DISCUSSION

F. J. Heymann[1] (*written discussion*)—The authors have presented a large amount of very instructive results, ranging over many facets of the liquid impingement erosion problem. Perhaps inevitably, under those circumstances, there are aspects of the data interpretation which are debatable.

In particular, the interesting comparison between rain erosion data and conventional fatigue data could have been put on a sounder basis by making use of more detailed knowledge, which we now have, concerning the magnitude and distribution of pressure generated by an impacting liquid droplet. A review of the various pieces of evidence[2] lead to the following conclusions: (1) the pressure even on a *one-dimensional basis* is higher than the simple "water-hammer pressure," because it is governed by the shock wave velocity and not the acoustic velocity; and (2) in the impact of a *rounded droplet*, the contact pressure is nonuniform and reaches its maximum at the edge of the contact area, and these maximum pressures, at moderate impact velocities, are likely to be two to three times as great as the one-dimensional impact pressures.

Some of the above conclusions have been confirmed by a later analysis,[3] based on a two-dimensional model of a rounded liquid body impacting a rigid plane surface. Figure 24, applicable to water, is derived from this analysis. The maximum impact pressure, at the moment that lateral outflow initiates, is shown by Curve *A*. Curve *B* shows the one-dimensional impact pressure according to footnotes 2 or 4, and Curve *C* is the simple water-hammer pressure corresponding to the authors' Eq 2. Clearly the latter vastly underestimates the maximum stress experienced by the specimen. Admittedly, this maximum stress is localized at the edge of the contact area, and the results of footnote 3 suggest that the highest pressures seen by the central portion of the contact area are very close to the one-

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[2] Heymann, F. J., "A Survey of Clues to the Relationship Between Erosion Rate and Impact Parameters," *Proceedings of the Second Meersburg Conference on Rain Erosion and Allied Phenomena*, 16–18 Aug. 1967, Royal Aircraft Establishment, England, 1 May 1968, pp. 683–760.

[3] Heymann, F. J., "High-Speed Impact Between a Liquid Drop and A Solid Surface," *Journal of Applied Physics*, Vol. 40, Dec. 1969, pp. 5113–5122.

[4] Heymann, F. J., "On the Shock Wave Velocity and Impact Pressure in High-Speed Liquid-Solid Impact," *Journal of Basic Engineering*, *Transactions*, American Society of Mechanical Engineers, Series D., Vol. 90, Sept. 1968, pp. 400–402.

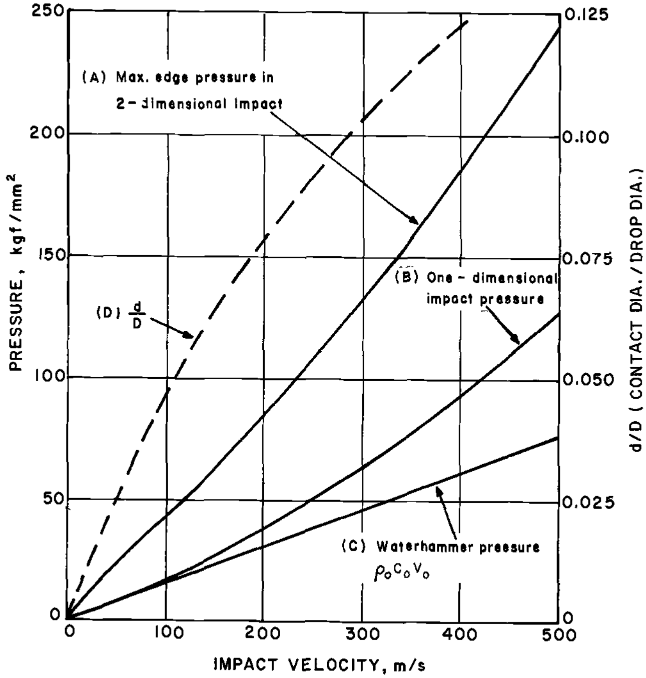

FIG. 24—*Maximum impact pressure due to round liquid drop; comparison of progressively improved approximations.*

dimensional pressure given by Curve *B*. The diameter of the contact area, at the moment radial outflow initiates, is given by Curve *D*. For a 1.2 mm drop impacting at 400 m/s, this diameter is only about 0.15 mm.

