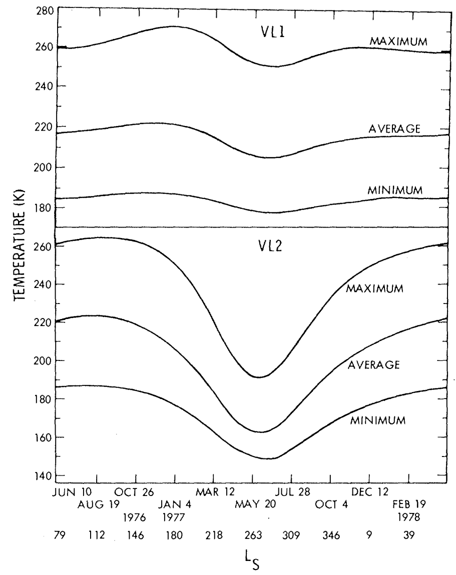

Fig. 1. Daily maximum, minimum, and average surface temperatures at the two Viking landing sites through a martian year. The maximum temperature occurs about 1 hour after noon; the minimum occurs at dawn, which varies from 4 to 8 a.m. at the VL2 site. Nighttime CO_2 frost forms at midwinter at the VL2 site.

If one uses laboratory measurements of particulate silicates at martian surface pressure (*13*), the thermal conductivity derived for the VL1 and VL2 soils can be translated into effective grain diameters of 0.05 and 0.03 cm, respectively (*6*). These values considerably exceed the particle size estimates for the Viking samples (*11*), which suggests that some bonding of the soil is present. Since k for dry, loose materials is determined almost entirely by the nature of the point contacts, it can be appreciably increased by a small amount of bonding. There is indeed evidence for bonding of the near-surface material at both Viking sites (*11*).

The computed range of subsurface temperatures for the Viking soils when sampled is shown in Fig. 2. The diurnal variation decreases exponentially with depth. The temperatures at a depth of 24 cm differ negligibly from the average surface temperature, 217 and 222 K at VL1 and VL2, respectively. The data in Fig. 2 do not include heat exchange with deeper layers; that annual effect causes a gradient of the diurnally averaged temperature of 0.05 and 0.1 K cm^{-1} over these depths at these seasons at the VL1 site and the VL2 site, respectively. The first sample trench at the VL1 site is in what appears to be nearly pure aeolian material. The temperature behavior for this material was calculated on the basis of $I = 6.5$, the average assumed for the equatorial region. Its diurnal range is 7 K greater than for the general VL1 soil, based on the parameters derived above. One can derive approximate values of the subsurface temperatures through the year by scaling the zero depth extremes

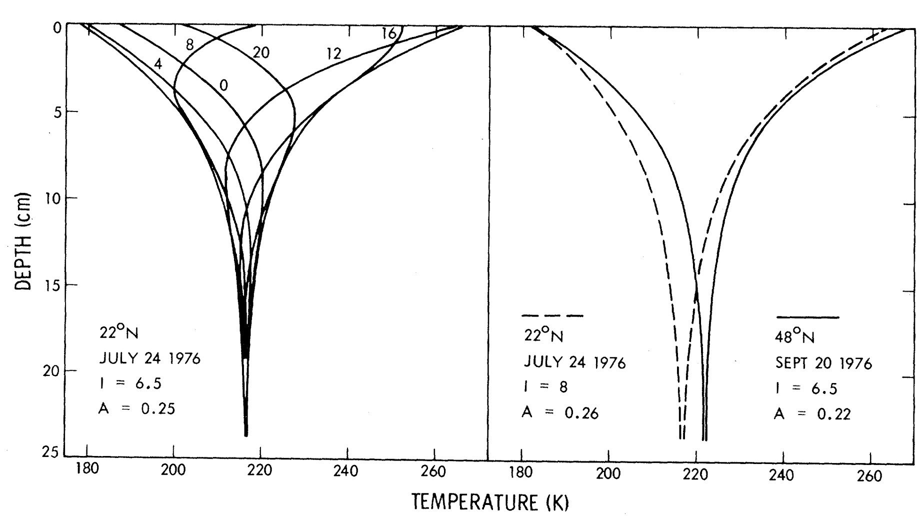

Fig. 2. Temperatures for the soils at the Viking lander sites at the landing seasons. The two envelopes (right) show the temperature extremes as a function of depth for the average VL1 (22°N) and VL2 (48°N) soils. The subsurface temperature profiles for somewhat finer-grained material at the VL1 site are shown at 4-hour (4/24 of a martian day) intervals (left).

