# SURFACE EROSION CAUSED ON MARS FROM VIKING DESCENT ENGINE PLUME*

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**Abstract.** During the Martian landings the descent engine plumes on Viking Lander 1 (VL-1) and Viking Lander 2 (VL-2) eroded the Martian surface materials. This had been anticipated and investigated both analytically and experimentally during the design phase of the Viking spacecraft. This paper presents data on erosion obtained during the tests of the Viking descent engine and the evidence for erosion by the descent engines of VL-1 and VL-2 on Mars. From these and other results, it is concluded that there are four distinct surface materials on Mars: (1) drift material, (2) crusty to cloddy material, (3) blocky material, and (4) rock.

## 1. Introduction

Extensive investigations were made of the effects of the Viking lander's terminal descent engine on simulated Martian surface materials during the design of the lander. The major portion of the investigations arose because the primary goal of the Viking Mission – the search for life on Mars – was to be accomplished by analyses of surface samples collected from an annular sector extending out to about 3 m in front of the lander. The onboard analytical experiments required that the amount of heating and erosion of surface materials by the descent engine gas plume be restricted so as not to affect the results of the analyses. Restrictions were also placed on the chemical constituents of the rocket gases to avoid undesirable chemical reactions with the Martian surface materials.

Another concern of the Viking Project was the influence of surface erosion on landing stability. This secondary concern was not unique to the Viking Program but had been studied in detail during the earlier Surveyor and Apollo Lunar programs (Roberts, 1968; Scott and Ko, 1968; Alexander *et al.*, 1966; Choate *et al.*, 1969; Hutton, 1971). Those earlier programs were largely concerned that the craters formed by the descent engines must not be large enough to cause the spacecraft to overturn during touchdown. This possibility took on added importance for the Viking lander because the Martian atmosphere would cause the engine plume to focus and produce higher impingement pressures than would be produced in the lunar environment. Other questions investigated were related to the dust and debris cloud created by the impinging gases. Items of concern were whether the cloud would substantially degrade the performance of the landing radar or

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the astronauts' vision, or whether debris would strike and damage the spacecraft. Most of these secondary questions were also considered during the Viking Program. Because of the experience gained during the lunar programs, Viking engineers were confident of their theoretical predictions related to the erosion that would be produced by the Viking Lander engines during landing.

The life detection experiments on the Viking Program presented new and challenging questions. Because of the potential for surface contamination, stringent requirements were placed on the descent engine to ensure minimal disruption of the Martian surface. The requirements were as follows:

(1) no more than 60% of the sample area shall experience more than 2 mm of erosion;

(2) the maximum allowable crater depth shall be 5 cm;

(3) no more than 8 mm eroded material shall be redeposited within the sample field, and

(4) no more than 20% of the sample acquired from the top 4 cm shall have been heated in excess of 40°C for at least 60% of the sample field.

Although these criteria were appropriate for mission objective such as the detection of life, they are in direct conflict with the goal of deducing physical properties of the Martian surface from erosion data. For that purpose, deep and extensive erosion is most desirable. Nonetheless, interactions of the exhaust gases with the surface materials did provide important information about their properties.

## 2. Erosion During Viking Terrestrial Tests

A series of tests were conducted during the engine design phase to assess the erosion characteristics of the various nozzle designs under consideration. In these tests, single-nozzle engines were found to produce excessive erosion in particulate materials under Mars atmospheric conditions because of the pressure distribution in the focused plume. In order to distribute the exhaust gas pressure more uniformly, a cluster of small nozzles was designed and tested. The test sequences consisted of simulated landings while the engine exhaust gases impinged onto surface covered with 'soils' of two different kinds. Tests also included measurements of impingement pressures on a flat, instrumented metal plate.

The findings from these tests led to the selection of an 18-nozzle configuration for the Viking landers. This configuration consists of 18 nozzles 3.734 cm in exit diameter arranged in two rings. The outer ring contains 12 nozzles canted 20° from the engine center line. The inner ring contains 6 nozzles canted 12° from the engine center line.

### 2.1. Impingement Pressures

Impingement pressures of a Viking engine were measured during its descent from 12.283 m down to 0.762 m at 1.56 m $s^{-1}$ (Romine *et al.*, 1973). During descent, the engine thrust level was 685 N and the engine chamber pressure was 451 kN $m^{-2}$. The pressure in the vacuum sphere increased from an initial pressure of 10.32 mbar to 19.30 mbar during the total 10.14 s engine burn time. The pressure measured at the center line impingement

