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SOME NEW METHODS FOR THEIR STUDY

Fluid Dynamics Branch
Office of Naval Research
Contract Nonr 220(44)

HYDRODYNAMICS LABORATORY

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FINAL REPORT

by

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ABSTRACT

New experimental observations are presented which support the high speed jet mechanism of cavitation damage. A general discussion of the basic hydrodynamic theory involved is given and the importance of certain parameters on damage are pointed out. New techniques for studying the collapse of single cavities are described and the concept and development of a high speed photographic system using a ruby laser is outlined. Magnifications of up to fifty times at picture repetition rates as high as 1,600,000 per second and exposure times of 20 billionths of a second have been achieved.

INTRODUCTION

Due to the large number of parameters involved and the many aspects of cavitation of interest to investigators in different fields, the literature has grown to great proportions since its beginning over one hundred years ago.[1] In spite of this long history, the basic mechanisms of cavitation, especially those involved in cavitation damage to solid surfaces, is still a matter of considerable controversy.[2, 3, 4] There still exists the old argument as to whether chemical corrosion or mechanical erosion is of greater importance in "practical" situations in the field. This is becoming less controversial as the result of more carefully designed experiments to separate these effects.[5] The view has also been expressed that usual field conditions do not emphasize chemical corrosion as much as had previously been generally accepted.[6] A more current and perhaps more important concern involves the basic hydrodynamic behavior of collapsing bubbles which leads to damage of nearby solids. It has been the primary purpose of the work reported here to clarify this question through direct observation and pertinent theoretical treatment of observed behavior. The major result has been to show that high speed jets can and do occur during bubble collapse and rebound as a result of pressure gradients or solid wall proximity, or both.[7] These jets are very similar to the "Munroe" jets which were apparently first noticed in 1792 and utilized so effectively in lined cavity explosives in World War II. The basic principles involved have been well described by Sir Geoffrey Taylor and others.[8]

Previous to the work described in this final report the generally accepted view of cavitation damage has been that it was caused by shock waves generated by a spherically symmetric collapse when the cavity is near minimal radius[9, 10, 11], although there have been suggestions of a jet damage mechanism without adequate experimental or theoretical support[12, 13]. The symmetric collapse would make factors such as bubble gas content of prime importance because of its large effect on cavity wall motion near small radius.[14] This is known to have an effect on damage, but it does not appear to be as important as the spherically symmetric collapse theory might lead one to expect. Furthermore, even if spherical collapse is assumed there have been recent theoretical calculations which show that the bubble would have to be relatively close to the solid for damaging pressures to exist.[15] For such proximity it is difficult to understand how spherical symmetry could be preserved, especially when the tendency toward surface instability during collapse is well known.[16]

An obvious way to attack these very basic questions is by direct observation, but this is not easy. Many hydrodynamic phenomena are sufficiently accessible to observation that required assumptions are made without conscious effort. In the case of small bubble cavitation, as distinct from supercavitating flow, the situation is different. Bubble lifetimes are measured in milliseconds, or even microseconds, and wall velocities may reach thousands of feet per second when bubble dimensions are so small as to require a high power microscope even if they were stationary. This combination of high velocities and small dimensions makes direct observations extremely difficult, since velocities as well as displacements are magnified as far as photographic recording is concerned. In addition to these problems there is the difficulty of finding a bubble in the field of view at the time a photograph is taken. If one hopes to do any analysis it is also important that there are no interactions with other bubbles and that the gross flow is not too complicated. Such things as boundary layers and turbulence should be minimized in an initial attack on the problem.

The Research Program

The points just mentioned made it clear that there would have to be a considerable effort devoted to development of experimental techniques before one could consider basic cavitation mechanisms based on a firm knowledge of actual cavity behavior. Some of these developments turned out to be time-consuming but, on the other hand, represented what is believed to be state of the art advances. These were not accomplished in the proper chronological order from the standpoint of the main objective of the project with the result that work still remains which could have been done had certain techniques been perfected earlier. This is almost inevitable in experimental research, however.

The total work done was not accomplished at one place or by one person. This report is intended only to summarize the main results. Details are available in the various published papers authored by the persons concerned. The success achieved was due in large part to the great cooperation of the Fluid Mechanics Division of the Office of Naval Research in furnishing and transporting essential equipment for use by the author while at the University of Cambridge on a National Science Foundation Senior Postdoctoral Fellowship. Other equipment designed and constructed by Dr. T. Brooke-Benjamin at Cambridge proved to be of decisive importance.

Work aimed towards the solution of two of the experimental difficulties was started in parallel at the beginning of the program at Caltech. These two problems were the design and construction of a water tunnel facility in which the dynamics of single bubbles could be studied, and the development of a suitable high speed photographic system for observing the dynamical behavior of small transient cavities. After work on these two problems had been essentially completed in Pasadena, a third problem was resolved at Cambridge in collaboration with Dr. T. Brooke-Benjamin. This latter consisted in the development of a technique whereby accurately spherical cavities of up to two inches in diameter and containing vapor with negligible amounts of permanent gas could be collapsed by a relatively small external pressure. This opened the way for more accurate observation of collapse in the absence of flow because of the lower velocities involved and because of the larger dimensions of the cavity. It also removed questions as to the content and temperature of the cavity which were present in the earlier work of Naudé and Ellis who studied spark generated cavities.[2]

After development of these three basic experimental techniques there did not remain much time for a proper study program with theoretical analyses of results. However, some very basic conceptions concerning cavitation damage mechanisms were formulated, especially as a result of the observations at Cambridge. It is felt that these conceptions will prove to be of considerable importance and will provide new stimulation to workers in the field. They will be outlined in the latter part of this report and are discussed in more detail in a paper presented to the Royal Society of London which is now in press.[7]

Development of the Cavitation Tunnel

The cavitation tunnel was designed with five major requirements in mind. These were:

1. Means for degassing and denucleation so that single bubbles could be produced and studied.
2. A low level of turbulence in order to keep the geometry of bubble collapse from being distorted.
3. A minimum volume of liquid involved to minimize denucleation treatment time and to permit more costly liquids than water to be used if desired.
4. A sufficiently large working section to make wall effects negligible for cavitation bubbles large enough to observe easily (e.g., about one-quarter inch in diameter).
5. A wide range of flow velocity and static pressure.

In addition the working section should provide for good photographic observation and the cost and upkeep of the entire facility should be low.

With the above points in mind it seemed clear that a tunnel of the blow-down type was most suitable and such a tunnel was therefore designed and built.[17]

In essence the tunnel consists of two 200 gallon water tanks joined by an 8-inch diameter pipe which contracts locally to a 2-3/4 inch square working section. Figure 1 is a schematic diagram of the tunnel, and Fig. 2 is a photograph of the entire installation. The working section is of lucite and the tanks and those pipes which are in contact with the water are glass lined. Joints are made with teflon gaskets and thus contamination of the water by corrosion is minimized. The tunnel is usually operated with about 200 gallons of water; this amount allows maximum running times to be achieved. The water is forced from the upper tank through the working section into the lower tank by compressed air. A spherical compressed air reservoir of about 3-ft. diameter is used for storage purposes and is connected to the top of the upper tank by four 1-1/4 inch diameter pipes each having a solenoid operated valve with a hand valve in series with it for flow control. To accommodate the accumulation of water in the lower tank and the decrease in air volume above it, air is allowed to escape from the top of the tank through two 1-1/4 inch solenoid operated valves. These valves also have hand valves in series with them.

The solenoid valves may be opened and closed in any prearranged sequence while the tunnel is operating and the air pressure in the upper and lower tanks thus controlled. It is the difference in pressure between the air in the upper and lower tanks that controls the velocity in the working section. The static pressure in the working section is dependent on the absolute values of the air pressure in the upper and lower tanks. Thus by regulation of the pressures in the water tanks during operation any combination of pressure and velocity in the working section within the available range can be achieved. Figure 3 is a photograph of the separated flow over a circular arc foil attached to the tunnel wall. Strong cavitation is visible with some isolated large bubbles. Flow velocities from 0 to over 100 feet per second are easily obtained.

Operation of the tunnel is automatic and the solenoid valves which control the air flow are energized at predetermined times during the blow-down process. The valves are relay operated by electric pulses from a controller. The controller consists of a 60 contact rotary switch which performs one revolution during the blow-down operation. The switch is driven by a synchronous motor through gears which are interchangeable for adjustment of the switching rate. The motor is so connected that it stops automatically after one revolution of the switch. For moderate tunnel speeds, i.e., in the range 30-50 feet per second, the gears are set so that one revolution of the switch takes place in 15 seconds. Thus the valves may be operated at 0.25-second intervals.

For cavitation studies distilled water is used. The removal of dissolved gases is achieved by evacuating the air above the water to nearly vapor pressure. Provision has been made for passing the water slowly through a vessel where it is subjected to an ultrasonic field to promote release of the gases. A filter capable of removing 0.5 micron particles is also incorporated to ensure that the water is relatively free from cavitation nuclei.

The nozzle is square in cross section, and upstream and downstream of the contraction the sides are parallel. The contraction profile was based on Tsien's analytical method[1] for an axi-symmetric contraction cone which converts a uniform velocity profile upstream from the contraction to a uniform flow downstream. The area ratio is 6.5. The nozzle was cast inside a concentric 10-inch to 4-inch iron reducer from an epoxy resin, and projects into the upper tank when bolted in place. To approximate a uniform flow upstream from the contraction a square bellmouth entrance, half-round in section, is attached to the upstream end of the nozzle.

The working section is 2-3/4 inches square by 14 inches long and is fabricated from 1-inch thick lucite. It is easily removed from the tunnel and disassembled for access to the model. In Fig. 4 it is

[1]H. S. Tsien, "On the Design of the Contraction Cone for a Wind Tunnel", J. Aeronaut. Sci., Vol. 10, 1943, p. 68.

shown with a circular arc model in place. At a cross section 2 inches from the upstream end of the working section a pair of platinum electrodes are mounted in the middle of opposite faces, flush with the inside wall surface. These electrodes are for the electrolytic seeding of a cavity in contact with a wall. The electrodes may also be useful for incorporation in an electro-magnetic flow-meter to obtain a continuous record of mean velocity in the working section.

In operation the water is first transferred to the upper tank by evacuating it or pressurizing the lower one. Thus the initial air pressure in the upper tank may be set at any desired value. The pressure in the lower tank is then about 5 psi greater due to the hydrostatic head. The valves venting the lower tank to atmosphere or vacuum may be set to control the outflow of air during the blow-down operation such that the pressure above the water, and hence the static pressure in the working section, is regulated. Tank pressures above atmospheric are obtained by throttling the escape of air to atmosphere; lower pressures are maintained by throttling the flow to a vacuum receiver. The valves admitting the compressed air to the upper tank are operated in the following way. Initially, sufficient valves are opened for a short interval to charge the upper tank to a higher pressure. Subsequently this pressure is regulated so that, in conjunction with the pressure in the lower tank, the required values of tunnel velocity and pressure are maintained by incremental operation of the valves. When the water level in the lower tank is nearing the top, the flow is brought to rest by opening the upper tank to atmosphere and closing the valves venting the lower tank. The compression of air then arrests the flow without shock.

Measurements of the rise time of the water surface in the lower tank have shown that the pressure drop between the upper tank and the working section gives a reliable estimate of velocity.

