greater exposure (more hits at higher velocities) would be expected to cause greater degradation. A velocity effect that is of interest is that at constant total kinetic energy of exposure a higher particle velocity actually causes less surface damage.[4]

Although their argument for using a value of zero for crater reflectance R_c seems satisfactory, considering the depth-to-diameter ratios they encountered for their craters, it is certainly not a general result. We have made measurements at NASA Lewis Research Center of R_c for metal targets impacted by a number of projectile materials 1 to 15 μ in diameter and find R_c to vary from 0.3 to 0.5, the amount of variation depending on the target as well as on the projectile.

With regard to presenting surface degradation normalized to damaged area or number of craters, it should be pointed out that a simple expression can be written[4] for the ratio of these two quantities. It is:

$$\frac{(\Delta R/R)/A}{(\Delta R/R)/N} = \left\{\frac{2\,E_{cr}}{3\pi^{1/2}(m_p v_p^2)/2}\right\}^{2/3}$$

where E_{cr} is cratering energy density of the target material and $m_p v_p^2/2$ is the kinetic energy of a single projectile. Hence the ratio of the two quantities would be expected to vary with target material for a given projectile and impact speed. Comparing these quantities as presented in Tables 2 and 3 of Ref. 1 causes some doubt regarding their measurements for aluminum and gold (for which this ratio rises instead of falling as it should, and as do the other such values with projectile speed).

Perhaps it is most important to point out that conclusions regarding the effect of exposure on α/ϵ of SS 304 should not be made from the data obtained in Ref. 1. It should be clear from the data in their Fig. 9 that, of all the materials exposed, only their SS 304 showed an α/ϵ before exposure less than 3. Obviously, the exposure could not be expected to reduce α/ϵ much further. In Ref. 4 the effect of exposure on SS 304 was as expected. The results there showed the α/ϵ of SS 304 to fall with exposure from 3.86 to 2.0. However, the equilibrium temperature of such a disk remained constant with this change in α/ϵ when the disk was placed in a simulated space environment. This was shown to be a thermal interaction between the disk and the simulated satellite on which it was mounted and from which it can not be perfectly isolated thermally.[7]

In conclusion, we must point out that although a great deal of work has been done and reported in Ref. 1, the results of this work cannot be used to determine the effect of micrometeoroid impact on satellite skin materials in space. This is especially true because the authors had no quantitative idea of the type, size, and mass of the projectiles causing the damage they recorded. For a single nominal projectile size, the range of size of craters formed in the target was so great (most are smaller than the original projectile) as to indicate that the greater part of the damage to optical properties was caused by incidental particles, making any kind of quantitative analysis impossible.

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Reply by Authors to H. Mark and M. J. Mirtich

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The objective of the work described in the subject article[1] was to investigate the change in optical properties of metals after being damaged by a process that simulated micrometeorite impingement. Since the experiments were not designed to correlate the change in optical properties with the impacting or cratering energy of the impinging particles, it is doubtful that the information given in Refs. 2–4 (were they all available) would have altered the presentation of the data. Reference 2 was not presented at the Fifth Symposium on Thermal Radiation of Solids in March of 1964, but was included only in the proceedings of the Symposium which were published in the summer of 1965, ten months after our paper was submitted to this journal. Similarly, Ref. 4 was not presented until four months after our paper was submitted. Reference 3, which was available at the time our paper was submitted, proposes a correlation between cratering energy and reflectivity, a problem beyond the scope of Ref. 1. To support our position that Refs. 2, 3, and 4 are not pertinent to the problem treated in our paper, we wish to point out that the authors of Refs. 2, 3, and 4, realizing this fact, did not deem it necessary to refer to our previous work (Refs. 5, 6, and 7) which was published as early as 1962.

Concerning the size of the impinging particles (the subject of Ref. 8), it appears necessary to restate that the major damage to the targets was caused by fine dust particles (<20 μ diam) and not by 100μ projectiles. The 100μ diam was merely the size of the original projectiles. As explained in the original paper,[1] the projectiles disintegrated into fine dust particles upon being accelerated to velocities as high as 23,000 fps. It was these fine dust particles that caused the surface damage. The comments of Mark and Mirtich concerning the impingement of 100μ projectiles are therefore without foundation.

It may have appeared unnecessary to the commentators to indicate that high velocity impacts caused more degradation than low velocity impacts. We felt, however, that in the case of a scientific area that is in a recognized state of disagreement, any agreement between experimental results and theory should be pointed out.

It is not surprising that the data presented does not agree totally with the ballistics expression given by Mark and Mirtich. In fact, it is safe to say, based on the present lack of agreement of the various ballistic theories, that there are several other expressions which the commentators could cite,

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with which the data do not agree. It is interesting, however, that in the cases of three of the five metals studied the experimental data agree with the results obtained from the commentators' analytical expression. It appears important, therefore, for a ballistic engineer to analyze the suggested expression and determine its limitations. Perhaps it is limited to hard metals, since the discrepancies were noted in the softest metals studied, gold and aluminum.

