An experimental study of the forces generated by the collapse of transient cavities in water

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The paper describes an experimental investigation of the pressures developed at the seat of collapse of cavities in water. Single transient cavities, generated by a spark discharge, are allowed to collapse on the end of a piezoelectric pressure-bar gauge which measures the variation of thrust with time. It is shown that both the peak force and duration of the cavity collapse pulse are functions of the cavity lifetime. From an estimate of the minimum radius attained by the cavity and the peak force, the peak pressure on collapse is found to be at least 10,000 atm. Streak schlieren photographs of the collapse process show that a shock wave is radiated into the water at the moment of collapse and that the cavity rebounds. At the collapse of the rebound cavities the pressures developed are comparable with those developed by the collapse of the initial cavity, and these probably contribute materially to cavitational surface damage.

1. Introduction

Cavitation erosion was first observed by marine and hydraulic engineers at the turn of the century, and its study is of particular importance in these fields. During the last fifty years there has been an impressive accumulation of data and ideas concerning the mechanism of cavitation damage. A good deal of evidence, both theoretical and experimental, has accrued which supports the view that the origin of the surface damage lies in the large-amplitude brief pressure pulses which are generated when transient cavities collapse against the surface. The actual process by which metal is removed from the surface is not fully understood, but it may be conjectured to arise from an association of chemical, electrochemical, thermoelectric and mechanical effects brought about by these large pressure pulses accompanying cavity collapse. In view of the fundamental importance of the collapse pressure pulse in the damage process, there is a need for a detailed examination of its magnitude and character.

A certain amount of experimental work has been reported on the observation of the pressure wave radiated in the liquid at the collapse of single transient cavities. Güth (1956) has obtained spark schlieren photographs of the radiated pressure wave, while Osborne (1947), Chesterman (1952), Harrison (1952) and Mellen (1956) have employed various types of piezoelectric pressure gauges to

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measure the variation of the pressure, whose peak value is in the range 2–10 atm, in the liquid at various distances from the seat of collapse of the cavity. It is doubtful whether such an experimental observation can furnish a reasonably accurate estimate of the peak pressure generated at the actual seat of collapse of the cavity. A more direct approach to the problem was provided by the work of Ellis (1956) who demonstrated the existence in solids of strain waves originated by bubble collapse. Using an ultra-high-speed motion picture camera, ultrasonic cavitation bubbles were photographed collapsing on the surface of a photoelastic specimen, and photographs of the resulting transient isochromatic pattern in the specimen due to strains caused by cavitation were also obtained. A quantitative interpretation of the phenomenon indicated that the local stresses due to cavitation were of the order of 2×10^5 lb. in.$^{-2}$, and a recording of the transient strains by a photocell showed that their duration was about 1 or 2 μs.

The present study is concerned with the measurement of the forces generated at the collapse of single transient cavities on to a solid surface. The magnitudes of these forces were obtained by measuring the stresses developed in the solid during the collapse of the cavity. In addition, streak schlieren photographs of the collapse phenomenon have been obtained using a rotating-drum camera.

2. Experimental method

2.1 *The pressure bar*

A cylindrical pressure bar is employed to measure the forces developed by the collapsing cavities. Cavities are created on one end of the bar, termed the 'pressure-end', by discharging a condenser, charged to a high voltage, through a gap between a tungsten needle and the end of the bar, which forms the earthed electrode. The energy liberated by the spark provides a source of extremely high local temperature in the region directly above the pressure end of the bar, thereby causing the water in this region to vaporize. Various sizes of cavity were produced by varying the spark gap width, charging potential and the capacity of the condenser. Stress waves are propagated in the bar, both during the growth and collapse of the cavity, which can be detected and measured in a variety of ways (see Davies 1956). In the present investigation, resistance strain gauges were first employed, but were found to be unsuitable owing to their comparatively low sensitivity. This method was therefore abandoned in favour of the pressure-bar gauge described by Edwards (1958), which employs a quartz disk to measure the average stress over the cross-section of a composite bar of duralumin and lead. One difficulty which was encountered at first, both when using strain gauges and quartz disks, was the disturbing effect of the radiation from the spark on the gauge signal. This effect could not be removed by shielding alone, since the greater part of the disturbance was introduced by direct conduction along the metal pressure bar. In order to overcome this difficulty a short length of insulator, of the same diameter as the pressure bar, was inserted between the duralumin section and the quartz disk. To ensure undistorted transmission of the stress pulses through this insulator, its acoustic impedance must match that of the duralumin. A heavy silicate flint glass was found to satisfy this requirement; this glass was supplied by Messrs Chance-Pilkington (No. EDF 38919, Type 653/335).

A diagram of the assembled pressure bar and its housing is shown in figure 1. 'Weston' oil seals are used for mechanical support of the bar and also to provide a water-tight connexion between the bar and the tank.

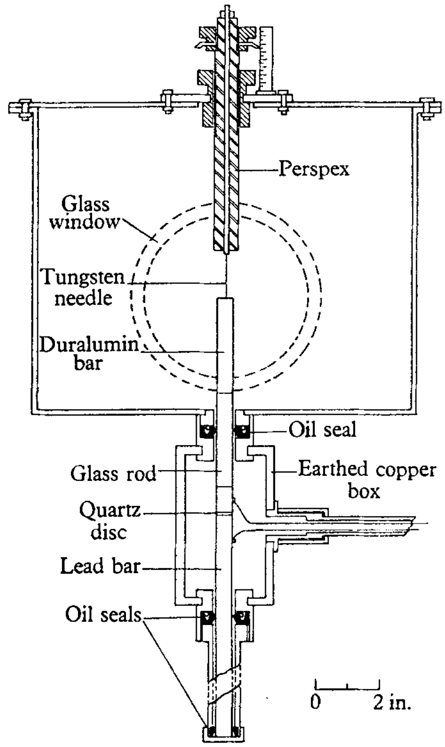


FIGURE 1. Diagram of the experimental tank, the spark-gap adjustment and the pressure bar and its housing.

