BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B70 03071

SUBJECT: Impairment of Terrain Visibility During LM Descent - Case 340

DATE: March 25, 1970

FROM: J. S. Dohnanyi
M. Liwshitz
T. T. J. Yeh

ABSTRACT

An analysis of a dust cloud generation by an exhaust plume suggests that the trajectory difference between Apollo 11 and Apollo 12 cannot alone explain the better visibility on Apollo 11. The lower trajectory of Apollo 11 should have produced more dust. While uncertainties in both theory and data preclude understanding at this time, turbulent effects, related to surface roughness on a strictly local scale, can be shown to be a plausible cause of difference. A semi-quantitative analysis of visibility suggests that the higher sun angle (11°) at the Apollo 11 site, relative to that at the Apollo 12 site (5°) was advantageous but could explain the difference only if the thickness of the dust layer generated in Apollo 11 was less than twice that in Apollo 12. If the illumination angle is dominant, Apollo 13 (nominal sun angle 9.9°) should have good visibility, comparable with Apollo 11, and better if an Apollo 12 descent is made. Recommendations for further study are made.

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MEMORANDUM FOR FILE

A. Introduction

As expected, during the terminal phase of LM descent in Apollo missions 11 and 12, the lunar surface was disturbed by the impact of the descent engine exhaust plume, and during the final ∿15 seconds moving sheets of dust totally obscured the astronaut's vision of surface features. Unless exclusive instrument landing is resorted to, the loss of ground vision may somewhat impair crew performance in the last moments before touchdown. A rough quantitative assessment of the dust problem appears, therefore, desirable, aimed at either prescribing descent maneuvers capable of alleviating ground obscuration, or at least predicting its onset and extent so as to reduce the crew's disorientation. Unfortunately, as will appear in the following, the theoretical basis for such an estimate is not firm enough, relevant physical parameters are too poorly known, and available empirical data are too ambiguous, so that no definite diagnosis of the dust problem is feasible at this time. Review of the evidence from the past two Apollo landings leads also to the recognition of additional factors to be taken into account for a realistic assessment of the dust problem.

This evidence consists of transcripts of the real-time voice communications with the astronauts of Apollo 11 and 12,[(1)(2)] the sequence camera descent pictures from the two missions,[(3)(4)] the astronaut debriefings,[(5)(6)] and the post-flight trajectory analysis.[(7)(8)]

Cursory inspection of the records indicates that dust became noticeable about 50-60 seconds before touchdown in both missions, and that ground visibility was gradually impaired, until total obscuration occurred in the last ∿15 seconds. Initial reports, coupled with faulty timing of the sequence camera pictures on Apollo 11[(9)] created the impression that visibility was far more seriously degraded in Apollo 12 than in Apollo 11, implying that equal rates of erosion occurred

in Apollo 12 at greater vehicle altitude than in Apollo 11. Later revised analysis of the LM descent profile in the two missions has somewhat reduced the contrast in altitude dependence of ground visibility between the two missions; but a noticeable difference still persists[10] (See Figure 1).

In searching for potential causes of the observed difference, generally only two factors have been taken into account; namely, the possible difference in soil properties at the two landing sites and the distinct LM descent profiles in the two missions. Available evidence from lunar soil samples and from oral and visual records of astronaut motion on the surface indicate at least qualitative similarity of soil properties at the two sites, though significant quantitative differences in dynamic properties cannot be excluded, before appropriate tests are performed. At any rate, results of such tests are not likely to ameliorate the visibility problem in future missions, since the soil properties of future landing sites become accessible only after landing, either through in situ testing of soil or by return of soil samples for later study on earth.

The other possible alternative that the different descent profile caused the observed difference in visibility appears therefore quite attractive.[10] Choice of proper landing trajectories would in principle eliminate the worst effects of dust obscuration.

It is the purpose of this note to examine this hypothesis, and in the light of the scant experimental evidence to assess the role of the descent trajectory as the major determinant of the observed difference, as well as to simultaneously point to other factors that are likely to effect surface erosion and dust entrainment. Such a factor may be turbulence, related to local surface roughness, the presence of boulders, etc. If these factors indeed play a major role in the generation of dust clouds, advance prescription for the amelioration of the dust problem appears to be very difficult.

B. A Look at the Mission Records, Related Experimental Results, and Theoretical Considerations

The chief source of information on dust impairment of visibility during the terminal LM descent are the on-board sequence camera films from the two past flights. Once the

correct frame rate is established, inspection of the photographs yields the time sequence of visibility degradation by dust. Although visual inspection entails some subjective judgment about the exact time of onset of the consecutive major phases in the process, this appears to be a minor source of uncertainty. The major source of ambiguity lies in the correlation of time and vehicle height, which was obtained by either correlating the photo time sequence with the time record of altitude obtained from flight instruments - radar altimeters, accelerometers - or by a geometrical analysis of the sequence photos themselves. The time record of horizontal motion is also obtained by means of the former method.