and deep average temperature of Fig. 2 to the annual behavior of the surface minimum, maximum, and average values shown in Fig. 1 (*14*).

Although most of the sample trench locations were chosen to be reasonably rock-free, samples were taken from under rocks at the VL2 site. These samples were modeled as a column of soil capped by a 20-cm cubical rock (*15*). The diurnal temperature extremes just under the rock were 201 and 230 K and lagged 1 and 6 hours, respectively, behind the exposed soil extremes. Since temperatures at this latitude are highest at the VL2 landing season, the material sampled from these locations has probably never been warmer than 234 K.

HUGH H. KIEFFER
University of California, Los Angeles

References and Notes

1. H. H. Kieffer, S. C. Chase, Jr., E. D. Miner, F. D. Palluconi, G. Münch, G. Neugebauer, T. Z. Martin, *Science* **193**, 780 (1976).
2. Analysis of the Viking soil samples by the inorganic and organic chemistry experiments and by the three biology instruments are reported in several articles in the 27 August 1976 and 1 October 1976 issues of *Science*.
3. T. A. Mutch *et al.*, *Science* **193**, 791 (1976).
4. H. Masursky and N. L. Crabill, *ibid.*, p. 809; *ibid.* **194**, 62 (1976).
5. T. A. Mutch *et al.*, *ibid.* **194**, 1277 (1976).
6. H. H. Kieffer, S. C. Chase, Jr., E. Miner, G. Münch, G. Neugebauer, *J. Geophys. Res.* **78**, 4291 (1973).
7. G. Neugebauer, G. Münch, H. H. Kieffer, S. C. Chase, Jr., E. Miner, *Astron. J.* **76**, 719 (1971).
8. The general agreement between the brightness temperatures measured in the several thermal passbands of the IRTM suggests that the surface emissivity ϵ is near unity. The difference between measured brightness temperatures and surface kinetic temperatures is approximately $[(1 - \epsilon)/4]T$ and is probably about 1 K.
9. S. L. Hess *et al.*, *Science* **193**, 788 (1976).
10. R. Arvidson, personal communication.
11. R. W. Shorthill, H. J. Moore II, R. F. Scott, R. E. Hutton, S. Liebes, Jr., C. R. Spitzer, *Science* **194**, 91 (1976); R. W. Shorthill, H. J. Moore II, R. E. Hutton, R. F. Scott, C. R. Spitzer, *ibid.*, p. 1309.
12. D. F. Winter and J. M. Saari, *Astrophys. J.* **156**, 1135 (1969).
13. A. E. Wechsler and P. E. Glaser, *Icarus* **4**, 335 (1965).
14. Thermal models to a depth of 2 m have been computed throughout the martian year for each case presented here. The detailed solution can be obtained from the author.
15. The soil column could communicate laterally to the exposed soil thermal profile. The rock had 125 thermal elements; the insolation and the radiative exchange with sunlit and shaded soil were computed separately for each face of the rock.
16. The three-dimensional thermal modeling was carried out by B. Jakosky. Financial support was provided under NASA contracts JPL-952988 and NAS 7-100.

