

4 Green, N., Wayne, and Mesler, Russell, "An Experimental Study of Transient Pressures Accompanying Vapor Bubble Collapse in Water," *The Role of Nucleation in Boiling and Cavitation*, ASME, 1970.

5 Hansen, B. W., and Rasmussen, R. E. H., "Cavitation Damage Experiments in a Rotating Disk Apparatus Especially With Regard to the Gas Content of Water," *Journal of Ship Research*, Vol. 12, No. 2, 1968, pp. 83-88.

6 Herring, C., "Theory of the Pulsation of the Gas Bubble Produced by an Underwater Explosion," NDRC Division 6, Report C4-Sr 20, 1941.

7 Hickling, R., and Plesset, M., "Collapse and Rebound of a Spherical Bubble in Water," *Physics of Fluids*, Vol. 7, No. 1, 1964, pp. 7-14.

8 Jones, I. R., and Edwards, D. H., "An Experimental Study of Forces Generated by the Collapse of Transient Cavities in Water," *Journal of Fluid Mechanics*, Vol. 7, 1969, pp. 596-609.

9 Lane, W. R., and Green, H. L., "Mechanics of Drops and Bubbles," *Surveys in Mechanics*, Batchelor, R. M., and Davies, R. M., eds., Cambridge Press, 1956.

10 Lehman, A. F., "Influence of Free Air Bubbles on Cavity Volumes and Associated Noise Signatures," ASME Paper No. 65-WA/FE-30.

11 Leith, W. C., and Thompson, A. L., "Some Corrosion Effects in Accelerated Cavitation Damage," *JOURNAL OF BASIC ENGINEERING*, TRANS. ASME, Series D, Vol. 82, No. 4, Dec. 1960, pp. 795-807.

12 Mousson, J. M., "Pitting Resistance of Metals Under Cavitation Conditions," *TRANS. ASME*, Vol. 59, 1937, pp. 399-408.

13 Naude, C. F., and Ellis, A. T., "On the Mechanism of Cavitation Damage by Nonhemispherical Cavities Collapse in Contact With a Solid Boundary," *JOURNAL OF BASIC ENGINEERING*, TRANS. ASME, Series D, Vol. 83, No. 3, Sept. 1961, pp. 648-666.

14 Pettacchi, G., *La Metallurgica Italiana*, Vol. 41, No. 1, 1949.

15 Plesset, M. S., "Cathodic Protection in Cavitation Damage," *JOURNAL OF BASIC ENGINEERING*, TRANS. ASME, Series D, Vol. 82, No. 4, Dec. 1960, pp. 808-818.

16 Rasmussen, R. E. H., "Some Experiments on Cavitation Erosion in Water Mixed With Air," *Proc. Nat. Phys. Lab. Symp. on Cavitation in Hydrodynamics*, Vol. 21, 1956, p. 1.

17 Shima, A., "The Behavior of a Spherical Bubble in the Vicinity of a Solid Wall," *JOURNAL OF BASIC ENGINEERING*, TRANS. ASME, Series D, Vol. 90, No. 1, Mar. 1968, pp. 65-89.

18 Shutler, N. D., and Mesler, R. B., "A Photographic Study of the Dynamics and Damage Capabilities of Bubbles Collapsing Near Solid Boundaries," *JOURNAL OF BASIC ENGINEERING*, TRANS. ASME, Series D, Vol. 87, No. 3, Sept. 1965, pp. 648-656.

19 Sirotiyuk, M. G., "Effect of the Temperature and Gas Content of the Liquid on Cavitation Processes," *Soviet Physics, Acous.*, Vol. 12, No. 1, 1966, pp. 67-71.

20 Song, C. S., and Silberman, E., "Experimental Studies of Cavitation Noise in Free Jet Tunnel," Minnesota University—St. Anthony Falls Hydraulic Laboratory—Technical Paper 33, Series B, 1961.

21 Warnock, F., *Proceedings A.S.C.E.*, Vol. 71, 1945, p. 1041.

22 Warren, G. R., and Rice, R. W., "The Interaction of the Gas Bubbles From Two Adjacent Underwater Explosions," U.K.A.E.A., Foulness Division Note, 1964.

23 Wheeler, W. H., "Indentation of Metals by Cavitation," *Proceedings of National Physical Laboratory Symposium on Cavitation in Hydrodynamics*, 1956, p. 21.

24 Plesset, M. S. and Chapman, R. B., "Collapse of an Initially Spherical Vapor Cavity in the Neighborhood of the Solid Boundary," *Journal of Fluid Mechanics*, Vol. 47, Part 2, 1971, pp. 283-290.

## DISCUSSION

### F. G. Hammitt<sup>4</sup>

I believe this is a very interesting paper in an area where relatively little has been done, i.e., the study of the detailed effects and mechanisms involved in the interactions between bubbles in a liquid.