Figure 1 and 2 present the relevant portions of the vertical descent profile and of the terminal horizontal motion in Apollo flights 11 and 12. If the dust abundance between the LM and the surface were only dependent on the vertical LM distance from the dust source at the surface, and the surface soil properties were the same at the two landing sites, it becomes evident from Figure 1 that visibility should have been degraded earlier in the Apollo 11 LM descent than in that of Apollo 12, independent of the particular choice between the two Apollo 11 descent profiles shown. But the reverse occurred, and if one is willing to admit that the intrinsic soil properties at the two sites were similar, the cause of difference has to be sought elsewhere.

In a discussion of the present problem by Scott[10], the difference in the dust production between Apollo 11 and 12 was tentatively attributed to the difference in their respective LM trajectories. It will be shown, however, that a more detailed, though still semi-quantitative, application of Scott's model leads to the inference that, keeping other factors constant, the known difference in the LM trajectories provides for greater surface obscuration by dust on Apollo 11 than on Apollo 12. This is, of course, contrary to observation.

Scott pointed out that the abundance of dust, generated by the exhaust plume interaction depends on the instantaneous local flow field of the exhaust gases as well as on the penetration of these gases into the surface, causing a delayed release of dust from the surface. Thus the observed dust abundance reflects not only the instantaneous intensity of the gas impact from the descent engine, roughly proportional

to the inverse square distance, h, of the engine to the surface, but is a time varying quantity that depends on the release of dust by means of gas diffused into the surface from impact of the engine exhaust plume. The amount of dust released in this manner will depend on the ratio $\Delta t/\tau$, where Δt is the exposure time of the surface to the vehicle exhaust plume, and τ is the characteristic time constant for the transfer of momentum from the diffusing gas to dust particles. A convenient measure for Δt is the nozzle exit diameter d divided by the horizontal velocity, V_H so that this ratio becomes $\frac{d}{V_H\tau}$. This momentum transfer being a rate process, a plausible form for the observed erosion rate, dy/dt, resulting from this process is then:

$$\frac{dy}{dt} \sim 1 - \exp\left(-\frac{d}{V_H\tau}\right) \tag{1}$$

where y is dust mass released per unit area. Once released, the dust is entrained in the deflected flow of the exhaust plume, moving with roughly constant velocity, which by orders of magnitude exceeds the typical vehicle horizontal velocity. Consequently, an observer looking in the forward direction of a moving vehicle, as was the case in the Apollo missions, will perceive an amount of dust proportional to the instantaneous erosion rate, given by Equation (1). In the backward direction, the situation is more complicated because the gas flow will entrain dust from past impact of the exhaust plume, if $\frac{d}{V_H\tau} < 0(1)$.

In these terms it is easy to predict a sharp contrast between visibility experienced by an observer on a vehicle hovering at given height and that experienced by an observer on a vehicle passing over the same area at the same height, but with appropriate horizontal velocity. The former would see a fully developed dust cloud [$\frac{d}{V_H\tau} \to \infty$ in Eq. (1)], whereas the amount of dust in the moving observer's line of sight would be reduced by an amount proportional to $\exp(-d/V_H\tau)$. Straight extrapolation from this particular situation seems to have led to the erroneous recognition of the trajectory difference as the chief determinant of the observed visibility differences between Apollo 11 and 12.

Before refuting the validity of this diagnosis, it is necessary to consider the salient features of the postulated time dependent process. That the erosion rate is not a pure function of nozzle altitude can be demonstrated from the results of laboratory tests on dust erosion.[11] In these tests, conducted in a vacuum chamber, a rocket engine nozzle was lowered towards a 4-inch deep surface layer of "soil", composed of particles of a given size, and the depth of erosion was measured as a function of time and radial distance from the stagnation point. In the course of the experiment, both engine and soil parameters were varied to study their parametric effect on soil erosion.

If response of the soil to the engine exhaust were instantaneous, and the erosion rate depended only on engine height, the erosion rate would stay constant after termination of nozzle descent. Unfortunately only the results of a few of the 32 tests performed contain pertinent information; in most tests, either thrust was cut off too soon, or the entire depth of the "soil" was eroded before end of descent. But in those cases where erosion was measured for sufficient length of time, the end of nozzle descent was not followed by a constant erosion rate. In several instances, the slope of maximum depth of erosion, y_m, changes with time in a manner compatible with an erosion rate dy/dt.

$$\frac{dy_m}{dt} \sim 1 - \exp\,(-t/\tau) \tag{2}$$

where t is time after end of nozzle descent, and τ the characteristic time of the process. This is the characteristic time dependence of a rate process, which dust release must be, if affected by diffusion of exhaust gases into the surface.

