GEOPHYSICAL RESEARCH LETTERS, VOL. 7, NO. 2, PAGES 121-124, FEBRUARY 1980

THRESHOLD WINDSPEEDS FOR SAND ON MARS: WIND TUNNEL SIMULATIONS

R. Greeley

Center for Meteorite Studies, Arizona State University
Tempe, Arizona 85281

R. Leach

University of Santa Clara and NASA-Ames Research Center
Moffett Field, California 94035

B. White

Department of Mechanical Engineering, University of California at Davis
Davis, California 95616

J. Iversen

Department of Aerospace Engineering, Iowa State University
Ames, Iowa 50011

J. Pollack

Space Sciences Division, NASA-Ames Research Center
Moffett Field, California 94035

Abstract. Wind friction threshold speeds (u_{*t}) for particle movement (saltation) were determined in a wind tunnel operating at martian surface pressure with a 95 percent CO_2 and 5 percent air atmosphere. The relationship between friction speed (u_*) and free-stream velocity (u_∞) is extended to the critical case for Mars of momentum thickness Reynolds numbers (Re_θ) between 425 and 2000. It is determined that the dynamic pressure required to initiate saltation is nearly constant for pressures between 1 bar (Earth) and 4 mb (Mars) for atmospheres of both air and CO_2; however, the threshold friction speed (u_{*t}) is about 10 times higher at low pressures than on Earth. For example, the u_{*t} (Earth) for particles 210 μm in diameter is 0.22 m s^{-1} and the u_{*t} (Mars, 5 mb, 200 K) is 2.2 m s^{-1}.

Introduction

A great deal of attention has been given to the problem of windblown particles on Mars, beginning with a paper by Sagan and Pollack (1969). Most investigations have involved estimations of wind speeds needed to initiate movement of particles of different sizes and densities based on the work originally done by Bagnold (1941) who described the physics for windblown sand on Earth. Extrapolations were made to Mars by substituting the appropriate parameter values for Mars in the equations derived by Bagnold for Earth (Sagan and Pollack, 1969, Arvidson, 1972, Iversen *et al.*, 1973, and others). Some studies (Chang *et al.*, 1968, Adlon *et al.*, 1969) incorporated into the extrapolations data from laboratory simulations of some of the conditions on Mars. An extrapolation taking interparticle force into account, more appropriate for martian pressures, was obtained by Iversen *et al.* (1976).

To provide better simulations, an open circuit wind tunnel (Martian Surface Wind Tunnel or MARSWIT) was constructed at NASA-Ames Research Center (the facility is described in Greeley *et al.*, 1977). Experiments from MARSWIT yielded estimates of wind friction speeds for particle movement on Mars in which nearly all the important parameters were physically simulated or otherwise taken into account. Two of the most important parameters for martian simulations are gravity and the atmospheric conditions at the surface. For simulations of Mars on Earth the primary effect of gravity may be accounted for partly by using proportionately lower density particles than those expected on Mars. The atmosphere is more difficult to simulate. Although MARSWIT is capable of operating down to about 3 mb pressure, the experiments presented by Greeley *et al.* (1976, 1977) were run not in an atmosphere of martian composition (primarily CO_2), but rather in 'Earth' air. Extrapolations were made to the martian atmospheric composition by taking into account the differences in molecular weight between CO_2 and 'Earth' air. However, because the dynamics of CO_2 at low pressures and at the relatively low Reynold numbers involved with the martian aeolian environment are so poorly understood, these extrapolations were open to question. Consequently, MARSWIT was modified to enable experiments to be run in a 95 percent CO_2 atmosphere. The experiments described earlier (Greeley *et al.*, 1976) were duplicated in the CO_2 atmosphere to generate a set of threshold curved for particle motion on Mars. The results of these experiments are the subject of this report.