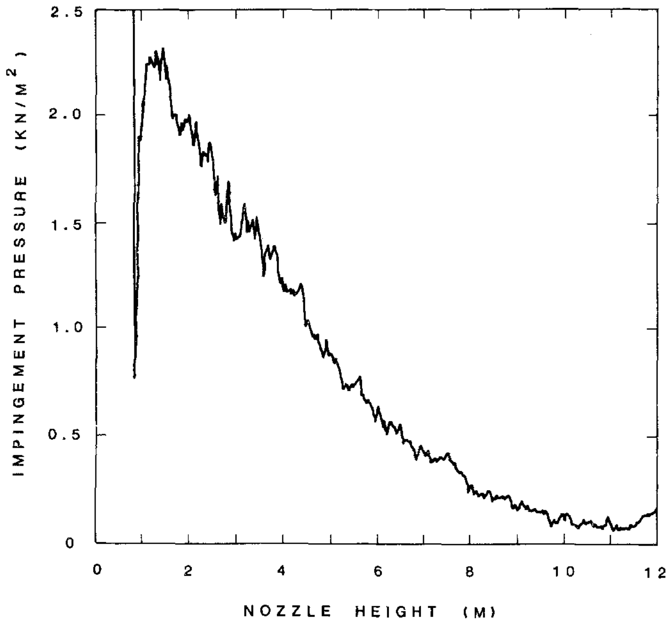


Fig. 1. Center-line impingement pressures and nozzle height for Viking lander terminal descent engine (Romine *et al.*, 1973; White Sands Test Facility Phase II – Test 11 K).

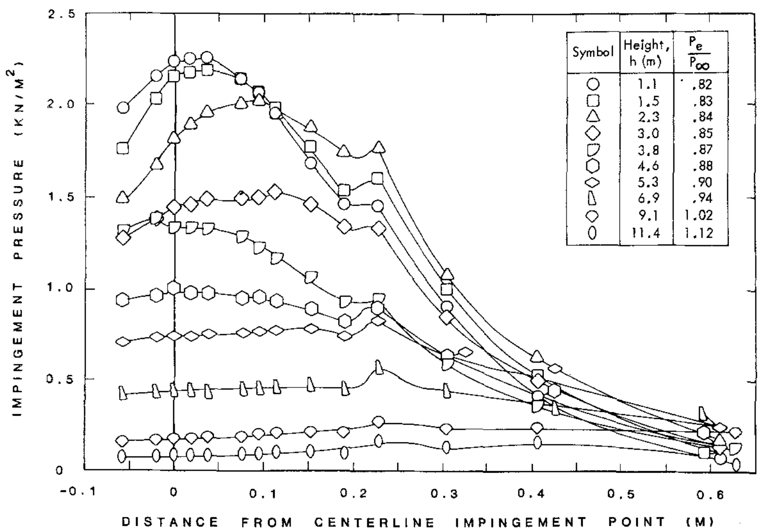


Fig. 2. Impingement pressures and distances from center line of impingement point for Viking lander terminal descent engine (Romine *et al.*, 1973; White Sands Test Facility Phase II – Test 11 K).

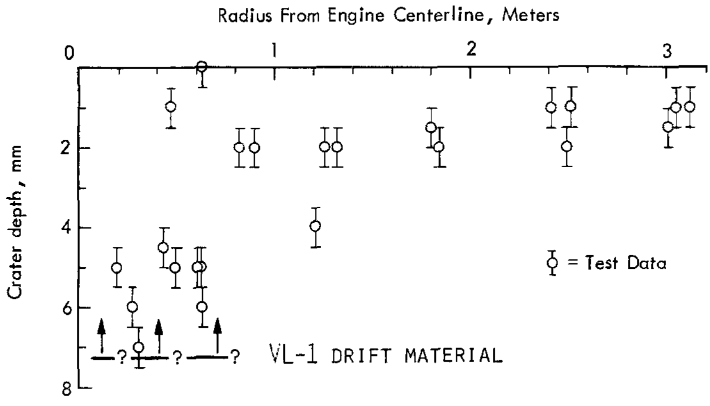


Fig. 3. Depths of crater produced by gas plume erosion of the lunar nominal model during test of Viking lander terminal descent engine (Romine *et al.*, 1973; White Sands Test Facility Phase II – Test 12 E).

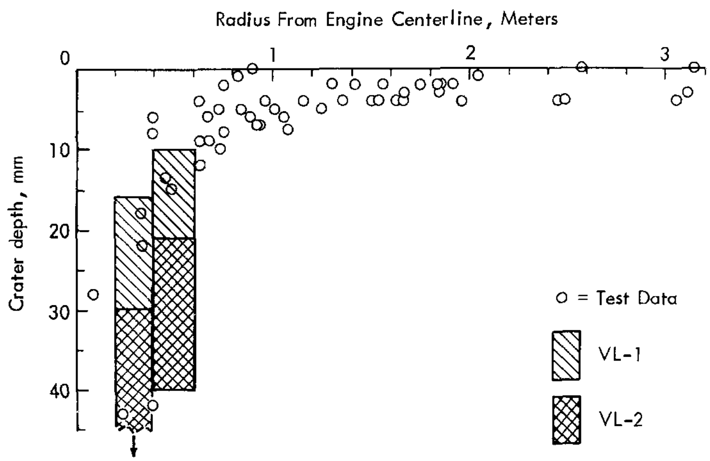


Fig. 4. Depths of crater produced by gas plume erosion of dune sand model during test of Viking lander terminal descent engine (Romine *et al.*, 1973; White Sands Test Facility Phase II – Test 12 F).

point increased as the engine descended (Figure 1). The peak impingement pressure of about 2.28 kN m$^{-2}$ occurred when the nozzle was about 1.3 m above the surface.