As far as quantitative estimates are possible from the test results, the typical value of τ appears to be on the order of seconds, in agreement with a rough theoretical estimate presented in Appendix A, rather than on the order of hundreds of seconds, the value quoted in Reference (10). But the crucial point has to be recognized (see Appendix A) that τ does not depend solely on the intrinsic soil properties but also on the ambient gas pressure at the surface. For an engine descending with constant thrust, this means that τ varies with altitude h, and is roughly proportional to h^2, i.e.,

$$\tau \sim Kh^2 \sim \tau_o \left(\frac{h}{h_o}\right)^2$$

where h_o is some reference height. In addition, it should be noted that the proportionality factor missing in Eq. (1) is proportional to h^{-2}, provided the vehicle height is substantially greater than the dimensions of the nozzle exit. For a fixed viewing angle, the distance of the observed region of the dust sheet to the stagnation point scales with h. Since the dust sheet expands radially, an additional factor of 1/h must be included.

$$\delta/\delta_o \sim [1 - \exp(-d\, h_o^2/V_H\tau_o h^2)](h_o/h)^3. \tag{4}$$

On the basis of Eq. (4), and the altitude and horizontal velocity time profiles, Figures 1 and 2, it is now possible to construct time profiles of dust depth δ. The ratio of theoretically expected dust depth δ on Apollo 11 to that on Apollo 12 is shown in Figure 3. Two such curves are presented, one for τ_o=1 sec, the other for τ_o=100 sec, and it is seen that in either case, the expected abundance for Apollo 11 exceeds the value predicted for Apollo 12. This discrepancy is, of course, larger for the larger value of τ_o, for in that case, by expanding to first order,

$$\delta/\delta_o \sim \frac{d}{V_H\tau_o}\left(\frac{h_o}{h}\right)^5$$

Thus, for example, at -21 sec, when h_{11}=17 ft., $v_{11} \approx 3.4$ fps, h_{12}=34 ft., $v_{12} \approx 0.6$ fps, the ratio of expected dust depth

$$\delta_{11}/\delta_{12} \approx \frac{v_{12}\, h_{12}^5}{v_{11}\, h_{11}^5} \sim 6 \tag{5}$$

In view of the logarithmic dependence of extinction on dust depth, the difference in visibility should then be even far greater, whereas analysis of the flight record indicates that at this particular time in both missions visibility was about equal.

The above simple considerations demonstrate clearly that the contrast in visibility between the two missions cannot be found in the reported trajectory difference, and that, in fact, on the basis of the latter difference an extinction ratio would be expected that is the reverse of the one that was actually observed.

C. Other Potential Causes of Visibility Contrasts

In the simple phenomenological model presented in the preceding section, the actual physical mechanism responsible

for the generation of dust clouds was glossed over. Since this model did not lead to the desired explanation of the observed facts, it is now necessary to touch on the problem of surface erosion and dust entrainment.

In fact, by including a time dependent process in the analysis, diffusion of rocket gas into the porous subsurface layer was implicitly assumed as a mechanism for the release of dust. While the experimental data discussed in Section B provide evidence for the presence of this process, it does not appear possible to explain the observed dust entrainment in terms of this process alone.

Roberts' theory,[12] on the other hand, which seeks to explain surface erosion and dust entrainment by horizontal shear stress does not appear to be a sufficiently complete description of the process. Comparison of theoretical calculations based on this theory and experimental results[11] indicates the need for further refinements of the theory. Since the shape of the theoretical erosion profile does not agree with the experimental profiles, numerical agreement between some of the observed quantities appears fortuitous.

It will be shown that turbulence is very sensitive to surface inhomogeneities, and, therefore, may offer an important clue to the observed visibility contrast. Unfortunately, no theory of surface erosion and dust entrainment including turbulence is likely to be developed that provides a detailed quantitative description of the phenomenon, but it is possible to make a few qualitative statements about the effects of turbulence on the two main phases of the phenomenon under study.

First, surface erosion will be facilitated by turbulent stress. Surface protuberances, such as boulders or smaller protruding agglomerations of soil will generate turbulent cells giving rise to turbulent stress, proportional to $\ell^2 \left(\frac{\partial v}{\partial y}\right)^2$,[13] where ℓ is the dimension of the turbulent cell, and $\frac{\partial v}{\partial y}$ the vertical gradient of horizontal velocity. Depending on the magnitude of ℓ, strong additional sources of momentum become, therefore, available for transfer of momentum from exhaust gas to surface dust particles.

Secondly, since the total source of energy is fixed by the engine thrust, then even under the assumption that the rate of surface erosion is unchanged, the flow velocity of the deflected exhaust plume is reduced, since the available kinetic energy is now shared between the energy of the streaming motion and that of the turbulent motion. The amount of dust seen from the vehicle is proportional to the erosion rate, as was indicated in Section B.

Then for a given erosion rate, or equivalently, given flux of dust entrained in the gas flow, a reduced stream velocity results in a higher dust concentration and higher dust abundance.