Pressure bars of two diameters, $\frac{1}{2}$ and $\frac{1}{4}$ in., have been used for measurement. These were calibrated by allowing shock waves in air of known strength, generated in a conventional shock tube, to be reflected at the pressure end of the bar. In addition, the dynamic behaviour of the bars was investigated by generating short duration stress pulses by the impact of steel balls on the pressure end. The observations are in agreement with those found by previous investigators (e.g. Ripperger 1952) that $\frac{1}{2}$ and $\frac{1}{4}$ in. diameter bars will faithfully transmit stress pulses of duration about 12 and 6μs, respectively.

2.2. *The tank and spark unit*

The experimental tank is constructed of $\frac{5}{32}$ in. thick sheet brass and is of square section of side 12 in. in length and $9\frac{1}{2}$ in. in height. Two circular water-tight observation windows, of 5 in. diameter, are set into opposite sides for purposes of photographic investigation; details are shown in the diagram of figure 1.

The open end of the tank can be covered with a sheet brass lid which is held securely in position by eight bolts. A device for varying the width of the spark gap, fixed centrally in the lid and insulated from it, enables vertical adjustment of the tungsten sparking needle, of diameter 0·08 cm, to be made. Vernier scales enable the width of the spark gap to be set to an accuracy of 0·01 mm. The spark is initiated by discharging a condenser by means of two thyratrons connected back-to-back (Mullard Type XH 16-200); the design of the circuit is similar to the one used by Mellen (1956). Although oscillatory discharge is not prevented, the total discharge time of about $10\,\mu s$ is sufficiently small, which is desirable in these experiments.

2.3. *The recording apparatus*

The voltage signal from the pressure-bar gauge is fed to the recording gear by means of a coaxial line contained in an earthed copper pipe. A wide-band amplifier, with a good high-frequency response, is used to amplify the signal before it is displayed on one beam of a double-beam cathode-ray oscilloscope; at the same time a timing wave is fed to the other beam from an oscillator. The time-base unit is initiated by a small voltage pulse which is derived from the spark-unit thyratrons when they become conducting. Since the interval between the voltage pulses obtained from the cavity growth and collapse is long compared with the duration of the pulses themselves, details of the recorded pulses would be lost if both were recorded on a long-duration sweep of the oscilloscope. Consequently, the time-base is designed to provide two successive sweeps when it is triggered, separated by a variable interval which can be determined accurately. In this way, the growth and collapse pulses are recorded on separate sweeps, while at the same time the time interval between them can be measured. A stationary plate camera is used to photograph the traces.

2.4. *The schlieren system and drum camera*

The schlieren system used for observing the shock wave radiated into the liquid when a cavity collapses is of the twin-lens parallel-beam type. The tank is placed between the two schlieren lenses, which have a focal length of 36 in. and aperture 6 in., with the glass observation windows aligned normal to the light beam. Variations of refractive index arising from density variations in the liquid are recorded as 'streak' pictures on a rotating drum camera. For this purpose a mask is placed over the tank windows in which a horizontal slit, 4 in. long and $\frac{1}{16}$ in. wide, is cut. The optical system gives an image reduction of $\frac{1}{5}$, and the maximum obtainable effective writing speed of the camera is about $0{\cdot}7\ \mathrm{mm}/\mu s$. The schlieren light source is a mercury flash lamp described by Edwards & Owen (1957) which is triggered by the spark-gap thyratrons.

3. Results

3.1. *The pressure measurements*

(*a*) *The $\frac{1}{2}$ in. diameter pressure bar*

In all the experiments described in this paper, the single cavities were created in tap water which had previously been allowed to stand in the tank for at least

24 h to permit the gas content to reach equilibrium. The water used for the experiments was thus assumed to be saturated with air at room temperature and pressure. The results under these conditions were repeatable.

The pressures recorded by the pressure bar are the mean values obtaining over the cross-section of the bar. Knowledge of the cavity diameter at any

Spark gap width (mm)	Capacity (μF)	Sparking voltage (V)	Cavity lifetime (μs)	Peak force (dynes × 10^{-6})
0·01	0·01	1500	208	2·30
0·02	0·01	2000	281	5·79
0·02	0·25	1800	472	16·9
0·01	0·50	2000	737	47·8
0·02	0·50	2000	900	65·5
0·04	1·00	2000	1059	88·6
0·03	1·50	1800	1027	88·0
0·04	4·0	1500	1463	105·9

TABLE 1. Typical results obtained for peak force and cavity lifetime for various sparking voltages, capacitors and spark-gap widths