15 November 1976

Temperatures of the Martian Surface and Atmosphere: Viking Observation of Diurnal and Geometric Variations

Abstract. *Selected observations made with the Viking infrared thermal mapper after the first landing are reported. Atmospheric temperatures measured at the latitude of the Viking 2 landing site (48°N) over most of a martian day reveal a diurnal variation of at least 15 K, with peak temperatures occurring near 2.2 hours after noon, implying significant absorption of sunlight in the lower 30 km of the atmosphere by entrained dust. The summit temperature of Arsia Mons varies by a factor of nearly two each day; large diurnal temperature variation is characteristic of the south Tharsis upland and implies the presence of low thermal inertia material. The thermal inertia of material on the floors of several typical large craters is found to be higher than for the surrounding terrain; this suggests that craters are somehow effective in sorting aeolian material. Brightness temperatures of the Viking 1 landing area decrease at large emission angles; the intensity of reflected sunlight shows a more complex dependence on geometry than expected, implying atmospheric as well as surface scattering.*

We report here several examples of martian thermal and reflection behavior as observed with the Viking infrared thermal mapper (IRTM): diurnal variation of atmospheric temperatures in a narrow latitude band; the thermal character of a high-altitude region and several typical craters; and the angular dependence of thermal and reflection properties at the Viking 1 (VL1) landing site. These studies were made possible by release of the lander capsule from the Viking 1 orbiter and by the asynchronous periods of both the Viking 1 and Viking 2 orbiters. First results from this investigation were reported previously (*1*). Additional studies of the north polar cap and landing site surface characteristics appear separately in this issue. Although a large amount of data has been received, thus far it has been possible to do only preliminary analyses of selected areas. The following discussion is intended to demonstrate some of the more obvious examples of how Mars differs from expectations prior to the Viking missions. Since a day on Mars is 3 percent longer than a day on Earth, the time terminology can be confusing. Throughout this report, local time of day is measured in units of 1/24 of a martian solar day, designated H, and is referenced to midnight.

Atmospheric temperatures. The 15-μm channel measures the thermal emission of atmospheric CO_2. Weighting functions for air masses between 1.0 and 6.0 are shown in Fig. 1 (*2*). Since our first report (*1*) global atmospheric temperatures have continued to show a strong latitudinal dependence in southern latitudes and diurnal variation as the predominant effect in the north. There is no evidence to date of fine spatial structure in the 15 μm brightness temperature (T_{15}) that would indicate the entrainment of dust by local dust storms to the pressure levels which are sampled. The decrease in T_{15} toward the limb (limb darkening), caused by the sampling of higher altitudes for oblique viewing, complicates the separation of the diurnal and latitudinal effects; deconvolution has been applied in one case to separate the diurnal variation in a latitude band.

A large amount of data on atmospheric temperatures in the + 40° to + 55° latitude band was acquired during site selection for the second Viking lander (VL2). Direct measurement of the vertical temperature profile during lander entry (at 9 H, 3 September 1976) resulted in the classic combination of remote global sensing and "ground truth," and provided an accurate means of correcting the global data for limb darkening and thus deriving the magnitude and phase of the diurnal variation. The entry temperature profile for VL2 is shown in Fig. 2. Wave structure evident above 20 km has been interpreted in terms of thermal tides (*3*). Based on the inferred smooth mean profile (*4*) above 20 km and the measured profile below that level, a prediction was made for the T_{15} values that would be measured with the IRTM at different air masses. This modeling incorporated the broadening of weighting functions that results from the finite size of the IRTM field of view. The predicted values were found to follow closely the function:

$$T_X = T_{1.0}X^{-0.027} \tag{1}$$

where X is the air mass. This function was applied to measured T_{15} values in the data from revolutions 5 to 15 of the Viking 2 orbiter (13 to 24 August 1976) to reduce them to air mass 1.0. Reduced temperatures from the latitude band + 46° to + 50°, involving an average air mass correction of 1.5 K, show a marked diurnal variation (Fig. 3). The data are fit well by a sinusoid having the expression:

$$T_{15}(t) = 175 + 10 \cos \left(\frac{\pi t}{12} - 3.74 \right) \tag{2}$$

where t is in H units. Although 15/24 of the day is covered, it is possible that a minimum is reached near dawn (~ 4.5 H) and that the true minimum is not as