Figure 4 shows the extreme sensitivity of the distribution of energy between streaming energy U, and turbulent energy ΔU to even small surface inhomogeneities.[14] Though one may well accept at present the general similarity of surface conditions at Apollo sites 11 and 12, the statistical character of this similarity has to be recognized and it has to be realized that on a strictly local scale, effective in the generation of turbulence, the two sites may differ significantly.

Whether or not the turbulent effects by themselves can account for the observed difference in visibility between the two missions, they should not be overlooked in a realistic assessment of the various possible factors involved.

D. Effect of Illumination

As a further consideration of the conditions effecting visibility through dust the sun angle has to be taken into account, at which the lunar surface is illuminated during a particular LM descent. Let I_o be the luminous flux incident from the sun, then in the absence of dust the brightness, B, of the lunar surface will be

$$B = I_o \psi(\theta)$$

where ψ is the lunar photometric function[16] and θ is the elevation angle of the sun above the horizon. In the following it will be assumed that the LM is in the phase plane, viewing the lunar surface at an angle $\phi=45°$. In the presence of a dust layer of the given thickness δ and extinction coefficient ε, the surface brightness, B', is

$$B' = \psi I_o \exp\left[-\left(\frac{1}{\sin\theta} + \frac{1}{\sin\phi}\right)\delta\varepsilon\right].$$

Using the reported values $\theta_{11}=11°$ for Apollo 11 and $\theta_{12}=5.1°$ for Apollo 12, one obtains for the surface brightness ratio of the two missions

$$B'_{11}/B'_{12} \approx 2 \exp\left[\left(12.67 - 6.66\ \delta_{11}/\delta_{12}\right)\delta_{12}\varepsilon\right].$$

Since surface obscuration depends on the loss of contrast between the surface and the dust layer, it is of interest to estimate the brightness of the dust blanket. If the latter is considered as another diffusely reflecting surface, its observed brightness under the indicated conditions is given by

$$B'' \approx \rho I_o \sin\theta \sin\phi$$

where ρ is the normal albedo. If B'/B" characterizes the contrast between surface and dust layer, the ratio of brightness contrast for the two missions is then

$$\left(\frac{B'}{B''}\right)_{11} \Big/ \left(\frac{B'}{B''}\right)_{12} = \frac{\sin\theta_{12}}{\sin\theta_{11}} \times 2 \exp\left[(12.67 - 6.66 \frac{\delta_{11}}{\delta_{12}})\delta_{12}\varepsilon\right]$$

$$\approx \exp\left[(12.67 - 6.66 \frac{\delta_{11}}{\delta_{12}})\delta_{12}\varepsilon\right]$$

For equal δ, the difference in the sun angle between Apollos 11 and 12 provides substantially better visibility for Apollo 11. If, however, $\delta_{11}/\delta_{12} \gtrsim 2$, the opposite is true. According to the estimate in Figure 3, this occurs at and persists after about 25 seconds prior to touchdown. Our semi-quantitative treatment, therefore, strongly suggests that illumination is an important factor in the visibility problem.

E. Conclusions and Recommendations

Using a simple phenomenological model for dust generation during the terminal LM landing phase, it was demonstrated that trajectory differences are unlikely to account for the contrast in visibility between Apollo missions 11 and 12. Nevertheless, analysis of the trajectory dependence of visibility may provide some guidelines for terminal landing operations; an example is given in Appendix B. For better assessment of time dependent effects, however, a new series of laboratory experiments may be useful, measuring directly the response of a lunar-like soil to the exhaust plume impact of a nozzle descending in both vertical and oblique paths.

An effort should also be made to obtain an improved record of the terminal LM descent profile and quantitative visibility measurements should be made.

It is possible that a major determinant of visibility conditions during LM descent are local variations in surface roughness which are effective sources of turbulence. In this case, unless very detailed high resolution maps of the prospective landing sites are available prior to landing, no reliable attempt at prediction of ground visibility is deemed possible. Study of the role of turbulence in the generation and transport of dust should be pursued. Alternatively, it appears that the

higher sun angle (11° compared with 5.1°) was definitely advantageous for Apollo 11. Light scattering experiments with lunar-like dust suspended over a lunar-like surface could test this theory. Practically, Apollo 13 (nominal sun elevation 9.9°) would be expected to have visibility comparable with Apollo 11, and better if a trajectory more like the Apollo 12 descent were flown.

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Attachments
Appendices A and B
Acknowledgements
References
Figures 1-4 and B-1

APPENDIX A

Theoretical Estimate of τ

The characteristic time τ in Eq. (1) for the generation of dust by the rocket exhaust plume is the momentum transfer time from the gas particles to the dust particles. From a simple kinetic consideration, τ may be written as

$$\tau = \frac{M_d}{M_g} \frac{1}{N_g \Sigma \nu} \qquad \text{(A-1)}$$

where M_d = mass of a dust particle

M_g = mass of a gas particle

N_g = number density of the gas

Σ = collision cross-section between gas and dust particle

$\cong \pi d^2/4$ where d is the diameter of a spherical dust particle

ν = characteristic collision velocity, being approximately the thermal velocity of the gas.