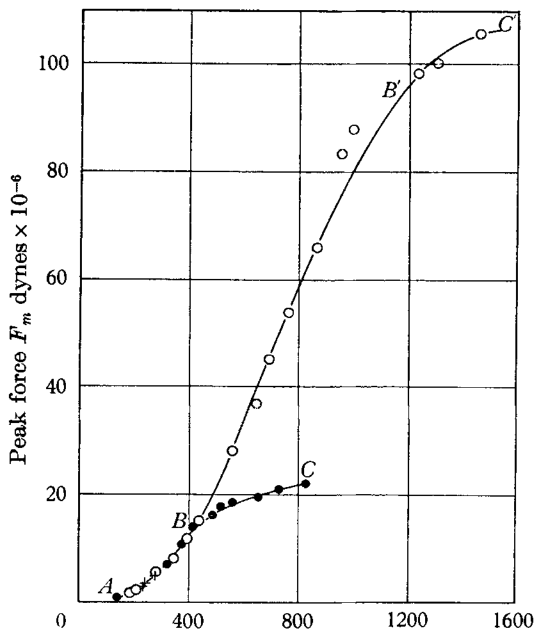


FIGURE 2

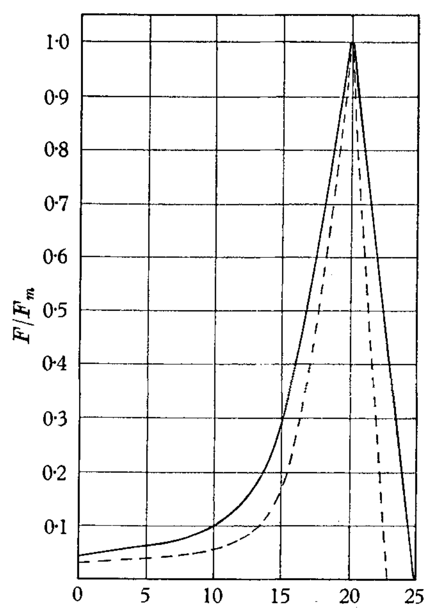


FIGURE 3

FIGURE 2. Curves showing the relationship between the measured peak force F_m of the collapse pulse and the cavity lifetime. ○, Data obtained with $\frac{1}{2}$ in. diam. bar; ●, data obtained with $\frac{1}{4}$ in. diam. bar; +, data obtained from cavity rebound experiments.

FIGURE 3. Force-time curves for the collapse pulses (corresponding to regions AB and AB' on curves of figure 2) obtained with $\frac{1}{2}$ and $\frac{1}{4}$ in. diameter pressure bars. —, $\frac{1}{2}$ in. diam. bar; cavity lifetime: 780μs, $F_m = 57 \times 10^6$ dynes; ----, $\frac{1}{4}$ in. diam. bar; cavity lifetime: 360μs, $F_m = 9{\cdot}9 \times 10^6$ dynes.

instant is required to relate the measured pressure to the actual pressure in the cavity at that instant; a discussion of the estimated actual cavity pressures will be given later. Thus if P denotes the applied pressure, assumed to be uniformly distributed over a small area a of the pressure end of the bar, then the total thrust F in the bar is Pa, and the corresponding voltage developed by the charge liberated by the quartz crystal is given by $d_{11}Pa/C$, where C is the total shunt capacity in farads and d_{11} is the piezoelectric modulus, whose value is $2{\cdot}2 \times 10^{-11}\, C/\mathrm{Kg}$ force. The main observations that can be made from the pressure-bar measurements are of the character of the force-time relationship during the collapse stage of the cavity and of the variation of the peak force with the cavity lifetime, which is defined as the interval between the growth and

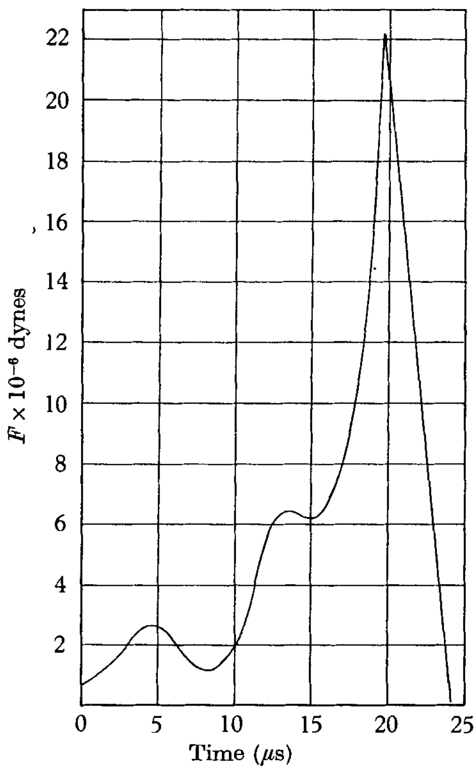


FIGURE 4. Force-time curve of collapse pulse corresponding to the region BC of curve of figure 2, obtained with $\frac{1}{4}$ in. diameter pressure bar. Cavity lifetime: 750μs, $F_m = 22{\cdot}4 \times 10^6$ dynes.

collapse pulses. Table 1 gives a typical set of observations obtained from records taken using the $\frac{1}{2}$ in. diameter pressure bar, and figure 2 shows the manner in which the peak force varies with cavity lifetime. The shape of the collapse pulse for a cavity of lifetime 780μs is given in figure 3.

(*b*) *The $\frac{1}{4}$ in. diameter pressure bar*

In order to establish whether the distortion of the recorded pulses, due to dispersion and attenuation of the stress pulses in the bar, was pronounced, all the results obtained with the ½ in. bar were repeated using a ¼ in. bar. The peak force *vs.* cavity lifetime relationship for this series of experiments is plotted for comparison on the same diagram, figure 2, as those obtained for the ½ in. bar, and the force-time curves for cavities of lifetime 360 and 750 μs are given in figures 3 and 4, respectively.

