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A study of the collapse of arrays of cavities

By J. P. DEAR AND J. E. FIELD
Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK

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This paper describes a method for examining the collapse of arrays of cavities using high-speed photography and the results show a variety of different collapse mechanisms. A two-dimensional impact geometry is used to enable processes occurring inside the cavities such as jet motion, as well as the movement of the liquid around the cavities, to be observed. The cavity arrangements are produced by first casting water/gelatine sheets and then forming circular holes, or other desired shapes, in the gelatine layer. The gelatine layer is placed between two thick glass blocks and the array of cavities is then collapsed by a shock wave, visualized using schlieren photography and produced from an impacting projectile. A major advantage of the technique is that cavity size, shape, spacing and number can be accurately controlled. Furthermore, the shape of the shock wave and also its orientation relative to the cavities can be varied. The results are compared with proposed interaction mechanisms for the collapse of pairs of cavities, rows of cavities and clusters of cavities. Shocks of kbar (0.1 GPa) strength produced jets of *c.* 400 m s^{-1} velocity in millimetre-sized cavities. In closely-spaced cavities multiple jets were observed. With cavity clusters, the collapse proceeded step by step with pressure waves from one collapsed row then collapsing the next row of cavities. With some geometries this leads to pressure amplification. Jet production by the shock collapse of cavities is suggested as a major mechanism for cavitation damage.

1. Introduction

The rapid collapse of a gas space or a cavity is important in a range of problems and our research covers some of these areas. For example, we are interested in cavitation erosion and also the role of the cavity in the ignition and propagation of explosive reaction.

Rayleigh (1917) considered the collapse of an isolated spherical cavity in a liquid under hydrostatic pressure. Assuming incompressible and inviscid behaviour of the liquid, it gives the time to collapse to reasonable accuracy, but predicts a collapse velocity (and hence pressure) which tends to infinity as the cavity radius approaches zero. In effect, the cavity cannot be considered to be empty during the final states of collapse when thermal effects (adiabatic heating of the gas, heat of condensation) and liquid compressibility need to be considered (Plesset 1964). Other workers have considered the effects of surface tension and viscosity (for reviews, see Plesset & Prosperetti 1971; Mørch 1979). The result is that cavity collapse can produce pressures as high as 1 GPa (10 kbar) which clearly have damage potential. These high pressures, however, fall off very quickly within a few bubble radii (Hickling & Plesset 1964).

Kornfeld & Suvorov (1944) were the first to suggest that cavities might collapse asymmetrically and produce a liquid jet. The jet is formed by involution of one side of the cavity. The jet passes across the cavity and penetrates the far surface. The experiments of Naude & Ellis (1961), using spark-induced cavities, were the first to give clear evidence of this jet formation but several other researchers have now provided photographic confirmation (see, for example, Schutler & Mesler 1965; Benjamin & Ellis 1966; Brunton 1967; Kling & Hammitt 1972; Mitchell & Hammitt 1973; Lauterborn & Bolle 1975; Lauterborn 1979).

If this asymmetrical collapse occurs near a solid surface and the jet forms in the direction of the solid surface, then there is liquid/solid impact with the generation of a 'water-hammer' pressure given by:

$$P = V\rho_1 C_1 \rho_2 C_2/(\rho_1 C_1+\rho_2 C_2), \tag{1}$$

where V is the impact velocity and ρ_1, ρ_2 and C_1, C_2 are the densities and shock-wave velocities of the water and solid respectively. The duration of this high pressure is given by:

$$\tau = r/C_1, \tag{2}$$

where r is the jet tip radius. For a cavity wall displaced from the solid surface, the impact of the jet on the opposite liquid wall produces a pressure pulse in the liquid of magnitude $P = \frac{1}{2}\rho CV$ which can subsequently interact with the solid, although this interaction will be less. Cavities containing gas will rebound, producing a shock, and if subsequently collapsed may rebound a second time.

Two situations arise which can lead to jet formation. The first is where jet formation takes place in an asymmetrical pressure field as produced near a solid surface, and has been examined by Plesset & Chapman (1971). The second is when a shock passes over a cavity, causing a jet in the direction of the shock. For the Plesset & Chapman model, the liquid was considered incompressible and inviscid, and the velocity of the free surface of the cavity was repeatedly calculated at a large number of points for small compression steps of the cavity. The jet formation, as expected, was most pronounced for cavities closest to the solid surface. Experiments by Lauterborn (1979), using laser-induced cavities formed at various distances from a solid wall, confirmed these predictions. For the case of shock wave collapse of the cavity, the conditions are somewhat different, in that the side of the cavity furthest from the shock is not initially aware of the collapse process. Consequently the dynamics of the collapse and the pressure profile around the cavity surface differ from the Plesset & Chapman hydrostatic studies. Mader (1965, 1979, 1985) has used numerical codes to model this process and other researchers (for example, Lesser, Private communication, 1984) have considered, analytically, shock wave collapse of cavities. Some of Lesser's work is discussed below. Both situations for jet formation are likely to take place during typical cavitation conditions, since pressure waves from the collapse and rebound of some cavities will pass over neighbouring cavities.

More recent work in this field has concentrated on how the collapse of neighbouring cavities is affected by their mutual interactions. This has raised much scientific interest as to possible focusing and cooperative effects that could occur with clusters of cavities. One situation of particular interest is where collapse of cavities in the body of a liquid can cause cavities near a solid surface to collapse in unison. Experimentally, Brunton (1967) had noted that cavitation damage in materials can often be considerably larger in dimensions than the diameter of a bubble and further, it is not necessarily the regions of liquid with the largest bubbles that produce the most damage. Also Vyas & Preece (1976) recorded pressure pulses from a cavitation field and showed that their duration and magnitude indicated clearly that they were the product of more than one or two cavity collapses. Some theoreticians have discussed a large hemisphere of cavities collapsing in consecutive shells from the outside inwards. Mørch (1979), Hansson & Mørch (1980) and Hansson, Kendrinskii & Mørch (1982) performed calculation along these lines, related to experimental observations by Ellis (1966). They showed that the collapse of each shell of cavities exposes the next inner shell to the hydrostatic pressure field which in turn initiates its collapse. At each stage, the energy of collapse is transferred to the inner shell resulting in a steady build-up of pressure. They found that this increased the collapse energy of the cavities at the centre of the cloud by an order of magnitude.