Experimental Procedure and Results

The test procedure was as follows: A bed of uniform-sized particles was placed in the wind tunnel test section and the surface was smoothed. For each test a 2.5 meter long bed of material was used, as previous tests showed (Greeley *et al.*, 1977) that a bed of this length would give very nearly the same results as an infinitely long bed whereas shorter beds resulted in increased saltation threshold values. The tunnel was located inside a large vacuum chamber which was evacuated to about 4 mb pressure using 'Earth' air. The tunnel was then started and the wind speed gradually increased until saltation threshold was reached. The tunnel was stopped and started several times at each test condition to obtain a number of data points. Three separate methods were used to determine saltation threshold: (1) A high resolution closed-circuit television system was used to observe the particle movement directly; (2) a laser-photocel system indicated saltation by the attenuation of the signal due to particles interrupting the laser beam; and (3) an electrostatic detector measured the current produced by saltating particles impinging on the detector element. For most experiments all the systems were used concurrently to detect saltation, with the electrostatic system being more sensitive for small particles and the television and laser systems more sensitive for the larger particles. Many materials were tested but ground walnut shells (specific gravity 1.1) were deemed to best represent martian particles (Greeley *et al.*, 1977) and were used to generate the data presented here.

The chamber was then filled with CO_2 to a pressure of about 80 mb giving a 95 percent CO_2 and 5 percent air mixture. Threshold tests were run at various pressures as the chamber pressure was again reduced to 4 mb. Finally, the chamber was purged with air and pumped to 4 mb for the third series of tests. Threshold speeds were again taken with air as the working

Paper number 9L1494.
0094-8276/80/009L-1494$01.00

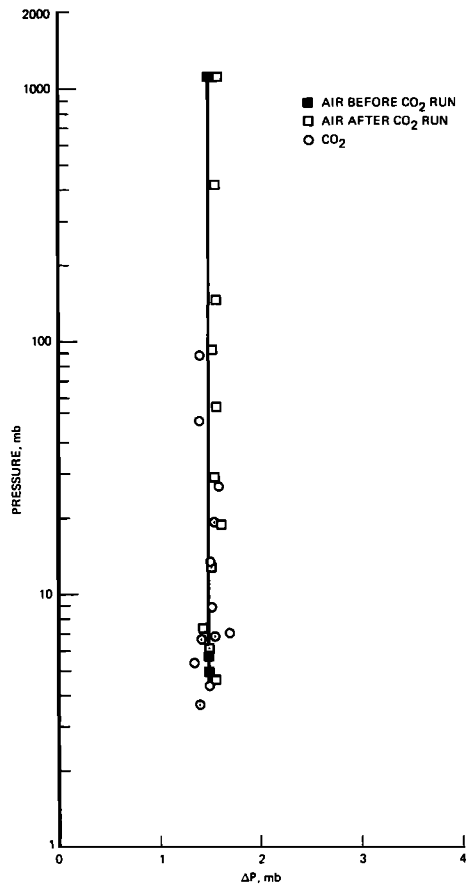

Figure 1. Dynamic pressure at the wind tunnel centerline to initiate particle saltation with 5 percent air and 95 percent CO_2 mixture for ground walnut shell particles 212 μm in diameter.

fluid, as the chamber was step-filled to atmospheric pressure to obtain threshold speeds for a range of pressures. With this technique it was possible to compare a particular bed of material with all conditions nearly identical except that the working fluid was changed from air to CO_2 and back to air. By comparing the initial air data with the final air data a good estimation of the repeatability of the data could be made. Figures 1 and 2 present typical data sets for a single test bed. Note that the dynamic pressure (Δp) is nearly constant for both air and 95 percent CO_2 and with chamber pressure (Fig. 1); the velocities (Fig. 2) are different due to the differences in properties of air and CO_2. This procedure was followed for each particle size tested over the range of diameters from 23 μm to 800 μm.

Data Reduction

The critical measurements in the wind tunnel are the differential pressure (Δp) between the total pressure (p_t) and the static pressure (p_s) at the tunnel centerline, and the chamber pressure and temperature. The tunnel centerline wind velocities can then be calculated from these measurements, as well as the friction velocity (u_*) for a given bed of materials taking into account the boundary layer profile and the surface roughness, as discussed in Iversen *et al.* (1973, 1976).

Time-averaged boundary layer velocity profiles were determined from differential pressure measurements between static pressure and a total head pressure tube that was transversed through the boundary layer. The tests showed the boundary flow to be essentially steady, two-dimensional, constant-property (i.e., maintaining a constant chamber pressure), and to have a constant free-stream velocity turbulent flow through the tunnel. A zero-pressure-gradient flow was achieved by increasing the top tunnel wall height with increasing downstream distance (thereby expanding the cross sectional area); the zero-pressure-gradient was verified by static pressure measurements at several positions in the tunnel. A naturally turbulent boundary layer developed for most of the flow conditions; however, at the lower pressures it was necessary to 'trip' the boundary layer by placing small pebbles on the tunnel floor in the entrance section of the tunnel. The test section was more than 25 boundary-layer thickness-lengths from the pebbles placed upstream, insuring a fully developed turbulent core region at low pressures.