An example of a single bubble in flow in this tunnel is shown in Figs. 5a, b which are selected from a full sequence. In this case the bubble was generated at the minimum pressure point on a circular arc hydrofoil. It was taken with conventional flash lamp photography and hence the resolution is not good enough to determine if a jet were present. Figure 6 also was taken before development of the laser photographic system. It does, however, show the shock wave from the bubble collapse. The flow velocity was 16.4 feet per second. The Kerr cell shutter technique was used here with an exposure time of about 2×10^{-7} seconds and a picture repetition rate of 5×10^{4} per second. Even though there was no attempt made to get shock wave pictures this is, to our knowledge, the first time a shock wave from flow generated cavitation bubble collapse has been observed. The relatively poor resolution does point up the need for the laser camera system, however.

The High-Speed Photographic System

Since the objective of the project was to study cavitation mechanisms by direct observation the photographic requirements were very stringent. Consider that in order to do damage to solids by either the shock wave or jet mechanisms one must expect interfacial velocities in the range of one to five thousand feet per second or higher. It is also to be expected from theory that, at least for the spherically symmetric collapse in water, the radius may be only two percent of its initial value when sonic velocity of the interface is reached[4]. If the initial size is 1 cm. in diameter (a rather large bubble), then the diameter will be 2×10^{-2} cm. when the velocity is about 1.5×10^{5} cm. per second. Thus, even if an error of ten percent in measurement is tolerated, the effective exposure time of the photograph must not be longer than 1.3×10^{-8} seconds. This extremely short time practically rules out all but laser light sources, particularly when appreciable magnification of the object is required. Previous Kerr cell shutter and Xenon flash lamp work by the author in 1952[18] used exposures about five times as long as this at magnifications of only about four.

To investigate the feasibility of laser illumination a ruby rod 3 inches long by 1/4 inch diameter was excited by an EGG FX-42 flash lamp in an elliptical reflector. The resultant 6943 angstrom beam was used to backlight a 0.13 cm. air bubble held stationary by a sound field. Figure 7 is the photograph obtained. Figure 8 shows approximately the same size bubble with a collimated mercury arc source substituted for the laser beam. These results were very encouraging, as a sharper image was obtained with the laser. Interference rings were also noticed, presumably due to dirt particles in the water. The picture was taken, however, with a relatively long exposure time of about 200 microseconds, and so the problem of obtaining very short pulses at high repetition rates had yet to be solved to make the system suitable.[19] Fortunately, this proved to be possible by controlling optical losses in the laser cavity with a Kerr cell. This "Q spoiling" technique was first used to generate single high power short duration laser light pulses by McClung and Hellworth.[20] The method consists of moving the partially reflecting mirror from one end of the ruby out into the air and inserting a Kerr cell in the intervening space. When an electric potential is applied to the cell it effectively alters the polarization direction of the light and limits the induced emission buildup in the ruby. When the potential is removed there is a sudden emission of about 20 billionths of a second duration at powers of up to the order of one hundred million watts. However, normally there will be a "deadtime" in which no more pulses can be emitted until the ruby atoms are again raised to an excited state by the incident light from the Xenon flash lamp.

In early tests it was found that light emission would not occur for every pulse when the Kerr cell was pulsed repetitively. It was also observed, however, that the higher the pulse rate the less likely the skipping became. This led to the idea that if the rate of buildup of photons in the ruby were limited then one could get good pulse trains at lower repetition rates. The limiting of buildup by increasing optical cavity losses did not seem the right thing to do because one would lose valuable energy and there might not be enough photons available to cause a rapid avalanche when the light pulse was called for. The obvious thing to do, if possible, would be to store photons in a region where they could not contribute to induced emission buildup, and yet still be available. It turned out that this could be done conveniently by merely increasing the inactive part of the optical cavity volume. The partially reflecting mirror was simply moved farther away from the end of the ruby on which a transmitting rather than a reflecting film was deposited. The Kerr cell was still placed between this end of the ruby and the movable ninety percent reflecting mirror, but its separation distance was not important. As one would expect, generation of constant intensity light pulse trains at lower repetition rates required longer distances from the ruby to the mirror. The details of performance are available elsewhere[21], but they will be summarized here briefly:

1. Light pulse repetition rates of from 8×10^4 to 1.6×10^6 per second were achieved. The lower limit was set by the pulses becoming unequal in intensity. The upper limit was not significant since it merely represented the limit of the electronic pulser which was available.

2. The peak output power in the light pulse was about 2×10^3 watts at a repetition rate of 10^6 per second. The output was approximately inversely proportional to the repetition rate at optimum mirror spacing.

3. The duration of a light pulse was about 2×10^{-8} seconds and this was nearly independent of the duration of the voltage pulse applied to the Kerr cell when the latter (10,000 volts) was varied from 6×10^{-8} to 4×10^{-7} seconds.

The fact that the light pulse duration was so short made the design of a camera very simple. No optical compensation to hold the image stationary on the film during the time of exposure was necessary. The camera was merely a rotating mirror placed at nearly the focal distance from the lens so that rays would not be lost for incoming nearly parallel light. Figures 9a and 9b show the plywood film housing and the four-sided rotating mirror with electrical pickup for synchronization. An aero ektar seven-inch focal length f2.5 lens happened to be in use when this picture was taken. Nine and one-half inch wide Eastman high speed infrared film designed for aerial photography is used in this housing. A somewhat better emulsion turned out to be Eastman "Shellburst". Image speeds over the film up to one inch per microsecond were available using a standard 100,000 RPM air turbine for mirror drive and a fifty-inch optical length from the mirror to the film.

Figure 10 illustrates the resolution possible. It shows a number of frames taken at a rate of 200,000 frames per second of a microscope scale on which the divisions are 0.1 mm apart. Figure 11 shows a spark generated bubble in water with accompanying shock wave. The camera has also been used to photograph shock waves from acoustically generated cavitation, to record forward light scattering from 0.285 micron spheres, and to photograph photoelastic patterns.

It is felt that the camera is extremely well suited for the problem of studying cavitation damage which provided the stimulus for its development. Unfortunately, time was not available to use it for studying flow cavitation in the blow down tunnel before the author left to continue work at the University of Cambridge. Patent has been applied for covering the high speed laser pulsing principle and it is hoped to continue its use for studying cavitation damage. The system has also been duplicated at the University of California at Berkeley for studying detonation waves.[22]

Cavity Collapse Studies

These studies were undertaken at the University of Cambridge during the last part of the contract. They were an attempt to extend the accuracy of observations of bubble collapse by using a new technique for generating relatively large and slowly collapsing bubbles. It was felt that although significant advances towards observing small bubbles collapsing very rapidly had been made, it was still worthwhile to also try to make the problem easier by extending the time scale of the phenomena.

The experimental technique for doing this was originated by Dr. T. Brooke Benjamin at the newly opened laboratory of the

Department of Applied Mathematics and Theoretical Physics at Cambridge. Most of the apparatus had been constructed by the time the author arrived but he did help to develop a reliable bubble generator capable of providing a small hydrogen gas bubble nucleus. This made it possible to eliminate the electrical spark generator used by Naudé and Ellis in earlier work.[2]

As shown in Fig. 12, the central part of the apparatus was a reinforced lucite box, of 9-1/4 in. square internal horizontal cross-section, which in the experiments to be reported was filled with water to a depth of about 10 inches. The box was closed by an air-tight lid, and the air space above the water surface could be exhausted by a jet pump; its pressure was generally made about 0.04 atm., the precise value being set by an adjustable leak into the vacuum system.

Before an experiment the water was degassed and rendered capable of withstanding small tensions without cavitating. This was done by putting the water under vacuum and vibrating the box vertically with an amplitude sufficient to produce vigorous and widespread cavitation. (Note that a vertical periodic acceleration with amplitude greater than $\underline{g}$ will create negative 'hydrostatic' pressures for part of each cycle.) The vibration was continued for about an hour, during which time the noise made by the cavitation became progressively sharper, indicating more violent collapse, and at the end of which the cavitation would cease if the tensions produced in the water were made less than a certain value. Thus the water appeared to have acquired a small but appreciable tensile strength.

In the experiments large vapor-filled cavities were grown from small hydrogen nuclei which were formed by electrolysis on a platinum electrode at the bottom of the box. The electrode was embedded in epoxy resin, with only a minute portion of its surface exposed to the water. Single nuclei with radii down to about 0.1 mm could be formed by passing pulses of current with suitable amplitude and duration through the electrode, and they floated upwards into the required position for generation of the large cavities. The characteristics of the pulse had to be adjusted rather carefully to insure that only a single nucleus broke clear of the electrode each time, and various refinements of technique in making electrodes for this purpose are still under study.

A novel method was used for generating the vapor cavities. When the tiny nucleus had reached the required position, at about the center of the volume of water, the box was struck downwards by a heavy bar suspended on a spring above it. As a result of the blow the sudden downward acceleration of the box, which was considerably greater than g, produced a large negative hydrostatic pressure in the water, and a cavity consequently opened up from the nucleus. The time for growth of the cavities to maximum size was generally comparable with the time of the subsequent collapse, typically about 0.005 seconds.

An important feature of the apparatus was a means for creating gravity-free conditions during the collapse of a cavity. The box was mounted on a platform which could slide freely upon two vertical columns, and prior to an observation being made, it was suspended by an electromagnet. In the process of striking the box so as to generate a cavity, the downward movement of the bar caused a break in the supply of current to the electromagnet, with the result that the box was in free fall subsequent to the blow. A fall of a few centimeters allowed sufficient time for the observed collapse of the cavity to be free from the effects of gravity.

The cavities were observed by means of high-speed photography, using a rotating-drum camera and back-lighting with a flash tube. A sequence of flashes, at a chosen rate and total duration, was initiated by the signal from an accelerometer which was fixed to the box and so responded to the impact of the bar.

Observations on Collapse Under Gravity

Figure 13 shows four successive views, at intervals of 2 msec, of a cavity formed near the center of the water, far away from the walls of the container. The free-fall device was not used in this experiment, and the curious behavior observed was undoubtedly an effect of gravity.

The first frame shows the cavity at nearly maximum size, with a diameter of 2.4 cm. The second frame shows it having contracted to about half this size, and as in the first frame there appears to have been no significant departure from spherical form. During the interval between the second and third frames, the cavity collapsed down to microscopic size, so that the third and fourth frames show the cavity on its rebound.

The remarkable situation depicted in the third frame may be explained as follows. During its previous history, particularly the time spent near maximum size, the cavity picked up a vertical impulse through the action of gravity (i.e., under the hydrostatic pressure gradient). This was small enough to produce no noticeable effect in the early stages of the collapse, as viewed in the first two frames; but the effect of the impulse became crucial under the enormous reduction of displaced volume in the final stages. A high-speed jet developed during this brief phase, of such vigor that it still persisted when the cavity had rebounded back to large size. The jet can be seen distinctly in the third frame of Fig. 13 passing upwards through the cavity and entering the liquid above with such force that a conical protrusion of the cavity surface was drawn up behind it. In the fourth frame the jet can still be seen, but it appears to have weakened to the extent that the previous excrescence at the top has been able to close up.

A similar cavity observed in gravity-free conditions showed no vestige of this behavior, confirming that gravity was the vital factor. This cavity is shown in Fig. 14.

