

a burnout weight of 2434 lb. Compared to the hydrogen-only system of Ref. 1, the total tank volume was reduced by 20%. This decrease in tank volume allows more space for payload. The dry weight was decreased by 17%. The losses from boil off were reduced by 24%. The dual fuel system, burning ammonia in the early stages of the mission, is able to deliver the same payload as the system in Ref. 1 with reduced tank volume, dry weight, and boil off losses.

A more detailed description of the work described in this Note can be found in Ref. 3.

Concluding Remarks

The results provide evidence that there are benefits to be gained from the use of a dual fuel configuration for a solar thermal orbital transfer vehicle. The target payload of 1000 lb could be achieved with an ammonia fraction of 14%. This fraction resulted in decreased tank volume, tank weight, dry weight, and boil off losses. More space is available for payload as a result of the decreased tank volume.

References

- Patel, S., and Emrich, W. J., Jr., "Solar Thermal Upper Stage (STUS) Feasibility Study," ASME/JSME/ISES International Solar Energy Conf., Maui, HI, March 1995.
- Sutton, G. P., *Rocket Propulsion Elements, An Introduction to the Engineering of Rockets*, 6th ed., Wiley, New York, 1992.
- Stewart, J. F., and Martin, J. A., "Dual Fuel Solar Thermal Propulsion for LEO to GEO Transfer: Ideal Rocket Analysis," AIAA Paper 95-2840, July 1995.

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Martian Surface Wind Speeds Described by the Weibull Distribution

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Introduction

THE Viking landers recorded meteorological data at two locations on Mars (Viking 1, 22°N 48°W; Viking 2, 48°N 226°W), enabling the identification of general conditions on the surface, atmospheric tides, seasonal effects, and dust storms.¹⁻⁴ Analysis to date has focused on hodographs and identifying the diurnal variations in wind speed and direction. These analyses, however, are not convenient for engineering and geophysical applications, where a probability of wind speed exceeding a given value often is required. Concise two-parameter descriptions of windspeed probability distributions, based on analysis of the hourly averaged windspeeds recorded by the Viking landers, are presented, which are much more useful than the simple mean speed that is usually reported.

Weibull Distribution

Wind-speed distributions are typically asymmetric, with a peak at low speeds and the probability of high speeds tailing off. A normal (Gaussian) distribution is a poor one for describing wind speeds, largely because of its symmetry. The Weibull distribution has found common application for describing wind speeds in the terrestrial field of renewable energy. The distribution is described by two parameters, c and k , representing a scale speed and a dimensionless shape parameter, respectively. Specifically, the distribution gives a probability density function

$$f(v) = (k/c)(v/c)^{k-1} \exp[-(v/c)^k] \quad (1)$$

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and a cumulative probability

$$P(<v) = 1 - \exp[-(v/c)^k] \quad (2)$$

The higher the value of k , the steeper the falloff of the distribution at high speeds: In a sense, then, low k values indicate a gustier environment. A typical terrestrial value for k is ~ 2 (e.g., 2.0 at Lagos, Nigeria⁵; 2.0 at Bahrain⁶; 2.05 over the North Sea⁷; and 1.8 at Hatyai, Thailand⁸) with scale speeds of 2.3, 6.9, 10.3, and 3.8 m/s, respectively. Lower and higher values (e.g., $k = 1.2$ at Ubon, Thailand⁹; 3.4 at Baghdad, Iraq⁹) also have been reported. Note that there is temporal variability in the values obtained, and the value of k obtained by a best fit is affected if the data sequence fitted is short (because higher, less probable, winds are less likely to be sampled, the fit will not need to account for higher wind speeds). Note also that there is a selection effect in that the parameters above were for regions chosen for wind energy potential.

A Weibull distribution does not account for calm periods ($v \sim 0$). It is common practice to reject calm periods from the data and rescale the remaining probabilities, such that they sum to 1, before fitting the Weibull function. This procedure has been adopted here because low wind speeds are typically not those that drive an engineering design. Further, the fitting of low wind speeds is sometimes difficult and leads to fits that are poorer for describing the highest wind speeds (frequently those of interest), so that it is sometimes useful to generate the fit only for wind speeds above some threshold value.