A comparison of this peak pressure with those exerted by the Surveyor and Apollo descent engines indicates the peak impingement pressure for all three spacecraft were similar in magnitude. For examples, the peak pressures exerted by the three-vernier engines during the static firing of Surveyor V ranged from 1.8 to 2.9 kN m$^{-2}$, while the peak pressure exerted during the Surveyor VI Lunar 'hop' ranged from 6.9 to 15.5 kN m$^{-2}$ (Choate *et al.*, 1969, Table 4-3). The peak pressure exerted by the Apollo descent engine just prior to landing was about the same as produced by Surveyors V and VI (Hutton, 1971, Figure 29).

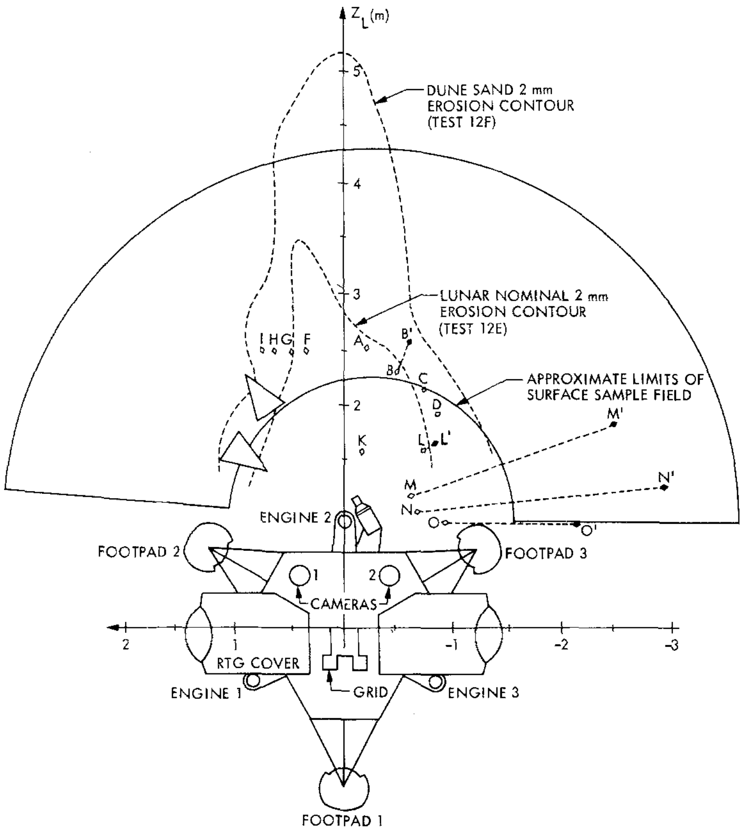


Fig. 5. Results of erosion tests for a single terminal descent engine superposed on Viking lander plan view and centered on engine 2. Dashed lines are contours including erosion depths of 2 mm or more (Romine *et al.*, 1973; White Sands Test Facility Phase II – Tests 12 E and 12 F); open diamonds represent locations of small rocks on test bed before Test 12 E; letters identify rocks; filled diamonds represent locations of small rocks on test bed that moved during Test 12 E; primed letters identify rocks; dashed lines join original and final positions of rocks that moved; large triangles show locations and sizes of wedges of test material.

The radial variation of impingement pressure, measured along a single radial line, is shown in Figure 2. The pressures shown for the higher nozzle heights should be representative of those at any azimuth, because the flow from the 18 nozzles would have been well mixed and nearly axisymmetric. As the nozzles approach the surface, the flow pattern becomes less axisymmetric, and the pressures measured along the single radial line must be considered to represent estimates of the average impingement pressure over all azimuth angles.