Observations on Collapse in Proximity to a Solid Boundary

For these experiments a sheet of lucite was fixed with its plane vertical across the internal span of the box, and cavities were grown from nuclei sited at various small distances from it. The free-fall device was not used. Examples from a large number of observations made this way are presented in Figs. 15, 16 and 17. The diameter of the spherical cavity shown in the first frame of Fig. 15 was 2.2 cm, and the other figures are reproduced to the same scale.

Figure 15 presents a choice of four representative views of a cavity collapsed fairly close to the wall, whose distance from the center of the cavity at maximum size, as shown in the first frame, was about 1.3 times the radius. (The position of the wall can be made out, on the right-hand sides of the pictures, from the reflection of the cavity in it. The bead-like features appearing in the cavity surface are merely images of bubbles that formed incidentally a long way behind and for which the main cavity acted as a spherical lens.) The second frame, taken 5 msec after the first, shows the cavity to have become considerably elongated in the normal direction as the collapse began. This exemplifies the effect discovered theoretically by Rattray.[23] In the third frame, 9 msec after the first, the cavity is clearly seen to have become involuted on the side further from the wall; and in the last frame, 10 msec after the first, the jet has passed right through the cavity. From these and neighboring frames on the film, the jet velocity was estimated to be about 10 m/sec. This value was exceptionally low, however, because the jet formed rather early in the collapse. (Note also that raising the environmental pressure to atmospheric, i.e., by a factor of about 25, would scale up all such velocities by 5.)

Figure 16 also is a good example of the elongation predicted by Rattray. Here the bubble is farther from the wall than it was in Fig. 15. In this situation the jet forms but never reaches the wall and so is incapable of doing damage.

Figure 17 is included for the sake of several extremely interesting features. In this experiment the cavity was grown from a nucleus sited at about 1.5 mm from the wall, that is, very much closer than in the previous experiments. The three frames in the top row of Fig. 17 cover an early phase in the growth of the cavity, before the presence of the wall had any appreciable effect. The second row of frames, covering a phase about 6 msec later, shows the cavity in roughly hemispherical form; and the next row shows it at about the same interval later again, by which time it had developed a curious stratified form. The sequence of six frames in the last two rows covers the final phase of the collapse at intervals of 0.2 msec. A remarkable feature is the bellows-like appearance of the contracting cavity, which may have been due to a vibration of the wall. Perhaps even more remarkable is the unmistakable evidence that a filamentary jet, very much thinner than the cavity at the time, developed in the interval between the first and second frames of this sequence. By measuring the distance traversed by the jet, we estimate its speed to have been at least 35 m/sec, and possibly a good deal higher. Hence, when allowance is made for the five-fold increase of speed that would result if the environmental pressure were raised to atmospheric, it may be appreciated that jets like this one could be highly damaging to a solid boundary.

Discussion of Parameters Affecting Cavitation

As regards the essential dynamics, the violent action of spherical collapsing cavities was demonstrated very clearly by Rayleigh's well-known analysis[9], which still remains the cornerstone for most theoretical thinking on the subject. In the first place he considered an isolated spherical void collapsing in an incompressible liquid under a constant pressure at infinity, and he showed that as the collapse nears completion the inward velocity of the cavity wall and the pressure inside the liquid become indefinitely large. He recognized, however, that a more realistic physical model is provided by allowing the cavity to contain a small quantity of insoluble gas, whose compression ultimately arrests the inward motion and causes the cavity to 'rebound'. Improved representations of tne effects of gas and vapor contents, and various other physical factors, have been included in the theory since Rayleigh's time; but almost all the work done so far on the problem has proceeded on the original assumption of spherical symmetry.

A reason for circumspection about analyses on this basis is that, as was shown by Birkhoff[24] and Plesset and Mitchell[16], the spherical form of a collapsing cavity is unstable to small perturbations. Nevertheless the instability is of a rather weak kind while the inward motion is not being significantly retarded by compression of the cavity contents, and experimental cavities can appear to remain approximately spherical throughout most of their collapse, provided the effects of hydrostatic and other 'environmental' pressure gradients are eliminated, as was illustrated in Fig. 14. But in the concluding stages of collapse, when enormous outward accelerations of the cavity surface occur under the pressure of the contents, the spherical form becomes violently unstable(25), the cause being essentially the same as the Taylor instability of a plane interface accelerated in the direction from the lighter to denser fluid.

The high values of internal pressure predicted by the Rayleigh theory are definitely misleading if one loses sight of the fact that they occur only when a cavity has shrunk to extremely small size, and that the amplitude of the radiated pressure wave diminishes with relative radial distance r/R at least as rapidly as $(r/R)^{-1}$. To test the relevance of their spherical-collapse analyses to the damage of solid boundaries, both Hickling and Plesset(4) and Ivany(15) estimated some values of peak pressure at distances from the center of collapse comparable with the initial (maximum) radius of the cavity. Ivany concluded that pressures sufficient to cause damage did not occur at such distances; and while Hickling and Plesset were able to obtain some marginally adequate values, the respective conditions for the cavity were so extreme that the overall model became of very doubtful physical validity (e.g., the initial pressure of the cavity contents had to be made unrealistically small; also the necessary final internal pressure according to this model, when allowance is made for attenuation of the very strong shock wave that is developed, seems unreasonably high - being apparently of the order of 10^6 atm.). The point to be emphasized is that probably any cavity producing a damaging effect in practice must, throughout its collapse, be so close to the solid boundary that very large departures from spherical symmetry are inevitable; and this class of situation presents a hydrodynamical problem significantly different and unfortunately much more difficult than the Rayleigh problem. An exception to this statement must be allowed in the case of a perfectly hemispherical cavity founded upon a solid boundary. Cavities with this form can be made experimentally by the electric-spark technique, but they are extremely unlikely ever to occur in cavitating flows, and even in sonically-generated cavitation, where they might be expected to occur occasionally, no evidence has been found of their being a common event.[26]

The focus of our initial conceptions about cavitation bubbles collapsing near a solid boundary lies in the fact that they can in various ways acquire translational motion towards the boundary. As a result of the collapse, during which the displaced volume may become an extremely small fraction of its maximum value yet its centroid still be brought up close to the boundary, this motion may lead to the delivery of a highly concentrated impulse against the boundary. The principle in view is simply one of momentum conservation, and accordingly the result may be regarded separately from the effects of high pressures developed by compression of the cavity contents. Thus, we believe, powerful effects can arise which are extra to the Rayleigh implosion mechanism.

An experimental fact worth noting concerns the rate of occurrence of manifestly destructive cavities, such as to produce individual pits in a test specimen of soft material. Especially in cavitating flows but also in cases of sonically-induced cavitation, this is found to be very small in comparison with the total rate of formation of cavities in the general neighborhood of the boundary. For example, from observations on the rate of pitting in an aluminium test section exposed to a cavitation cloud in a water tunnel, Knapp estimated that only one in 30, 000 of the transient cavities swept into the region of the test section caused a damaging blow.[27] This fact gives good reason to frame an explanation for cavitation damage as depending on a rather crucial combination of conditions for individual cavities. It may be that conditions are just right (or just wrong, one should perhaps say) when the translational movement of a cavity is just enough to bring the center of collapse up to the solid boundary, and to cause a jet to form just before the cavity reaches minimum volume and maximum internal pressure; then the jet may have the largest possible velocity, and its impact against the boundary may optimally reinforce the simultaneous effect of the high collapse pressure.

The theoretical question central to the discussion is what general effect does a translational movement have on a collapsing cavity? To answer this the momentum of the fluid must somehow come into consideration, and consequently one needs to be rather careful - no less than one generally needs to be careful when considering the momentum of a fluid set in motion by the translation of a rigid body. The basic difficulty is quite well known; it has been discussed, for instance, by Lamb(28) and more thoroughly by Birkhoff(29). But in order to develop any secure argument in terms of momentum, one must recognize that the classical perfect-fluid theory poses a paradox inasmuch as the total momentum of an infinite fluid may be indeterminate, notwithstanding that the motion of a finite body through the fluid is related in a simple, definite way to the propulsive forces.

The best rationale for the matter is the one originally proposed by Kelvin when he initiated this part of hydrodynamics. We consider the impulse $\underline{I}$ that would have to be applied to the body in order to generate any given motion from rest. (If the body is not symmetrical about an axis in the direction of motion, $\underline{I}$ must comprise an impulsive wrench, but this case need not concern us here.) The impulse thus defined is not in general equal to the momentum of the body and fluid together, because its application will generally produce an impulsive reaction in the fluid at infinity. This reaction, and hence the total momentum of the fluid, depends on how the infinite envelope of the fluid is specified. For example, if one insists that the fluid is contained in an infinite rigid box, it follows that the momentum must be in the direction opposite to the motion of the body, since the centroid of the fluid is obviously displaced this way; then the reaction at infinity exceeds the part of I due to the fluid. Again, Theodorsen[30] showed that if one considers the fluid in a huge cylinder, taking its axis in the direction of motion and making its length infinitely greater than its width, then the impulsive reaction at infinity vanishes and the Kelvin impulse I equals the total momentum in this case. But the choice of conditions at infinity is really immaterial, because obviously the actual motion of the body will not depend on what happens at infinite distances away. Thus, to be definite, one should always reason in terms of the Kelvin impulse, not in terms of the fluid momentum whose value is in fact immaterial to the physical problem.

Let F denote the external force acting on the body. (The obvious generalization to a vector force, and resolution of I into orthogonal components, need not delay us here; it will suffice to assume F acts along some specific axis about which the body is symmetrical.) Considering the motion of a rigid body under an external force, Kelvin proved that:

$$\frac{dI}{dt} = F , \qquad (1)$$

and this important formula is the key to the present problem. For, when Kelvin's argument leading to (1) is re-examined, it appears to hold equally well for a deformable body, even one whose volume changes during the motion. (The latter case demands caution, of course, because any volume changes produces a net flow at infinity.) Hence a closed cavity is included in the range of application, being equivalent to a deformable solid body with negligible mass, and I is then attributable wholly to the inertial effect of the surrounding fluid.

One useful idea upon which we may draw is, therefore, that a bubble projected through an infinite liquid creates a motion with either a constant Kelvin impulse, in the absence of external force, or an impulse that changes at a rate equal to the force in the direction of motion. The effect of a pressure gradient $\partial \bar{p}/\partial x$ extending over the environment of a bubble whose instantaneous volume is V may, of course, be interpreted as a force $-(\partial\bar{p}/\partial x)V$ in the x-direction; for example, the buoyancy force $-\rho gV$ due to a hydrostatic pressure gradient ρg in the downward vertical direction. As a further point of interpretation, appeal may be made to the complementary definition of the Kelvin impulse, namely that an equal but opposite impulse must be applied over the surface of the bubble to arrest its motion at any instant.

