DISCUSSION

F. G. Hammitt[1] (*written discussion*)—I would like to commend the authors on their very interesting paper, which produces valuable data on the effects of suppression pressure on cavitation damage in a vibratory facility, thus aiding significantly in the understanding, interpretation, and application of such data. I believe the observations from the present tests can be tied in with other tests wherein different parameters in some cases have been varied, as I will discuss briefly. First some more general remarks are appropriate.

The paper discusses characteristic volume-loss rates in terms of a so-called "steady-state volume-loss rate." As is evident from the curves presented and as also mentioned in the paper, this rate actually corresponds to a minimum rate reached in most cases after an initial maximum, but in the present tests followed in most cases by a second rising rate. In other tests in other facilities no minimum has been found after the initial maximum[2] but rather a steadily falling rate. In tests in our own laboratory[3] which have been carried to a great enough total volume loss to make such an observation we have found a minimum followed by a second rise as in the present paper (Fig. 20). The behavior after the first maximum is passed is interesting but not particularly useful in the rating of materials, since its detailed characteristics result from the complex interaction of many variables such as the effect of changing surface geometry upon the fluid dynamics of the cavitation field, perhaps gas entrapped in the cavities,[4] cold-work, and fatiguing of material, etc. In general, these later phases of the test correspond to conditions which are in any case unacceptable for the operation of prototype machines. In view of all the above it appears to me highly misleading to call this a steady-state volume-loss condition. A more useful condition both from the viewpoint of comparing materials in a meaningful way and from the viewpoint of economy of test time is the rate corresponding to the first maximum, which I think it would be useful

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[2] Plesset, M. S. and Devine, R. E., "Effect of Exposure Time on Cavitation Damage," *Transactions*, American Society of Mechanical Engineers, *Journal of Basic Enginnering*, Dec. 1966, pp. 691–699.

[3] Hammitt, F. G. and Garcia, R., Discussion on "Effect of Exposure Time on Cavitation Damage," Plesset, M. S. and Devine, R. E., *Transactions*, American Society of Mechanical Engineers, *Journal of Basic Engineering*, Dec. 1966, pp. 701–702.

[4] Ripken, J. F., "Further Observations on Surface Outgassing as an Influence in Cavitation Damage," *1968 Cavitation Forum*, American Society of Mechanical Engineers, pp. 11–12.

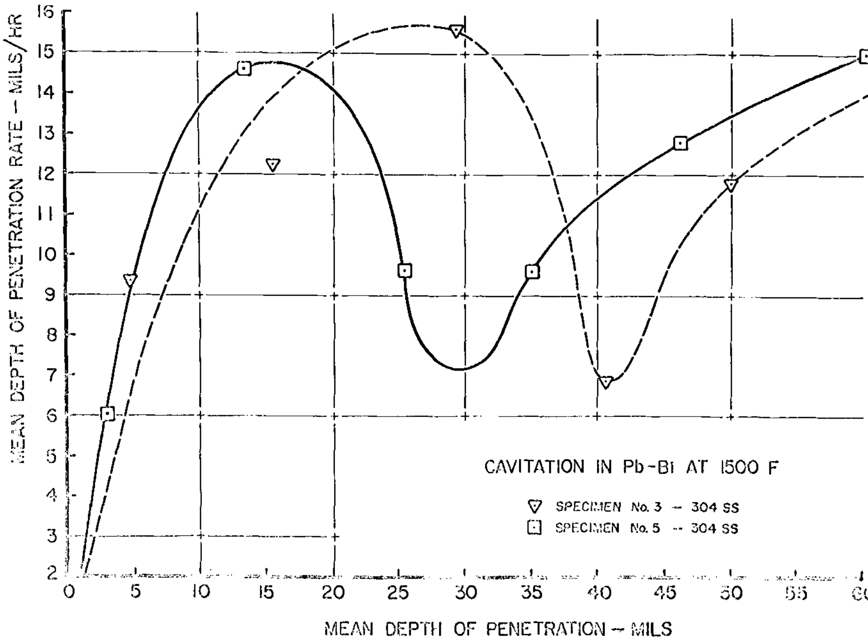

FIG. 20—*Cavitation damage rate in lead-bismuth alloy at 1500 F.*

to tabulate here. An excellent recent overall review of this situation is provided by Heymann.[5]