The data were reduced taking into account Mach number and slip flow effects in the velocity determination. Each profile was numerically curve fitted by means of a multi-piecewise cubic spline technique.

For the turbulent boundary layer the value of the friction speed u_* is dependent on the value of the momentum thickness Reynolds Number

$$Re_\theta = \frac{u_\infty \theta}{\nu} \tag{1}$$

where u_∞ is the free-stream wind-tunnel speed, ν is the kinematic viscosity, and θ is the momentum-deficit thickness. The momentum-deficit thickness is defined as the thickness of the layer as measured from the wall of an external stream (at constant speed u_∞) containing a momentum flux equal to the loss of momentum flux due to the presence of the wall. It is convenient to define the momentum-deficit thickness θ in terms of mean velocity profiles as

$$\theta = \int_0^\delta \frac{u}{u_\infty}\left(1 - \frac{u}{u_\infty}\right) dy \tag{2}$$

where δ is the boundary layer height at which the value of velocity u is 99 percent that of u_∞, and y is the vertical height. The momentum thicknesses were determined from integrating the resultant curve fit by a numerical quadrature technique.

An analysis of the zero-pressure-gradient turbulent boundary layer for low Reynolds numbers has been made by Coles (1962); from this work the surface shear stress τ_0 can be determined from the velocity profiles obtained in the wind tunnel. This is accomplished by assuming that the velocity obeys the logarithmic law

$$\frac{u}{u_*} = \frac{1}{\kappa} \ln \frac{u_* y}{\nu} + C \tag{3}$$

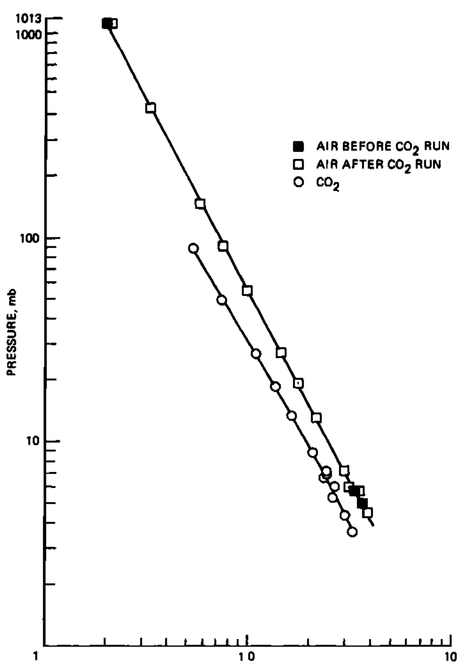

Figure 2. Wind tunnel centerline velocity to initiate particle saltation threshold with air and 95 percent CO_2-air mixture for ground walnut shells 212 μm in diameter.

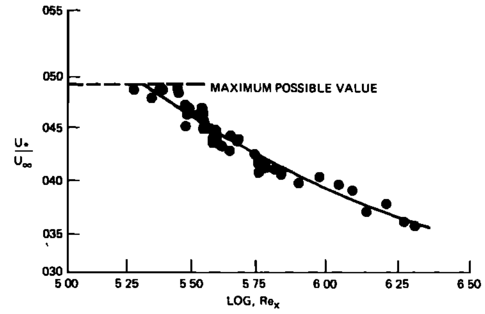

Figure 3. The ratio of friction velocity (u_*) to wind tunnel centerline velocity (u_∞) as determined by boundary layer surveys and presented as a function of Reynolds number (R_{ex}) based on the distance from the beginning of the wind tunnel to the test point.