According to these lines of reasoning, the impulse associated with a moving bubble presents much the same intuitive physical picture as the momentum of a rigid projectile in free space, and hence the feasibility of impact effects in the process of cavitation damage is immediately appreciated. To account with any certainty for the case of a bubble moving up to a solid boundary, however, the argument so far developed is clearly inadequate, because (1) holds only for a body infinitely remote from any other boundary of the fluid. Several simple extensions of the argument can be used for this case, and though none of them is entirely free from objection the general conclusion reached seems fairly sound. One way is to consider a bubble started towards a finite fixed solid body which is initially at such a distance away that it does not share significantly in the starting impulse. We assume for simplicity that no external force applies other than that necessary to hold the body in place. As the bubble moves up to the body the Kelvin impulse of the composite system will remain constant; and hence we deduce that there must be a forward impact force against B, because when the motion has been arrested the external reaction keeping the body in place has delivered an impulse equal but opposite, and so cancelling, the original impulse to the bubble.

We go on to consider how the effects of the Kelvin impulse may be concentrated when a bubble is collapsed. For bubbles that become seriously distorted away from spherical form a very difficult analytical problem is presented, and cumbersome approximation methods provide the only way to explicit solutions. A few interesting properties of the possible motions can be inferred by general arguments, however, and for these Reference 7 should be consulted. Let it suffice to say here that it can be shown that the translational motion may gain kinetic energy at the expense of the motion relative to the centroid; and indeed the possibility has appeared that the whole energy of collapse (i.e., the pressure difference at infinity times the initial volume, very nearly) could be drawn into the translational motion, provided the impulse I were large enough so that the required volume reduction. making M finally small enough, were still insufficient for a significant fraction of the total energy to be imparted to the cavity contents. This line of reasoning supports a general intuitive judgment that the possession of a Kelvin impulse by the system will enfeeble the collapse of a cavity in so far as events might be viewed from the centroid. In the external view, however, the transferred energy may be manifested with physical consequences that appear no less important than those of energy concentration in the cavity contents.

An instructive question to ask oneself with regard to this point is, "What happens ultimately to the shape of a cavity that is shrunk smoothly down to nothing while moving through an infinite liquid?" According to the principles just explained the translational motion must speed up, of course, but an infinite velocity of translation in the limit appears impossible for a cavity with uniform pressure over its surface. Again, if the liquid remained simply-connected as the cavity closed up, the Kelvin impulse would have to vanish, which we cannot allow in the absence of an external retarding force. The only reasonable answer is that the cavity must deform in such a way as to make the liquid multiply-connected. Circulation can then appear in the liquid, and we are left in the limit with a vortex system possessing the original Kelvin impulse. For example, the cavity may take on the form of a torus, which makes the liquid doubly-connected, so that a hollow vortex ring is produced. The cavity can then be compressed to indefinitely small size while still preserving the same impulse. And clearly the original cavity must fold in from the back (i.e., be threaded through in the direction of motion) in order to produce a circulation with the right sense.

This nicely explains what has sometimes been observed to happen when a cavitation bubble is collapsed after having acquired a translational motion relative to the liquid in its neighborhood. A jet forms by involution of the back of the cavity, and something well describable as a hollow vortex ring finally appears. Ellis observed such behavior in a bubble collapsed sufficiently slowly (i.e., under a small enough pressure) to be considerably affected by gravity[18], and a fine example of it has recently been recorded by Ivany. Also in support of this general idea we should note the calculations made by Kolodner and Keller[31], with application to explosion bubbles rising under gravity, which were developed to a stage where the supervention of vortex-ring formation was clearly indicated.

As a general interpretation of the phenomenon of jet penetration through collapsing cavities, one can simply say that the liquid is finding the only possible way to preserve its impulse as the cavity size decreases. Or one can say, perhaps more tellingly, that when the impulse is too large to be manifested by translational movement of the cavity in approximately spherical form, the cavity tends to form a torus because the vortex ring evolved is the only flow capable of manifesting the impulse for indefinitely long under the handicap of the reduced volume displacement available. The crucial parameter is the magnitude of the impulse in relation to cavity size.

It remains to consider briefly the theoretical problem of cavities collapsing under the influence of solid boundaries. Perhaps foremost amongst relevant bits of theory there is the very well known result that a pulsating body is attracted towards its 'image' in a rigid plane. In the case of a sphere pulsating with small amplitude this effect can be explained by a neat argument discovered by C. A. Bjerknes nearly a century ago. It is much more difficult, however, to account for the corresponding effect that is observed to occur when a bubble undergoes large contractions in proximity to a rigid plane, although considerable progress towards understanding this case has been achieved through analyses based on the assumption that the bubble remains strictly spherical (i.e., its symmetry is imagined to be maintained by kinematical constraints which do no work during the motion). Extensive calculations on these lines were set out in a war-time report by M. Shiffman and B. Friedman and more have been made since then by Green[32]. This work shows clearly that whenever a cavity begins its collapse from a position of rest fairly close to a rigid wall, say when the nearest distance between the two at the start is about equal to or is less than the cavity radius, large movements of the centroid towards the wall are to be expected. Nevertheless, the constraints on the form of the cavity seriously limit the range of application to cavitation bubbles, even if not so much to explosion bubbles which do not suffer quite such large contractions and consequent distortions from spherical form.

An analysis allowing for shape perturbations was made by Rattray.[23] Unfortunately his method of approximation became unreliable at a degree of deformation that is still fairly small, and though some evidence of jet formation was found this was not very conclusive. The most interesting property established by Rattray's calculations is that an initially spherical cavity collapsing under the influence of a rigid wall at first becomes elongated in the normal direction; it is only at a later stage that the cavity flattens on the side further from the wall and may go on to develop a jet. This behavior is presumably accountable to the greater mobility of radial flow in the direction parallel to the wall than in the normal direction. In the calculations made by Naudé and Ellis[2] a particular type of jet formation was clearly demonstrated for initial conditions of a stationary cavity already partially in contact with the wall.

Apart from the generalized Bjerknes effect, in which the attraction is induced by the volume changes, there are several other effects whereby a cavity might be propelled towards a solid boundary in a flow system. For example, if a cavity is carried by a flow under a tangential pressure gradient along a boundary, its relative motion parallel to the boundary will produce an attraction, since relative velocities in the liquid will be higher and hence pressures lower on the near side. Again, in a low pressure region where cavities originate, pressure gradients normal to the boundary will generally be such as to propel individual cavities towards it, since minima of pressure cannot occur inside the liquid. However, augmentation of the Bjerknes effect will not necessarily increase the damage capability of collapsing cavities. Indeed just the opposite may be true because too large a normal movement may precipitate jet formation too early in the collapse for it to be most effective, the cavity being folded up into toroidal form before the highest possible velocities and pressures are reached. We can now support this statement by analogy with the simpler case considered earlier in this theoretical discussion; the interpretation of jet formation as an impulse-conserving mechanism certainly carries over in a general sense to the present case, though it must be recognized of course that positive pressures exerted against the boundary finally annul the impulse of an approaching cavity.

An experimental fact perhaps significant in this regard is that cavitation damage induced by flow is often most severe in the neighborhood of stagnation points downstream from the low-pressure zone, notably at the tail end of the large 'fixed' cavity (overlaid by a cloud of small transient bubbles) that may form on a body held in a water-tunnel.[27] In such a region the normal pressure gradient will be positive towards the boundary, so tending to retard approaching small bubbles. It seems reasonable to conjecture that optimal conditions for a damaging blow may occur when an occasional bubble is swept up to the boundary with such a speed and size that the collapse concludes against the boundary, and that the effect of the pressure gradient offsets the Bjerknes effect to just the right extent to delay the formation of a jet until the end.

Conclusions

Both experiment and theory suggest very strongly that the jet mechanism of cavitation damage is at least as important, if not more important, than the classical spherical collapse mechanism.

Very important parameters affecting the hydrodynamics of cavitation damage are seen to be:

1. Pre-collapse relative translational velocity of the bubble.
2. Pre-collapse shape of the bubble.
3. Pre-collapse rate of deformation of the bubble.
4. Pressure gradients as well as pressure.
5. The proximity and shape of other interfaces, both rigid and free.

The fact that some of the parameters listed have not heretofore been generally recognized as important in cavitation damage is felt to indicate a step forward in understanding the mechanisms involved. However, the diversity of factors that may influence the rate at which a cavitation bubble approaches a solid boundary, coupled with those influencing its rate of collapse, debars any comprehensive interpretation in the present state of knowledge; and it must be accepted that the conditions for a maximum damaging effect must await further studies.

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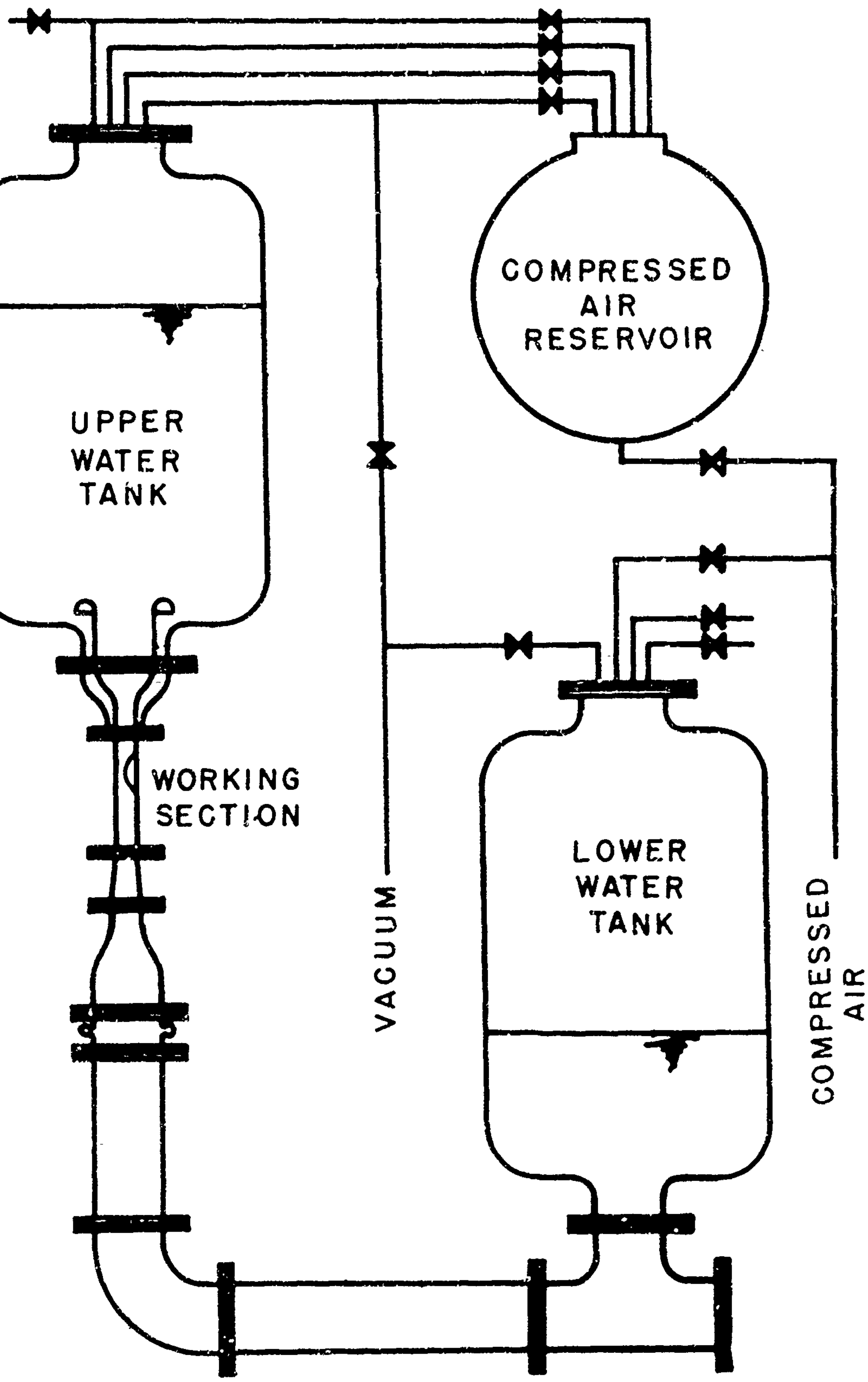