It is noted from Table 5 of the paper that the mean depth of penetration rate (corresponding to the minimum after the first maximum) in the damaged area increases by a factor of 20 to 30 when the pressure is raised from 1 to 4 atm. The increase of pressure should affect damage rate through at least two competing mechanisms:

1. The number and average diameter of bubbles would be decreased as the suppression pressure is increased, assuming constant amplitude and frequency of the horn.
2. The collapse velocities would be greater, and the subsequent radiated pressures, for a given diameter of bubble, as the suppression pressure is increased.

In these tests apparently the second mechanism is overriding. However, it is obvious that the damage rate will be decreased eventually if the suppression pressure is raised sufficiently, since cavitation will cease entirely for sufficiently high pressure.

It is mentioned in the paper that cavitation damage in higher pressure

[5] Heymann, F. J., "Erosion by Cavitation, Liquid Impingement, and Solid Impingement," Engineering Report E-1460, Westinghouse Electric Corp., March 1968.

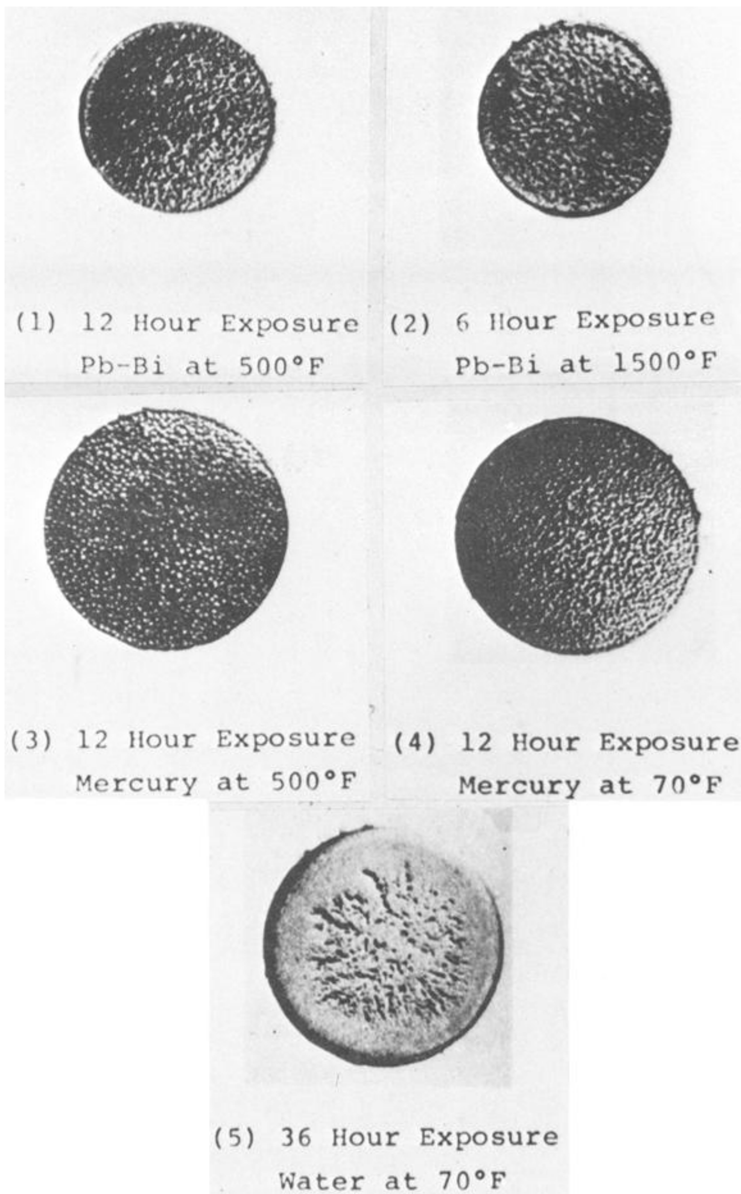

FIG. 21—*Type 316 stainless steel vibratory specimens cavitated in mercury, lead bismuth, and water, $\frac{9}{16}$-in.-diameter specimens*

