DISCUSSION

J. H. Brunton[1] (*written discussion*)—Very intense stress waves will be produced in the specimens by impacts in the velocity range investigated. The reflection of these waves in the boundaries of the specimen and their subsequent interference can lead to extensive failure. This mechanism of failure is likely to be particularly noticeable in small specimens with sharp corners and edges. Some early work of ours, using a high-speed water jet in the velocity range Mach 2.0 to 4.0, showed that for ceramic and polymeric materials stress wave damage was more important than any other single failure mechanism. In tests where edge effects need to be eliminated this might be done by potting the specimens in a material of greater acoustic impedance. This would allow the impact energy to pass out of the specimen and prevent adverse focussing of stress leading to premature failure.

Another point of interest would be the comparison of damage produced in sled tests with that produced by multiple impacts using the high-speed jet equipment.[2] Impact variables such as velocity, drop size, surface temperature, angle, and the number of impacts on the same area (presumed small in the sled tests) could be reproduced fairly readily with the gun technique. A straight comparison would show whether this simple and inexpensive technique (this is perhaps its big advantage) could be used as a quick sorting test on new materials.

G. F. Schmitt, Jr. (*author's closure*)—The suggestion for use of a potting material of greater acoustic impedance is a good one, and I thank Dr. Brunton for it. The phenomenon of stress wave damage of which he speaks is definitely acting in the case of these sled tests. The modes of failure of the various ceramics (cracking and chunking out of pieces) reflect (sorry, no pun intended) this interaction at the boundaries.

The use of the multiple impact, high-speed jet equipment on selected materials of those investigated in the sled tests is being attempted by Dr. Frederick Hammitt and his co-workers of the University of Michigan. The results are not yet available, but the comparison will be interesting. The use of a simple device for such screening has been employed at Georgia Institute of Technology utilizing a shotgun and lead shot. Mr. Fyall of Royal Aircraft Establishment has shown the lead acts surprisingly like water on impact, and it has been useful in screening ceramic coatings for

[1] University Engineering Department, Cambridge, England.

[2] Bowden, F. P. and Brunton, J. H., *Proceedings of the Royal Society*, London, Series A, Vol. 263, 1961, p. 433.

impact resistance. The primary mode of failure for improved ceramic coatings in the sled tests is an impact fracture. A correlation was obtained between the shotgun results and sled test results.

Olive G. Engel[3] (*written discussion*)—The thermal effects at high Mach numbers appear to introduce a variable that has not been considered. Is it really substantiated that the observed damage is the result of drop impingement alone?

Mr. Schmitt—The thermal effect at high Mach numbers has been considered in this work but not included in the MDPR sin θ–V sin θ analysis. At Mach 4.0, charring of most organic resin materials (laminates, bulk plastics) was pronounced. However, at Mach 3.0 or below no thermal effects were detected on any of the materials investigated except a neoprene coating at Mach 3 (only). Certainly a temperature factor needs to be introduced into the analytical relationships describing erosion since the combined elevated temperature-rain impingement effects would be and are considerable.

A. A. Fyall[4] (*written discussion*)—I must agree with Dr. Engel that the kinetic temperature of the test materials may have a fundamental effect on the measured rain erosion characteristics. This is particularly true for polymeric materials where a temperature change in the test cell, of say, 10 C, can have a profound influence on the dynamic behavior of the material.

I would like to make a general comment on Mr. Schmitt's paper. It is very tempting to squeeze the last drop of statistical data from a test, but sled techniques have limitations in this direction. I feel that they have their place as being useful for material evaluation and for quality control of finished products, for example, radomes. It is, however, somewhat dangerous to attempt to derive empirical formulae from observation of sled results.

On the subject of data interpretation, I would like to sound a word of caution regarding the use of mean depth of penetration rate (MDPR) as a parameter. If the material has eroded uniformly, it may be of some limited value for sled tests. However, the sled test evidence of many materials is of surfaces damaged in some areas and unscathed in others. This means that either the undamaged portion has been hit by less drops or that its erosion resistance is better than that of the adjacent material. It is, obviously, quite wrong to use MDPR under these circumstances.

On the performance of specific materials, I would feel that Pyroceram

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9606 is a particularly bad example on which to attempt to evaluate any dependence. The modes of its failure are various and certainly, in my experience, do not qualify as "eroding uniformly."

Certain glasses do erode slowly at low speed, that is, there is no catastrophic shattering. For example, Chemcor 0313 is pitted uniformly at 500 mph in 1 in./h rain to such an extent that it would be rejected for loss of transmission before it failed structurally.

Mr. Schmitt—The temperature change effect on polymeric materials which Mr. Fyall refers to is discussed in a paper by Dr. H. Oberst of Farbwerke Hoechst AG entitled "Rain Erosion and Molecular Properties of Synthetic Materials." This report (RAE Translation No. 1335) is available from the Defense Documentation Center, and I thought mention should be made of it here.

The analysis of data from the sled tests is hampered seriously by the lack of knowledge of the environment that really exists at the time of a run. In fact, the unknowns of this rain environment (actual droplet sizes and rainfall rates at the moment of launch) have prevented us from analyzing the data on a mass loss ratio (mass of material eroded to mass of water impinged) basis which would be nondimensional and desirable in my opinion. On the other hand, the mean depth of penetration rate which we have developed is synthesized from the weight loss which occurred and does assume uniform erosion over the exposed specimen surface. For most ceramics and glasses, this is not the case, as Mr. Fyall points out, and MDPR is quite artificial for these materials. This limitation is not as severe for other classes of materials. However, the analysis is useful in exhibiting velocity-erosion damage relationships for all classes. I would point out that Pyroceram 9606 was only one of approximately 25 ceramics investigated and was included here because of the widespread interest in it; its erosion behavior is difficult to analyze. We are working on other ways to meaningfully analyze the ceramic data currently. The limitations of sled test techniques have been recognized for a number of years and that is why the Air Force Materials Laboratory recently has sponsored the development of a supersonic rotating arm apparatus.

Our experience with the Chemcor 0313 glass at 500 mph, 1 in./h rain, has been contrary to that of Mr. Fyall. We did in fact see uniform pitting over the surface of the glass after a long exposure period (in excess of 100 min); however, shortly thereafter, we experienced catastrophic failure as the surface compression layer was penetrated and stress relieving occurred. The transmission properties may have been impaired sufficiently prior to shattering (although they were not tested specifically) to reject use of this glass. A contributing factor to the catastrophic failure may have been the amount of support the specimens had in mounting on the rotating arm device.