Fig. 1 - Schematic Diagram of Tunnel

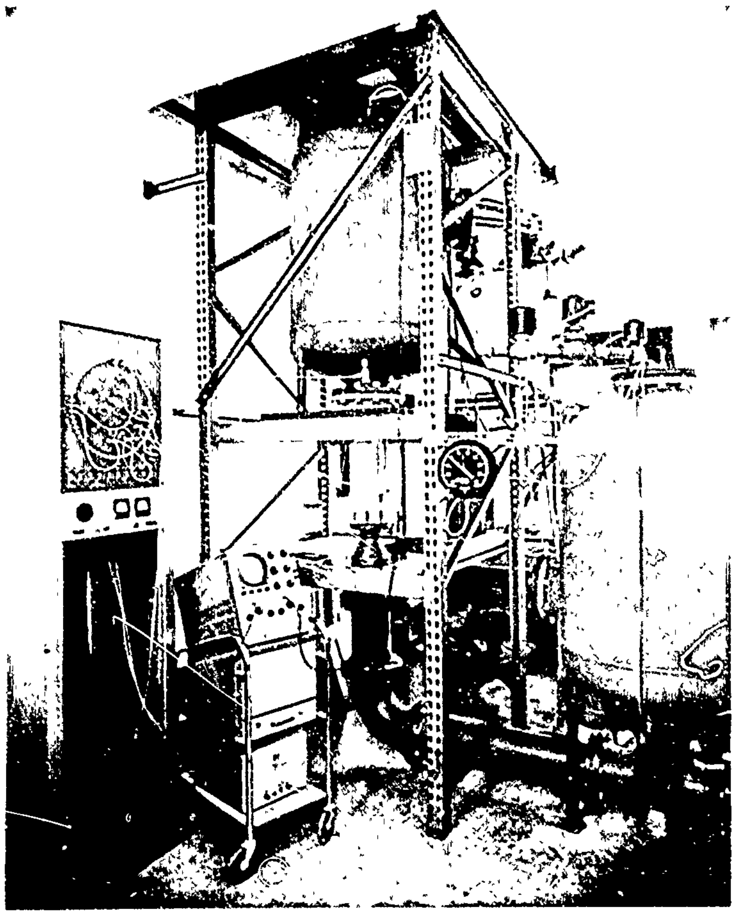


Fig. 2 - Blow-down Tunnel

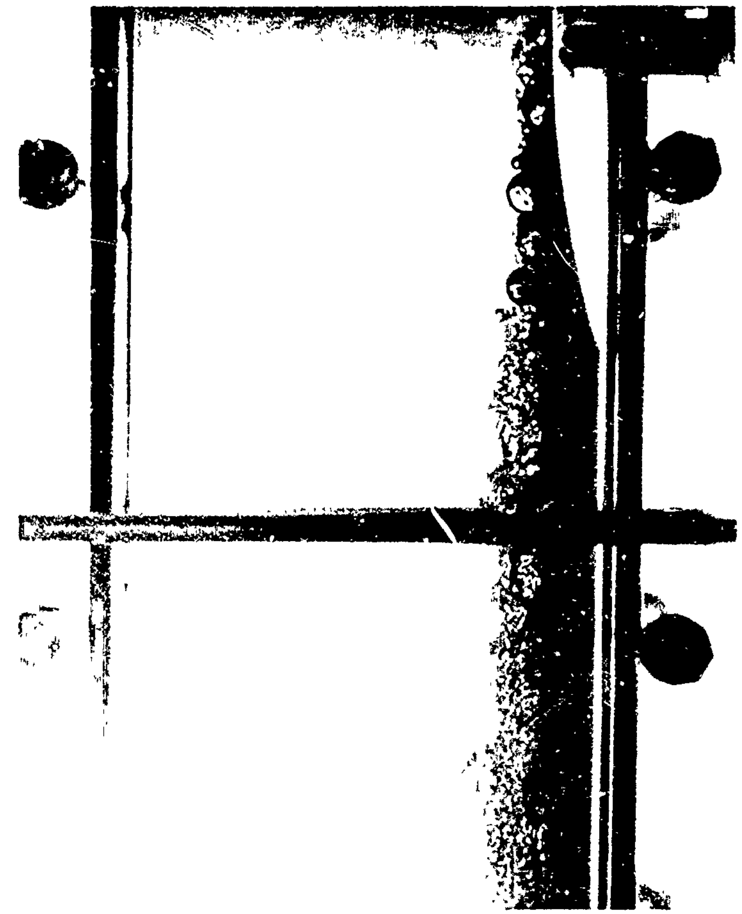


Fig. 3 - Cavitation on a Circular Arc Hydrofoil

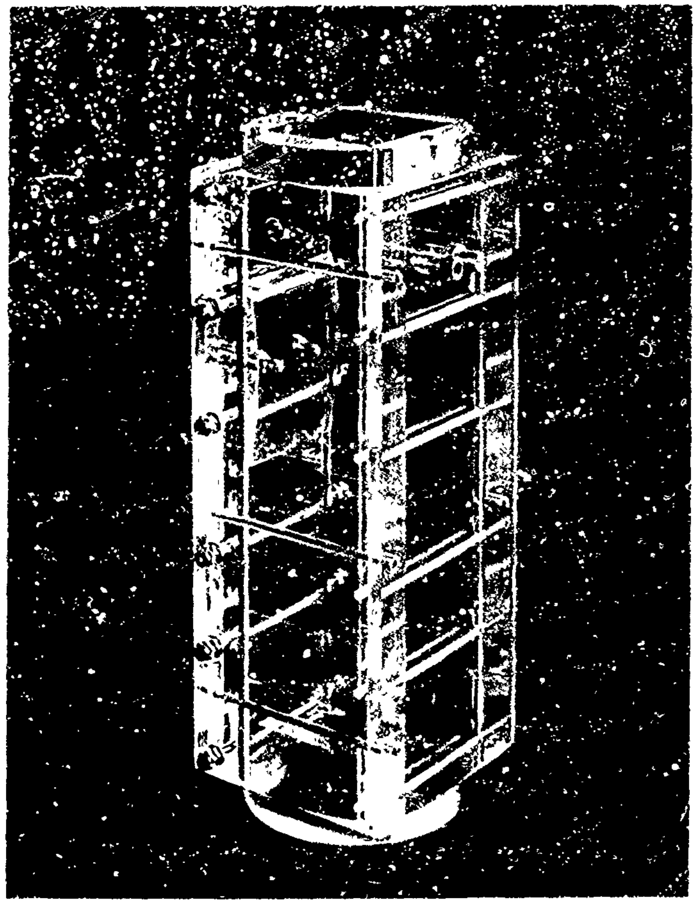


Fig. 4 - The Working Section

Fig. 5a, b - A bubble generated at the foil minimum pressure point and moving downstream