Let us now see how all this affects the conclusions reached by the authors: (a) if the stresses given by Curve *A* are used instead of the water-hammer pressures, then all the rain erosion points on the authors' Figs. 9 and 10 would be displaced upwards by a factor of about three; and (b) it seems questionable whether the authors correctly calculated the number of impacts for making the analogy with the number of cycles in fatigue. The proper quantity to use is surely the number of impacts experienced by any given *point* on the surface and *not* the number of droplets impacting per unit area as the authors state. The former, which we may call "specific number of impacts" N_i, can be expressed as follows, if the droplets are assumed to be spherical, uniform in size, and uniform in distribution:

$$N_i = \tfrac{3}{2}\psi \frac{V_o t}{D} \left(\frac{d}{D}\right)^2$$

where:

ψ = "liquid volume concentration" (the same as the authors' rain density),
V_o = impact velocity,
t = exposure time,
D = diameter of droplets, and
d = diameter of effective impact area, that is, that area over which high impact pressures are generated.

As an example, take the lowest velocity for pure aluminum, from the authors' Fig. 5. At $V_0 = 100$ m/s, the incubation time t_K is about 400 min or 24×10^3 s. Using the values $\psi = 7.2 \times 10^{-6}$ and $D = 1.2 \times 10^{-3}$ m, the quantity $1.5\psi V_o T_K/D$ becomes 2.2×10^4, and taking $d/D = 0.047$ from Curve D, we obtain $N_i = 48$ as compared to 10^4 from the authors' Fig. 9. This low number seems quite believable, when combined with the fact that the maximum impact pressure at 100 m/s is not 16 kg/mm^2 as assumed by the authors, but would be about 44 kg/mm^2 according to Curve A, or greatly in excess of the material's yield strength. (In this particular instance, of course, the material will flow plastically under each impact, so that the target cannot be considered rigid and Curves A and D do not strictly apply; but the example illustrates my point.)

I would now like to turn to the comparative erosion rates which the authors obtain for various stellites and 13 percent chromium steels. The difference between the stellites and the steels is surprisingly small and does not seem to be consistent either with service experience or with other published test data, as shown in Table 5. This table shows results, from several sources, for materials which approximate as closely as possible those tested by the authors. The erosion rates for the latter were measured from the authors' Fig. 16, and by that criterion the conventional forms of Stellite 6 seem only 2 to 3 times as good as the X20Cr13 steel. By contrast, using the same criterion of maximum erosion rate, the other sources show Stellite 6 to be 10 to 30 times as good as a comparable steel. Since there is no reason to doubt the data presented by the authors, some rational explanation of this anomaly must exist and would be of great interest. Perhaps the authors could comment on that.

With reference to the authors' remarks on practical applications of stellite, I should like to point out that at Westinghouse we successfully apply rolled stellite strips to twisted steam turbine blades, by means of a semiautomated and controlled brazing process. The strips are initially

[5] Baker, D. W. C. et al, "The Erosion Resistance of Steam Turbine Blade and Shield Materials," *Proceedings of the Second Conference on Rain Erosion and Allied Phenomena*, 16–18 Aug. 1967, Royal Aircraft Establishment, England, 1 May 1968, pp. 449–516.

[6] Hobbs, J. M., "Practical Aspects of Cavitation," *Philosophical Transactions*, Royal Society of London, Series A, Vol. 260, 1966, pp. 267–275.

TABLE 5—*Relative erosion resistance of stellite and 13 percent chromium steel.*

Source	Material	Vickers Hardness	Max Rate of Weight Loss	Relative Resistance
This paper	X20Cr13 steel	275	7.0	1.0[b]
	Stellite 6, No. 4	377[a]	5.0	1.4
	Stellite 6, No. 6	428[a]	2.4	2.9
Baker et al (footnote 5)	En56A steel	180	117	0.74
	En56A steel	253[a]	86	1.0[b]
	Stellite 6B (Deloro)	413[a]	9.1[a]	9.5
	Stellite 6B (Osborn)	463[a]	4.85[a]	17.7
	Stellite 6 (as cast)	390	8.6[a]	10.0
	Stellite 6 (vacuum arc remelted and extruded)	413	2.57	33.4
Hobbs (footnote 6)	En56C steel	197	39.0	0.8[b]
	Stellite 6	434	1.24	25.0
Westinghouse data (vibratory cavitation test)	Type 410 Cb steel	274	27.6[a]	1.0[b]
	Stellite 6B, wrought	421	2.4	11.5
	Stellite 6, Cast	493	2.0	13.8

[a] Average of several specimens.
[b] Assigned value.

straight in the rolling direction but are curved in the transverse direction to fit the aerodynamic shape of the blades.