Other types of interaction between cavities were investigated by Lauterborn (1979). Bubbles were generated in pairs in a liquid with each bubble of the pair being a different size and they were then collapsed by hydrostatic pressure. The interaction between the two bubbles caused them to involute and produce jets. Depending upon the relative size of the pair of bubbles, the jets were either formed towards or away from the neighbouring bubble. Further, if the pair of bubbles were near a solid wall, this influenced the direction in which the jets formed. Similar effects have been observed by Brunton (1967) and Chaudhri, Almgren & Perrson (1982) who used a plane shock wave to collapse pairs of bubbles simultaneously. Chaudhri *et al.* (1982) observed that the direction of the jets were not normal to the shock wave but were deviated away from each other. The result differed when the bubbles were collapsed onto a solid wall by the shock as then the jet directions were deviated towards each other (Tomita, Shima & Ohno 1984). In the following experiments, arrays of 3 and more cavities show these effects in detail.

2. Experimental

The idea of using disk-shaped bubbles for studying cavity collapse was first suggested by Brunton (1967). The general arrangement was to introduce a small amount of liquid in a narrow gap between two transparent plates and introduce a bubble in the liquid relying on surface tension to obtain the required circular form of bubble. A shock wave, generated by impact, was used to collapse the cavity. An advantage of using this two-dimensional method is that the processes occurring within and around the bubble can be observed without refraction and other problems inherent with spherical bubbles.

An extension of this technique which has given better control over the size and position of cavities in the liquid is to add 12% by weight of gelatine to the liquid. This is then cast into a thin sheet and the required cavities are then cut out. We have shown that the impact velocities and strain rates are high enough for the water/gelatine mixture to behave as a fluid. The gelatine is dissolved in water at 330 K and then added to a vertical mould of dimensions $200 \times 200 \times 3$ mm^3 which is also raised to this temperature. Each of the mould faces had been lightly greased and covered with a thin plastic film. After slow cooling to reduce shrinkage, the mould is disassembled and the sheets placed horizontally. The layers with plastic sheets attached can be kept for several days. The liquid/gelatine layer with cavities introduced is then placed between spaced glass blocks and a striker, fired from a rectangular bore gas gun, projected between them. Velocities of up to *c*. 300 m s^{-1} have been achieved. The striker triggers an Imacon framing image converter camera by intersecting a laser beam just before impact. The shocks are visualized using schlieren optics. A schematic diagram of the apparatus is shown in figure 1. The two-

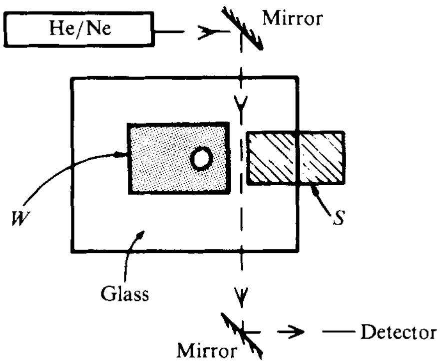

FIGURE 1. Impact geometry. W is the liquid/gelatine containing the cavity and S is the impacting striker.

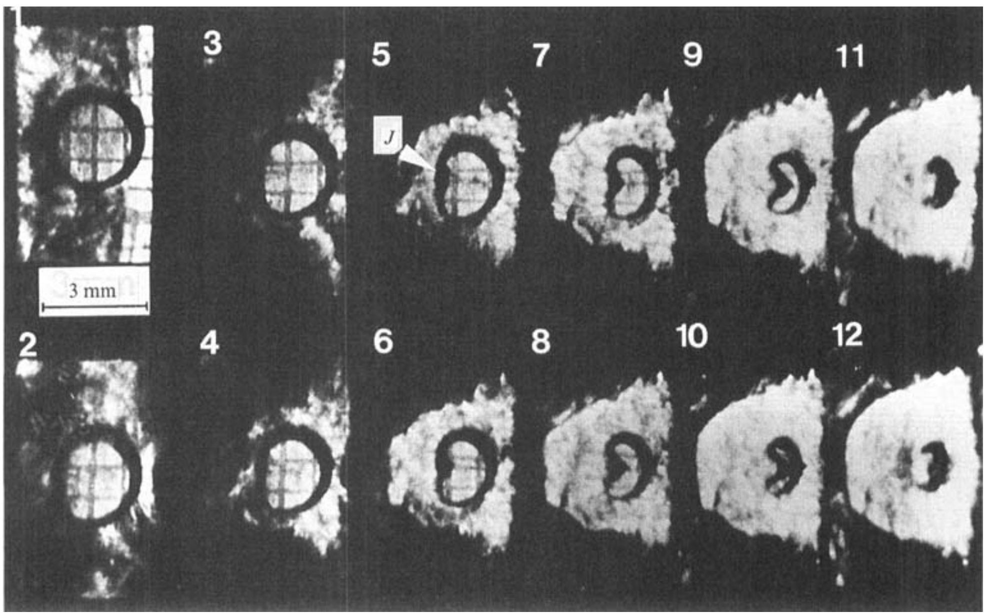

FIGURE 2. Two-dimensional cavity, diameter 3 mm, collapsed by a shock wave travelling left to right. The rear surface involutes to produce a jet J of c. 400 m s^{-1}. Interframe time, 0.96 μs.

dimensional gelatine technique can be adapted to a wide variety of other shock collapse or impact studies, for example liquid wedge impact (Field *et al.* 1983, 1985), liquid drop impact (Dear, Field & Swallowe 1984; Dear & Field 1988), and shaped-charge configurations (Dear 1985).

3. Results

3.1. *Single cavity collapse*

Figure 2 shows the collapse of a circular two-dimensional cavity (diameter c. 3 mm) by a shock wave of strength c. 0.26 GPa (2.6 kbar). This is produced by slider impact at a velocity of 150 m s^{-1} as described above. The shock wave can be seen encircling the cavity in frame 1 and the jet starts to form in frame 5 (labelled J);