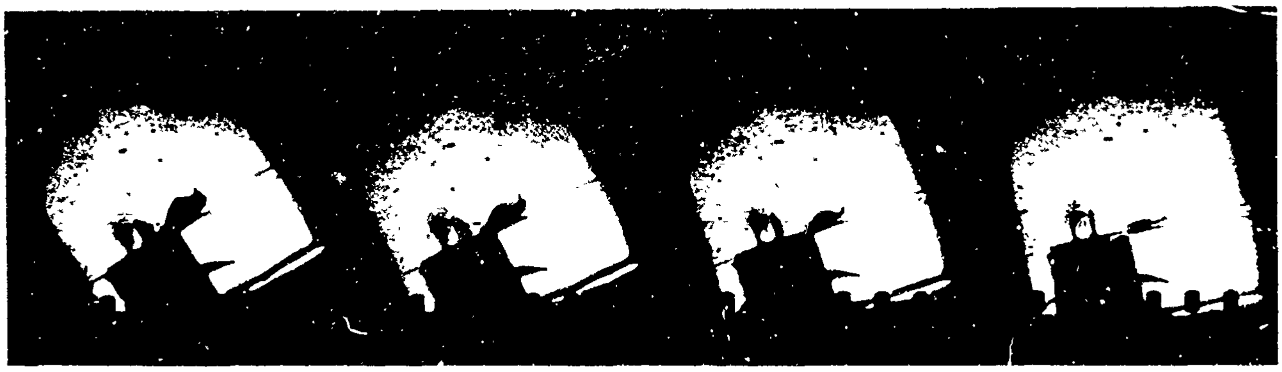


Fig. 6 - Sequence showing shock wave generated by bubble collapsing downstream

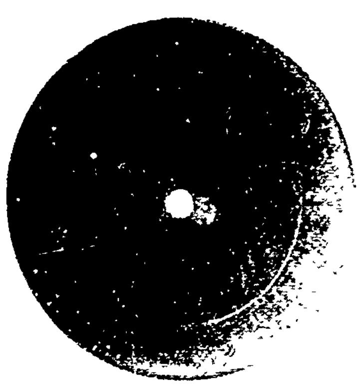
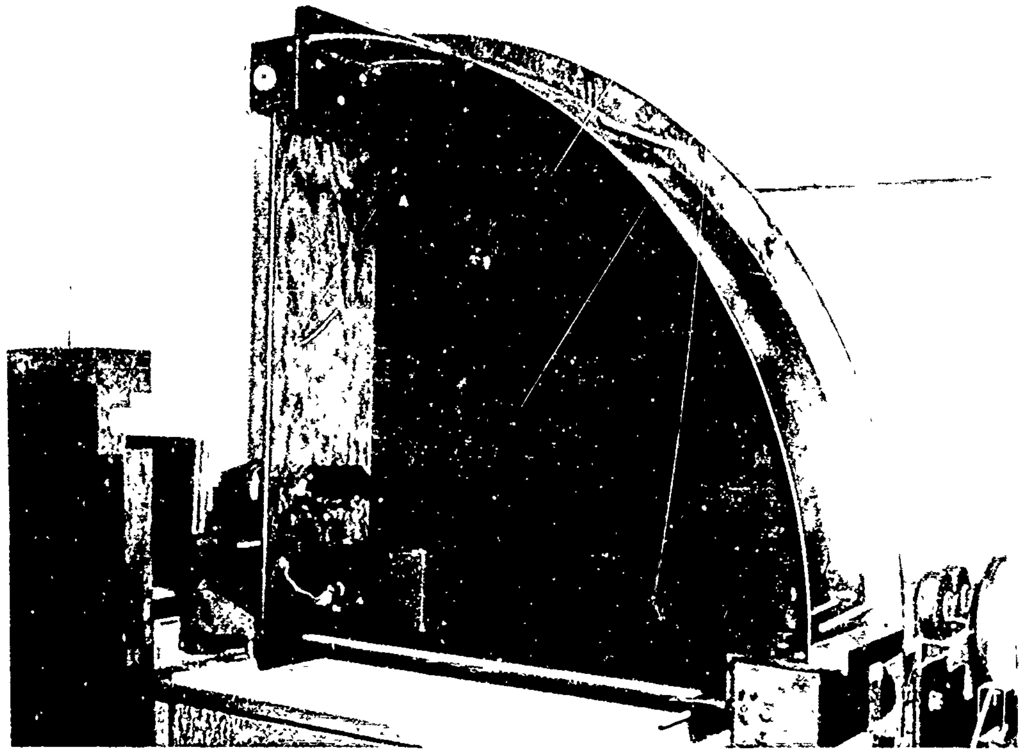
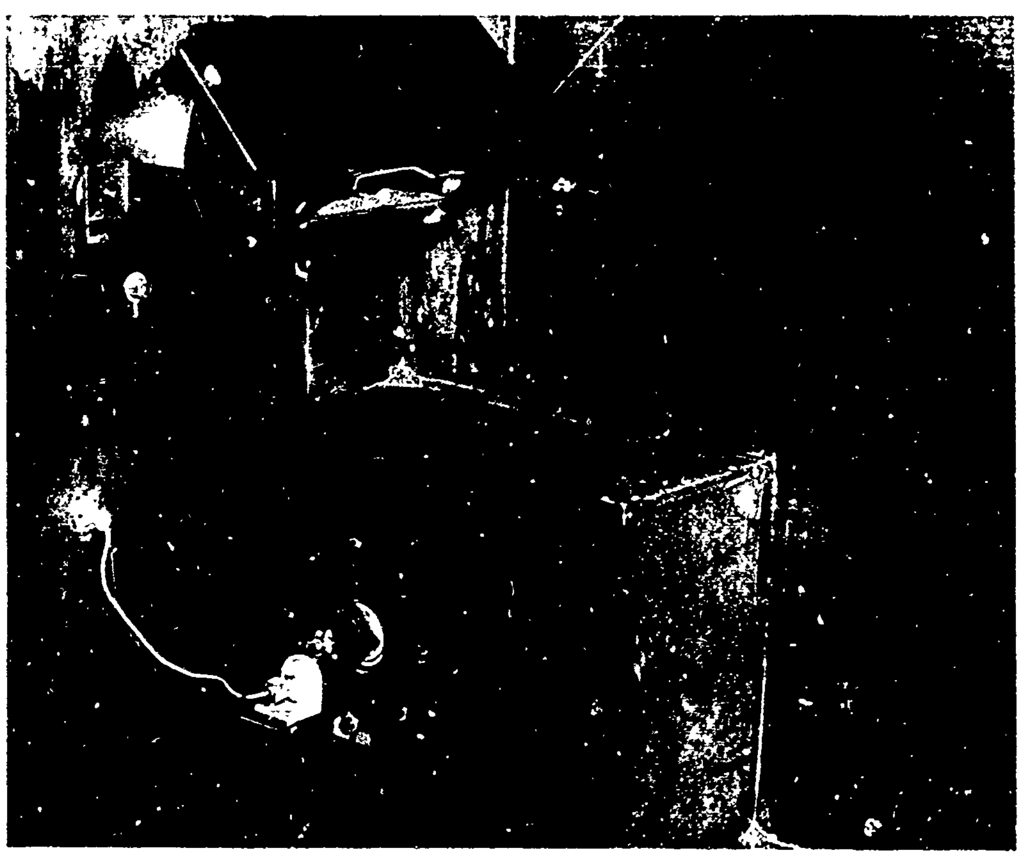


Fig. 7 - A 0.13 cm bubble photographed with light from a ruby laser.

Fig. 8 - A bubble similar to Fig. 7 photographed with light from a mercury arc.



(a)



(b)

Fig. 9a, b - Fifty inch radius film housing and rotating mirror

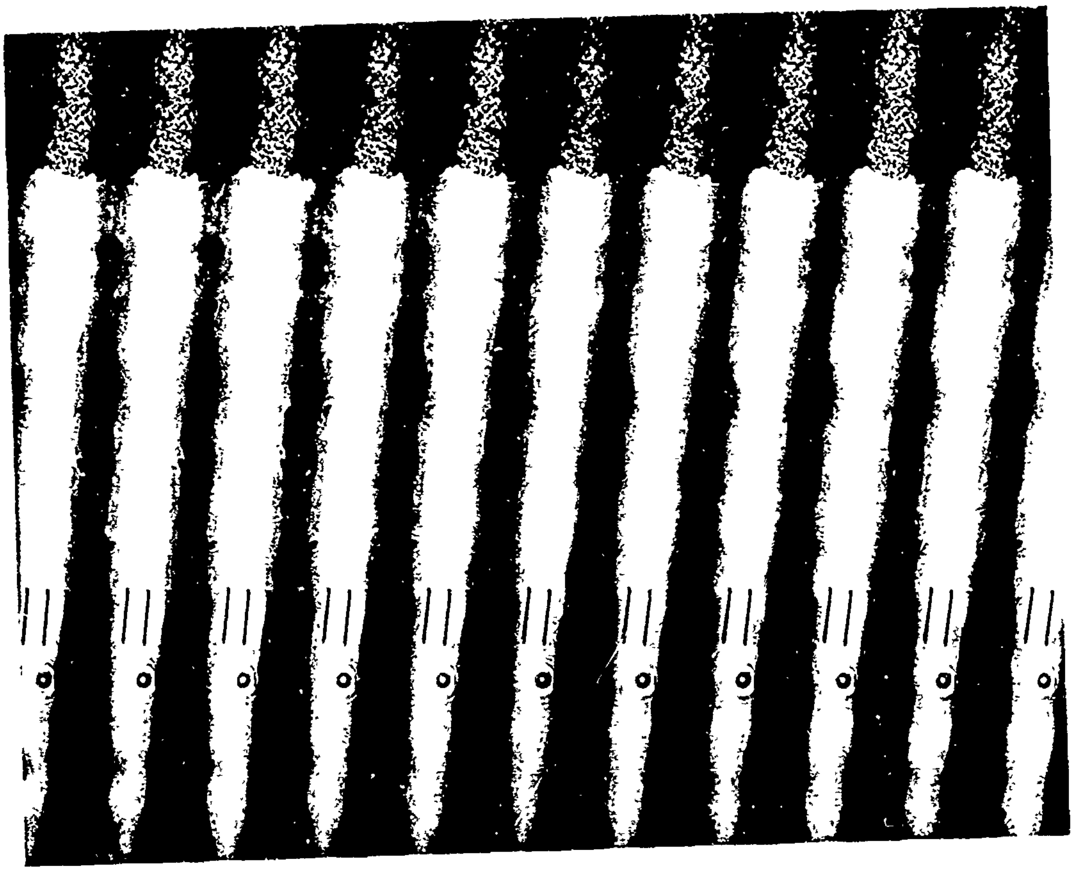


Fig. 10 - Repetitive pictures of a glass microscope scale. Divisions are 0.01 centimeter apart. Picture rate is 200,000 per second. Ruby laser light pulse duration about 2 x 10^{-8} seconds.

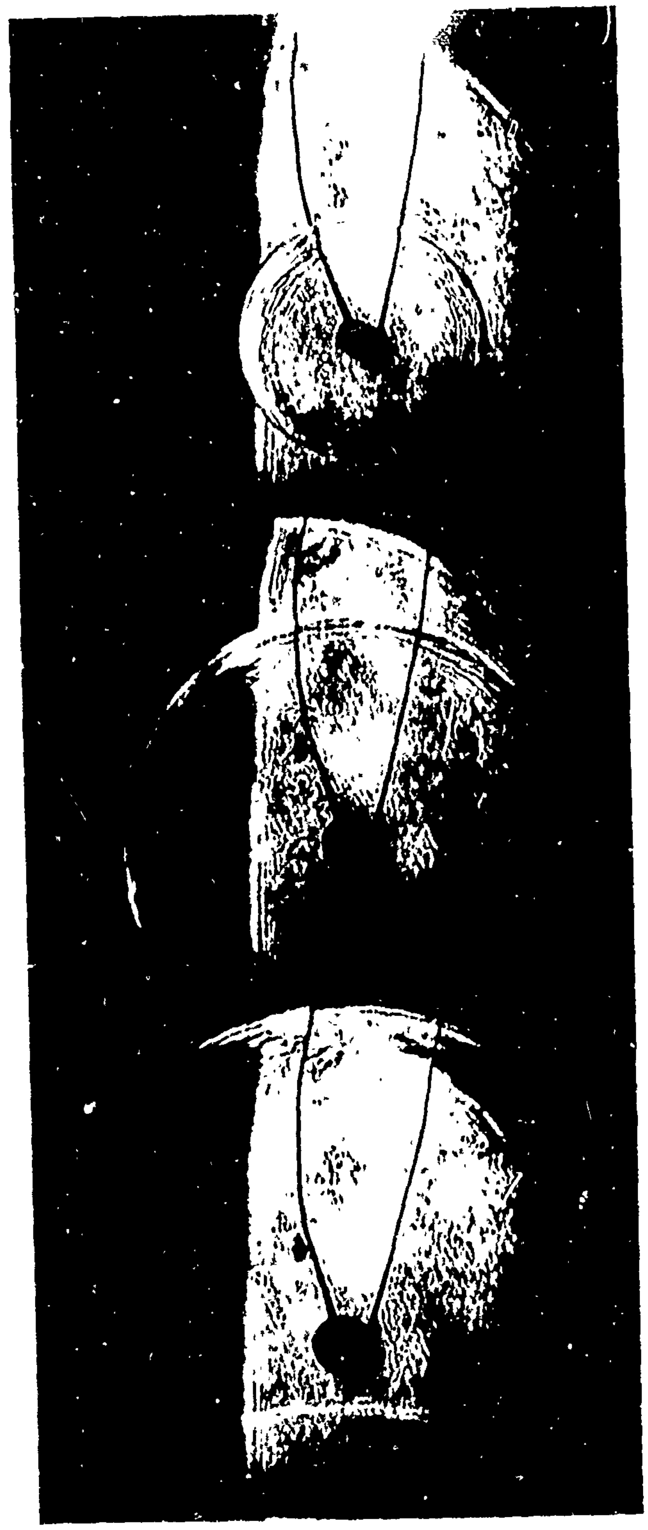


Fig. 11 - Shock wave in water due to an electrical discharge.
200, 000 pictures per second.