(*c*) *Cavity rebound observations*

Following the collapse of a transient cavity, another cycle of growth and collapse may subsequently occur; this phenomenon of cavity oscillation, termed 'rebound', has been observed by numerous investigators, e.g. Knapp & Hollander

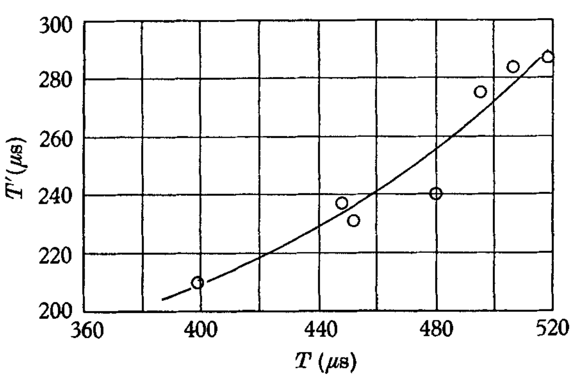


FIGURE 5

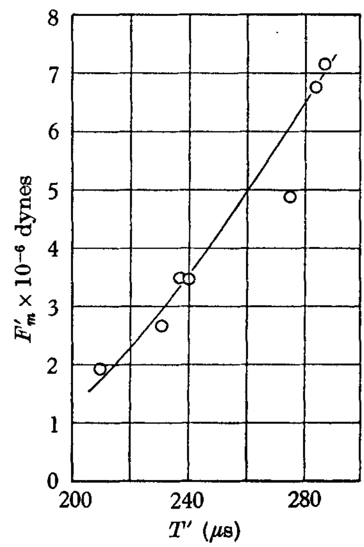


FIGURE 6

FIGURE 5. Observed relationship between the rebound cavity lifetime T' and the initial cavity lifetime T.

FIGURE 6. Variation of peak force F_m due to collapse of the rebound cavity with cavity lifetime T.

(1948), Harrison (1952), Chesterman (1952), and Mellen (1956). Evidence of rebound has been found for the cavities generated in the present work, and a brief investigation of the phenomenon was undertaken. The manner in which the rebound cavity lifetime T', defined as the time between the first and second collapse pulses, and the peak force F'_m due to the collapse of the rebound cavity, vary with cavity lifetime T is shown in figures 5 and 6. The values of (F'_m, T') are also plotted on the curves of figure 2; they are seen to be in excellent agreement with the values of (F_m, T).

3.2. *The streak schlieren photographs*

A portion of a streak schlieren photograph obtained when a cavity of lifetime 800 μs collapses on the plane surface of a ½ in. diameter pressure bar is shown in figure 7 (*a*) (plate 1); the main features of this photograph are labelled in the line drawing of figure 7 (*b*). A small length of the bar was allowed to project into the field of view, and this has given rise to the slightly dark band of constant width which runs down the length of the photograph. The completely dark band superimposed on the pressure bar shadow is due to the cavity, and its width corresponds to the diameter of the cavity at any instant. The estimated value of the minimum radius attained by the cavity is 0·049 cm, which is approximately the same as the radius of the tip of the tungsten sparking needle (0·04 cm) which, in the present arrangement, inevitably appears in the field of view. For this reason a good estimate of the minimum cavity radius is not possible, but the value of 0·04 cm may safely be assumed as an upper limit; in all probability the true value is less than this. At the point of collapse a spherical shock wave is radiated into the water. The resolution obtainable on the records, however, does not permit of definite conclusions to be drawn concerning either the fine structure of the shock wave or the variation in its velocity in the close vicinity of the cavity wall. Average values of the velocity over a distance of a few centimetres obtained in a few experiments are given in table 2. It is seen that these values are sonic or just a little greater whereas near the cavity wall the records show that much higher values obtain.

Cavity lifetime (μs)	Velocity of shock wave (m/s)
350	1409
445	1630
800	1473
815	1421
843	1581

TABLE 2. Measured values of average shock wave velocity for various cavity lifetimes. Velocity of sound in water at 13 °C = 1441 m/s

4. Discussion

4.1. *The peak force-lifetime curves*

The peak force-lifetime curves, figure 2, obtained for the two pressure bars show that the peak force, for a given ambient pressure, is a continuous function of the cavity lifetime and hence of its maximum volume. Two distinct regions can be identified on these curves: (*a*) the portions AB, AB' which are concave upward, and (*b*) the flattened portions BC and $B'C'$ where the peak force increases comparatively slowly with increasing cavity lifetime. The transition points B, B' are fairly well defined and occur at roughly 1100 and 460 μs, respectively. Since the attenuation and dispersion effects of the stress pulses are different for the two pressure bars, the close agreement observed for the two curves in the region AB strongly supports the view that a true measure of the value of the peak force is provided by both bars. The discrepancies and change in character of the curves in the regions BC and $B'C'$ are attributed to the fact that the maximum cavity diameter exceeds the pressure bar diameter; consequently the collapse of the cavity will not be uniform and it will probably divide into a number of smaller cavities. This fact has been confirmed by rotating-drum camera photographs. Moreover, it will be noted that the character of the collapse pulse in this region differs from that of the collapse pulse corresponding to the region AB'; whereas pulses in the latter region are smooth (figure 3), pronounced irregular oscillations are found on the initial portions of the collapse pulses for cavity lifetime in the regions BC, $B'C'$ (figure 4).

4.2. *The collapse pulse*

In the present work the duration of the collapse pulse is defined as the time interval, measured on the force–time curve, during which F rises above one-tenth its maximum value F_m. The two collapse pulses shown in figure 3, corresponding to cavity lifetimes of 780 and 360 μs, are of 10 and 7 μs duration, respectively. It was already verified that the frequency response of the pressure bar is adequate to deal with pulses of this duration; consequently these values could be taken to be a true measure of the pulse durations. This appears to be the first reliable experimental estimate of the collapse pulse durations. Moreover, it is seen from figure 3 that the duration of the collapse pulse increases with the cavity lifetime. In §1 it was noted that Ellis & Sutton (1956, 1957) found collapse pulse durations of about 2 μs, which is a considerably lower value than those found here. The cavities studied by these authors were generated by a 20 kc/s sound field and had lifetimes of the order of 30 μs. Furthermore, they were created in fairly well degassed water (Ellis 1959). From this observation and the present results it may be inferred that purely vaporous cavities will give rise to sharper pressure pulses than gaseous ones.