In Eq. (A-1) $M_g N_g$ is just the mass density of the gas, ρ, which is inversely proportional to the square of the vehicle height h.

The value of ρ and ν may be obtained from the LM descent engine characteristics.[15] At h = 20 ft, these values are approximately $\rho \sim 2\text{x}10^{-7}$ gm cm^{-3}, $\nu \sim 5\text{x}10^3$ cm sec.$^{-1}$ Typical values for the dust particles may be taken as d=10 microns, and dust mass density of 2 gm cm^{-3}. With the above values, τ given by Eq. (A-1) is

$$\tau \sim 0(1) \text{ sec.}$$

APPENDIX B

Comparison of Dust Entrainment from a Vertical and an Oblique Descent Trajectory

In this Appendix, a direct comparison is presented of the dust entrainment from two different trajectories, a vertical and an oblique descent, both with the same initial and terminal positions. These two trajectories have the same vertical velocities so that at any time before touchdown they are at the same height. The amount of dust depth at any altitude h is

$$\delta_{obl} \approx \left\{ 1 - \exp\left[- \frac{d}{V_h \tau_o} \left(\frac{h_o}{h}\right)^2 \right] \right\} \left(\frac{h_o}{h}\right)^3 \qquad \text{(B-1)}$$

for the oblique trajectory, and

$$\delta_{ver} = \left\{ 1 - \exp\left[- \frac{h_1 - h}{V_v \tau_o} \left(\frac{h_o}{h}\right)^2 \right] \right\} \left(\frac{h_o}{h}\right)^3 \qquad \text{(B-2)}$$

for the vertical trajectory. Here V_h and V_v are the horizontal and vertical velocities respectively. d is the diameter of rocket nozzle exit, h_1 is an altitude for the incipience of dust, and τ_o is the characteristic time for the dust generation, at given vehicle height h_o.

We define a value of δ such that when $\delta^* = e^{-1}$ the obscuration of view becomes serious. For this value of δ^*, $h=h^*$ may be calculated from (B-1) and (B-2). We have taken three different values for τ_o for this purpose. The following table provides the comparison of the critical vehicle height (and the time before touchdown) for the two trajectories. Typical parameters are chosen to be V_h = 2.5 fps, V_v = 2 fps, h_o = 20 ft., h_1 = 100 ft., and d = 5 ft.

TABLE B-1

Critical Height h* for $\delta=\delta^*=e^{-1}$

h* (ft) / τ_0 (sec) \ case	Oblique Trajectory	Vertical Trajectory
1	23.6 (11.8)	28.2 (14.1)
10	17.4 (8.7)	26.6 (13.3)
100	11.0 (5.5)	19.5 (9.75)

In the above table, the number appearing in the parenthesis indicates the time in seconds before touchdown. The above table and the accompanying Figure B1 do, of course, not by themselves indicate a preferred trajectory, but merely provide a rational basis for a choice, which is predicated on operational criteria, such as minimum time of surface obscuration -- favoring the oblique trajectory -- or longest undistrubed overview of the touchdown area -- favoring the vertical descent.

ACKNOWLEDGEMENTS

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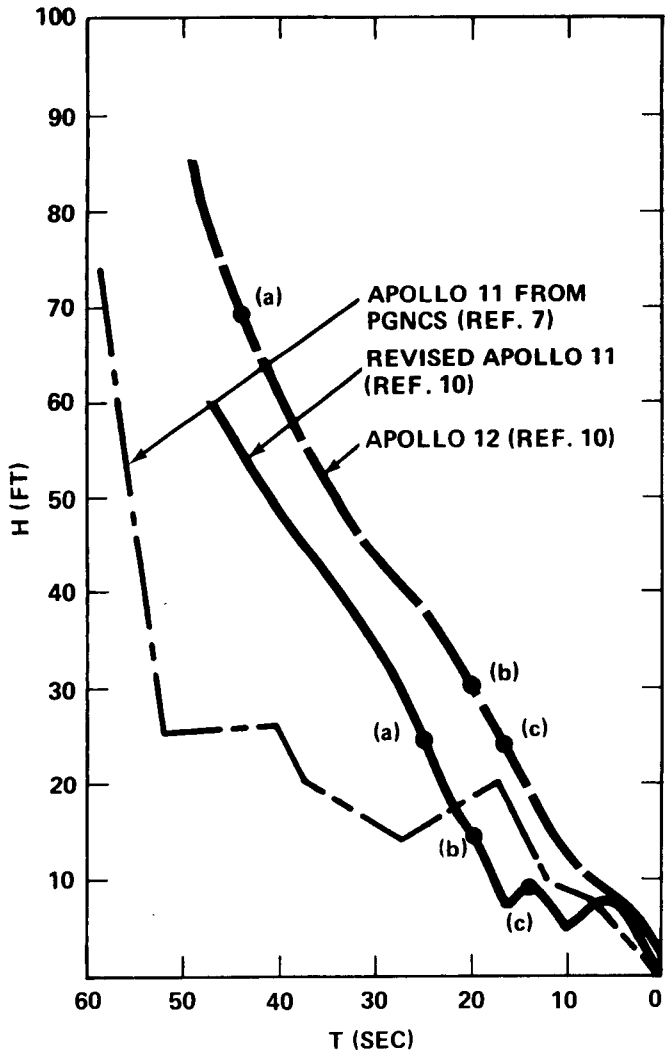