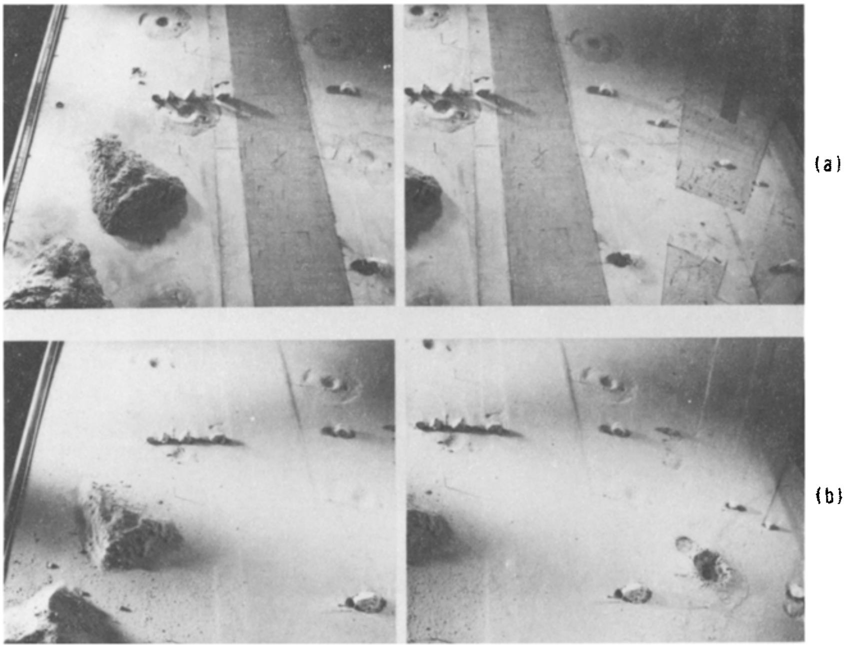


Fig. 6. Stereoscopic views of the (a) pre-test surface and (b) post-test surface for test using lunar nominal model (see Figures 80 and 81 of Romine *et al.*, 1973, Test 12 E). Right-hand photograph of (a) shows rocks I, H, G, and F aligned by crater (upper left part), K and L are in lower right, and A, B, C, and D form line from upper center to right center (compare with Figure 5); movement of rocks K and L can be seen by comparing right-hand photographs of (a) and (b). Note partial filling of craters in (b). Fresh appearing crater in lower right corner of right-hand photograph of (b) produced by post-test shear vane measurement. Dark stripe of test material is 0.3 m wide.

## 2.2. Surface Erosion During Terrestrial Tests

Erosion depths measured after the engine descended to surfaces covered with Lunar nominal test material * and dune sand ** were a function of distance from the engine centerline (Figures 3 and 4). Most of the surface sample field was eroded less than 2 mm, as required by the design criteria (Figure 5). For lunar nominal, less than 5% of the sample field was eroded to depths greater than 2 mm and, for dune sand about 20% was eroded to depths greater than 2 mm. During the test with the Lunar nominal soil, the engine descended at 1.61 m $s^{-1}$ from 12.25 m to 0.65 m above the surface. During the constant speed descent, the engine thrust level was 665 N. The initial and final nozzle heights were

* The Lunar nominal (Hazen) model was made from a volcanic rock (latite) aggregate from Table Mountain, Golden, Colorado, so as to simulate the particle size distribution of a lunar regolith sample returned from the Apollo 11 mission; it is well graded and weakly cohesive ($\simeq 10^3$ N $m^{-2}$); 90 wt.% has a grain size between 13 and 1200 $\mu$m, and the median is 60 $\mu$m (Test 12E, Romine *et al.*, 1973).

** The dune sand was volcanic sand collected from a dune near Sunset Crater, Arizona in the Elden Ranger District of the Coconino National Forest; it is poorly graded and cohesionless; 90 wt.% has a grain size between 230 and 1100 $\mu$m, and the median is 600 $\mu$m (Test 12 F, Romine *et al.*, 1973).

