# DISCUSSION

*J. H. Brunton*[1] (*written discussion*)—It is important to stress the point made by the author, that the commonly looked for correlation between the erosion behavior of materials and their mechanical properties, as determined in quasistatic tests, is likely to have only a limited success. The reason for this is that the time scale of the loading in erosion is very different from that at present attainable in even the more sophisticated methods of dynamic testing.

Suppose we consider a small water droplet, 100 $\mu$m in diameter, impacting against a hard surface at say 500 m/s. Repeated impacts of this kind are known to cause the eventual breakup of high-strength solids. The duration, $T$, of the central water-hammer pressure is determined by the time it takes for release waves to move into the central zone. It can be shown that $T$ is given by,

$$T = \frac{R}{V}\left(1 - \sqrt{1 - \left(\frac{V}{C}\right)^2}\right)$$

where:

$R$ = radius,
$V$ = impact velocity, and
$C$ = compression wave velocity for the appropriate pressure in the liquid.

For the values given above, $T$ is found to be of the order of $10^{-9}$. An estimate of the peak peripheral pressure, associated with jetting of the liquid at the instant the outward flow of liquid begins, can be made, and this too, for the chosen conditions, is again of the order $10^{-9}$. These extremely short loading times result from the small dimensions of the drop and the high impact velocities and stress wave velocities.

What differences in material behavior can be expected under these loading conditions? Among engineering materials metals are the least strain-rate sensitive, but even here, with steels, for example, increases in yield strength by factors of two to three are found for microsecond loading times. Increases of this kind are not related simply to the statically determined mechanical properties. For the much shorter loading times found in drop impingement and in bubble collapse more extreme changes can

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be expected. For example, $10^{-9}$ to $10^{-8}$ is about the time needed for dislocation loops to be generated by the Frank-Read mechanism. The failure of this process to bring about a rapid increase in plastic strain could prevent relaxation of the impact stress in the metal. Further differences could be considered—the prevalence of fine slip lines at high rates of strain and of coarse slip bands at normal strain rates. Again, there could be a size effect in the solid. In erosion very small areas of the surface are loaded individually, a very different situation from that found in most mechanical tests where large volumes are under stress. In this respect it commonly is found to be the case that failure processes which depend on flaw distributions, and in metals this includes dislocation networks which require higher stresses as the dimensions of the loaded area are reduced.

If differences of the type outlined above are important, then it would be as well to treat erosion as a special type of failure in the sense that brittle fracture, creep, and fatigue are special types of failure. Instead of attempting to classify materials in terms of known mechanical properties it is probably more useful to work directly in terms of their erosion properties as determined in a standardized test. Perhaps a vibratory test or a wheel and jet test would be suitable for this purpose. Over the long term it seems probable that erosion studies will follow a similar pattern of development to that taken in the related subject of fatigue. Erosion tests will provide quick answers to practical problems, while an elucidation of the basic mechanisms in terms of material constants is likely to be a lengthy process.

*F. G. Hammitt*[2] *(written discussion)*—This introductory paper is interesting in pointing out both those questions upon which agreement exists as well as those where it does not. In the former category, much has been said recently regarding the importance of microjet impact in cavitation damage, and I believe it generally is agreed that this is indeed an important, though not exclusive, mechanism. An interesting point which I believe needs consideration is the fact that rapid and extensive damage is caused upon materials such as stainless steels and even stellites by rotating wheel impact facilities wherein the impact velocity is only about 300 ft/s. which corresponds to a "water-hammer" pressure of about 20,000 psi. Since this is well below even the fatigue strength of such materials, it is apparent that either actual pressures are well in excess of the water-hammer pressure, or other mechanisms importantly are involved, such as perhaps secondary cavitation in this case.

In the nature of controversies, the assumption of a proportional relation between cavitation damage and strain energy, reported by Hydronautics, is in my opinion a serious error (as further discussed in my paper at

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this symposium). For some types of materials such as tool steels, the relation between cavitation resistance and strain energy is in fact inverse. I believe that the body of data available from all sources today shows a much better proportionality between ultimate resilience and damage resistance, as is reported in both my own paper today and that by Frank Heymann. However, the correlation with ultimate resilience also leaves much to be desired.

Further in the nature of controversy I do not believe in the existence of a final "steady-state zone" of damage rate as reported by the Hydronautics investigators, and in fact I have never seen data which in my opinion supports this hypothesis. Rather the damage appears to continually drop off, depending on the length of test. In some cases (as shown, for example, in the paper by Young and Johnston[3]), it again increases after a minimum at a rapid rate in some cases. I believe that most of these effects are due to changes in "flow geometry." When the damage becomes large, the flow field is affected and the damage rate becomes unpredictable. Its behavior depends very much on the particular material-fluid combination. Thus I feel that the maximum rate attained in a test is the only practical one to be used, both for the reasons cited above and for the usual economic necessity of conserving test time to practical limits.

Finally, I would like to comment on the relation between damage and flow velocity in cavitation tests. While in some cases damage is indeed very sensitive to velocity as reported by Dr. Eisenberg, there are other cases where it is not. Such a case has been found in our own tests with a simple conical diffuser and was previously reported.[4] I believe this relationship depends upon the sensitivity of pressure to velocity in the collapse zone, which is much greater for some flow geometries and cavitation conditions than for others.

For related surveys of present thinking on cavitation damage, I would like to mention the very comprehensive recent American Society of Mechanical Engineers book on this and other cavitation subjects.[5]

[3] See p. 67.

[4] Hammitt, F. G., "Damage to Solids Caused by Cavitation," *Philosophical Transactions*, Royal Society of London, Series A, No. 1110, Vol. 260, July 1966, pp. 245–255.

[5] *Cavitation State of Knowledge*, American Society of Mechanical Engineers, 1969.