FIGURE 1 - HEIGHT VS TIME BEFORE TOUCH-DOWN. LETTERS IN PARENTHESES INDICATE EVENTS: (a) SUBSTANTIAL STREAKING, (b) STREAKS FULLY DEVELOPED, (c) LOSS OF VISIBILITY.

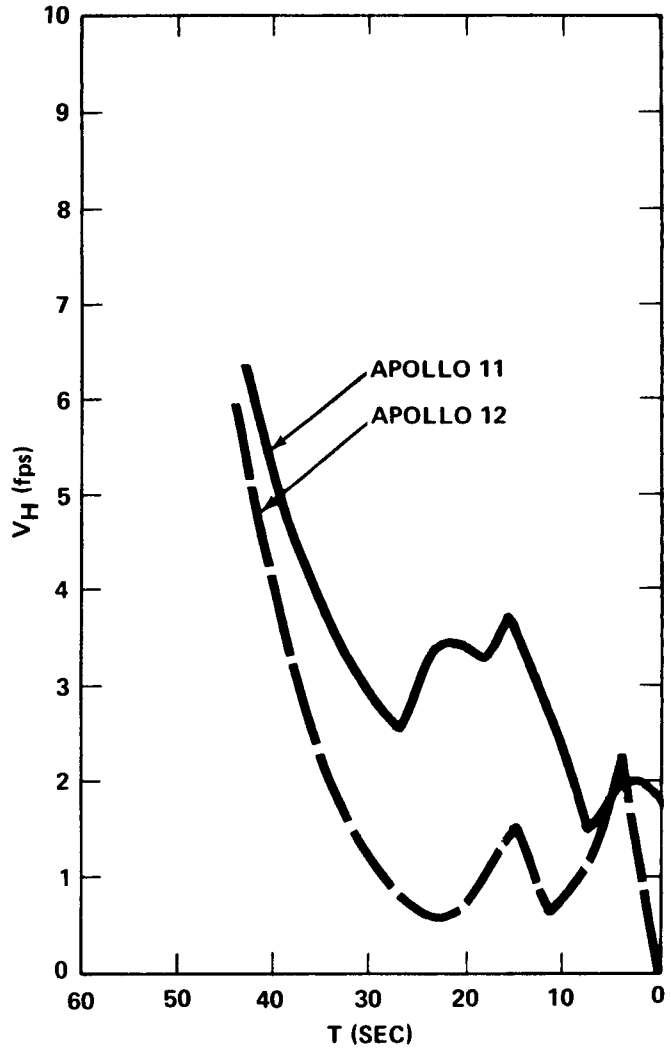

FIGURE 2 - HORIZONTAL VELOCITY VS TIME BEFORE TOUCH-DOWN.