Finally, the authors' Fig. 23 is qualitatively consistent with the impact stress distribution suggested earlier; it would be interesting to know the distance between the twin formations shown on it and the size and velocity of the drop causing it, so that the quantitative prediction of Curve *D* could be checked. As the authors point out, in solid particle impact the pressure distribution should be quite different, probably more like a Hertzian distribution. One should not expect to find much correlation between solid impingement and liquid impingement results.

G. Hoff, W. Herbert, and H. Rieger (*author's closure*)—Mr. Heymann provided our talk with some interesting topics for discussion which must be dealt with briefly in the following paragraphs.

Ref: *The relation between rain erosion and fatigue tests*

The authors wanted to compare in aluminum alloys the exponents m of the velocity dependence on incubation time (see Eq 1a) with the slopes of σ–N curves received in fatigue tests. At no time was it planned to come to a quantitative decision about the many curves caused by rain erosion and fatigue tests. Since, in the authors' opinion, not enough is known about the tension distribution in a material at the drop impact. Neither does Mr. Heymann's amended derivation on impact pressure and impact area at

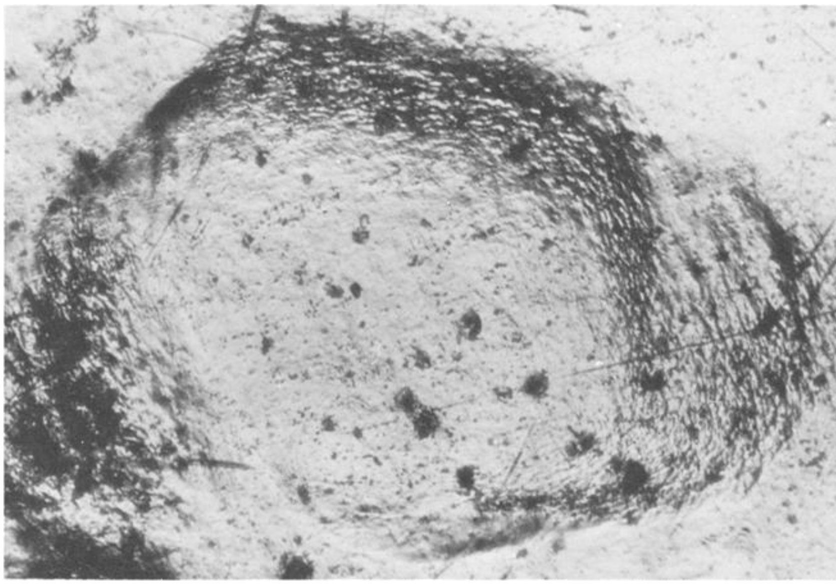

FIG. 25—*Crater in aluminum produced by a waterdrop of 2.1 mm diameter and a velocity of 400 m/s* (×50).

the moment of drop impact alter the situation. This statement must be qualified briefly:

It means quite simply that the tensile bend and shear stresses mainly cause the material destruction, and the contribution of mere pressure stresses on the other hand is to be disregarded. Therefore, neither the so-called water-hammer pressure nor the estimated impact pressure for material destruction seen in Mr. Heymann's modified formula are responsible primarily for the material destruction but only for the tensile bend and shear stresses, which under test conditions arise from fluid impact. As long as little is known about stress distribution caused by fluid impact, it is impracticable at present to establish quantitative connections in the manner suggested by Mr. Heymann.

Mr. Heymann's other objection to the authors' assumption that the diameter of the deformed surface area d following the impact of a single drop is equal to the drops diameter D, is justified partly. This assumption is in fact only an approximation, since under experimental conditions it is guaranteed that d is not only dependent on the diameter of the drop but also on impact velocity.