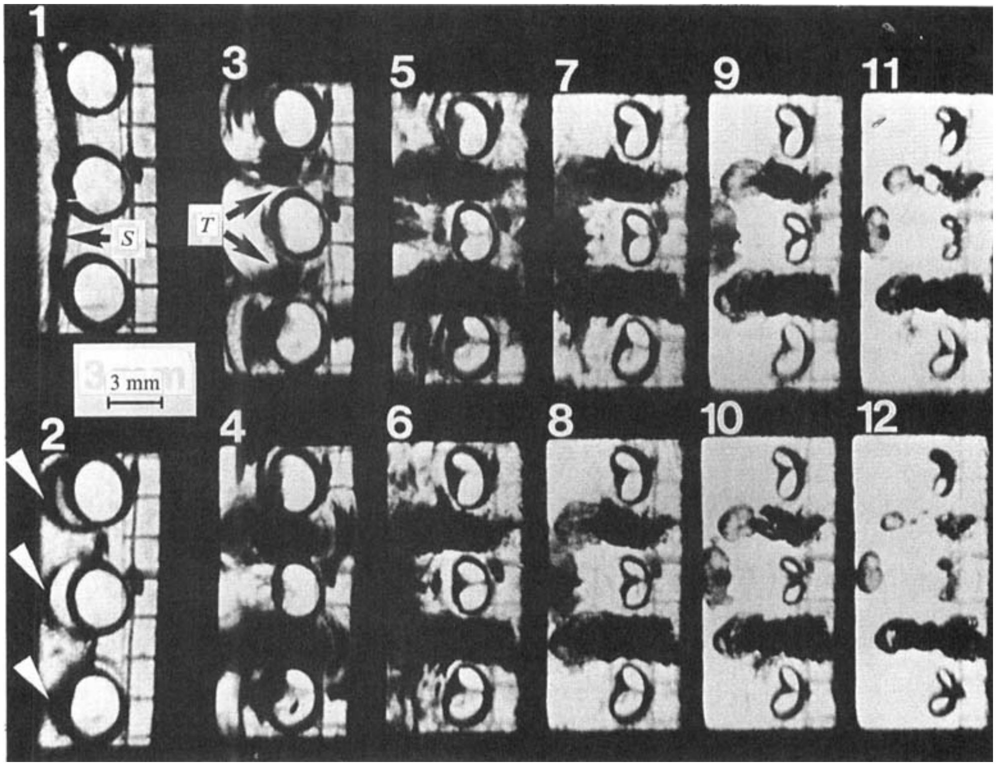

FIGURE 3. Three cavities, diameter 3 mm, 6 mm apart, parallel to the shock wave *S*. The jet velocities are *c*. 400 m s^{-1}, but note the fine lines of droplets ahead of the main jets from frame 5 onwards. The jets in the outer cavities diverge slightly. Interframe time, 0.96 μs.

a cusp-shaped front to the collapsing cavity surface develops in frame 7. The velocity of the jet averaged over the following frames is *c*. 400 m s^{-1}. The interframe time for this and subsequent sequences is 0.96 μs for figures 2–7 and 4.25 μs for figures 8–11.

3.2. *Arrays of cavities*

3.2.1. *Vertical arrays*

In all the cases of cavity arrays, the diameter of the cavities was 3 mm and the shock wave strength 0.26 GPa. Figure 3 shows a shock wave, *S*, moving perpendicularly to a row of three cavities. The cavity centres are separated by 6 mm. Frame 2 shows well the reflected waves (see arrows) from the three circular cavities. These reflected waves (now tensile) overlap in the regions between the cavities and result in the darkened regions labelled *T* in frame 3, which are caused by cavitation at the liquid/glass interface. The jets in the cavities are well-formed and it is to be noted that those in the outer cavities have the directions of their jets forced away from the central one. The jet divergence in this sequence is partly due to the small amount of shock curvature (see frame 1), but as other sequences show (figure 4 is an example) the effect is a general one, and is due to compression waves arriving after the cavitated regions *T* form. The jets which cross the cavities all have velocity of *c*. 400 m s^{-1}. Careful examination of the regions ahead of the main cusp-shaped jets show a fine line of droplets (see for example, frame 6). This phenomenon, which gives important information about the jet formation process, is discussed later.

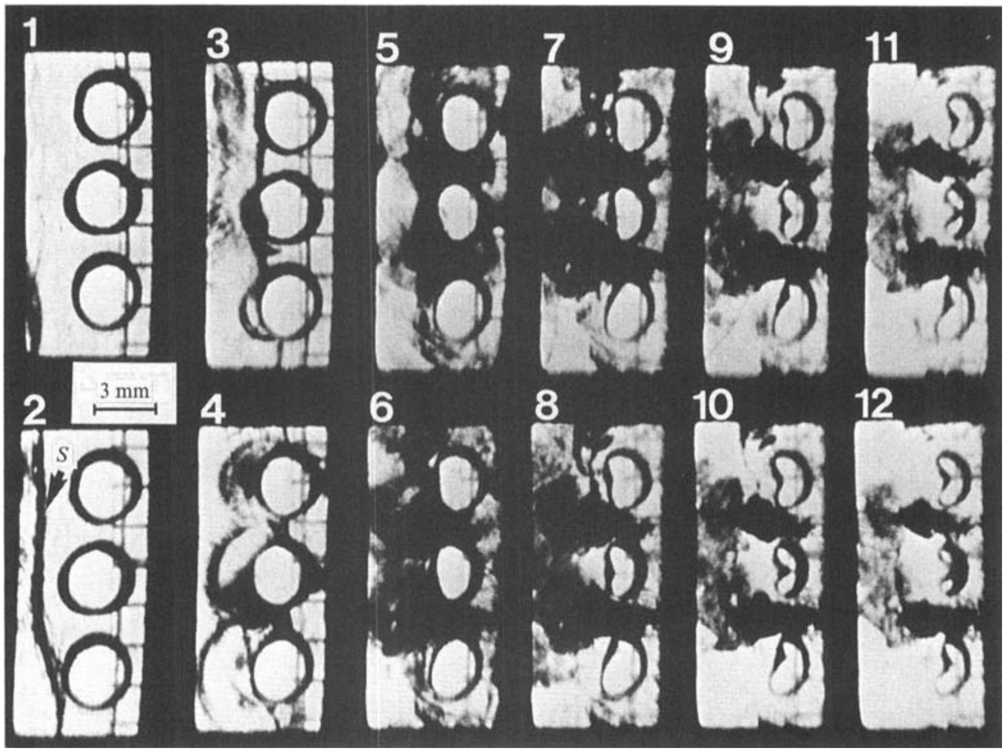

FIGURE 4. Three cavities, diameter 3 mm, 5 mm apart, parallel to the shock wave S, which in this case has been designed to interact with the lower cavity first. Interframe time, 0.96 µs.

For figure 4, the separation of the cavity centres was reduced to 5 mm. An additional feature is that for this sequence, the incident wavefront was given a definite bulge aligned to interact with the lower cavity first. This leading part of the shock wave met at a position and angle so as to produce a jet that should converge on the others. However, as the later frames of this sequence show, this jet finally matches, in divergence and shape, the jet from the cavity at the upper end of the row, the jet formed in the upper cavity being produced by a plane section of the main shock wave. This suggests that the interaction is sufficiently strong to override small perturbations in the shape of the incident shock wave.