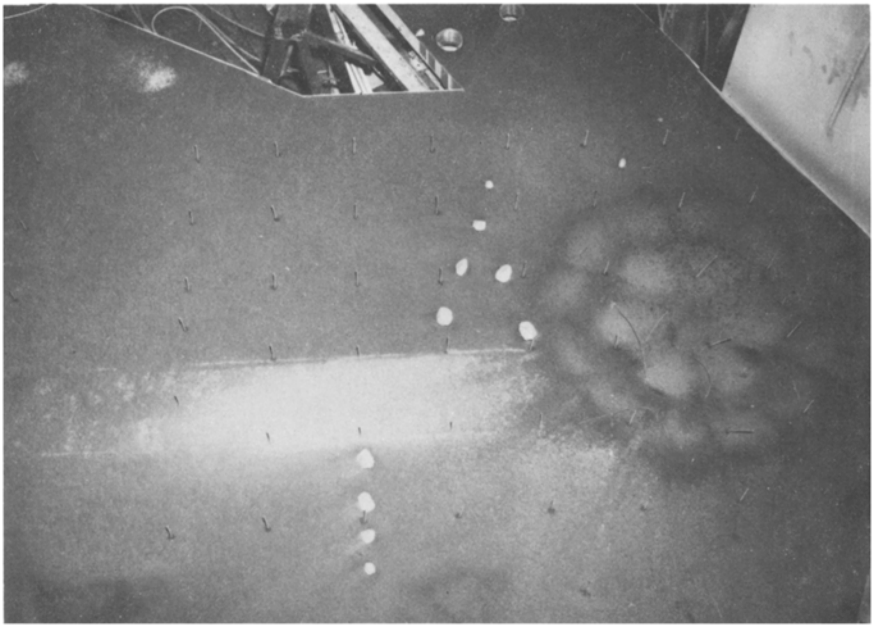

Fig. 7. Photographs of post-test surface for test using dune sand (see Figure 88 of Romine *et al.*, 1973, Test 12 F). Light-floored craters and dark crater rims form rosette pattern at right center; there are 18 craters (with light-colored floors) which were produced by the 18 nozzles of the terminal descent engine. Small light-colored rock at edge of test bed of upper center was moved to its location by exhaust gases; large light-colored rock nearest rosette and line of rocks was also moved; other rocks were not displaced outward.

the same in the dune sand tests, but the descent rate was $1.64 \mathrm{~m~s}^{-1}$ and the engine thrust level was 667.2 N. Also shown on Figures 3 and 4 are estimates of erosion depths produced on Mars during the landings.

On the Lunar nominal surfaces, the area directly below the engine center point was severely scrubbed and did not exhibit a discrete crater, nor were there smaller craters corresponding to the individual nozzles. In contrast, when the gases impinged onto the dune sand, a central area measuring 1.5 m in diameter was cratered by the gases. Within this area 18 small craters corresponded to the 18 nozzles of the engine. The deepest depression in the middle of the crater was 3.8 cm below the original surface. Ridges formed between the depressions were 3.8 cm above the original surface, producing a total topographic relief of 7.6 cm. Various rocks, wedge-shaped mounds of 'soil', and craters were present in the test bed. Five of the thirteen rocks on the Lunar nominal test bed moved during the test (Figures 5 and 6). Both low- and nominal-density soil wedges showed similar changes. No change in surface relief was detected, but the surfaces of the wedges were slightly roughened by the exhaust gases. Facets of fluffy, low-density soil wedges facing the engine were extensively scrubbed, and craters near the engine were partly destroyed by erosion and deposition.

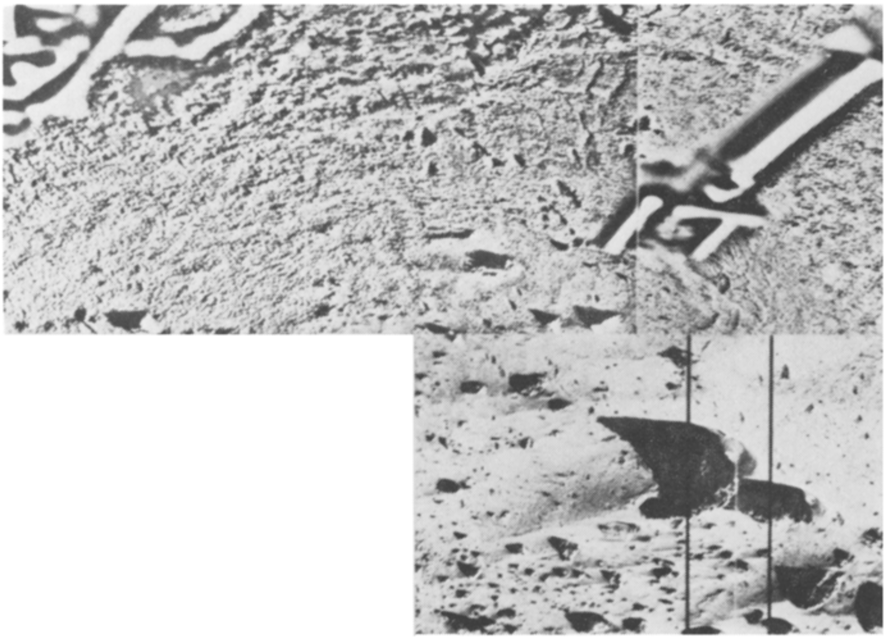

Fig. 8. Craters and tracks in drift material produced by rocks or clods dislodged and propelled by the terminal descent engine exhaust gases of Viking Lander 1 during landing. Alignment of pits and their elongations suggest exhaust gases from engine 2 and engine 1 dislodged the clods or rocks; pits are several millimeters across. Area of view is sector between footpad 2 and engine 2 (compare with Figure 10). Rod and brush at lower left is the backhoe magnet cleaning device; cables and other spacecraft appear at lower right.

In the dune sand test, the objects having greatest topographic relief suffered the most erosion (Figure 7). The features appeared to be sandblasted; surface features with relief were cleanly cut away near the engine, and those at some distance were neatly faceted. Some rocks actually tumbled radially inward because their bases were undercut by the faceting action.