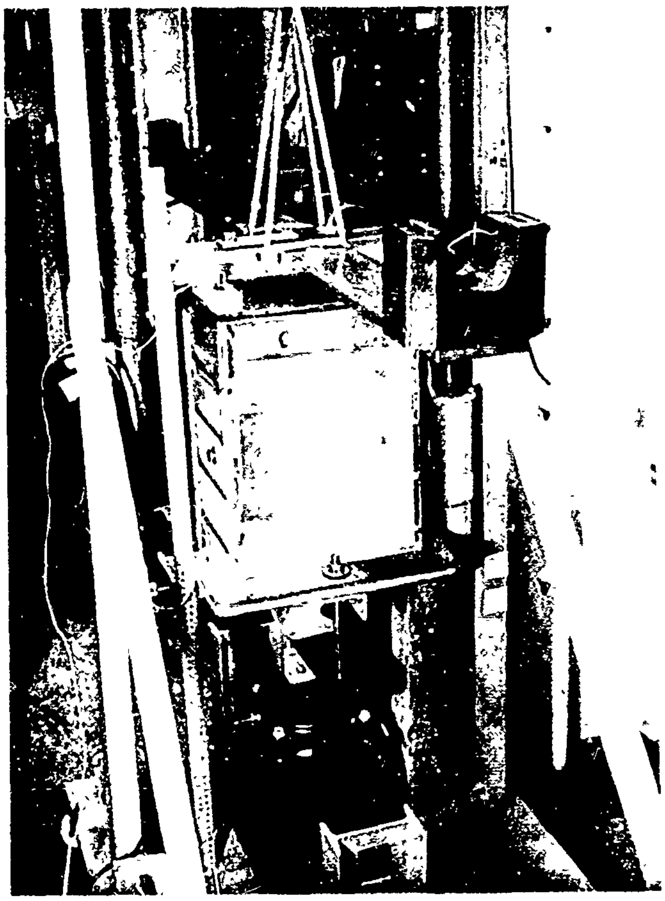


Fig. 12 - Lucite container for single bubble studies set up for sinusoidal vertical oscillation. System is resonant at 17 cycles for degassing process. Weighted cross beam is removed for bubble growth by downward acceleration.

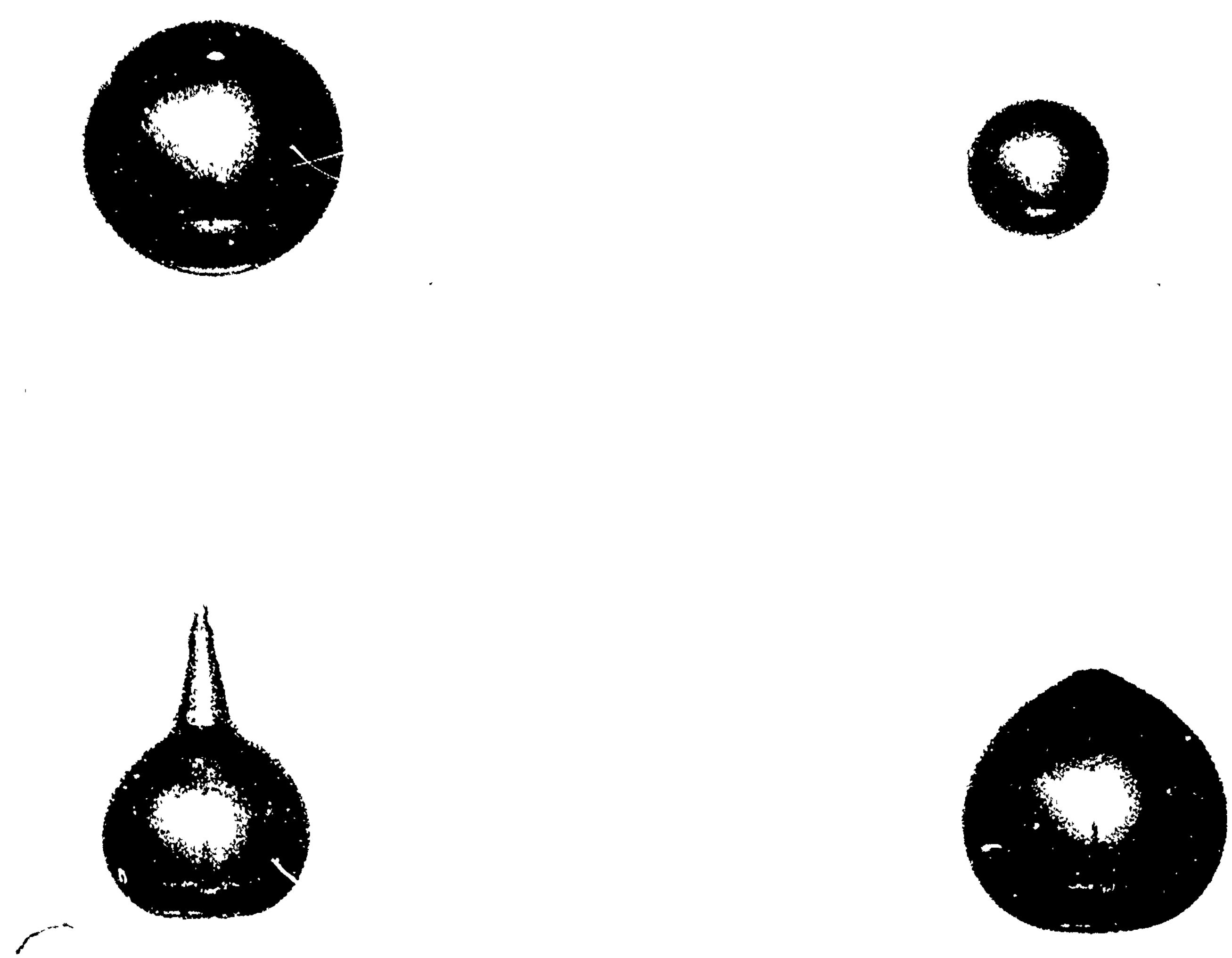


Fig. 13 - Photographs taken during collapse (a, b) and rebound (c, d) of cavity far from boundaries but in a pressure gradient. The interval between pictures is two milliseconds.

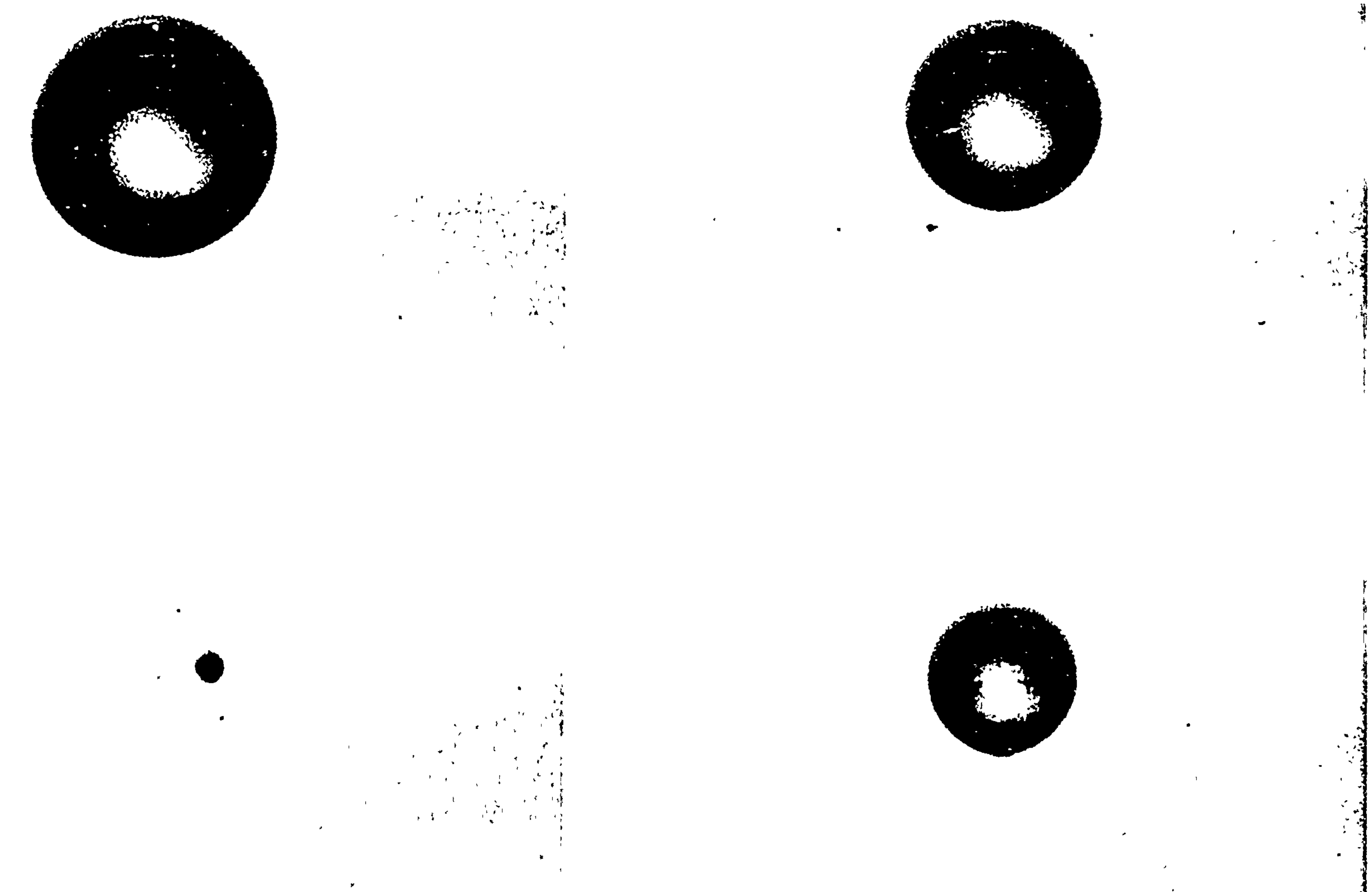


Fig. 14 - Similar to Fig. 13 except nearly zero pressure gradient.