The closer the cavities are spaced the greater the interaction effects from the neighbouring cavities. Figure 5 shows the behaviour when the distance between cavities is reduced to 4 mm. Not only do the jets in the end cavities diverge but each cavity now involutes to produce two jets! There appear to be at least two situations which can cause such events. The first is if the cavity wall is irregular (for example, dimpled). The second is if the shock front has perturbations, or multiple shocks, involved.

Figure 6 shows two frames selected from a sequence in which the side of the cavity to be struck by the shock wave has a dimple introduced, labelled D, in frame 1. This has the effect of producing two jets, arrowed in frame 2, each one formed by the collapse of its respective concave surface. The equivalent result in three dimensions would be a cylindrical jet tube. However, this would probably be unstable and break up into a crown-like ring of jets. As well as pre-forming the cavity to produce more

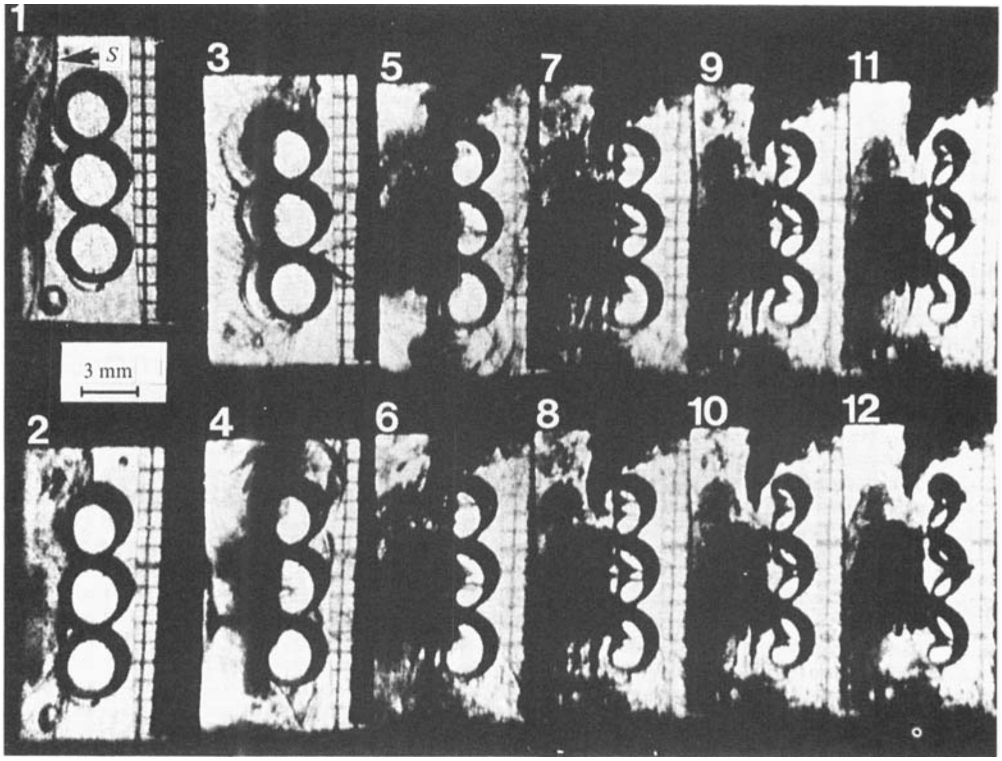

FIGURE 5. Three cavities, diameter 3 mm, 4 mm apart, parallel to the shock wave S. Note that double jets develop. Interframe time, 0.96 μs.

than one jet, it is possible to control the shape of the shock wave to produce the same effect. Figure 7 shows two frames selected from a sequence in which a slider with an appropriately shaped impact face gives rise to two circular waves, labelled S, in frame 1, symmetrically impinging upon a circular cavity. In frame 2, the arrows point to the jets which are starting to form. The double jets in figure 5 are thought to be due to the main shock plus a perturbing shock from the nearest cavity. It appears that the cavities have to be close, otherwise the perturbing shock is either too attenuated or does not arrive early enough to have an effect.

3.2.2. *Horizontal arrays*

In figure 8, three cavities have been formed in a horizontal column with the shock wave, labelled S in frame 1, travelling from left to right. The first cavity is collapsed by the shock wave and a jet can clearly be seen in frame 2. By frame 3, the cavity is totally collapsed and a rebound shock wave S' is formed. During this time of collapse (*c*. 10 μs), the second cavity has been shielded from the initial shock wave and has only experienced a slight lateral compression (see frame 3), but when the rebound shock wave from the first cavity reaches its lower surface, it too starts to collapse to produce a jet. The third cavity in the line is collapsed in a similar way by the collapse and rebound of the second cavity. A chain reaction along a line of cavities is thus feasible given the right conditions of shock strength, cavity diameter and spacing.

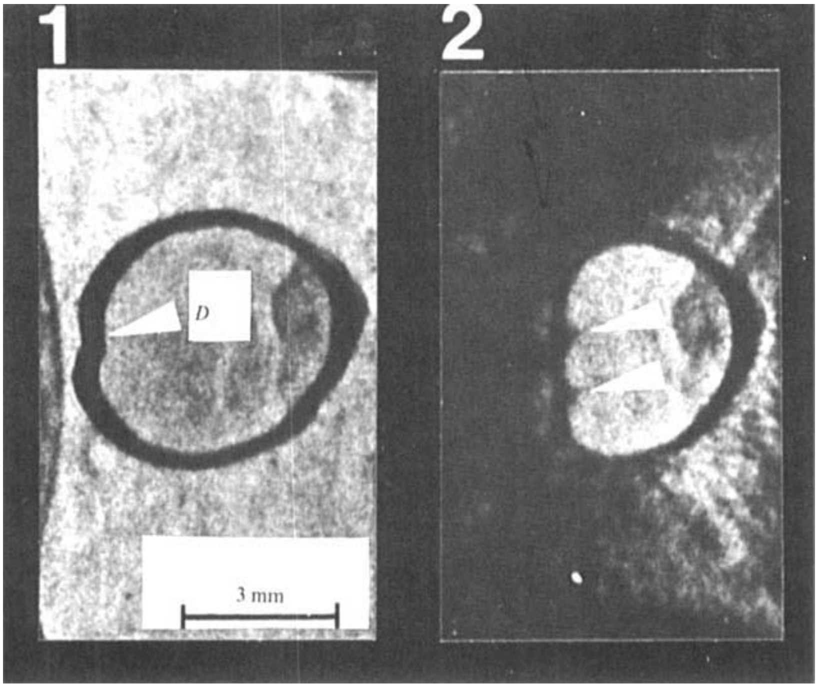

FIGURE 6. Two frames from a sequence showing a 6 mm diameter cavity with a dimple, D, which produces two jets (arrowed). The second frame is c. 6 μs after the shock reaches the cavity.