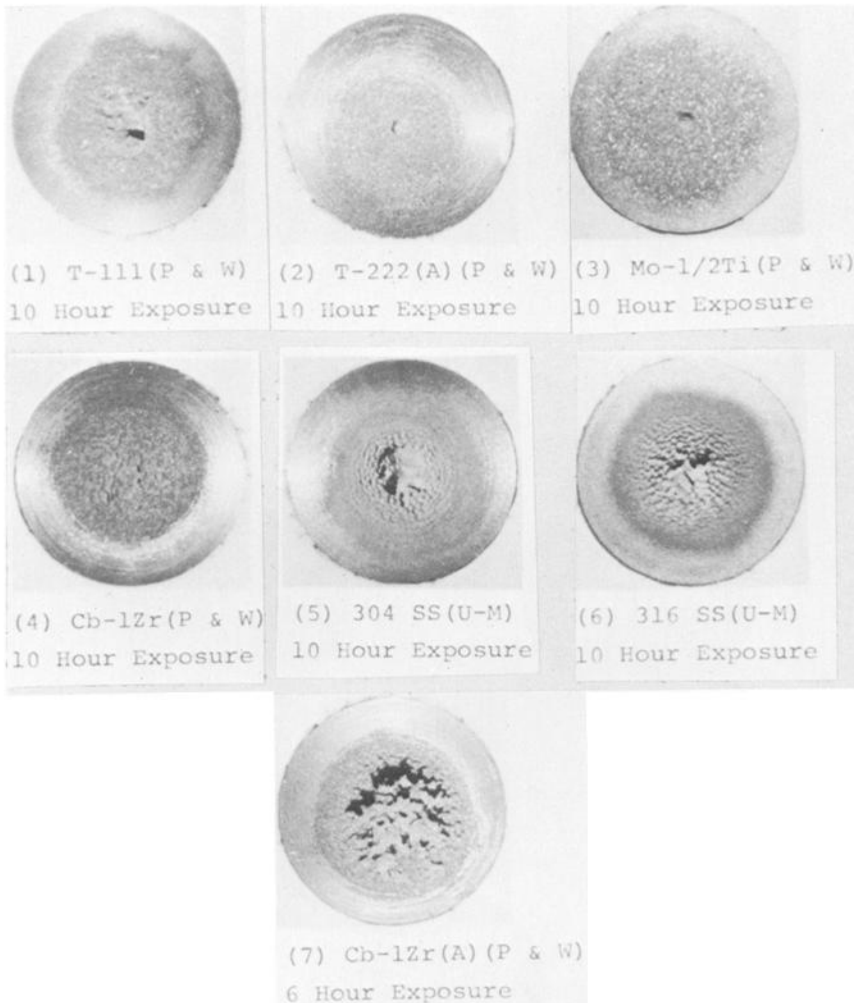

FIG. 22— *Vibratory specimens cavitated in lithium at 500 F.* $^9\!/_{16}$*-in.-diameter specimens.*

regions of a pump, if the bubbles penetrate to that point, is greater than in low pressure regions.

This observation for a flowing system also was reported from our laboratory for tests with a cavitating venturi,[6] where the damage increases further into the diffuser where only the larger bubbles can penetrate and where the suppression pressure is high.

[6] Hammitt, F. G. et al, "Initial Phases of Damage to Test Specimens in a Cavitating Venturi," *Transactions*, American Society of Mechanical Engineers, *Journal of Basic Engineering*, June 1965.

