DISCUSSION

A. F. Conn[1]—Once again the authors have, as we have come to expect from the laboratories at Cambridge, broken new ground and provided us with unique and valuable information pertaining to erosion by both cavitation and liquid impingement. My questions pertain to certain details of the dynamic properties of the piezoelectric crystal which was used to make the pressure measurements, and the similar properties of the plastic material which was used to imbed this crystal. Could the authors supply the values of the wave speed, density, and impedances of each of these materials? Also, would they provide some details of their techniques to calibrate this system for making these dynamic pressure measurements. The authors are to be congratulated for managing to continue to stay at the forefront of this difficult field of erosion, and for providing a clear path for many of us to follow.

F. G. Hammitt,[2] *J. B. Hwang,*[3] *and Y. C. Huang*[4]—The authors are to be congratulated for this most interesting study, particularly the experimental measurements of local pressure under the impacting drop as a function of time and position. We are of course especially grateful to note their statement that the results agree with our previous numerical calculations for the impact of spherical drops on rigid surfaces. This should help to end doubts which have been expressed concerning the accuracy of these numerical calculations, which in fact do not agree with previous simplified analyses of the same problem (as Messrs. Rochester and Brunton state).

We have made a specific comparison between our previous calculated results[*13,14*] and the present experimental results, and are happy to note that the agreement in terms of magnitude, time, and spatial distribution of maximum pressure is indeed very good. From Table 4 (data

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TABLE 4—*Numerical values of normalized pressures at different impact velocities.*

Reference	Impact Velocity, m/s	Liquid Mach No., V_0/C_0	Maximum Normalized Pressure $\frac{p_{max}}{\rho_0 C_0 V_0}$	$\frac{p_{max}}{\rho_0 C V_0}$
Present paper	60	0.040	0.62	0.575
	80	0.053	0.615	0.568
	100	0.066	0.686	0.646
	120	0.080	0.655	0.565
	140	0.093	0.64	0.542
[*14*]	300	0.200	0.69	0.495
			0.80[a]	0.65[a]
	750	0.500	1.07	0.52
			1.23[a]	0.625[a]

[a] No-slip boundary condition.

extracted from Refs *13* and *14* of paper, plus the present experimental data) we note that our calculated maximum pressure, if normalized to the corrected water-hammer pressure, is nearly independent of liquid Mach number, with a value slightly less than (but close to) the experimental values, which are also almost independent of liquid Mach number. The value ranges approximately between 0.5 and 0.6. The maximum pressure if normalized to "uncorrected" water-hammer pressure grows with Mach number, particularly as the Mach number becomes appreciable, for both calculated and experimental values.

Our previous calculations[*13,14*] were done for both nonslip and full-slip boundary conditions at the material-liquid interface, although the fluid was assumed to be inviscid in all cases. As shown in Table 4, the higher pressures are predicted for the nonslip boundary condition (as would intuitively be expected). Comparison with the experimental values indicates that tthe true value may be approximately a simple average between these extremes, that is, about 0.57 for low Mach numbers ($M \leqslant 0.5$) and spherical drops.

Another factor which can be compared with the present experiment and our previous calculations is the duration of the high initial pressure caused by the impact. Pressure versus time curves from both the present paper and Huang et al[*13,14*] have a peak after which the pressure drops to approximately the stagnation pressure. Huang's results show that this occurs at $(Ct/D) \cong 1.5$, where C = sonic velocity in liquid, t = time, and D = droplet diameter. For a droplet of 5-mm diameter, we can then predict that the duration of pressure before reaching stagnation pressure is

$$t \cong \frac{1.5D}{C} \cong \frac{(1.5)(5 \times 10^{-3}\ \text{m})}{1500\ \text{m/s}} \cong 5 \times 10^{-6}$$

This matches exactly the experimental result of the present paper.

We would also like to request from the authors further information on their experimental arrangements. What are the diameter, material, and response rate of the pressure transducer? What is its general form of construction?

The authors mention strain energy to fracture as a failure criterion. Is this engineering strain energy or ultimate resilience? Along with numerous other investigators (for example, refer to the discussers' paper in *Characterization and Determination of Erosion Resistance, ASTM STP 474*, 1970), we have found the former to give statistically a very poor correlation to damage rate, while the best correlation (still not good) is generally provided with ultimate resilience (perhaps combined with hardness).

M. C. Rochester and J. H. Brunton (authors' closure)—We should like to thank Dr. Conn and Professor Hammitt and his colleagues for their comments. Both discussers would like to know more about the properties of the piezoelectric ceramic and the material in which it was imbedded, and Professor Hammitt would like to know how the gage was constructed. Large sheets of the ceramic were obtained from Brush Clevite, Ltd. and ground on a polishing wheel to the dimensions given in the paper. The plastic bullet was made from a sheet of cloth-laminated plastic known in the U.K. as Tufnol and supplied by Tufnol, Ltd. The physical properties of the ceramic are given in Table 5.

The ceramic was electroded with conducting epoxy and glued with epoxy resin in a groove cut in the front surface of the Tufnol bullet. The response time of the gage was taken to be the time a stress wave takes to cross the ceramic, that is, about 0.2 μs.

Despite the excellent agreement between the results in the present paper

TABLE 5—*Physical properties of the piezoelectric ceramic used in the pressure gages.*[a]

Material	Density, kg/m^3	Sound Speed, m/s	Acoustic Impedance, kg/m^2-s
PZT 4	7.5×10^3	4600	34.5×10^6

[a] Piezoelectricity, Brush Clevite, Ltd. 1966.

and the calculations of Professor Hammitt and his colleagues, more recent experimental results[5] show an important difference in the pressure distribution over the central region of impact. Measurements of the impact pressure distribution for a 5.0-mm-diameter drop struck at a velocity of 100 m/s were obtained using a gage of much improved design. The impact pressure distribution was found to be symmetrical about the center of impact but the maximum pressure occurred 0.5 mm either side of the center. The pressure at the center was about 0.7 $\rho_0 c_0 V$ and at the edges about 1.8 $\rho_0 c_0 V$. The difference between these more recent results and the results presented in this paper is due to both an improvement in the design of the gage and a considerable reduction in the size of the piezoelectric ceramic. The ceramic used to obtain the results in this paper was 0.9 mm wide (about one fifth of the diameter of the drop) whereas the one used in the later paper was only 0.33 mm wide (about one fifteenth of the diameter of the drop). It is likely that the larger gage used in the aforementioned work missed the high edge peaks which were found to act over a very small area (for a 5.0-mm-diameter drop, it was less than 0.3 mm wide), and gave only an average value over the region measured.

[5] Rochester, M. C. and Brunton, J. H., "Surface Pressure Distribution During Drop Impingement," Report No. CUED/C—MAT/TR 15, Engineering Department, University of Cambridge, Cambridge, England, 1974; also, 4th International Conference on Rain Erosion and Allied Phenomena, Meersburg, West Germany, 1974.