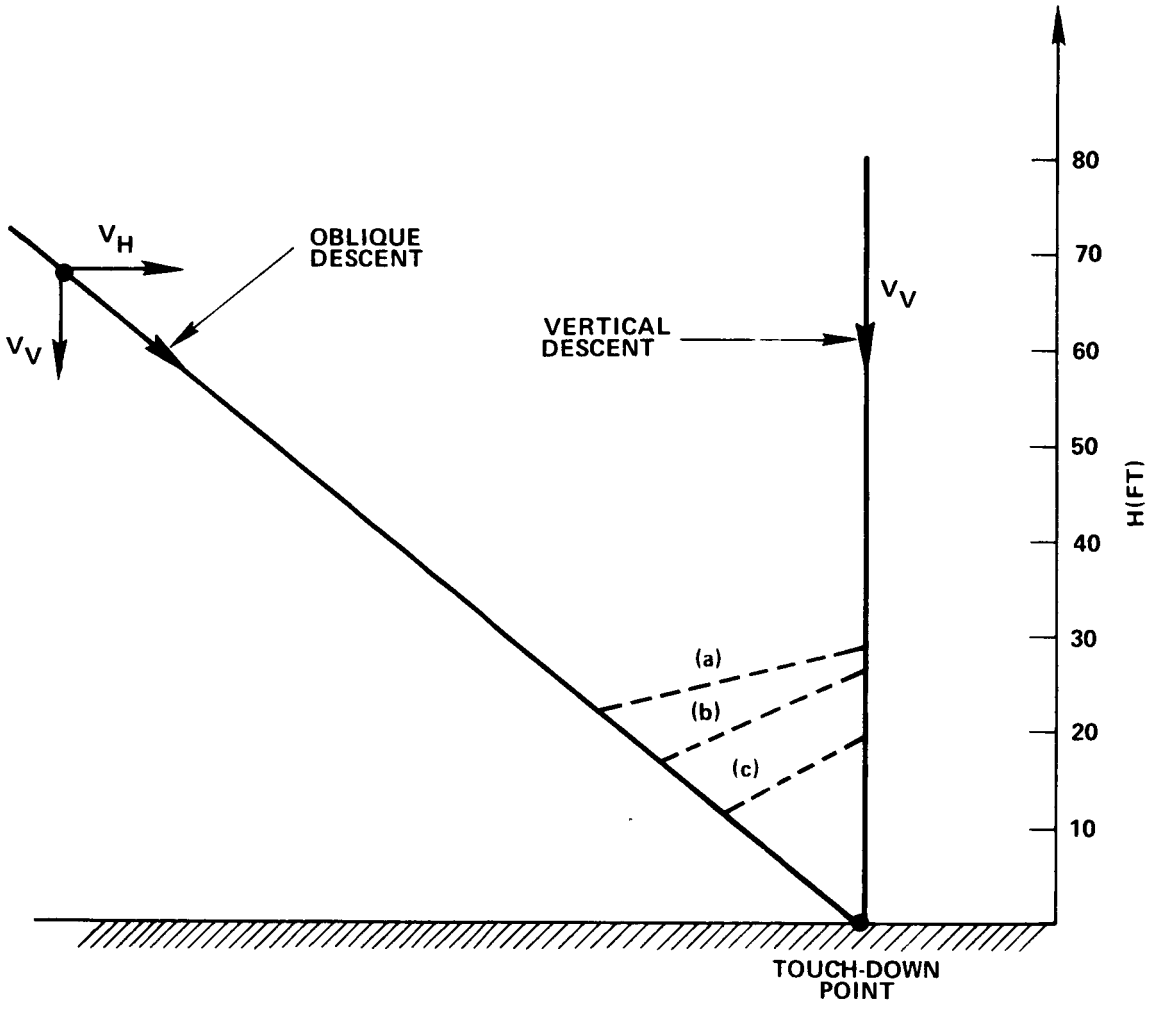

FIGURE B1 - COMPARISON OF DUST ENTRAINMENT FROM VERTICAL AND OBLIQUE TRAJECTORIES. DOTTED LINES INDICATE CONSTANT DUST, (a) τo = 1 SEC, (b) τo = 10 SEC, (c) τo = 100 SEC.