It is shown in the present tests that as the suppression pressure is increased the damaged area becomes more centralized and the relatively undamaged rim around the outside diameter larger (Fig. 11 of paper). Precisely the same effect was observed[7] in our own tests when the fluid density was changed using a variety of fluids from mercury (13.6 g/cm^3) to lithium (0.5 g/cm^3) at constant suppression pressure, that is, the effect upon damage distribution of increasing suppression pressure for the same test fluid is the same as decreasing test fluid density for the same suppression pressure. In either case the effect is that of increasing the NPSH, that is, "net positive suction head," borrowing from pump terminology, or suppression "head," that is, pressure/density. From classical fluid-dynamic considerations, if amplitude and frequency are held constant, an increase of NPSH would reduce the extent of the cavitating field, concentrating it toward the center line where the pressure oscillations induced by the horn motion are maximum, that is, where the pressure oscillation reductions ascribed to edge effects are a minimum. Figure 21 and 22 shows the comparison between test specimens from mercury, lead-bismuth alloy, water, and lithium in order of decreasing density at constant suppression pressure from our own tests.[7]

J. H. Brunton[8] (*written discussion*)—The importance of external pressure on cavitation damage has been demonstrated clearly by the authors. To what extent does a change in the solubility of argon in sodium at high temperatures affect the results? High solubility might be expected to cushion the collapse and reduce damage, while a small amount of gas might aid the nucleation process and thereby increase damage. In the present work was there any evidence of this influence on the damage, or was the overall solubility sufficiently small that it could be neglected?

S. G. Young and J. R. Johnston (*authors' closure*)—The authors appreciate the discussions and the supporting experimental data from F. G. Hammitt's cavitation damage tests in water and other liquid metals.

The question of rating materials on the basis of steady-state volume-loss rate has long been a matter of controversy. Other investigators have used this same approach (Ref *6* of paper). In our tests a fairly well defined constant volume-loss rate region was observed for all of the materials. It is for that reason that this criterion was chosen, since it provided a convenient and repeatable mode of comparison. It is true that somewhat longer test times are involved in reaching a so-called steady-state region than in reaching the first maximum or peak rate; however, the test time involved to

[7] Garcia, R. and Hammitt, F. G., "Cavitation Damage and Correlations with Material and Fluid Properties," *Transactions*, American Society of Mechanical Engineers, *Journal of Basic Engineering*, Dec. 1967, pp. 753–763.

[8] University Engineering Department, Cambridge, England.

reach a relatively constant damage rate is generally only 2 to 3 h for most of the materials and conditions of our tests. Compared to the uncertainty associated with establishing the exact peak damage rate (in many cases this is nearly impossible due to the very rapidly changing rate), it is considered more desirable to carry out the tests for slightly longer times to obtain a more reliable and consistent rating.

The authors recognize the existence of the two competing mechanisms associated with increasing pressure on the damage rate. In this investigation, we determined the effect of increasing suppression pressure within relatively narrow limits (1 to 4 atm) and also at one temperature. Additional increases in suppression pressure as well as other temperature conditions should be investigated to more fully establish the effect on cavitation damage. Our use of a normalizing factor (which takes into account varying rim widths found for different test conditions) is an initial attempt to establish the true relationship between damage and pressure.

With regard to the comment that changes in fluids (with different densities) can change the damage distribution and change the effect suppression head, the authors certainly agree. In previously published work (Ref *4* of this paper) the authors describe the damage patterns for specimens tested in sodium and mercury. Specimens tested in mercury have damage patterns that are strikingly similar to those presented in the discussion. Care should be used, however, in attributing effects due to pressure (or head) primarily on this basis because of the possible chemical and mechanical effects introduced by fluid changes.

To answer the question regarding solubility (of argon) in sodium: as suggested by J. H. Brunton, the authors believe the solubility of argon was small. Although the effect of argon solubility on damage was not investigated, it is believed that the solubility of this inert gas would decrease with increasing temperature, and have very little effect, especially at high temperatures. Sodium vapor is believed to be the major factor for any cushioning effect at high temperature.