### 3. Soil Erosion During Martian Landing

Pictures of the Martian surface showed clear evidence of erosion produced during the landing. The first evidence of erosion is found in the first pictures taken by both landers starting 25 s after touchdown, in which the surface was obscured at the beginning part of each picture. This obscuration is believed to be a dust cloud created during landing (Moore *et al.*, 1977). Small elongated craters formed along radial lines primarily emanating from the axis of the landed position of engine 2. These craters appear to have been formed by fragments or clods propelled by the engine exhaust gases. Especially good examples of these impact craters were produced in *drift material* (terminology of Moore *et al.*, 1979) on the left side of the lander near footpad 2 (Figure 8).

a

b

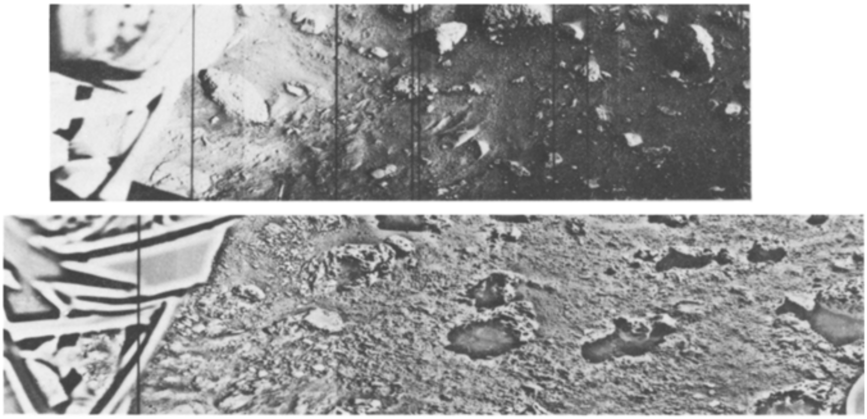

Fig. 9. Sectors of surface between engine 2 and footpad 3 of (a) Viking Lander 1 and (b) Viking Lander 2 (compare with Figure 10). Base of surface sampler boom housing and mounting frame appear in left part of both (a) and (b) and edge of footpad 3 appears in lower right corner of (b). In (a), note surface material has been stripped away so that fractured, planar substrate is exposed and rim of erosion crater with fragments to 1 cm across (in lower left – a); near center some rocks or clods have been removed by exhaust gases. In (b), note rim of erosion crater with fragments to 2 cm across and strewn fragments beyond rim (in lower left – b); craters and tracks produced by clods and rocks may be seen at lower right of (a).

For both landers, the engine 2 exhaust gases scrubbed the surface, removing a layer of fines and exposing the coarser material below (Figures 9(a) and 9(b). The erosion craters produced in front of the landers had rims of mixed fine material and platy equidimensional fragments of soil and rocks. At VL-1, the erosion crater produced in the *blocky material* (Moore *et al.*, 1979) on the right side of engine 2 has fragments with intermediate diameters near 1 cm embedded in the rim about 0.5 m from the engine center line. Thus, the depth of erosion was probably 1–2 cm. In contrast, the direct views of the drift material to the left of the engine do not show extensive scouring, despite the fact that the spacecraft tilt should have favored more erosion there (see Figure 10). Thus, the evidence indicates the blocky material of VL-1 is more susceptible to exhaust gas erosion than the finer grained drift material of VL-1.

In *crusty to cloddy material* at VL-2 (Moore *et al.*, 1979), there appears to be more erosion on both sides of engine 2 than at VL-1. The rims of the craters are less clearly defined. At distances near 0.5 m to 0.6 m from the engine center line, fragments of rocks and soil exposed in the rim are roughly twice as large as those at VL-1. Thus the exhaust gases may have eroded to depths of 2–4 cm.

The rims of the erosion craters determined from the Martian pictures are outlined in the plan view drawing shown in Figure 10. The sketch shows, for example, that the erosion crater was primarily confined to the area between the lander and the sample field. The slightly larger erosion crater of Lander 2 probably was due to the sudden increase in thrust that occurred about 0.4 s before the touchdown of Lander 2 (Shorthill