Viking Data

Wind speeds were recorded¹ by hot film anemometers on the Viking landers, about 1.6 m above the ground. The data were made available on the Planetary Data System by James Tillman of the University of Washington. The data set used here is VL1/VL2-M-MET-4-BINNED-P-T-V-V1.0 covering Lander 1 sols 1-45 and Lander 2 sols 1-1050. The data used are the hourly averaged wind speeds (the most common type of data used in terrestrial wind energy studies) and the Lander 2 data set is shown in Fig. 1. Note the data dropout at ~ 550 sols and the peaks in maximum wind speeds at ~ 400 and ~ 1000 sols.

For this study, segments of the data were extracted and used to generate a distribution using 1.0-m/s wide bins. Data in the 0- to 1-m/s bin (the calm fraction, which includes data dropouts as well as calm periods) were rejected and the other values rescaled accordingly, and the best-fit (least-squares) Weibull distribution was found with k values specified to ± 0.02 and c values to ± 0.05 m/s.

Results

Results are listed in Table 1. Because the data in Fig. 1 show episodes when the wind intensities are distinctive, Weibull fits were generated for the more quiescent (e.g., 0-100, 650-750 sols) and windier (350-450, 950-1050 sols) episodes. These are shown in Fig. 2. The windier episodes have lower k values and higher c values, both of which would be expected. Note that the windy episodes are defined only by inspection of Fig. 1; they do not necessarily correspond to dust storms.

Table 1 Best-fit Weibull parameters for Viking Lander data

Lander	Sols	Comments	c , m/s	k	Calm fraction
1	0-45	—	3.35	1.48	0.167
2	0-45	—	2.40	1.50	0.07
2	0-1040	—	3.85	1.22	0.137
2	0-1040	($v > 5$ m/s) ^a	4.60	1.04	0.137
2	0-530	—	4.0	1.20	0.046
2	0-530	($v > 5$ m/s) ^a	4.55	1.06	0.046
2	0-100	Quiescent	2.60	1.58	0.064
2	650-750	Quiescent	2.55	1.68	0.063
2	350-450	Windy	7.6	1.48	0.023
2	950-1050	Windy	7.45	1.48	0.119
2	35-45	Epoch 1	2.65	1.60	0.122
2	153-162	Epoch 2	4.90	1.28	0.124
2	204-215	Epoch 3	3.85	1.28	0.098
2	296-307	Epoch 4	7.90	1.60	0.095
2	166-170	Dust storm	6.85	1.44	0.27
2	267-280	Dust storm	5.45	1.26	0.08

^aThe fit was made only for wind speeds greater than 5 m/s.

Interestingly, the simple arithmetic mean of the quiescent and stormy distributions seems to describe the overall data set (0–1050 sols) very well, even without tuning the distribution by scaling the two fits by values other than 0.5 to take into account possible nonequality in the relative lengths of windy and quiescent conditions. Alternatively, the overall data set may be described by $k \sim 1.22$ m/s, $c \sim 3.85$ m/s. This distribution has a k value somewhat lower than is typical for the Earth, especially considering that the Viking data were recorded at 1.6-m altitude, where gusts might be expected to be attenuated more than at the 10 m used in terrestrial studies.