The shape of the stress pulse propagated in the pressure bar is similar to that observed by Mellen (1956) in the body of the liquid. A possible qualitative description of the phenomena, during various phases of the collapse process, which give rise to this type of pressure pulse is as follows. Initially the cavity is assumed to contain gas and water vapour, so that as the cavity starts to collapse the water vapour condenses at a rate governed by the wall motion. No appreciable effect on the solid will be observed during this stage. As the wall velocity increases the pressure of the gas inside the cavity begins to rise; this phase corresponds to the slow initial rise of pressure observed. When the wall velocity becomes appreciable, large pressures and temperatures are generated in the gas inside the cavity; this stage is observed in the solid as a sudden steepening of the front of the stress pulse. During this stage the wall velocity can reach supersonic values depending on the initial gas content of the cavity. This is followed by a rapid deceleration of the cavity wall, as the minimum volume is approached; at this stage a large compression pulse or shock wave is radiated into the surrounding liquid.

4.3. *The peak value of the collapse pressure*

Before the peak value of the pressure generated by the collapsing cavity can be estimated from the peak force measured by the pressure bar, a knowledge of the minimum diameter attained by the cavity is required. Furthermore, the following three assumptions are made concerning the final collapse phase of the cavity: (i) the force acts over a circular area at the end surface of the bar; (ii) the cavities remain in contact with the bar during collapse; (iii) the pressure distribution at the end of the bar is of the form shown schematically in the diagram of figure 8(*a*) in which the pressure is uniform inside the cavity and zero everywhere in the liquid outside the cavity wall. A sequence of spark shadow photographs of the growth and collapse of a cavity confirms the

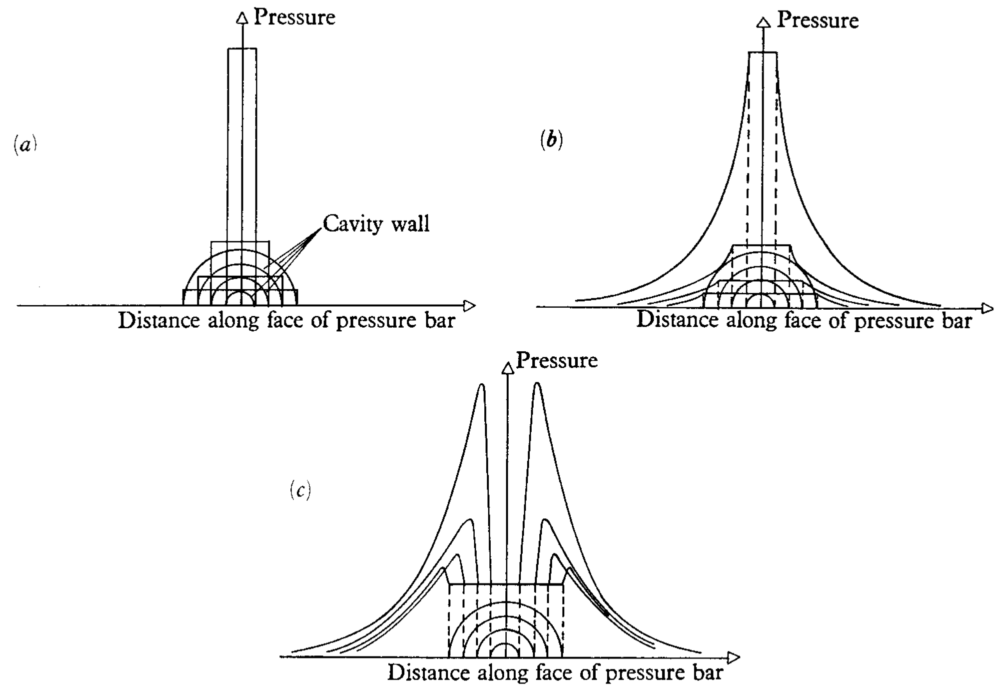


FIGURE 8. Schematic representation of the pressure-distance distributions on a solid surface due to the collapse of a hemispherical cavity. The ideal distribution assumed in the present calculations is shown in (*a*) and that for a gas or vapour cavity in (*b*) where the maximum pressure occurs at the cavity wall; (*c*) refers to a Rayleigh cavity in which the maximum pressure is at some distance into the liquid.

validity of assumptions (i) and (ii). Such a series of photographs is shown in figure 9 (plate 2) for a cavity whose total lifetime is approximately 800 μs and the pressure bar diameter is $\frac{1}{2}$ in. (The time intervals between successive photographs are not accurately known in this experiment but this information is not essential for present purposes.) These photographs clearly show that the cavities do in fact remain sensibly hemispherical during collapse and, what is of more importance, that they remain in contact with the bar at a stage approaching the final collapse volume. On this evidence the authors feel justified in concluding that the cavity remains in contact with the bar throughout most of its history, which implies that the total lifetimes of these cavities are too short for buoyancy forces to have an appreciable effect.