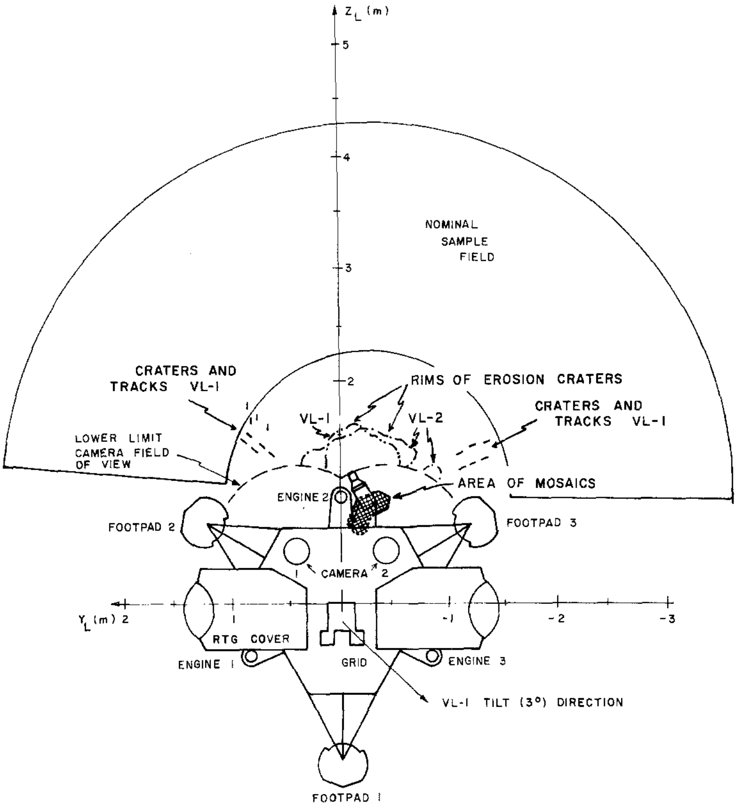


Fig. 10. Plan view sketch showing location of rims of craters produced by engine 2 exhaust gases. Crater rim for VL-1 is about 0.5 m from the engine center line; crater rim for VL-2 is generally 0.6–0.7 m from engine center line. Data do not permit delineation of 2 mm erosion contour as in Figure 5. Location of craters and tracks of Figure 8 appear to left of erosion crater rim; those of Figure 9(a) appear above footpad 3. Patterned area near camera 2 indicates locations of area on surface of mosaics in Figure 11.

*et al.*, 1976). Also indicated in Figure 10 are the locations of the elongated impact craters that were produced by clods and debris propelled by exhaust gases in the drift material around VL-1.

Pictures of the Martian surface beneath the right side of engine 2 of both landers were obtained using mirrors mounted on the boom housing. Mosaics of seven individual pictures beneath each engine 2 reveal the characteristics of the eroded surfaces (Figures 11(a) and 11(b)). Each mosaic covers an area approximately 10–20 cm wide and 50 cm long. The areas lie within 0.1 m to 0.5 m of the engine center line (Figure 10). The VL-1 surface (Figure 11(a)) is dominated by a single large crescent-shaped crater, approximately 10 cm by 20 cm, eroded by the engine exhaust gases to a depth of about 1 cm. This crater apparently lies within the larger crater observed in direct views of the surface in front of the lander, because its center is about 0.3 from the engine center line. The corresponding total topographic relief for VL-1 is then estimated to be about 2.0–3.0 cm

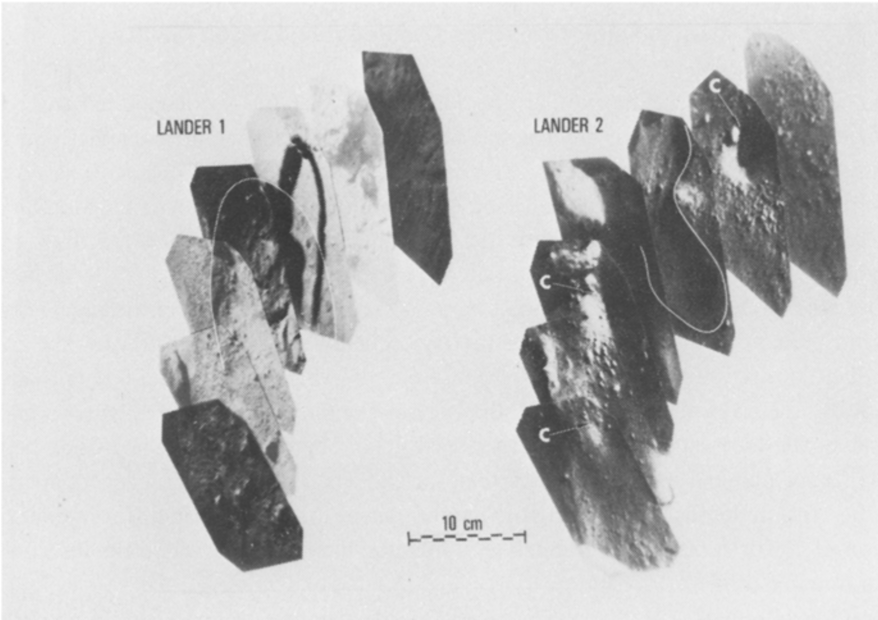


Fig. 11. Mosaic of pictures to right of engines 2 of Viking Landers 1 (left) and 2 (right). Approximate location of pictures indicated in Figure 10. Radial symmetry suggests that the areas covered by mosaics are chiefly within the rim of a larger erosion crater. The surface of Lander 1 is dominated by a large crescent-shaped crater (outlined in white) about 1 cm deep and centered about 0.3 m from the engine center line; an 8 cm rock occurs in the upper part of the second and third frames from the top; dark area in the third frame from the top is the shadow of a spacecraft part; note residue of lumps, clods, and fractured chunks over most of surface. The surface of Lander 2 shows three craters (labelled C) produced by gases from three of the 18 nozzles; craters are about 6 cm across and as deep as 2.5 cm; a large kidney-shaped depression (outlined in white) was probably produced by gas flow across rock seen in the upper parts of the fourth and fifth frames from the top. Sun is to the left in the Lander 1 mosaic (Sun angles from top to bottom are 41.3°, 42.5°, 76.4°, 53.0°, 46.3°, 39.5° and 25.8°). Sun is to the right in the Lander 2 mosaic (Sun angles vary from 26.7° at top to 22.3° at bottom).