<sup>4</sup> Professor-in-charge, Department of Mechanical Engineering, University of Michigan, Ann Arbor, Mich. Mem. ASME.

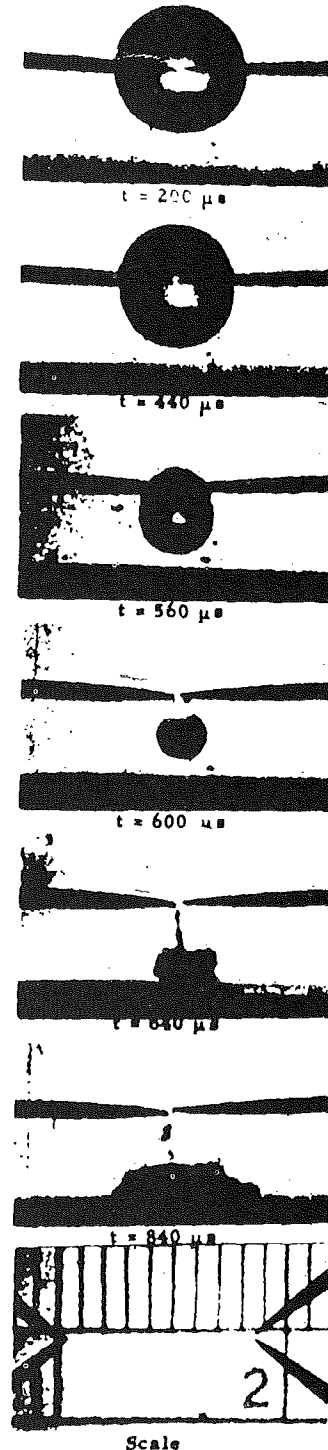


Fig. 11(a)

I would like to include in the record at this point somewhat related experiments which we have done with spark generated bubbles in a small, transparent tank in water. High-speed motion pictures (Fig. 11 of discussion, reproduced from reference

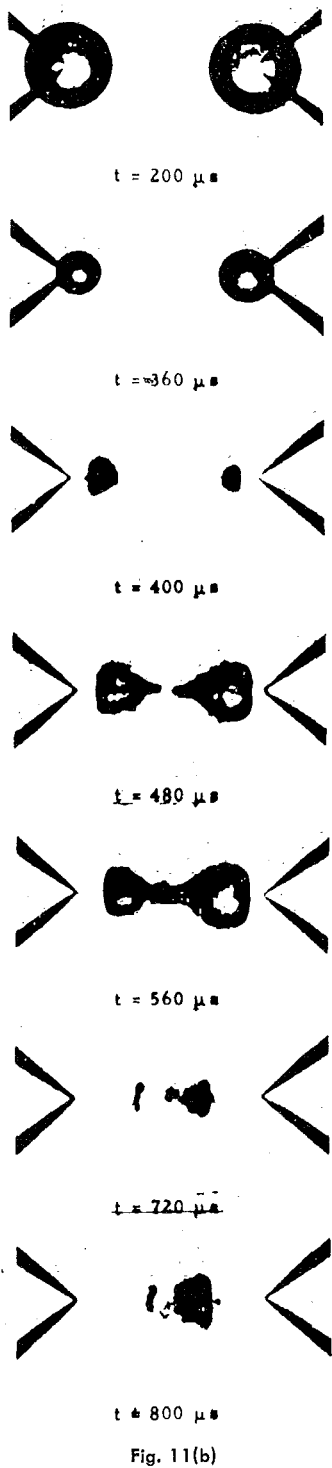


Fig. 11(b)

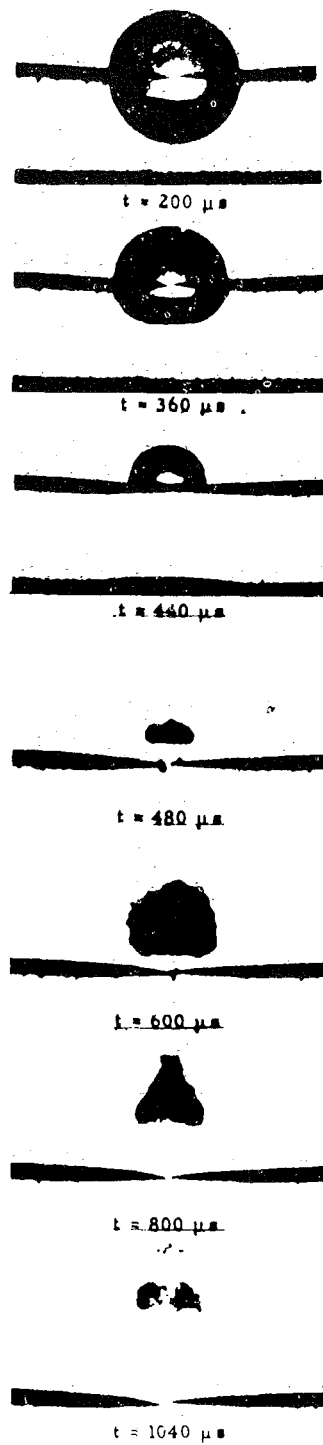


Fig. 11(c)