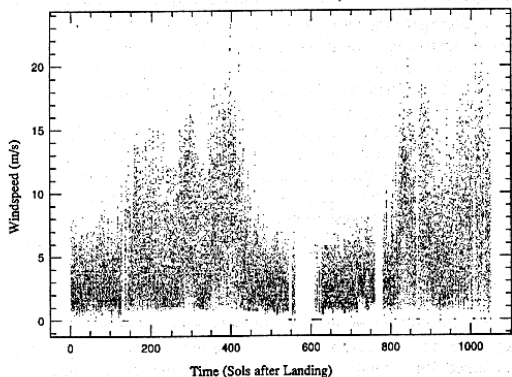
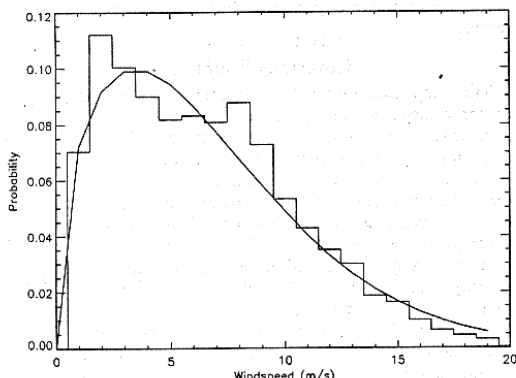
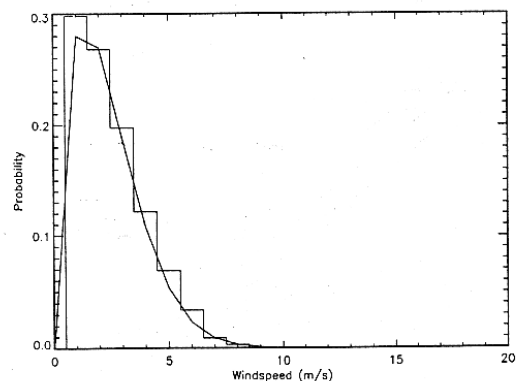


Fig. 1 Hourly average wind speeds as recorded by the anemometer on Viking Lander 2.



a) Windy; sols 950–1050: $c = 7.45$ m/s, $k = 1.48$



b) Quiescent; sols 0–100: $c = 2.6$ m/s, $k = 1.58$

Fig. 2 Histograms of hourly wind speeds for Viking Lander 2 over two periods with corresponding Weibull fits.

The 1050-sol distribution appears to slightly underestimate the frequency of high winds ($v > 15$ m/s). If the fit is applied only to the data exceeding 5 m/s, better agreement is obtained for $5 < v < 15$ m/s with $c = 4.60$ m/s, $k = 1.04$. This parameter pair, however, appears to slightly overestimate wind speeds for $v > 15$ m/s. If the distribution is being used to predict probabilities of wind speeds exceeding some value, then clearly it is useful to optimise the range of speeds used for the fit (or their relative weight).

The Viking Lander 2 wind data for sols 1–45 were examined on an hourly basis to compare with the results reported by Hess et al.,² which state that the wind becomes gusty shortly after sunrise and remains so until midafternoon. At night (hours 20–24), winds are light $1.3 < c < 2.7$ m/s with $1.7 < k < 2.3$ (i.e., somewhat variable), whereas during the day (hours 5–20) k remains constant at 2.3, with the wind speeds stronger (> 3 m/s), strongest at hours 8 and 9. This apparent discrepancy is attributable to the fact that (as stated elsewhere²) the wind direction as well as magnitude varies, so that the vector average wind speeds are low. This is a clear limitation of using hourly averaged data. Parameters also have been computed for two dust storms described by Tillman et al.³ and four epochs identified by Ryan et al.⁴—the dust-storm c values indicate elevated wind speeds, although the data sequences are probably too short for the k values to be relied upon. Epochs 1 and 2 have moderate variation in wind speed, with light and strong winds, respectively. The wind speeds are reflected in their low and high c parameters, with $k \sim 1.60$, typical of quiescent conditions. Epochs 2 and 3 have a regular sequence of weather disturbances, with strong northerly and weak southerly winds—the c values of 3.85 and 4.9 m/s are intermediate between those for epochs 1 and 4, whereas the k values are low (1.28), indicating variable conditions.

Applications

It has been found that the Weibull distribution is effective for describing wind speeds recorded on the Martian surface. Two wind-speed regimes have been identified: quiescent (described by $k \sim 1.6$, $c \sim 2.6$ m/s) and windy ($k \sim 1.48$, $c \sim 7.6$ m/s). The overall wind-speed distribution for 1050 sols can be described as the arithmetic mean of these distributions, or alternatively by $k \sim 1.22$, $c \sim 3.85$ m/s. This distribution has a k value somewhat lower than is typical for the Earth.