It is difficult to assess the usefulness of the idealized pressure distribution on the end of the bar proposed in (iii) above. In the absence of any theoretical distribution, however, it appears to be the only reasonable assumption that can be made at present. During the collapse of a gas or vapour cavity the pressure distribution on a surface is likely to be of the type shown schematically in figure 8(*b*), where the maximum pressure occurs at the cavity wall and thereafter the pressure decays gradually in the region outside the cavity and not abruptly, as envisaged in the ideal case. On the other hand, in a Rayleigh cavity some arbitrary constant pressure obtains within the cavity throughout the collapse process and the maximum pressure occurs at some distance outside the cavity wall. The pressure distributions appropriate to this case are shown in the sketch of figure 8(*c*). In all probability the pressure distribution which actually occurs during collapse in the present experiments is a mixture of the type of distributions shown in figure 8(*b*) and (*c*). Consequently the estimated values of the peak pressures from the peak force data must be regarded as tentative. The method does, however, give an accurate force–time curve over most of the duration of the collapse pulse.

Another factor which increases the element of uncertainty in the calculated peak pressures is the inconclusive nature of the information available about the minimum diameter of the cavity. A precise estimate of this quantity is difficult to make, and the various determinations made by various investigators differ by several magnitudes. For example, Harrison (1952) observed on his photographs that a fog of about 0·02 in. diameter remained after the disappearance of the cavity, and he therefore assumed that this represented the minimum diameter attained by the cavity. On the other hand, Sutton (1957) postulated that the peak collapse pressure acted on an area having a diameter of 0·001 in., this being the diameter of the small pits appearing on a plastic specimen subjected to cavitation. In the present study the experimental arrangement only permitted an upper limit of 0·032 in. to be defined for the minimum diameter, since the tip of the tungsten sparking needle interfered with the field of view. On this assumption the peak stress developed locally at the pressure end of the bar during the collapse of a cavity of lifetime $800\mu s$ is 10^4 atm. This value, of course, represents the lower limit of the peak pressure and although it agrees with that obtained by Sutton, if this author's estimate of the minimum volume were to be taken, then a predicted peak pressure of 10^7 atm would result. The minimum volume may be a function of cavity lifetime, and this is a point which requires investigation, consequently such a high value may be unrealistic. It is reasonable to assume, however, that from the results of the present work together with previous evidence, that the peak pressures developed are probably in the neighbourhood of 10^5 atm. Such large pressures would be expected to cause mechanical damage to a surface since they are well in excess of the yield strength of any material; e.g. the yield strength of the best steel is $\sim 10^4$ atm. Furthermore, from the few results which have been obtained for rebound, it is evident that the peak pressures developed at the collapse of rebound cavities can, and probably do, contribute materially to the disruption of a solid surface.

4.4. *The schlieren photographs*

The variation of cavity radius with time, derived from the schlieren photographs, is given in figure 10; the origin of time t has been arbitrarily chosen such that

$t = 0$ when the radius R of the cavity is the maximum radius R_0 attained by the part of the cavity appearing in the field of view of the optical system. For the purposes of comparison, figure 10 also includes a computed curve showing the time history of collapse of a hemispherical cavity having the same maximum radius R_0 and collapsing according to Rayleigh's theory. Due to the spherical symmetry of Rayleigh's result, the theory can be applied to the collapse of a hemispherical cavity having a zero or arbitrarily constant internal pressure on a semi-infinite body in an incompressible non-viscous liquid provided frictional losses at the liquid-solid interface are neglected. The experimental cavities are, of course, not of the Rayleigh type so that a comparison of the behaviour of the

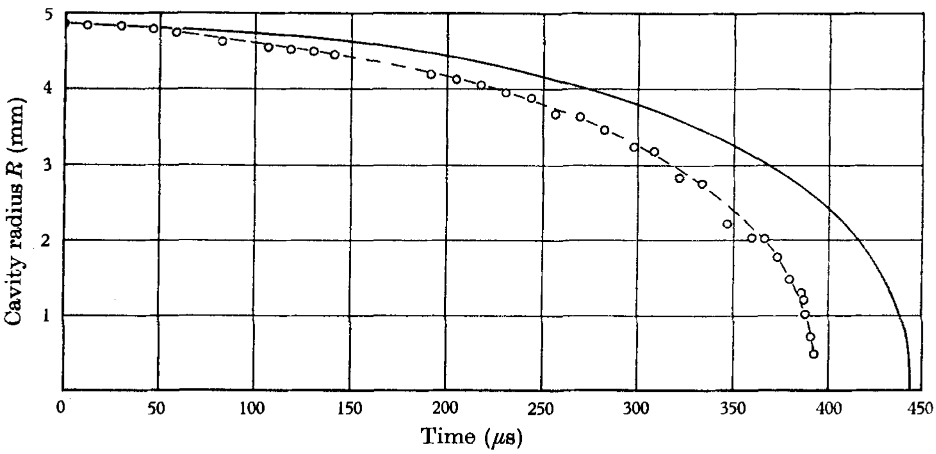


FIGURE 10. Variation of radius of cavity with time derived from the photograph of figure 7. Cavity lifetime 800 μs; maximum radius of cavity 0·49 cm. Experimental points, ○—○. ———, Rayleigh hemispherical cavity.

two is not strictly justified. Although the shapes of the experimental and the computed curves agree reasonably well, it is seen that the total collapse time of the experimental cavity is about 10 % shorter than that of the Rayleigh cavity. This result is surprising since one would expect frictional effects to prolong the lifetime of the experimental cavity compared with that of the equivalent Rayleigh cavity, and in fact Rattray (1951) has shown that the collapse time of a cavity situated near a wall is increased by about 20 % compared with that of a cavity in the body of the liquid. The discrepancy between the observed and experimental values must, therefore, be attributed to error in estimating the maximum radius of the cavity from the records. It will be noted that the smallest value of the radius measured is 0·049 cm; neither the quality of the record nor the fact that the radius of the tungsten sparking needle is itself 0·040 cm permits a persual of the (R, t) analysis further than this point.