for the wall region ($y < 0.2$) excluding the viscous sublayer. In this study, $\kappa = 0.418$ and $C = 5.45$, as determined by Patel (1965). Converting to $\log_{10}$ gives

$$\frac{u}{u_*} = 5.5 \log_{10} \frac{u_* y}{\nu} + 5.45 \qquad (4)$$

The ratio u_*/u_∞ is well fit by the empirical equation ($600 > Re_\theta > 2000$)

$$\frac{u_*}{u_\infty} = 0.702 \, (\log_{10} R_{ex})^{-1.59} \qquad (5)$$

as shown by Figure 3. In this equation the relationship is presented as a function of R_{ex}, the Reynolds number based on the distance from the beginning of the wind tunnel to the test point. For flows with lower values of Re_θ ($Re_\theta < 600$) the ratio u_*/u_∞ becomes a constant value of approximately 0.049. This is the maximum value that u_*/u_∞ can obtain in a turbulent boundary layer at low Reynolds numbers (White, 1979 and Barr, 1979). For values of Re_θ less than 425 the boundary layer flow is laminar and is of no importance in flows of saltating particles.

Using these relationships the data are presented as a function of particle size versus friction threshold velocity for various pressures (Fig. 4). These data are valid for particles larger than about 60 μm, but some adjustment upward may be necessary for the smaller particles as indicated by the following analysis:

Tests were conducted to determine if the angle of repose, which is a function of various interparticle forces, was affected by reducing the ambient pressure. Results show that smaller sized particles are affected; for example, particles 20 μm in diameter have a much lower angle of repose at 4 mb than at 1 bar, if the tests were run immediately upon reaching the lower pressure. If, however, the particles were allowed to remain at the lower pressure for 24 hours before the test was made, the angle of repose was the same at 1 bar. Evidently, interparticle air acts as a lubricant as it escapes, causing the particles to flow over one another more readily in a low-pressure environment. If allowed to remain at low pressure for a period of time (many hours), the interparticle air slowly outgasses and no longer affects the angle of repose. Ideally, the smaller test particles should be allowed to stabilize in the evacuated wind tunnel for a sufficient period of time for all interparticle gas to escape before saltation threshold tests commence. This, however, was not possible within the limitations of MARSWIT. Thus, the data for the particles less than 60 μm show lower thresholds than if the material had been held at low pressure long enough for all interparticle gas to escape. (For an analysis of the relationship between angle of repose and the threshold velocity see Bagnold, 1941, Chapter 7.) Because of this effect the two smaller sizes of particles tested showed a decrease in dynamic pressure required for saltation with decreasing chamber pressure in contrast to the larger sizes tested. This decrease is attributed to the lubricating effect of the escaping interparticle gas, and correcting for this effect by assuming a constant Δp, the final data curve Figure 5 is presented as the best experimental determination of threshold friction velocity u_{*t} for particles on Mars. These data are also adjusted for representative martian temperatures by the method presented by Iversen *et al.* (1976).

The particle threshold curves presented here indicate that somewhat lower wind speeds are required to move particles on Mars than had been predicted by earlier studies. This is due primarily to a more refined method of determining the relationship between free stream velocity and friction velocity as well as a better simulation using CO_2 as the working fluid.

Discussion and Comparison with Conditions at the Viking Lander Sites

We have used the results to make a preliminary assessment of the ability of winds to move sand sized particles at the Viking Lander Sites. To do this, we first relate friction velocity to winds measured by the lander meteorology experiment at a height of 1.6 m above the surface and winds at the top of the planetary boundary layer. Both lander sites are characterized by fairly flat terrain covered with fine grained material, but littered with numerous rocks (Mutch *et al.*, 1976a, b). A reasonable choice for the roughness height Z_0 of these surfaces is about 0.1 to 1 cm (Sutton *et al.*, 1979). Fortuitously, a surface having these values of Z_0 requires a threshold wind speed at the top of the boundary layer V_{gt} that is almost identical to the one needed for a surface containing only sand grains (see Fig. 3 of Pollack *et al.*, 1976a, b). Thus, good estimates of V_{gt} at the lander sites may be made by multiplying the laboratory threshold friction velocities by the ratio of V_{gt}/u_* appropriate for a sand only case (~50). This conversion is indicated by the Case 1 scale of Figure 5. Analysis of the Viking meteorology results suggest that the ratio, r, of the wind speeds measured by the Viking Meteorology Instrument to those at the top of the boundary layer equals about 0.4 (Leovy and Zurek, 1979).