Wind-speed distributions of the type described above have a number of potential applications. First, a Weibull parameterization is perhaps better than a mean and standard deviation for describing wind speeds for climate studies.

Second, the design of equipment for the Martian surface requires environmental models to define expected conditions: Poorly defined models can lead to overdesign (with a cost and payload mass penalty) or underdesign (with unacceptable risk of failure). This situation is particularly acute for the design of impact-attenuation systems for lander vehicles for which the assumed horizontal (wind) velocity is a strong design driver.¹⁰ An additional application here is wind energy, which offers considerable potential on Mars¹¹—the fraction of time a turbine would be inoperative because of winds too slack to harness, or strong enough to cause damage, can be estimated.

Third, many natural phenomena, such as dune formation or erosion, depend on wind speeds exceeding some threshold value (e.g., the saltation threshold for particles of a certain size). A useful measure of formation time of features¹² requires some estimate of how frequently such speeds occur, and a Weibull distribution offers this possibility.

Conclusions

It is emphasized that the Weibull distributions reported here describe only the recorded (hourly) data for the sites specified. The technique is useful for anticipating temporal variability (especially where the largest data set has been used), but the corresponding distributions for other locations may be radically different—cf., the variability in terrestrial values. (Note also that there is some recent evidence that Mars' atmosphere may have been dustier during the Viking epoch than at present.) Further, this type of description of wind speeds takes no account of directionality or very short-term variability in wind speed. However, after taking these caveats into account, it is seen that the Weibull distribution offers a convenient

means of defining an engineering model of the Mars surface wind environment.

Acknowledgment

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References

- ¹Hess, S. L., Henry, R. M., Leovy, C. B., Ryan, J. A., and Tillman, J. E., "Meteorological Results from the Surface of Mars: Viking 1 and 2," *Journal of Geophysical Research*, Vol. 82, No. 28, 1977, pp. 4559-4574.
- ²Hess, S. L., Henry, R. M., Leovy, C. B., Ryan, J. A., and Tillman, J. E., "Early Meteorological Results from the Viking 2 Lander," *Science*, Vol. 194, No. 17, 1976, pp. 1352, 1353.
- ³Tillman, J. E., Henry, R. M., and Hess, S. L., "Frontal Systems During Passage of the Martian North Polar Hood over the Viking Lander 2 Site Prior to the First 1977 Dust Storm," *Journal of Geophysical Research*, Vol. 84, No. B6, 1979, pp. 2947-2955.
- ⁴Ryan, J. A., Henry, R. M., Hess, S. L., Leovy, C. B., Tillman, J. E., and Walcek, C., "Mars Meteorology: Three Seasons at the Surface," *Geophysical Research Letters*, Vol. 5, No. 8, 1978, pp. 715-718.
- ⁵Ojusu, J. O., and Salawu, R. L., "An Evaluation of Wind Energy Potential as a Power Generation Source in Nigeria," *Solar and Wind Technology*, Vol. 7, No. 6, 1990, pp. 663-673.
- ⁶Som, A. K., and Ragab, F. M., "A Preliminary Study of Wind Power Potential in Bahrain," *Renewable Energy*, Vol. 3, No. 1, 1993, pp. 67-74.
- ⁷Coelingh, J. P., van Wijk, A. J. N., Cleijne, J. W., and Pleune, R., "Description of the North Sea Wind Climate for Wind Energy Applications," *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 39, 1992, pp. 221-232.
- ⁸Exell, R. H. B., "Wind Energy Potential of Thailand," *Solar Energy*, Vol. 35, No. 1, 1985, pp. 3-12.
- ⁹Darwish, A. S. K., and Sayigh, A. A. M., "Wind Energy Potential in Iraq," *Solar and Wind Technology*, Vol. 5, No. 3, 1988, pp. 215-222.
- ¹⁰Steckemetz, B., Wiens, W., Bradbury, B., Pickett, A., Natenbruck, P., and Roumeas, R., "Flight and Impact Dynamics of Landers for Mars Exploration," 44th Congress of the International Astronautical Federation, Paper IAF-93-Q.1.379, Graz, Austria, Oct. 1993.
- ¹¹Haslach, H. W., "Wind Energy: A Resource for a Human Mission to Mars," *Journal of the British Interplanetary Society*, Vol. 42, 1989, pp. 171-178.
- ¹²Lorenz, R. D., Lunine, J. I., Grier, J. A., and Fischer, M. A., "Prediction of Aeolian Phenomena on Planets: Application to Titan Paleoclimatology," *Journal of Geophysical Research*, Vol. 100, No. E12, 1995, pp. 26,377-26,386.

