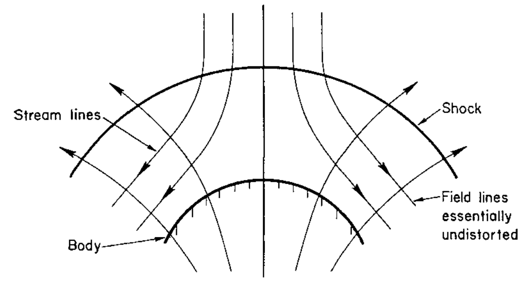

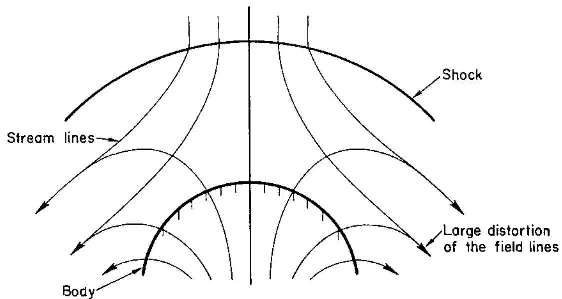

Fig 3 Magnetic field lines for a) small conductivity and b) laıge conductivity

Discussion of Results

A plot of the standoff distances and Q_m in Fig 1 indicates that, when the value of Q_m exceeds 0 20 (for Re 1000, R_m = 1 0), the quantity $(r - r_b)/r_b$ increases drastically, so that

$$d/dQ_m[(r - r_b)/r_b] \rightarrow \infty$$

Because of this phenomenon, the numerical solution for the case Q_m greater than the critical value mentioned previously becomes impossible Similar difficulty was also observed by Bush[1] The meaning of the critical Q_m was first pointed out by Bush[4] in a note published after Ref 1 He has shown that, if we accept the result of infinitely large shock standoff distance, the finite value of critical Q_m implies an infinitely strong magnetic field at the body This can be seen from the plot given in Fig 2 where the magnetic field components at the body are plotted as a function of the magnetic parameter

To assume that the magnetic field is given at the shock does give considerable mathematical simplification, but evidently for high conductivity the solution obtained by using this boundary condition no longer represents the physical problem This fact can be realized by considering the weakly conducting case ($\sigma \rightarrow 0$) and the infinitely conducting case ($\sigma \rightarrow \infty$) The magnetic field lines for these cases are shown in Figs 3a and 3b In the case ($\sigma \rightarrow 0$), the applied dipole field is essentially not distorted (Fig 3a) However, where ($\sigma \rightarrow \infty$) the distortion of the field lines becomes so large that the field strength at the shock wave vanishes (Fig 3b) This situation violates the basic assumption of a field H_0 at the shock

Another flaw of the present method is that since r and H_0, at the shock, are not natural characteristic quantities of the problem, a plot of these quantities vs Q_m, R_m, and Re is not quite meaningful An improved method of approach is underway and will be reported later

References

[1] Bush, W B , "Magnetohydrodynamic-hypersonic flow past a blunt body, ' J Aerospace Sci 25, 685–690, 728 (November 1958)

[2] Wu, C S , "Hypersonic viscous flow near the stagnation point in the presence of a magnetic field,' J Aerospace Sci 27, 882–893, 950 (December 1960)

[3] Bellman, R , Kagiwada, H , and Kalaba R E , "Orbit determination as a multi-point boundary value problem and quasilinearization," Proc Natl Acad Sci 48, 1327–1329 (1962)

[4] Bush, W B , "A note on magnetohydrodynamic hypersonic flow past a blunt body ' J Aerospace Sci 26, 536–537 (1959)

Determination of Cratering Energy Densities for Metal Targets by Means of Reflectivity Measurements

Herman Mark,* Gary Goldberg,† and Michael J Mirtich†
NASA Lewis Reseaıch Center, Cleveland, Ohio