We are now in a position to compare the velocities measured by the Viking meteorology experiment with threshold values for the optimum grain size, i.e., the grain size easiest to move (~100 μm). During the early portion of the Viking mission (northern hemisphere summer), the surface pressures at the landers was about 7.5 mb, while close to the time of the second global dust storm (southern hemisphere summer) the pressure had increased to about 9.5 mb (Ryan *et al.*, 1978). Using the results of Figure 5 and a scale factor of 20 to convert friction velocities to velocities at the height of the meteorology sensors we estimate that the measured wind had to exceed about 30 and 25 m s, respectively, for saltation to occur. During the summer season in the northern hemisphere, the measured wind speed did not exceed 10 m s^{-1} at either lander (Hess *et al.*, 1976a, b) and hence saltation should not have occurred, in accord with lander camera observations (Mutch *et al.*, 1976a, b). The strongest winds measured to date were observed at the first lander site shortly after the onset of the second global dust storm. Sustained wind speeds of 18 m s^{-1} were recorded, with peak gusts of up to 28 m s^{-1} (Ryan *et al.*, 1978). Thus, the winds came quite close to reaching threshold conditions. This prediction is in reasonable accord with lander camera results. Movement did occur in sand piles placed on top of the lander, where threshold conditions are lower, but no alteration was observed to occur on the surface, except for a few isolated places (Sagan *et al.*, 1977 and Jones *et al.*, 1979). Conceivably, during martian years of somewhat enhanced global dust storm activity, the saltation threshold is exceeded at the lander sites, especially Viking Lander 1.

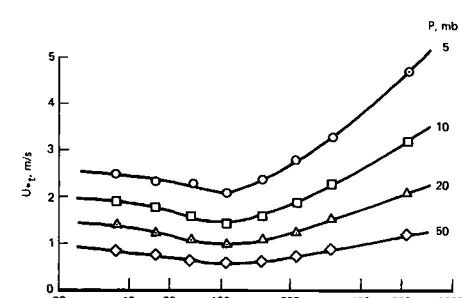

Figure 4. Friction threshold velocity as a function of particle size as determined in wind tunnel tests using ground walnut shell and 95 percent CO_2-air mixture.

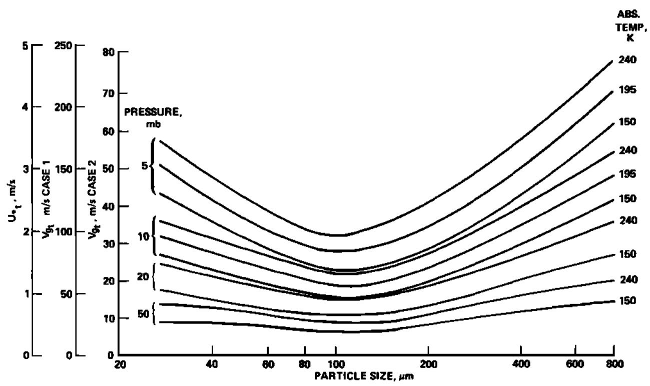

Figure 5. Particle threshold curves as a function of particle size for martian surface pressures and higher, and for representative martian temperatures. Case 1 scale is free stream velocity (above boundary layer) for winds blowing over a flat surface of erodible grains; Case 2 surface containing cobbles and small boulders.

Acknowledgment. This work was supported by the Planetary Geology Program Office, National Aeronautics and Space Administration.

References

Adlon, G. L., R. K. Weinberger, and D. R. McClure, Planetary environment simulation: Martian sand and dust storm simulation and evaluation, NASA CR-66882, 1969.

Arvidson, R. E., Aeolian processes on Mars: Erosive velocities, settling velocities, and yellow clouds, *Geol. Soc. Am. Bull. 83,* 1503 - 1508, 1972.

Bagnold, R. A., *The Physics of Blown Sand and Desert Dunes.* London: Methuen, 1941.

Barr, P. K., Calculation of skin-friction coefficients for low-Reynolds-number turbulent boundary layer flows, unpubl. M.S. Thesis, University of California, Davis, California, 1979.

Chang, T. S., W. C. Lucas, and W. W. Youngblood, Laboratory simulation of the Mars atmosphere: A feasibility study, NASA CR-61188, 1968.

Coles, D. E., The turbulent boundary layer in a compressible fluid, Rand Corp. Report 403-PR, Santa Monica, California, 1962.

Greeley, R., B. R. White, R. N. Leach, J. D. Iversen, and J. B. Pollack, Mars: Wind friction speeds for particle movement, *Geophys. Res. Letters, 3,* 417-420, 1976.