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Navier-Stokes Calculations for Rotating Configurations: Implementation for Rockets

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Nomenclature

$b_{s,i}$	= heat flux
H	= total enthalpy
p	= pressure
(u, v, w)	= Cartesian velocity
(x, y, z)	= Cartesian coordinates
ρ	= density
$\tau_{s,i,j}$	= shear stresses
Ω	= rotating rate
Ω_{ref}	= reference value of rotating rate

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Introduction

MANY rockets are stabilized by spinning generated by their fins. Among the aerodynamic coefficients needed for flight simulation is the rolling moment coefficient. The rolling moment contains two terms; the forcing term, which is induced by the fins for a nonspinning configuration, and a damping term, which is a dynamic term arising because of spinning. In Ref. 1 the capability to predict the equilibrium spin rate, and the forcing and damping rolling moments for the M829 projectile using a parabolized Navier-Stokes computational code, is reported.

Our primary goal is to derive the forcing and damping rolling moments and to find the rotation rate of the rocket for a given velocity. The forcing rolling moment was calculated for a nonspinning rocket for nonzero angles of attack. Good results as compared with wind-tunnel tests are shown. For a rotating configuration, only zero angle of attack is considered. The flow is periodic and the computations are performed only on one-quarter of the space. For the nonzero angle-of-attack case the flow is not symmetric and the calculations are performed on the whole space with no rotation. For a rotating configuration the flow is generally time dependent. For zero angle of attack, when the Navier-Stokes equations are formulated in a rotating coordinate system with constant rotation rate, the solution is steady state. In this Note, the transonic and supersonic flowfield about rockets with wrap around fins having a small differential cant angle is calculated by solving the three-dimensional Navier-Stokes equations in a rotating system.

The total rolling moment calculated for the rotating configuration contains both the forcing and damping terms. The rolling moment obtained for a rotating configuration is a monotonic function of the rotation rate. The rotation rate at which the rolling moment vanishes indicates the equilibrium rotation rate of a free rocket for a given velocity along its trajectory. Comparison of the calculated rotation rates and those measured in flight tests show very good results.

Governing Equations

The compressible Reynolds averaged Navier-Stokes equations are formulated in a Cartesian reference frame rotating with constant angular velocity Ω around the main rocket axis. For the flow variables, relative to the body rotation, the far-field velocity has a circumferential component, which is a function of the distance from the configuration axis; the far-field boundary condition then depends on the location of the far-field boundary. This could cause a loss of accuracy. To avoid this difficulty the equations are recast in the absolute flow variables defined in the inertial system for which the velocity is uniform in the far field. A similar formulation for the Euler equations is obtained in Ref. 2.

The rotating coordinate system (x, y, z) is shown in Fig. 1. The rotational velocity for a configuration rotating about the main axis x with angular velocity Ω is

$$u_{\Omega} = 0 \quad v_{\Omega} = -\Omega z \quad w_{\Omega} = \Omega y \quad (1)$$

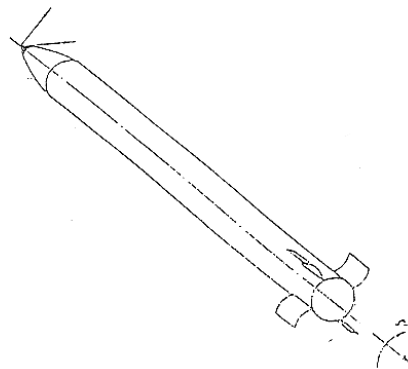


Fig. 1 Typical rocket geometry in a rotating system.