More important than the discrepancy cited by Mark and Mirtich is the agreement between the experimental data and the theoretical expression of workers at the Marshall Space Flight Center at Huntsville, Ala.[9] This correlation was found to be true for all metals tested, including gold and aluminum.

The argument of the commentators pertaining to the α/ϵ value of SS 304 is not clear. It is not obvious that the already low α/ϵ value of SS 304 could not be expected to be reduced on particle impact. Quite the contrary is true. In the Fig. 9, we showed that gold, platinum, and chromium plated copper all had lower α/ϵ values after impacting than SS 304 did. The commentators' references to their own work (Ref. 4) shows that the α/ϵ of SS 304 did decrease from 3.86 to 2.0. Contrary to this, they found that the equilibrium temperature of a SS 304 disk remained constant when heated by solar radiation before and after impact. They explained this by the thermal interaction of the disk and the simulated satellite on which it was mounted during the measurement. If such a thermal interaction did take place, then a large portion of their findings are meaningless, since one of the purposes of their work was to determine the equilibrium temperature of disks heated and cooled by thermal radiation only. Although a small but known amount of nonradiant interaction may be accommodated, any interaction that allows the α/ϵ ratio to be reduced by nearly 50% without showing a change in the equilibrium temperature should be investigated and defined.

Contrary to the conclusions of Mark and Mirtich, one of the values of the subject article[1] is that it experimentally substantiates an analytical expression[9] relating changes in optical properties of metals to surface damage. Once it becomes possible to estimate the satellite surface damage caused by the micrometeoroid flux, it should now be possible to calculate the expected change in optical properties with more confidence.

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More Results on Solar Influenced Libration Point Motion

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THE influence of the sun on the motion of an artificial satellite moving in the vicinity of the stable earth-moon libration point L_4, was considered in Refs. 1–4. Reference 2 presented a numerical integration of the equations of motion to 2500 days. The results indicated that the motion is oscillatory and has a gross period of approximately 1450 days, with the excursion envelope reaching a maximum amplitude of 160,000 miles. The authors suggested a long-term pulsation for the amplitude of the satellite motion and concluded that the motion was stable. The purpose of this study is to consider the motion for an extended period of time with a view towards an examination of this conclusion. The perturbing effect of the sun is restricted to its gravitational attraction and does not include solar radiation pressure. The earth and the moon are assumed to move about their barycenter in circular orbits. The barycenter, in turn, is assumed to move in a circular orbit about the sun. The earth-moon orbital plane is assumed to be inclined to the ecliptic at a constant angle of 5.15°. Each of the bodies is treated as a mass point. The equations of motion are integrated numerically using the program of Ref. 5. The numerical values for the constants of the problem are identical to those used in Refs. 1 and 2, as are the maximum allowable error and the allowable range of step size. Initial time is taken at inferior conjunction.

Fig. 1 presents the excursion from L_4 for the 5000 day duration of the study. In studying this result, one observes initially a periodicity in the motion envelope of about 1450 days, as noted in Ref. 2. However, the nature of the motion changes after approximately 3700 days. Whereas during the first 3700 days the largest displacement encountered was 167,710 miles, which is approximately two-thirds of the distance between the libration point and the earth or the moon, the magnitude of the displacement for $t > 3700$ days becomes increasingly larger until, at 5000 days, it reaches 52,200,000 miles and the satellite obviously is out of cislunar space and has entered a heliocentric orbit.

The problable explanation for this behavior is the fact that at the "critical" time, the satellite passes at close proximity to the moon, as shown in Fig. 2, which illustrates these passages in the time period 4225 to 4434 days. It is conjectured that the combination of the sun's attractive force and the high satellite velocity during close encounter acts so as to increase the satellite energy sufficiently to escape cislunar space.

It should be pointed out that these results are not believed to be affected grossly by computation errors, since a com-

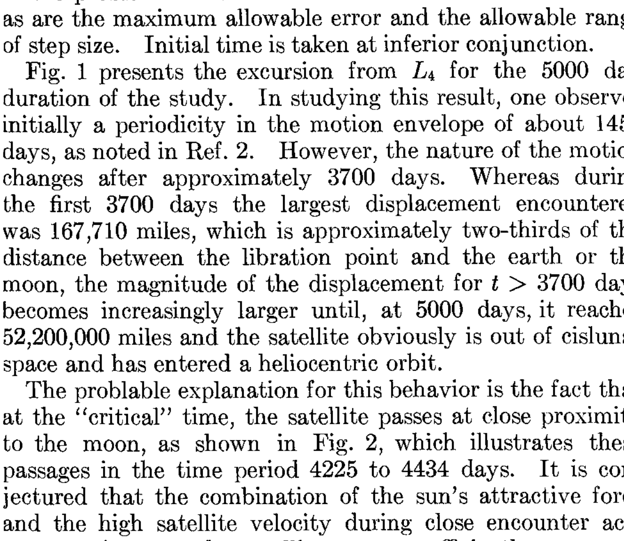

Fig. 1 Excursion of satellite from L_4. (Scale at right refers to $t > 4200$ days.)

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