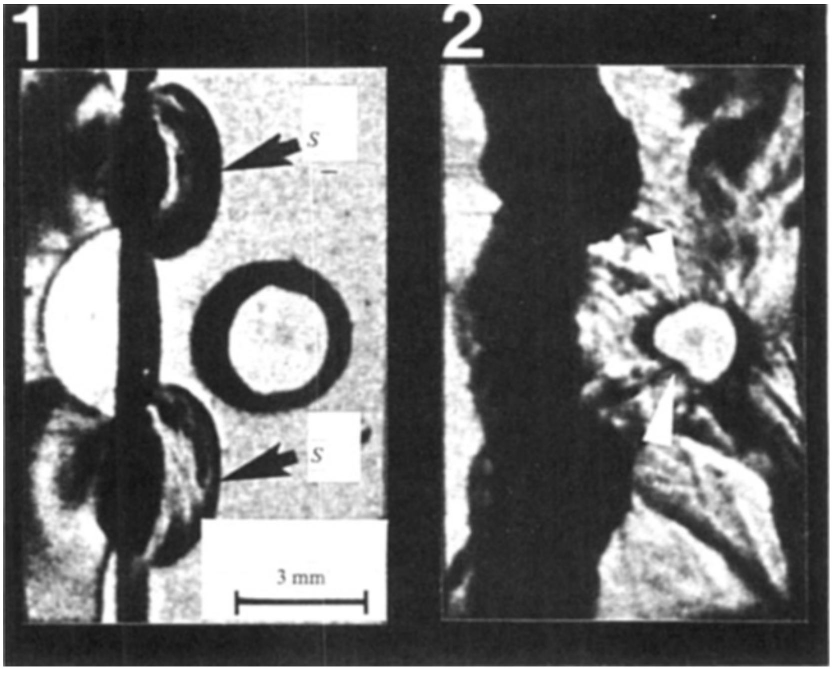

FIGURE 7. Two frames from a sequence showing a specially shaped slider impacting the gel and producing two shocks S which subsequently interact with a 3 mm diameter cavity. The second frame, c. 6 μs later, shows two jets starting to form.

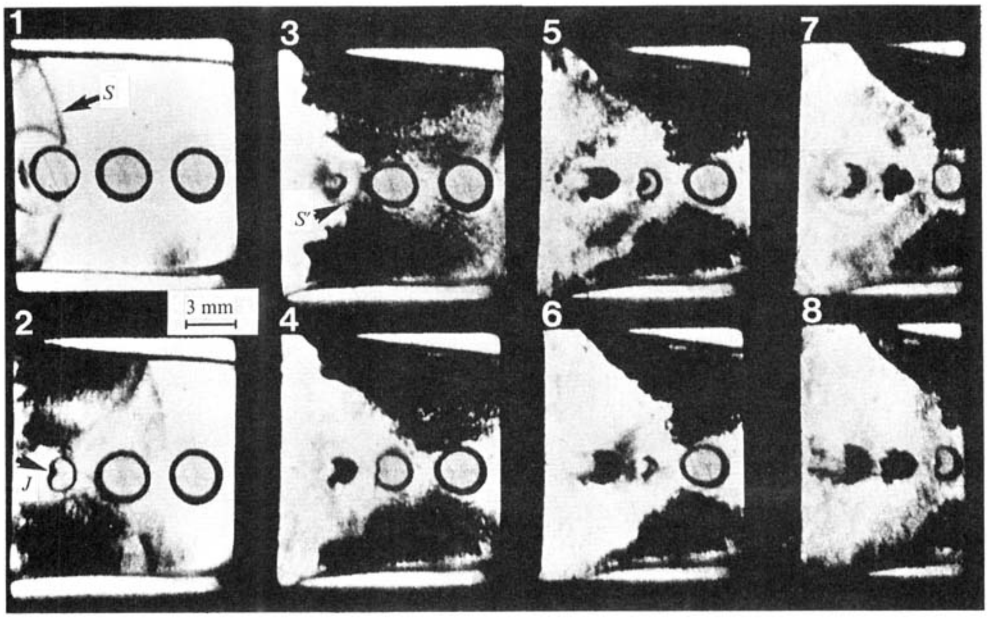

FIGURE 8. Three cavities, diameter 3 mm, perpendicular to the shock wave S. J is the jet and S' the rebound shock wave from the first cavity. Note the step-by-step-collapse. Interframe time, 4.25 μs.

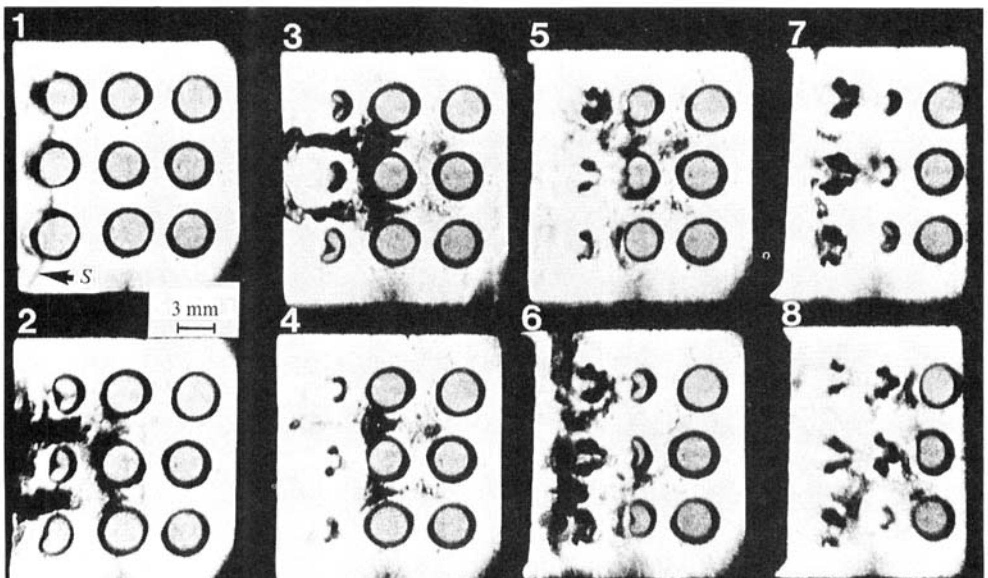

FIGURE 9. Rectangular array of nine cavities, diameter 3 mm, collapsed by shock wave S. Note the layer-by-layer collapse. Interframe time, 4.25 μs.