In §4.1 it was concluded that a cavity which just totally covers the pressure end of a bar must have a lifetime corresponding to that of the transition points B and B' on the (F_m, t) curves of figure 2. The lifetime of the cavity illustrated in figure 7 is 800 μs, and the maximum diameter attained is 0·98 cm. The assumption of a linear relationship between lifetime and maximum diameter implies that a cavity having a maximum diameter of 1·27 cm (i.e. a cavity just covering the end of a $\frac{1}{2}$ in. diameter bar) would have a lifetime of 1140μs. This value agrees closely with the value of 1100μs. appropriate to the transition point B' of the (F_m, t) curve for a $\frac{1}{2}$ in. diameter bar and thus confirms the correctness of the above conclusion.

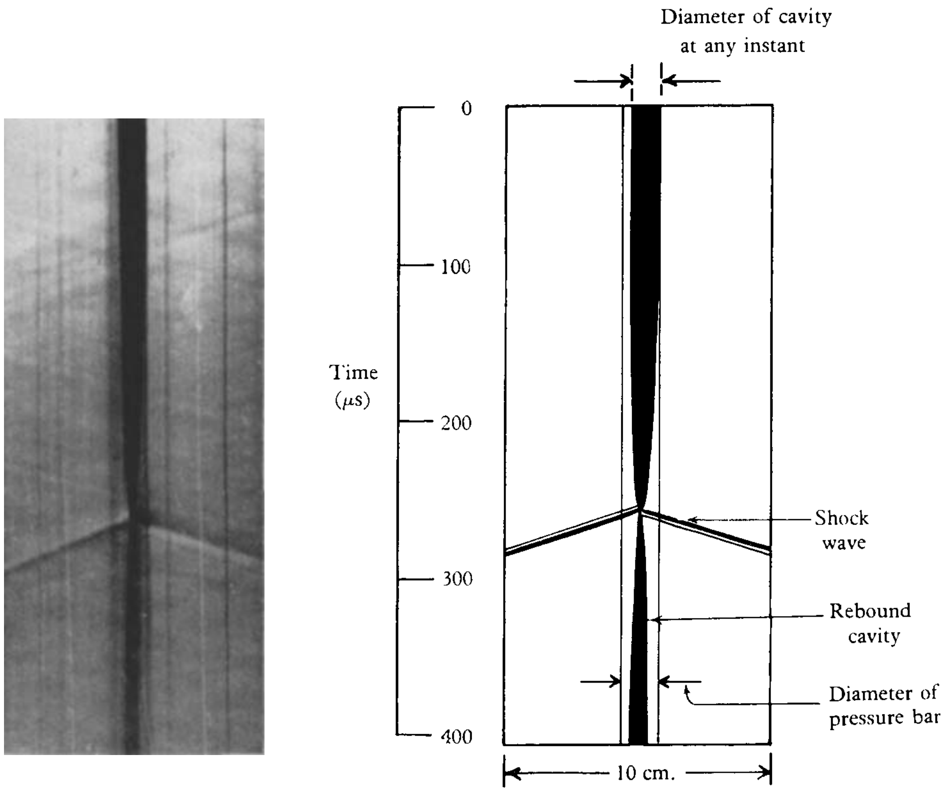
4.5. *Gas content of the cavities*

In the preceding discussion no mention has been made of the influence of the gas content of a cavity on the dynamics of the collapse process. It is evident, however, that the gas content will have an important bearing on the phenomenon. For example, Eisenberg (1953) has suggested that cavity rebound occurs if the initial gas content exceeds a certain lower limit, and Osborne (1947) finds that the peak pressure, measured at a distance from the cavity, decreases with increasing initial gas content. One important question which arises is whether the initial gas content decreases the damage potential of the cavity, i.e. does the presence of gas in the cavity attenuate the collapse pressure measured at the seat of collapse? In the present experiments rebound is observed, which implies that the initial gas content must be appreciable as would be expected, since gas is evolved by electrolysis and by release from solution. In spite of this fact, however, the pressures measured at the seat of collapse exceed the elastic limit of the material of the pressure bar. It may thus be concluded that damage can be produced by the collapse of cavities having an initial air content less than a certain upper limit as well as by the collapse of purely vaporous cavities.

5. Conclusions

It is shown that the pressure-bar method is suitable for measuring the peak force developed by the collapse of a single transient cavity in a liquid and for studying the shape of the collapse force-time pulse. The peak force in the collapse pulse is found to be a function of the duration of the pulse and of the cavity lifetime. The minimum radius of 0·040 cm attained by the cavity, estimated from the streak photographs, yields a value of peak pressure at the seat of collapse of 10^4 atm. Consideration of the uncertainties in this estimate, however, together with values proposed by other investigators, indicate that the pressures are probably higher than this value and are more likely to be $\sim 10^5$ atm. Rebound of the cavity is observed both with the pressure and photographic recordings, and the peak pressure generated on collapse of the rebound cavity is of the same magnitude as that developed at the collapse of the initial cavity. Preliminary work on the observation of the shock wave radiated from the point of collapse show that its velocity at a short distance away from its point of origin is slightly greater than sonic. Although the recordings do not permit a precise estimate of the shock wave velocity near the cavity wall to be made, it is reasonably certain that here it is well in excess of sonic velocity.

The authors wish to thank Dr T. G. Jones for his assistance in obtaining the schlieren photographs.



(*a*) (*b*)

FIGURE 7 (plate 1). (*a*) Portion of a streak schlieren photograph of the collapse and rebound of a cavity of lifetime $800\mu s$; (*b*) labelled drawing of (*a*).