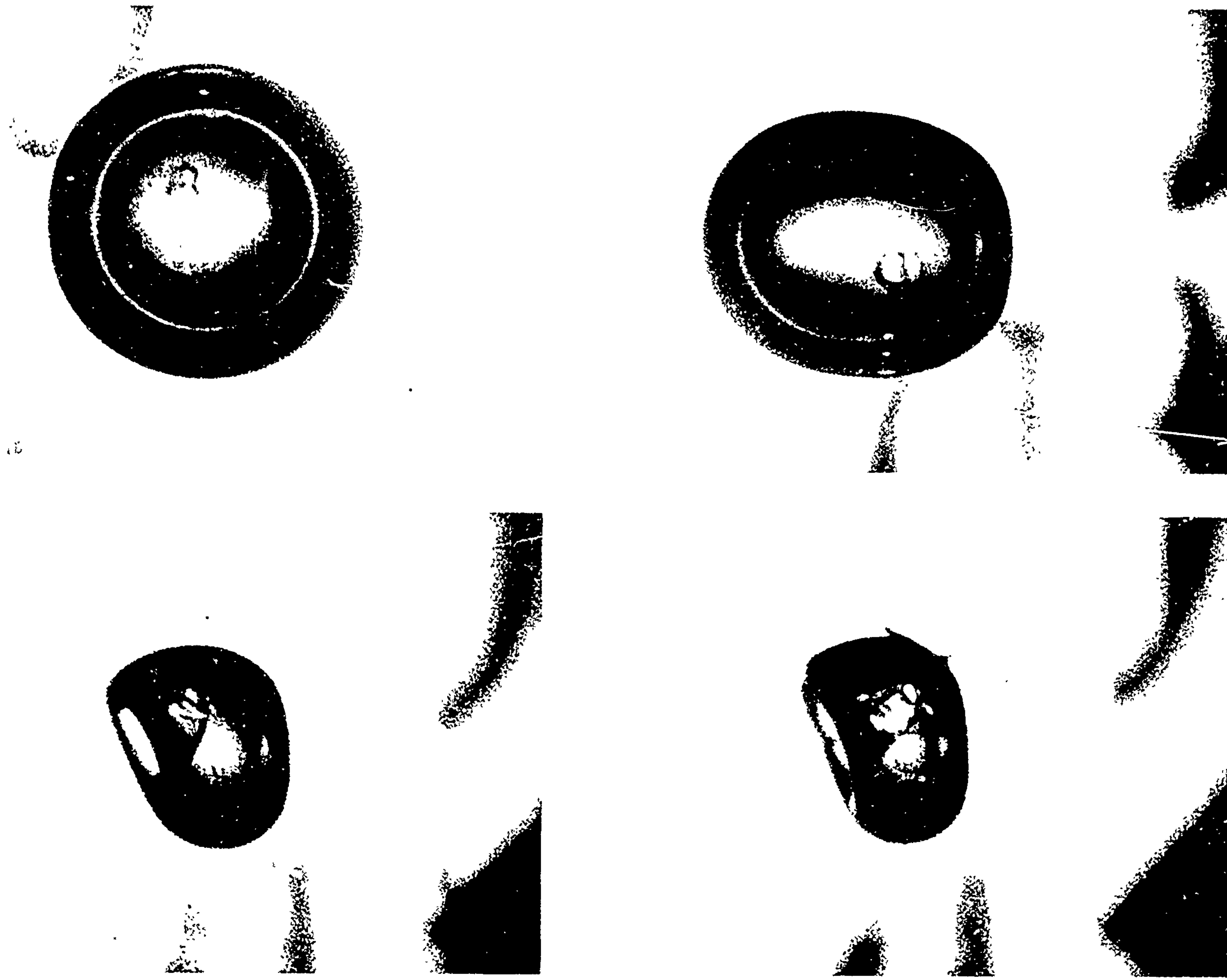


Fig. 15 - Collapse of cavity near a solid wall. Pictures at 0, 5, 9, 10 m sec.

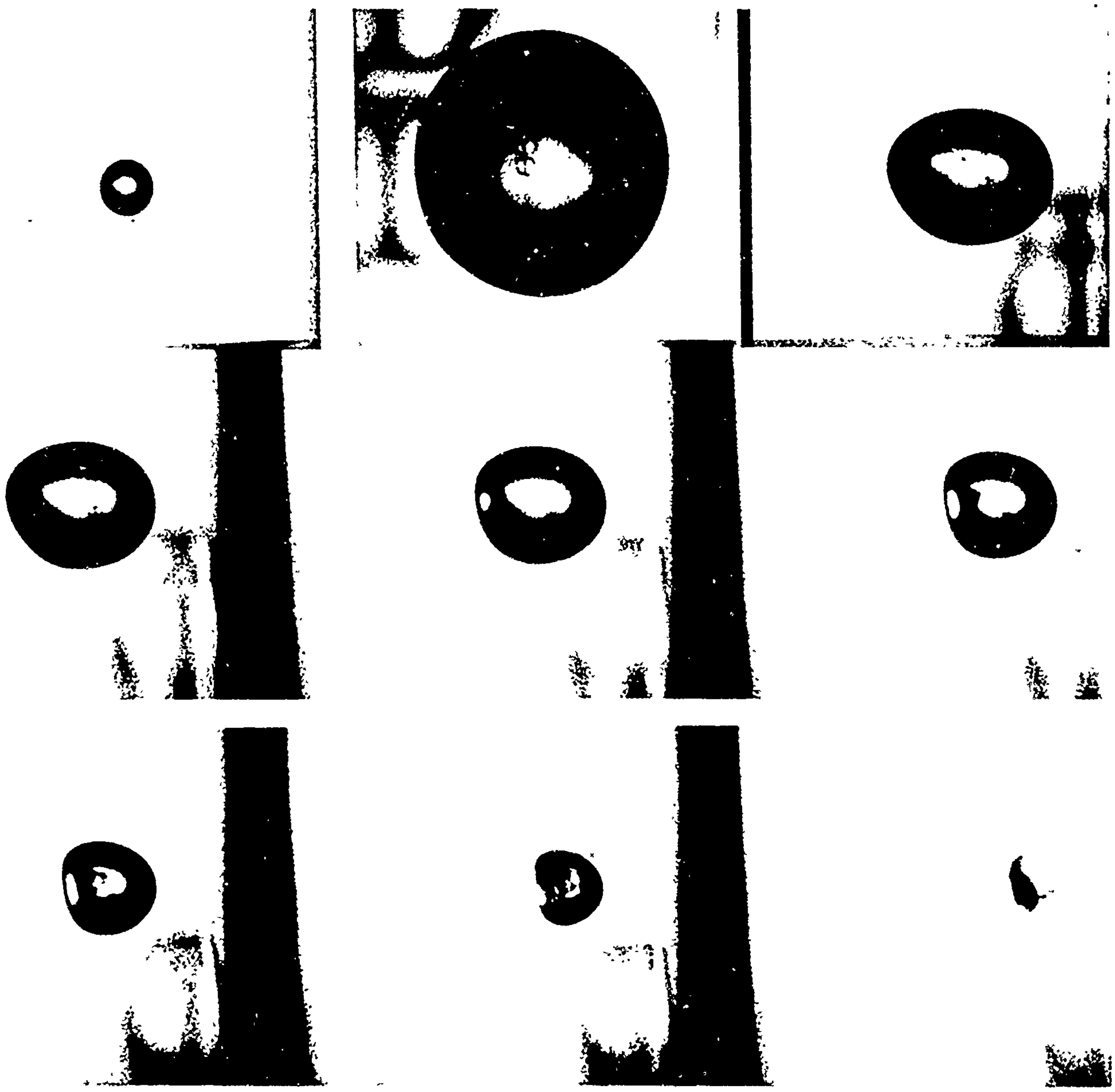


Fig. 16 - Growth and collapse of cavity farther away from the wall. Pictures at 0, 5.8, 8.8, 9.4, 9.6, 9.8, 10.0, 10.2, 10.4 m sec.

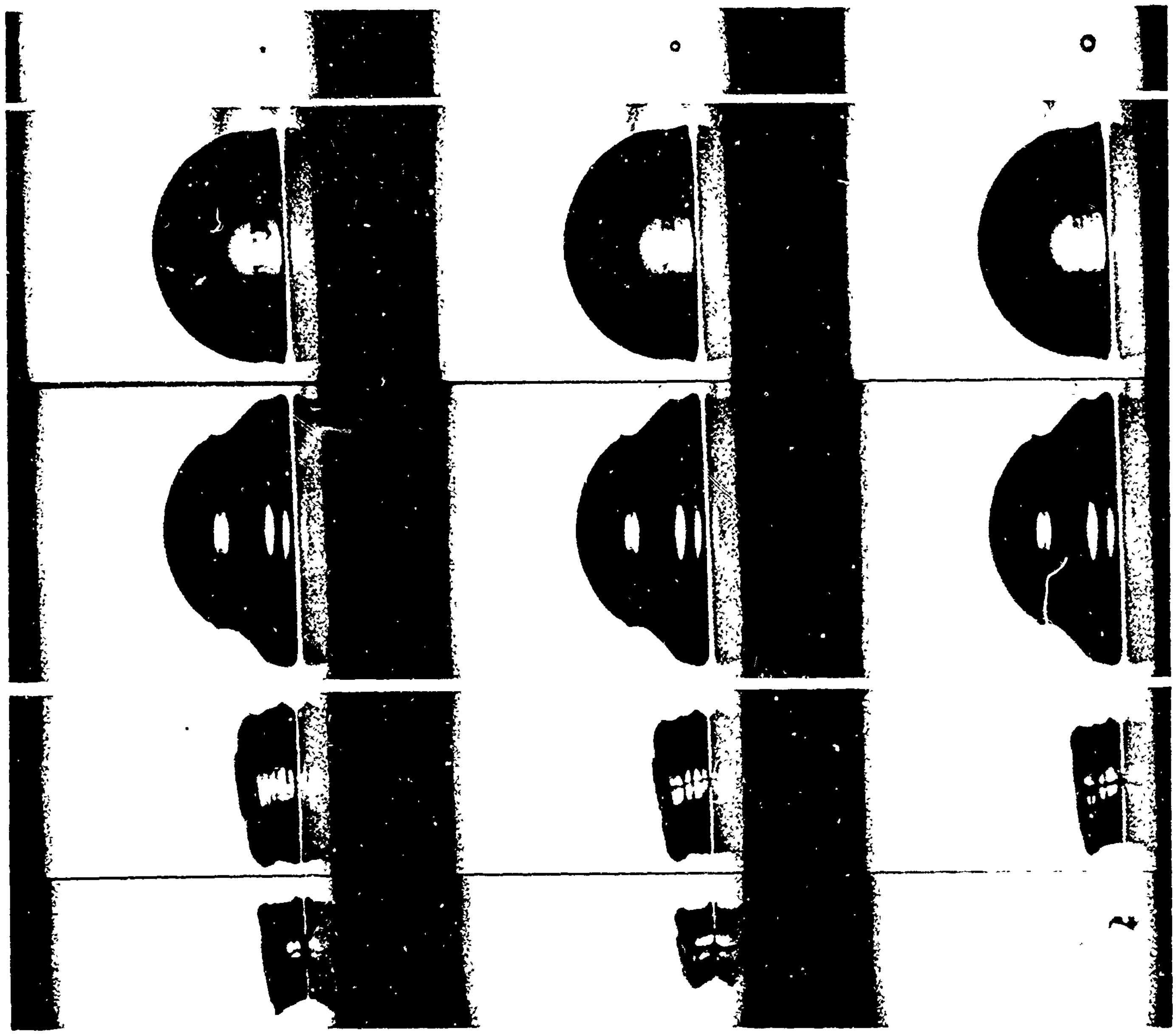


Fig. 17 - Growth and collapse of cavity very close to a solid wall. Pictures at 0; 0.2, 0.4, 5.8, 6.0, 6.2, 11.4, 11.6, 11.8, 16.8, 17.0, 17.2, 17.4, 17.6, 17.8 msec.

List of Publications and Theses
Prepared Under Contract Nonr 220(44)

1. Ellis, A. T., Slater, M. E., and Fourney, M. E., "Some New Approaches to the Study of Cavitation", Proceedings of the International Association for Hydraulic Research Symposium, Sendai, Japan, 1962.

2. Ellis, A. T. and Fourney, M. E., "Application of a Ruby Laser to High Speed Photography", Proceedings of the Institute of Electrical and Electronics Engineers, Vol. 51, No. 6, June 1963, pp. 942-943.

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4. Barnard, B. S., Ellis, A. T. and Slater, M. E., "The Unsteady Flow Cavitation Tunnel at the California Institute of Technology", ASME Symposium on Cavitation Research Facilities and Techniques", May 1964.

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13. ABSTRACT

New experimental observations are presented which support the high speed jet mechanism of cavitation damage. A general discussion of the basic hydrodynamic theory involved is given and the importance of certain parameters on damage are pointed out. New techniques for studying the collapse of single cavities are described and the concept and development of a high speed photographic system using a ruby laser is outlined. Magnifications of up to fifty times at picture repetition rates as high as 1,600,000 per second and exposure times of 20 billionths of a second have been achieved.

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Liquid Jets						
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