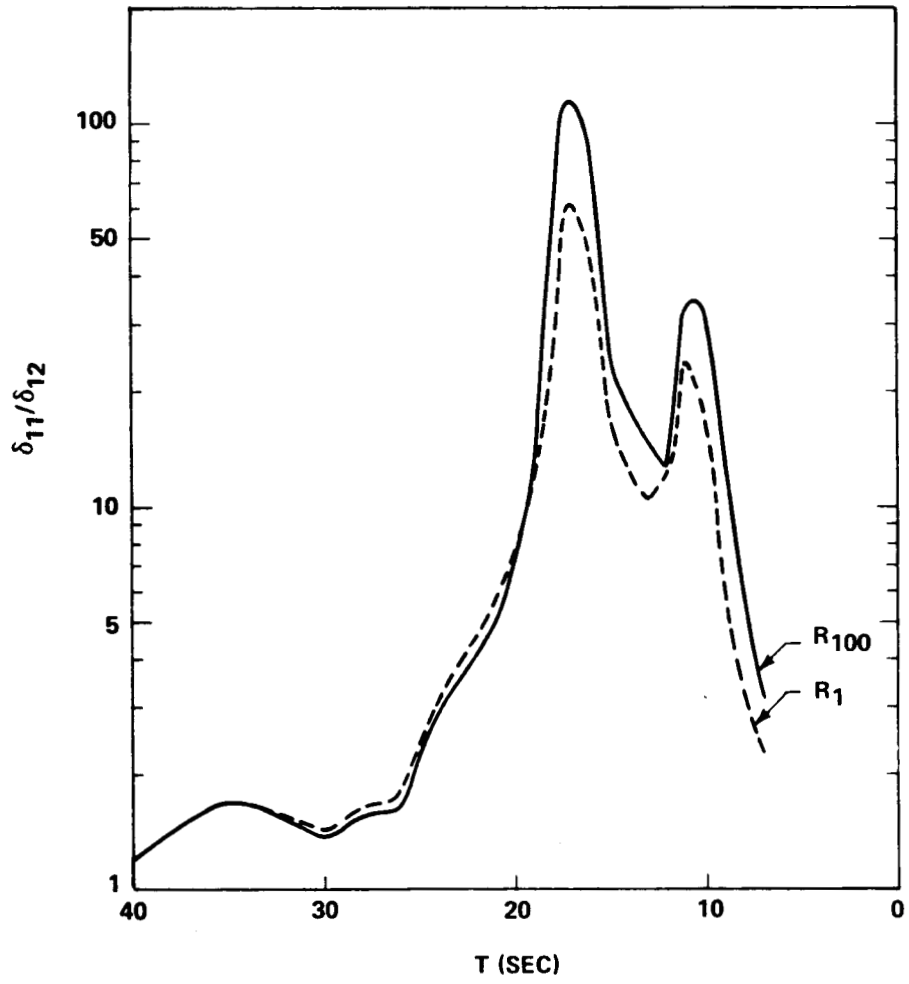

FIGURE 3 - δ_{11}/δ_{12} VS TIME BEFORE TOUCH-DOWN R_1 IS FOR τo = 1 SEC, R_{100} FOR τo = 100 SEC.

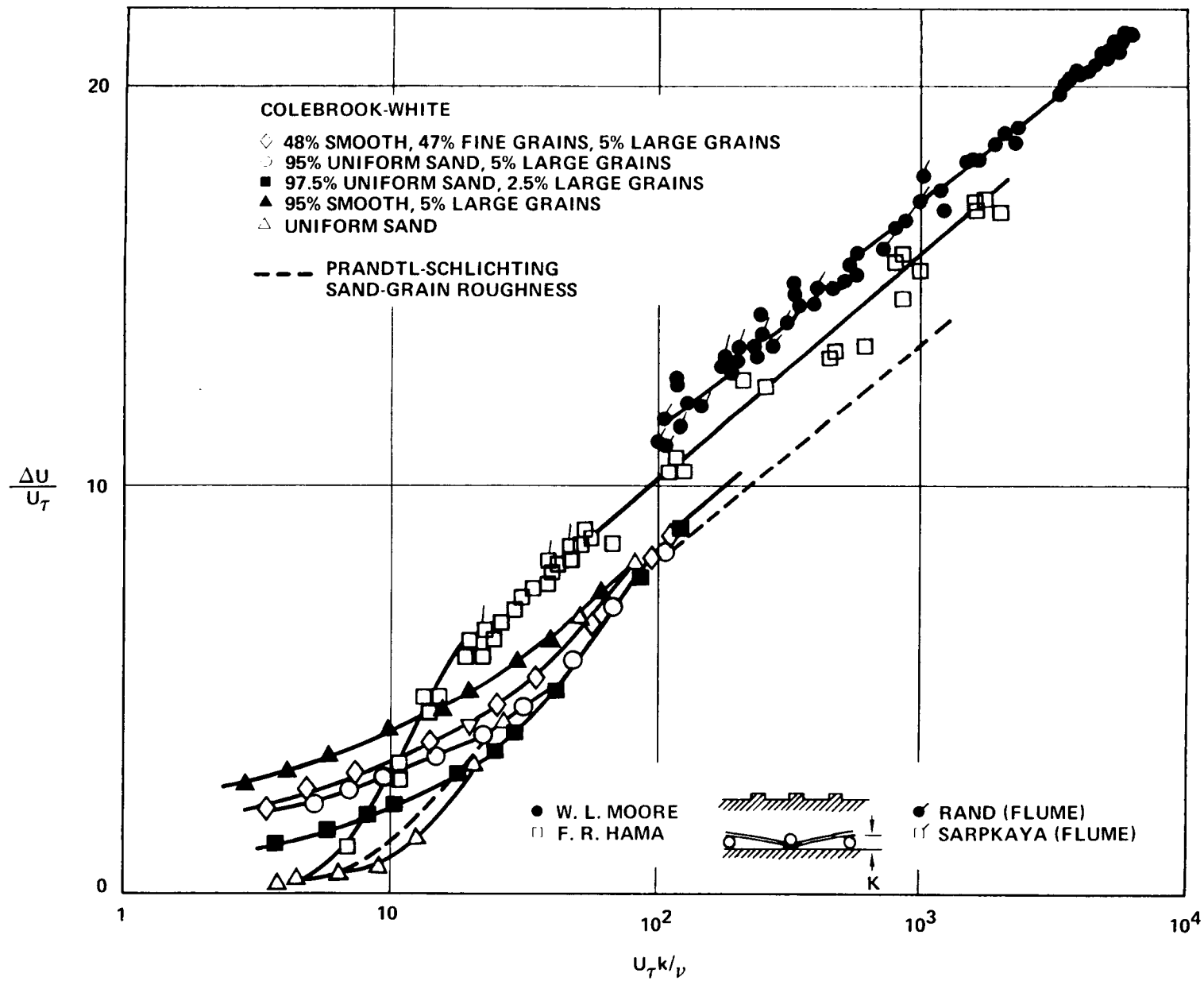

FIGURE 4 EFFECT OF ROUGHNESS ON UNIVERSAL TURBULENT VELOCITY PROFILE – REDUCTION OF STREAMING VELOCITY (ORDINATE) VERSUS ROUGHNESS REYNOLDS NUMBER (ABSCISSA).

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