Fig. 11 Spark bubble collapse as function of adjacent objects

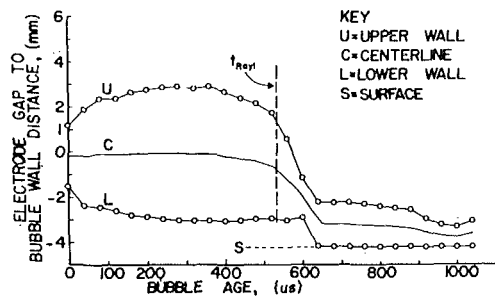


Fig. 12(a)

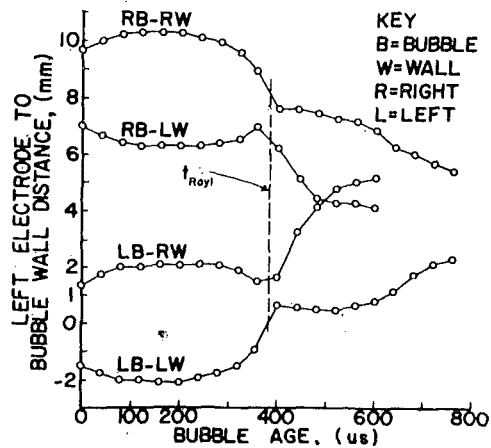


Fig. 12(b)

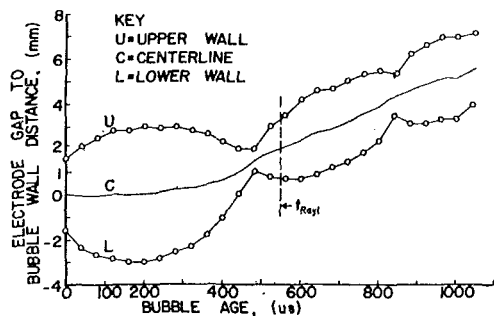


Fig. 12(c)

Fig. 12 Wall motion of collapsing bubble near adjacent objects

[13]<sup>5</sup> of discussion for convenience) show collapse sequences (a) close to a solid plate, (b) two bubbles of similar size collapsing in proximity to one another, (c) a bubble collapsing close to a rubber diaphragm (backed by an air cushion). As expected from numerous theoretical analyses (reference [14], e.g.) the bubble collapsing close to a solid surface is attracted toward the surface during the collapse. The "double-bubble" case (Fig. 11(b) of discussion) is similar in that it is almost equivalent to a single bubble near a solid wall. A hypothetical solid wall would thus form a plane of symmetry for the double-bubble case.

The bubble collapsing close to a flexible membrane has been investigated recently by Gibson (reference [15]). The case is somewhat similar to a bubble near a free surface, where it is known that the bubble will be repelled from the surface during its collapse (reference [16], e.g.). The same is true of a sufficiently flexible membrane as is shown by Fig. 11(c) of this discussion. In addition, the jet formed during collapse is oriented away from the surface. Fig. 2 (from reference [13] also) shows the velocity of upper and lower bubble walls during each of these collapse sequences. These latter facts may be of considerable importance in explaining the surprising cavitation damage resistance capability of some rubber and elastomeric coatings. Experiments of this type also appear to offer hope for a rational design of a cavitation-resistant soft material.

#### Additional References

- 13 Timm, E. E., and Hammitt, F. G., "Bubble Collapse Adjacent to a Rigid Wall, a Flexible Wall, and a Second Bubble," *1971 ASME Cavitation Forum*, 18-20.
- 14 Kling, C. L., and Hammitt, F. G., "A Photographic Study of Spark-Induced Cavitation Bubble Collapse," ASME Paper No. 72-FE-20 (to be published, *Trans ASME, J. Basic Engr.*).
- 15 Gibson, D. C., "The Kinetic and Thermal Expansion of Vapour Bubbles," CSIRO, Division of Mechanical Engineering, Melbourne, Australia, 1970.
- 16 Cole, R. H., *Underwater Explosions*, Princeton University Press, 1948, Dover Edition, 1965.

#### Authors' Closure

The authors wish to thank Dr. Hammitt for his interest in the paper. His discussion provides a valuable addition to the paper.

<sup>5</sup> Numbers 13-16 in brackets designate Additional References at end of discussion.