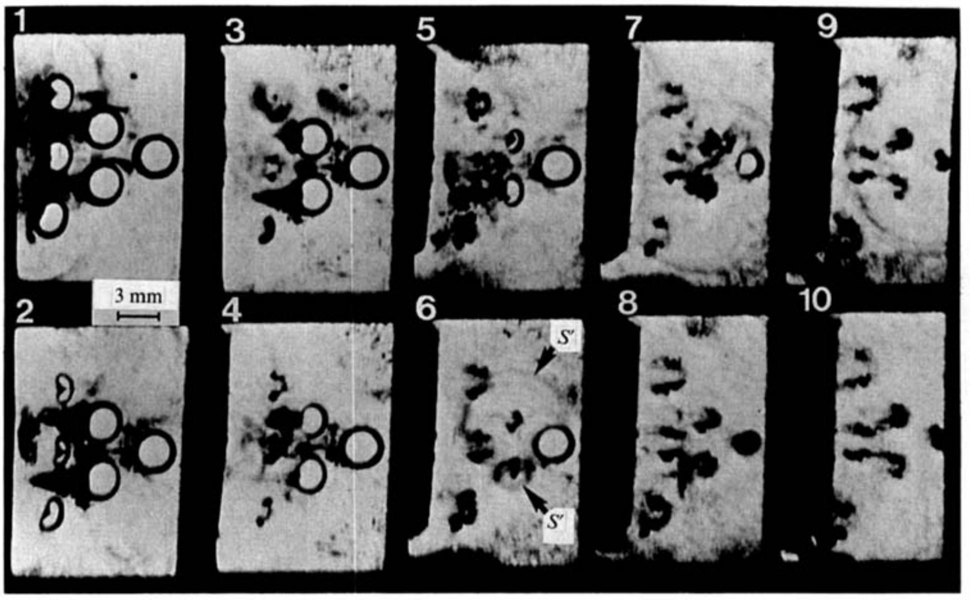

FIGURE 10. Triangular array of cavities, diameter 3 mm, collapsed by a shock. Note the rebound shocks S' in frame 6. Interframe time, 4.25 μs.

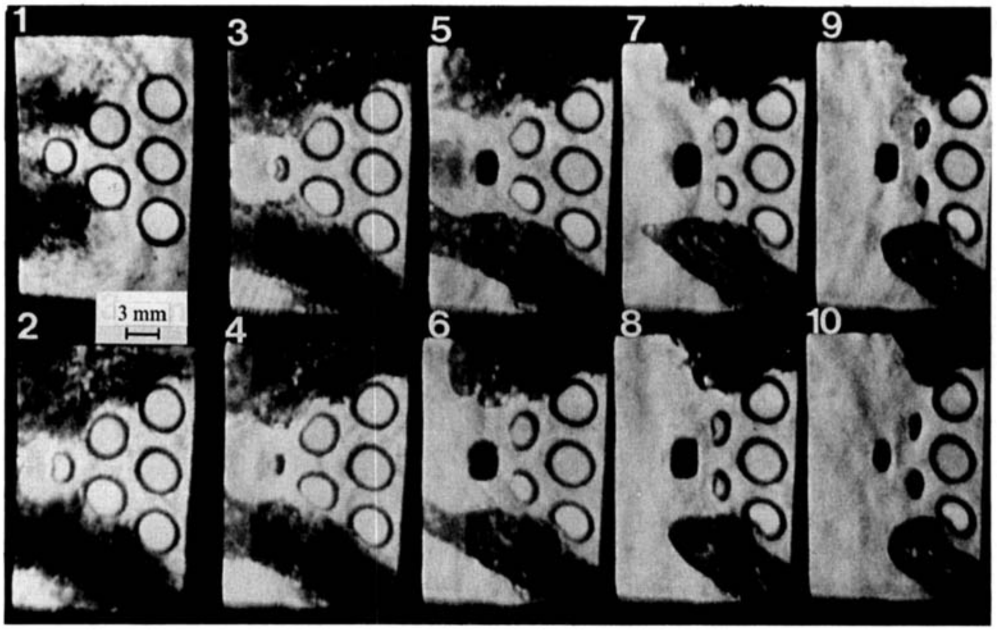

FIGURE 11. Triangular array of cavities, diameter 3 mm, collapsed by a shock, but with the apex interacted with first. Interframe time, 4.25 μs.

3.2.3. *Rectangular arrays*

The above suggests that a rectangular array of cavities with each row directly behind the next row would allow little of the main wavefront to pass the first row. Hence the collapse of the second row of cavities should be mostly due to shock waves radiating from the collapse of the first row. Figure 9 examines this possibility with an array of 3×3 cavities. As already found, the outside cavities of the first row produce slightly diverging jets. The second row of cavities, as predicted, were collapsed by the radial rebound shock waves arising from the collapse of the first row. These three shock waves radiate from three jet impact sites more widely spaced than the centres of the cavities with the effect of reducing the divergence of the jets in the second row.

3.2.4. *Triangular arrays*

The next objective was to assess the degree of penetration of the primary shock wave between the cavities of the first row. To do this a triangular set of cavities with each row staggered in a three, two, one array was used. Thus, the shock wave passes between the cavities in the first row and impinges directly onto those in the second row. Figure 10 shows the results obtained and the first point to note is that the impacting slider strikes the liquid (gel) at a slight angle. The jets in the first row of cavities, is aligned to the slider shock wave, are directed slightly to one side of the cluster centre. Despite this and the one outside jet being started earlier than the others, frame 2 shows well the diverging outside jets and the central jet moving ahead of the others. Frame 2 also shows that some of the main shock wave has passed between the cavities in the first row. This is made evident by the triangular, darkened zones of cavitation produced by the reflection of the primary shock wave into a reflected tensile wave by the second row of cavities. Also, as frames 2 and 3 show, the inner surface of the cavities in the second row are already taking on the form of a jet. This is before the shock waves, emanating from the collapse of the first row of cavities, reaches the second row. Thereafter, however, the chain reaction begins to take over as in previous experiments. The collapse of the bubble at the apex of the triangle shows the chain reaction particularly well as little if any of the primary shock wave has reached it, and its collapse is mostly due to the shock waves, labelled S', emanating from the previous rows of cavities. This apex cavity sees shock waves from cavity collapse in the first and second rows. However, the main collapsing forces appear to come from the nearer second row of cavities.