beneath the engine. Flat surfaces of cohesive material have been exposed on the bottom of the crater. The VL-2 mosaic (Figure 11(b)) is strikingly different from that of Lander 1 because three small craters, marked 'C', are present. Each crater, about 6 cm across, was probably produced by exhaust gases from separate nozzles of the engine. These small depressions also apparently lie within the larger crater observed by direct viewing in front of the lander, because they are about 0.3 m from the engine center line. The crater near the top of the scene is about 1.9 cm deep. The total depth of these craters is about 4–8 cm below the original surface when their depths are added to the estimated depth of the larger crater. Small ridges are visible around the craters in the VL-2 mosaic. The kidney-shaped depression outlined in the VL-2 mosaic was caused by exhaust gases deflecting around the exposed corner of a rock. Rocks and clods ranging in size from about 1 mm to 10 cm are visible in both mosaics.

## 4. Martian Surface Properties Deduced from Erosion Results

In an overall sense, the erosion of the Martian surface by the engine exhaust gases indicates that the amount of erosion was not substantially different from that observed during the earlier Earth-based tests. As a result, it appears that the engine design objectives of limiting erosion were indeed met. Upon a closer examination of the Martian surface erosion and a comparison with the Earth-based test results one can draw some general conclusions concerning the Martian surface materials.

The erosion depth estimates for VL-1 were 1–2 cm about 0.5 m from the engine center line and perhaps an additional 1 cm in the region below the engine. For VL-2 the corresponding depths were 2–4 cm about 0.5 m from the engine center line and perhaps an additional 1.9 cm in the region below the engine. The Earth-based tests (Figures 3 and 4) indicated the dune sand erosion depths ranged up to about 4 cm, and the erosion depths in the Lunar nominal model were less than 0.8 cm. The Martian erosion depths are more like the erosion depths in the dune sand model, except for the Martian drift material. The erosion of the drift material was much less and more like that observed in the tests on the Lunar nominal model.

Another observation that suggests the coarser Martian surface material is more like the dune sand is indicated in the erosion response to the 18 individual nozzles of the engine. The VL-2 mosaic shows evidence of three individual craters formed within the field of view below the engine (Figure 11b), much like those in the dune-sand surface (Figure 7). The Lunar nominal test surface did not show distinct craters but rather a general scrubbing of the surface.

These observations imply that the Lunar nominal test material compares best with the Martian drift material seen at VL-1 and the dune-sand model compares best with the coarser Martian surface materials around VL-1 and VL-2. The observed erosion of Mars, when combined with other data, places some constraints on the grain size of the surface materials. Because trenches excavated by the surface sampler show that drift material has a very low cohesion, like that of Lunar nominal (Moore *et al.*, 1977), the small amount of erosion by the exhaust gases suggests that the grain size of drift material is equal to or smaller than that of the lunar nominal model. Blocky and crusty to cloddy material appears to have rather large effective grain diameters that are comparable to those of dune sand. These materials are, in contrast with dune sand, composed of materials ranging from clods and rocks a centimeter or so across to grains below the limit of photographic resolution ($\simeq 0.07$ cm).

These erosional observations, along with information provided by the lander cameras, surface sampler operations, comminution of the soil samples, and other data sources, have resulted in a grouping of the surface materials at the Viking sites into four categories (Moore *et al.*, 1979):

*drift material* (at VL-1);
*crusty to cloddy material* (at VL-2);

*blocky material* (at VL-1);
*rocks* (both VL-1 and VL-2).

The *drift material* is fine grained and the weakest of the four categories but the most resistant to erosion by exhaust gases. The *crusty to cloddy material* appears to be stronger than the drift material and is more easily eroded by exhaust gases. The *block material* appears to be the strongest soil-like material and is more easily eroded by exhaust gases than drift material. *Rocks* are the strongest of all the categories, and stationary ones were not eroded by the exhaust gases. None of the rocks appear to have been chipped, scratched, or spalled when pushed or pulled by the surface sampler collector head and backhoe. During the VL-2 landing, footpad 3 landed on a rock. Photographic evidence does not reveal any fracturing, crushing, or spalling of the rock as a result of the landing impact.

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