Any attempt to estimate the lifetime of satellites or satellite components exposed to the high-speed meteoroid environment in the vicinity of the earth requires information in two areas First, knowledge is required of the damage to a structure surface resulting from an encounter with a single meteoroid (if not the understanding of all the complex phenomena that occur during such an impact) Then, reliable information is required regarding the number of encounters with meteoroids of different size, speed, and composition which can be expected to occur in a given time in orbit Unfortunately, for the satellite lifetime estimates, information in both these areas is either unsatisfactory or lacking The work reported herein was undertaken to determine the damage to surface optical properties due to exposure to impact with high-speed micron-size particles and thus to contribute some information in the first area previously mentioned

Polished aluminum surfaces were bombarded by clouds of high-speed SiC particles having an average diameter of 6 μ The number, size, and velocity of the particles was either known or measured, and with the total kinetic energy of the cloud characterizing the exposure, changes in reflectivity of the exposed surfaces were measured with an infrared spectrometer A good correlation of the measured reflectivity, before and after exposure, was obtained with the equation[1]

$$\bar{\rho}_f = \bar{\rho}_i\{1 - [1 - (\bar{\rho}_\infty/\bar{\rho}_i)](1 - e^{-K_1 \epsilon})\} \quad (1)$$

where

$\bar{\rho}_f$ = average final reflectivity of area A_0 after exposure to ϵ

$\bar{\rho}_i$ = average initial reflectivity of area A_0, (0 97 for polished Al)

$\bar{\rho}_\infty$ = average reflectivity after infinite exposure, (0 15 for target assumed coated with projectile material)

K_1 = empirical constant, 0 229/joule falling on A_0

$\epsilon = \sum_{i=1}^{N} \frac{1}{2} m_i v_i^2$, total kinetic energy of particle cloud falling on area A_0, joules

In the development of this equation, it becomes clear that the constant K_1 is the percentage of fresh area damaged per unit impact energy With the assumption that hemispherical shaped craters are formed on impact,[2] K_1 is related to E_c,

Received January 20, 1964

* Chief, Aero-Space Environment Branch Associate Fellow Member AIAA

† Aerospace Engineer, Space Environment Section

Table 1 Comparison of calculated and experimental values of cratering energy density

Target	Projectile Material	Projectile Density ρ, g/cm³	Particle velocity v_p	E from Eq (8), ergs/cm³	E_c, from experiment, ergs/cm³	Reference
Al-1100	SiC	3 2	8,400 fps	$6\ 26 \times 10^9$	$2\ 36 \times 10^{10}$	Eq (6)
Al-2014	WC	15 6	<49,200 fps	$1\ 28 \times 10^9$	$2\ 25 \times 10^{10}$	Ref. 3
Al-75 St	Steel	7 83	<49,200 fps	$2\ 56 \times 10^9$	$3\ 90 \times 10^{10}$	Ref 3
Al-2024-T3 and 24 St	Al	2 7	8,000 fps	$7\ 42 \times 10^9$	$2\ 49 \times 10^{10}$	Ref 4

the cratering energy density, that is, the projectile energy required per unit volume of the crater formed in the target

Over the range of impact energies of interest here, the rate of surface damage can be assumed proportional to remaining undamaged area Thus

$$dA_D/d\epsilon = K_1[A_0 - A_D(\epsilon)] \tag{2}$$

where

$A_D(\epsilon)$ = area damaged by exposure to ϵ
A_0 = area of undamaged $\frac{15}{16}$ in -diam disk