Observations of single impact craters show however that the diameter of the distinguishable plastic deformed zone is by no means as small as was to be expected from Mr. Heymann's estimated curve for the ratio

d/D. Thus, for a velocity of 400 m/s for instance, Mr. Heymann's curve gives a ratio of $d/D = 0.125$. On the other hand, Diagram 1 shows that the impact of a single drop of water from 2.1 mm ϕ at a velocity of 400 m/s causes a crater with an average diameter of about 1.8 mm to be formed, corresponding to a ratio of $d/D = 0.86$. The reason for these large discrepancies between the calculated and actual value for d/D are, in our opinion, to be found in the fact that Mr. Heymann only examined the area of maximum impact pressure and not that of the maximum tensile bend and shear stresses responsible for material destruction. Therefore, the assumption we came to concerning the ratio d/D in the calculation of load frequences at drop impact agrees more with the experiment than Mr. Heymann's calculations. For a better approximation it would be desirable to determine the velocity function of the ratio d/D from the study of craters or to calculate by theory which of the tensile, bend, and shear stresses to be found in material subjected to impact are to be taken into account.

J. H. Brunton[7] *(written discussion)*—The rapid evaporation of the impacting drop will remove heat not only from the solid surface but also from the liquid in the drop. If the initial water temperature is low, as it might be in practical cases of rain erosion, this could lead to ice formation on the surface and in the spreading liquid. Is there any evidence that this takes place? The presence of ice in the flow might be expected to have a big effect on erosion damage.

The comparison between erosion and fatigue endurance curves is interesting and worth emphasizing. Quantitative agreement between the two kinds of test results is not to be expected for the reasons given by the authors. Apart from the unknown microstresses in erosion which arise from the application of water-hammer pressures, jetting pressures, and shear forces of the flow over surface discontinuities, there is a big difference in time scale between a drop impact load and one cycle of a fatigue test. Despite these differences the qualitative agreement remains remarkably good. It might be interesting to use the same technique for a material with a well-defined fatigue limit and see whether a similar limit can be found in the erosion test. We found something of this kind with mild steel[8] where the erosion curve for mild steel flattened out at low impact velocities in the same way as the fatigue curve. A similar flattening was not observed with an age-hardening aluminium alloy.

Messrs. Hoff, Herbert, and Rieger—It is certainly possible that ice may form in drops which have been broken up and which as a result of surface

[7] University Engineering Department, Cambridge, England.
[8] Hays, L. G., Turbine Erosion Meeting, NASA Technical Memorandum 33–354, Jet Propulsion Laboratory, Dec. 1966.

expansion have evaporated rapidly. This, however, has not been established as yet. The most that we could determine is the diameter of the resultant ice crystals. The air cushion in front of the specimens strongly discourages such small ice particles in such a way that they are able to make no remarkable contribution to erosion.

D. E. Elliott[9] (*written discussion*)—The authors have graded possible turbine blade materials in order, using relatively large water droplets. Although this probably places materials in the correct relative order, the absolute level of erosion damage per unit mass of water impacting is very much higher than would occur in an actual turbine. Therefore, the relative rate of erosion between one material and another, as assessed in these experiments, may be appreciably different from how they would perform in tests conducted with droplet size ranges similar to those occurring in turbines. Thus, it may be unfair to reject plasma spray coatings, since they may perform better in a small droplet environment.

Messrs. Hoff, Herbert, Rieger—We used water drops with a diameter of 1.2 mm for our stellite tests. Stellites resistance to erosion by drops of 0.5 mm diameter to a large extent are comparable to resistance to larger drops. Our methods of testing allowed us to measure qualitatively the resistance of individual materials. A direct comparison with the turbine is not possible in such test conditions, since water distribution and the size of drops in turbines are more varied than under test conditions.

Messrs. Hoff, Herbert, and Rieger (*general closure*)—Mr. Heymann pointed out the discrepancy between the behavior of Steel X20Cr13 and stellites. He added that other authors had found an even greater difference in the resistance of rain erosion. The degrees of hardness were quoted in the tables as parameters. Apart from the degrees of hardness the effect of the velocity, drop size, and the setup must be mentioned in comparison. Besides this the results with Stellite showed that qualities such as porosity, hardness, and cold work hardening also must be taken into consideration. As long as these qualities are not considered, we do not find it appropriate to speak of inconsistent results.

If the data of the authors mentioned by Mr. Heymann were itemized to the above mentioned parameters, we would find it very interesting to carry out a comparison. We are also very ready to try out in our test facilities the tests carried out by the authors for comparative purposes, if these tests are placed at our disposal.

[9] Professor, Department of Mechanical Engineering, University of Aston, Gosta Green, Birmingham, England.