Figure 11 shows the same triangular array of cavities but in this sequence, the shock wave closes with the apex cavity first. This gives more information as to the interactions of the main shock wave and the rebound shock wave with the second row of cavities. The first cavity is collapsed to produce a well-formed jet (see frames 2 and 3) which is normal to the shock wave. The next two cavities, however, are partly in the shadow of the first cavity and hence this next row of cavities have an asymmetrical capture of energy from the main shock wave. This has the effect that the jets are not so well-formed and are directed inwards to be convergent (see frames 4 and 5). Upon total collapse of the first cavity, a strong rebound shock wave is emitted which radiates into the shadow zone. This reduces the convergence of the jets, as frames 7 and 8 show. Similar effects occur in the third row of cavities.

4. Discussion

The problem of the shock wave collapse of a cavity has been considered numerically by Mader (1965, 1979, 1985) and analytically by Lesser (private communication, 1984). The Lesser approach is briefly noted here since it helps in understanding the mechanics of the jet production.

Figure 12(*a*) shows a planar shock wave interacting with a circular cavity. Reflection of the shock wave, S, occurs at the free liquid surface to produce a corner

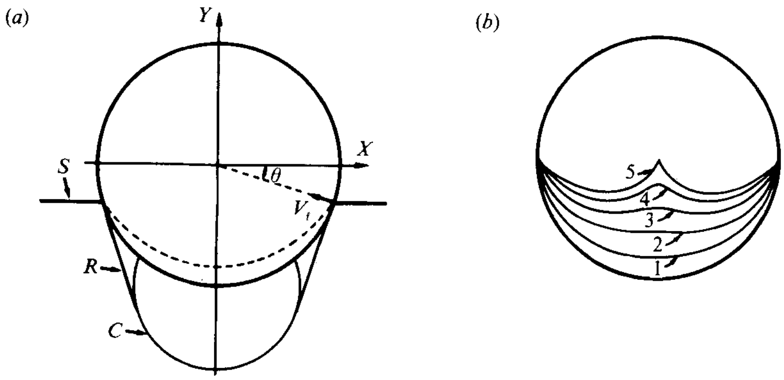

FIGURE 12. (*a*) A plane shock wave S interacts with a circular cavity producing a corner wave C and a reflected wave R. (*b*) Resulting shapes of cavity wall for non-dimensional times $\bar{t} = 1$–5 (after Lesser).

wave, C, and a reflected tensile wave, R. It can be shown that the velocity imparted to the free surface is given by $V_f = 2V \sin\theta$, where V is the particle velocity behind the shock wave. Linearized shock relations are assumed in the liquid of the form $P = \rho C V$. To calculate the perturbed surface shape, Lesser then assumes that the particles in the liquid surface travel with the initial velocity imparted to them. The resulting shapes for various non-dimensional times and $V = 150$ m s^{-1} ($C = 1500$ m s^{-1}) are given in figure 12(*b*), the non-dimensional time $\bar{t}$ being defined as $\bar{t} = tC/R$ where R is the radius of the cavity. The maximum velocity of the cavity wall is attained at the centre of the cavity where the wall velocity is twice the particle velocity behind the shock. After time $\bar{t} = 5$, corresponding to the time when particles of liquid from opposite sides of the cavity meet, the cavity wall forms a cusp. The shapes that the Lesser treatment predict are reasonably close to what we observe. However, his jet tip velocity of $2V$ is likely to be low since he does not allow for convergence and nonlinear effects: Mader's (1965) numerical treatment for an 8.5 GPa shock passing over a cavity in nitromethane suggests that convergence effects can increase the final jet velocity by a factor of 1.5 times the free surface velocity $2V$. In our experiments at 0.26 GPa, $2V = 300$ m s^{-1} but the jet velocities were measured at *c*. 400 m s^{-1}. This is reasonable since the convergence and nonlinear effects are likely to be less than a factor of 1.5 at the lower pressures. Jet velocities of this magnitude would clearly have damage potential. For example, if the cavity collapse took place near a metal surface pressures of order 1 GPa would be generated.

The shape of the cavity wall agrees well with the Lesser treatment. However, if the jet tips are examined in detail a fine spray of liquid can be seen to precede each jet. An enlarged view taken from one sequence is given in figure 13(*a*). In Lesser's model the jet is formed by particles of liquid 'spalling' from the cavity wall and coming together to give the jet. When these liquid particles collide they will themselves form a jet as is shown schematically in figure 13(*b*). The precursor jet is much too fine to be important in cavitation damage but its presence helps substantiate the model for cavity collapse by a shock wave.

There appear to be two types of interaction between cavities in well-ordered arrays. The first occurs between adjacent cavities in a row collapsed at the same time by a shock wave. The second is the chain reaction effect in a column of cavities where one cavity causes the collapse of another. For a row of cavities parallel to the incident shock wave (figures 3–5), the jet direction and its form are affected by the reflected

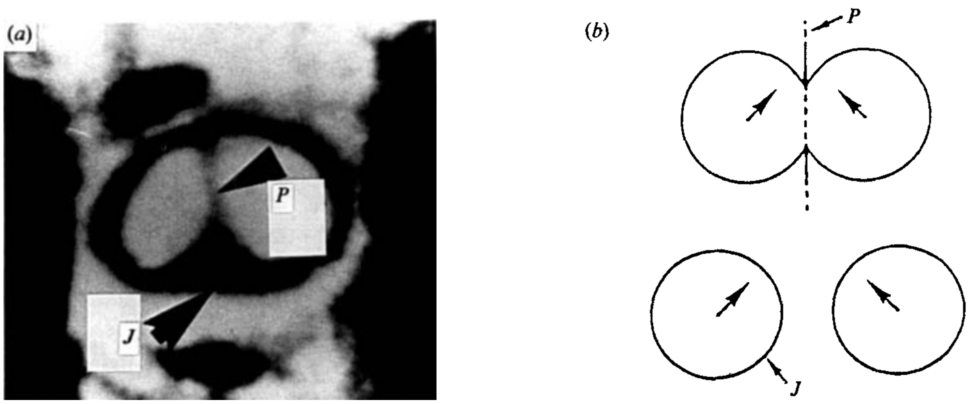

FIGURE 13. (*a*) Enlarged view showing precursor jet, *P*, and main jet, *J*. (*b*) Collision of droplets in the jet producing the precursor jet, *P*.

tensile waves from neighbouring cavities. These reflected waves from adjacent cavities affect the flow of liquid into the jet and the overall collapse of the cavity. For a row of cavities, the regions of liquid between the cavities where the tensile reflected waves overlap experience a drop in pressure below the ambient value resulting in microscopic cavitation, evident as a darkened region between the cavities in figures 3 and 4. The failure in these regions sends out pressure waves. At the ends of a row of cavities, the pressure waves interact with one side but not the other. This produces an asymmetric flow of liquid into the jet resulting in the jet direction in the cavity being forced away from its neighbour. These observations of interaction confirm those of Chaudhri *et al.* (1982), Tomita *et al.* (1984) and Lauterborn (1979). Further, when cavities are very closely spaced double jets form (figure 5). Two situations have been identified which can cause double jets. The first is if the cavity surface has an imperfection or dimple (figure 6) and the second is when two shocks from different angles pass over a cavity at nearly the same time (figure 7).