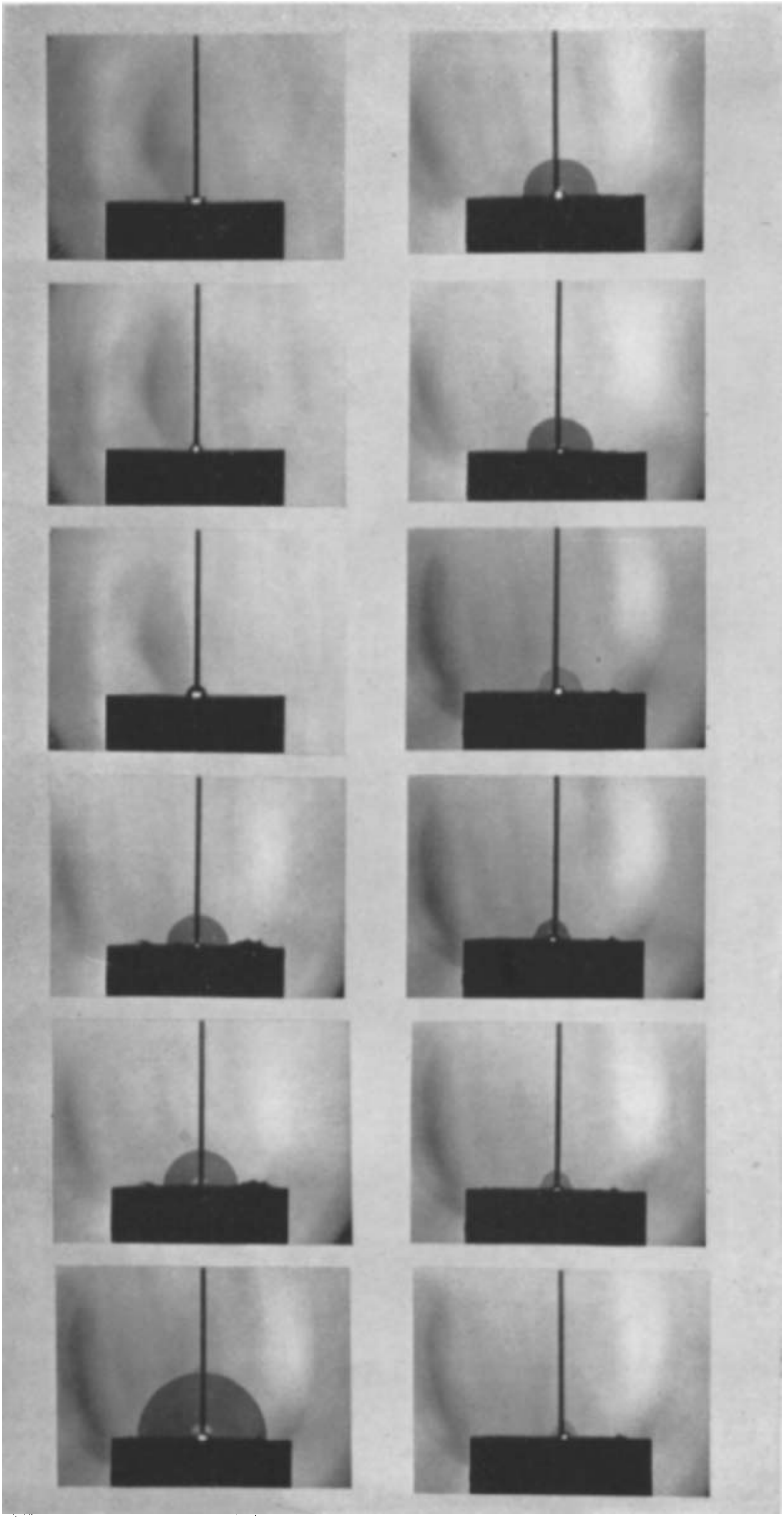


FIGURE 9 (plate 2). Series of spark photographs of the growth and collapse of a cavity generated by a spark discharge in water. Total cavity lifetime is roughly $800\mu s$, and the pressure bar diameter is $\frac{1}{2}$ in.

REFERENCES

Chesterman, W. D. 1952 *Proc. Phys. Soc.* B, **65**, 846.

Davies, R. M. 1956 Surveys in Mechanics: G. I. Taylor 70th Anniversary Volume (Ed. by G. K. Batchelor and R. M. Davies). Article: Stress waves in Solids, pp. 76–94. Cambridge University Press.

Edwards, D. H. 1958 *J. Sci. Instrum.* **35**, 346.

Edwards, D. H. & Owen, J. D. 1957 *J. Sci. Instrum.* **34**, 161.

Eisenberg, P. 1953 *David Taylor Model Basin Rep.* 842.

Ellis, A. T. 1956 *Proc. Symp. 'Cavitation in Hydrodynamics', N.P.L.*, paper no. 8. London: H.M.S.O.

Ellis, A. T. 1959 Private communication.

Güth, W. 1956 *Acustica*, **6**, 526.

Harrison, M. 1952 *J. Acoust. Soc. Amer.* **24**, 776.

Knapp, R. T. & Hollander, A. 1948 *Trans. Amer. Soc. Mech. Engrs*, **70**, 419.

Mellen, R. H. 1956 *J. Acoust. Soc. Amer.* **28**, 447.

Osborne, M. F. M. 1947 *Trans. Amer. Soc. Mech. Engrs*, **69**, 253.

Rattray, M. Jun. 1951 Ph.D. thesis (Cal. Inst. of Tech.).

Ripperger, E. A. 1952 *Tech. Rep.* no. 13. Division of Engineering Mechanics, Stanford University.

Sutton, G. W. 1957 *J. Appl. Mech.* **24**, 340.