The simplest procedure for relating K_1 and E is to consider the initial condition of an undamaged surface Then, for the first hit $A_D(0) = 0$, and Eq (2) can be written

$$(dA_D/d\epsilon)_{\epsilon\approx 0} = K_1 A_0 \tag{3}$$

If the crater volume is proportional to the projectile energy, the left side can also be written

$$\left(\frac{dA_D}{d\epsilon}\right)_{\approx 0} = \frac{(3\pi^{1/2} m_p v_p^2 / 4E_{cr})^{2/3}}{(\frac{1}{2} m_p v_p^2)} \tag{4}$$

where the numerator is the damaged area due to the first hit, and the denominator is the kinetic energy of first particle impingement, here in ergs From Eqs (3) and (4)

$$K_1 = \frac{2}{A_0}\left(\frac{3\pi^{1/2}}{4E}\right)^{2/3} \frac{1}{(m_p v_p^2)^{1/3}} \tag{5}$$

or

$$E_c = \frac{3\pi^{1/2}}{2^{1/2}(K_1 A_0)^{3/2}(m_p v_p^2)^{1/2}} \tag{6}$$

For our experimental condition (with v_p = 8400 fps) the value for E obtained from Eq (6) is given in Table 1 for an Al target Table 1 also contains the experimental value for E_c from Refs 3 and 4, as determined by impacting high-speed projectiles against Al targets and measuring the volume of the crater formed in the targets It can be seen in Table 1 that the value for E_c, as determined from Eq (6), compares well with the experimental values of Refs 3 and 4. It should be pointed out that the value for K_1 necessary for this calculation was obtained from only six reflectivity measurements These reflectivity measurements were quite good, but further experimentation would provide a more accurate value for K_1

In Ref 5, the following equation is presented for the penetration of high-speed projectiles into semi-infinite targets:

$$p/D = 2\ 28(\rho_p/\rho_T)^{2/3}(v_p/C)^{2/3} \tag{7}$$

where

p = penetration
D = diameter of particle
ρ_p = projectile density
ρ_T = target density
v_p = particle velocity
C = speed of sound in target

This equation has been extensively used to determine the number of penetrations expected to occur in satellite penetration experiments [6] From this equation, E_c is

$$E = (C^2/94\ 4)(\rho_T^2/\rho_p) \tag{8}$$

Values for E calculated from Eq (8) are also presented in Table 1 for comparison with the experimentally determined values Notice that Eq (8) underestimates, considerably, the cratering energy density as compared with the experiments and, hence, would overestimate penetrations expected to occur in Al This suggests that great care must be taken when trying to determine meteoroid flux from satellite penetration experiments, and that flux estimates from these experiments may be low and are very approximate at best The possibility of measuring micrometeoroid flux in the vicinity of the earth with a calibrated reflectivity sensor is being considered

References

[1] Mirtich, M J and Mark, H, "Alteration of surface optical properties by high speed micron size particles," Fifth Symposium on Thermal Radiation of Solids, Univ of Calif (March 4-6 1964), Session IV, no 9

[2] Kornhauser, M, "Prediction of cratering by meteoroid impacts," *Proceedings of the Fourth Annual Meeting of the American Astronautical Society* (January 1958), pp 33-1-33-13

[3] Eichelberger, R J and Gehring, J W, "Effects of meteoroid impacts on space vehicles, Ballistic Research Lab Rept 1155 (December 1961)

[4] Herrmann, W and Jones, A H, "Survey of hypervelocity impact information ' Massachusetts Institute of Technology, Aeroelastic and Structures Research Labs, Rept 99 1 (September 1961)

[5] Summers, J L, "Investigation of high-speed impact: Regions of impact and impact at oblique angles, ' NASA TN E 94 (1959)

[6] Davison, E H and Winslow, P C, ' Space debris hazard evaluation " NASA TN D-1105 (1961)

Calorimetric Heating-Rate Probe for Maximum-Response-Time Interval

ROBERT H KIRCHHOFF*
NASA Ames Research Center, Moffett Field, Calif

Nomenclature

c = slug specific heat
k = thermal conductivity
q = heating rate
t = temperature
t_m = maximum allowable front face temperature
x = length dimension
α = thermal diffusivity
δ = length of slug
ρ = slug density
θ = time

Received February 10, 1964

* Thermo- and Gas-Dynamics Division