An important effect which has been identified is the chain reaction mechanism whereby the collapse and rebound of one row of cavities generates strong radial shock waves which then collapse the next row. The photographic evidence (figures 8 and 9) shows well that the speed of the chain reaction depends upon the size of the cavities and the velocity of the jets formed. It does not equal the main shock wave velocity and is only related to this through the shock pressures produced and their influence on the collapse. The experiments also show that a high fraction of the collapse energy (*c*. 80–90 % estimated from the ratio of the jet velocities squared) of one collapsing row is transmitted to the next. For a large array of cavities arranged in a hemispherical cloud as analysed by Hansson & Mørch (1980), this would indicate that there would be a focusing of the collapse energy towards the centre of the cloud. This is consistent with Hansson & Mørch's predictions of increase of collapse energy and pressure as the centre of the cloud is approached.

There is still debate about the precise causes of cavitation damage and the relative importance of various damage mechanisms. However, a recent paper by Tomita & Shima (1986) has given considerable clarification. The possibilities for pressure pulses to be produced are numerous and include:

(i) The rapid collapse of a void as envisaged by Rayleigh (1917).

(ii) The rebound shock (Hickling & Plesset 1964; Fujikawa & Akamatsu 1980).

(iii) Further rebound shocks as a gas-filled bubble oscillates. It appears that the second rebound can be of similar magnitude to the first (Lauterborn & Bolle 1975; Tomita & Shima 1986).

(iv) The jet production as envisaged by Plesset & Chapman (1971) which can produce pressure pulses (see equations (1) and (2)) either by direct impact with a solid or by impact with the cavity wall. However, these jets appear to have velocities only of order 100 m s^{-1} and many authors have questioned their damage potential. Further, with gas-filled cavities the gas slows the jet and cushions its impact (Shima & Nakajima 1977; Fujikawa & Akamatsu 1980).

(v) Jet production caused by a shock passing over a cavity as studied in the present paper. As pointed out by Tulin (1969), this form of collapse takes place in a real cavitation situation since the collapse of cavities away from a surface can generate stress pulses which then collapse cavities located close to, or attached to, a surface. The jet velocities in this case can be appreciably higher. As shown in this paper, velocities of *c.* 400 m s^{-1} are possible for shocks of 0.26 GPa (2.6 kbar). Recently Avellan & Karimi (1987) have shown that during vortex cavitation the collapse of a vortex can produce a shock of pressure *c.* 1 GPa (10 kbar). If such shocks passed over a cavity near the surface, they would produce very high velocity jets in excess of 1000 m s^{-1} and 'water hammer' pressures of order 20 kbar. It is interesting to note that in the related area of detonation phenomena, Mader (1965) has shown that when an 8.5 GPa (85 kbar) shock with a particle velocity of 1700 m s^{-1} passes over a 200 μm void in nitromethane, the free surface velocity is initially 3400 m s^{-1} (i.e. $2V$) but is increased to a jet velocity of 5200 m s^{-1} by convergence effects. If a jet has an angled front profile and the contact periphery expands supersonically, then pressures greater than ρCV can be reached. For the particular case of the contact velocity being just supersonic, then these pressures are close to 3 ρCV (Field *et al.* 1985). Grant & Lush (1987) have modelled the cases of flat-ended and wedge-shaped jets impacting an elastic–plastic solid. In our view, jet production by shock interaction is a key damage mechanism in cavitation erosion.

(vi) As pointed out by Tomita & Shima (1986), if collapse takes place near a surface the outward-flowing jet can interact with the contracting cavity surface and produce an annular ring of small drops. When these are struck by the rebound shock they themselves can collapse producing jet damage. Convincing evidence for this mechanism is given in their paper.

A second area where cavity collapse is of interest is in the initiation and propagation of fast reaction in explosives (see, for example, Bowden & Yoffe 1952, 1958). The rapid collapse can generate 'hot spots' by at least two mechanisms. The first is by adiabatic heating of the gas in the cavity; a detailed study of this has been made by Chaudhri & Field (1974). The second is the 'hot spot' produced by shock heating in the regions where the jet impacts (Mader 1965); this mechanism becomes more important at very high shock pressures (several GPa). Many commercial explosives are sensitized by the addition of gas spaces. The gas can be added in different ways but a common method with emulsion explosives is to add micro-balloons. The shock from the detonator collapses the gas spaces forming 'hot spots' which sustain the detonation. The density of gas spaces (porosity of the explosive) is similar to those studied in this paper and the present results are thought to be relevant to the explosive problem. In present research we are using image intensifiers to record the luminescence created at the 'hot spots' as cavities collapse (Dear *et al.* 1988). The gel technique, as described in this paper, is proving particularly useful for this new study.

5. Conclusions

A new technique has been described which allows the collapse of arrays of cavities to be studied. Advantages of the liquid/gel two-dimensional method are that cavity number, shape, size and position can be controlled and high-speed photography, together with schlieren optics, used to observe all the details of the shock interaction and the cavity collapse. It is shown that:

(i) Jets of *c.* 400 m s^{-1} velocity are produced in millimetre-sized cavities when subjected to shocks of 0.26 GPa (2.6 kbar) strength. Such jets would produce 'water hammer' impact pressures of *c.* 0.9 GPa (9 kbars) on impact with a metal surface. For higher collapse pressures, the jet velocities would be correspondingly higher.

(ii) In a linear array of cavities parallel to the shock front, the jets in the outermost cavities diverge slightly (figures 3, 4 and 5).

(iii) With very closely spaced cavities, two jets may form in the collapsing cavity (figures 5 and 7). A double jet can also develop if a shock interacts with a dimpled cavity (figure 6).

(iv) With clustered arrays of cavities, the collapse takes place layer by layer since shielding takes place. The pressure waves from the first collapsed layer collapse the next and so on. With suitable geometries, this can lead to pressure amplification.

(v) Jet velocities produced by shock interactions are higher, and frequently much higher, than those caused by the asymmetric collapse near a boundary mechanism analysed by Plesset & Chapman. Such jet impacts are probably a major source of damage in many hydraulic machinery cavitation situations.

(vi) The techniques described in this paper have much wider application to cavitation, liquid impact and other fluid mechanics situations, and further research is in progress.

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