Greeley, R., B. R. White, J. B. Pollack, J. D. Iversen, and R. N. Leach, Dust storms on Mars: Considerations and simulations, NASA TM-78423, 1977.

Hess, S. L., R. M. Henry, C. B. Leovy, J. A. Ryan, J. E. Tillman, T. E. Chamberlain, H. L. Cole, R. G. Dutton, G. C. Greene, W. E. Simon, and J. L. Mitchell, Mars climatology from Viking after 20 sols, *Science, 194,* 78, 1976a.

Hess, S. L., R. M. Henry, C. B. Leovy, J. L. Mitchell, J. A. Ryan, and J. E. Tillman, Early meteorological results from the Viking 2 lander, *Science, 184,* 1352, 1976b.

Iversen, J. D., R. Greeley, J. B. Pollack, and B. R. White, Simulation of martian aeolian phenomena in the atmospheric wind tunnel, NASA SP-336, 191-213, 1973.

Iversen, J. D., J. B. Pollack, R. Greeley, and B. R. White, Saltation threshold on Mars: The effect of interparticle force, surface roughness, and low atmospheric density, *Icarus, 29,* 381-393, 1976.

Jones, K. L., R. E. Arvidson, E. A. Guiness, S. L. Bragg, S. D. Wall, C E. Carlston, and D. G. Pidek, One Mars year: Viking lander imaging observations, *Science, 204,* 799-806, 1979.

Leovy, C. B. and R. W. Zurek, Thermal tides and martian dust storms: Direct evidence for coupling, *J. Geophys. Res., 84,* 2956-2968, 1979.

Mutch, T. A., A. B. Binder, F. O. Huck, E. C. Levinthal, S. Liebes Jr., E. C. Morris, W. R. Patterson, J. B. Pollack, C. Sagan, and G. R. Taylor, The surface of Mars: The view from the Viking 1 lander, *Science, 193,* 791, 1976a.

Mutch, T. A., S. V. Grenander, K. L. Jones, W. Patterson, R. E. Arvidson, E. A. Guiness, P. Avrin, G. E. Carlston, A. B. Binder, C. Sagan, E W. Dunham, P. L. Fox, D. C. Pieri, F. O. Huck, C. W. Rowland, G. R Taylor, S. P. Wall, R. Kahn, E. C. Levinthal, S. Liebes Jr., R. B. Tucker, E. C. Morris, J. B. Pollack, R. S. Saunders, and M. R. Wolf, The surface layer of Mars: The view from the Viking 2 lander, *Science, 194,* 1277, 1976b.

Patel, V. C., Calibration of the Preston tube and limitations on its use in pressure gradients, *J. Fluid Mech., 23,* 185-208, 1965.

Pollack, J. B., R. Haberle, R. Greeley, and J. D. Iversen, Estimates of the wind speeds required for particle motion on Mars, *Icarus, 29,* 395-417, 1976a.

Pollack, J. B., C. B. Leovy, Y. H. Mintz, and W. VanCamp, Winds on Mars during the Viking season, predictions based on a general circulation model with topography, *Geophys. Res. Letters, 3,* 479-482, 1976b

Ryan, J. A., R. M. Henry, S. L. Hess, C. B. Leovy, J. E. Tillman, and C. Walcek, Mars meteorology: Three seasons at the surface, *Geophys. Res. Letters, 5,* 715, 1978.

Sagan, C., D. Pieri, P. Fox, R. E. Arvidson, and E. A. Guiness, Particle motion on Mars inferred from the Viking lander cameras, *J. Geophys Res., 82,* 4430-4438, 1977.

Sagan, C. and J. B. Pollack, Windblown dust on Mars, *Nature, 223,* 791-794, 1969.

Sutton, J. L., C. B. Leovy, and J. E. Tillman, Diurnal variations of the martian surface layer meteorological parameters during the first 45 sols at the two Viking lander sites, *J. Atmos. Res.,* in press, 1979.

White, B. R., Low-Reynolds-number turbulent boundary layer flows, paper presented at the ASME 21st Annual Meeting, *Symposium of Turbulent Boundary Layers,* Niagara Falls, New York, June, 1979.

(Received September 11, 1979;
accepted October 18, 1979.)