The Effect of Shock Waves on a Hailstone Model

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ABSTRACT

The effect of explosively generated shock waves on ice cubes has been investigated in the laboratory. Impact tests on cubes previously exposed to shock demonstrate that the action of the latter weakens the cubes, the effect being markedly greater when the latter contain a water column. The phenomenon observed is discussed in terms of the theory of shock waves; the weakening of the ice cubes appears to be plausible on the basis of shock-induced cavitations within the water columns inside them. Insofar as ice cubes containing a water column very crudely simulate hailstones, the results observed suggest the possibility that explosive shock waves might similarly weaken actual hailstones. Thus, rocketborne explosive charges could conceivably be a practical way of reducing damage from hailstorms.

1. Introduction

The effect of explosions on hailstorms has long been a controversial topic, e.g., Roncali (1960a, b), List (1963), and Vittori (1965). The use of rocketborne explosive charges as a practical means of reducing the destructive action of hail has gained popularity in such European countries as Italy, Switzerland, Austria, and Kenya, as described in a publication by the Italian Technical Bureau Against Hail,[3] as well as in reports by Vittori[4] (1960), and H. W. Sansom (1965). Testimonies of farmers who have used anti-hail rockets are reported in footnotes 3, 4, and in Vittori (1960). According to these, firing rockets into the hailstorm results in a softening of the hailstones which then splatter on impact with the ground. The resulting "soft" stones are alleged to be less damaging to the crops. The farmers have observed that a delay takes place between the moment when the firing of rockets begins and the time when hailstones reaching the ground change from hard to soft. Vittori calculated that this delay is equal to the time of free fall of stones of average size from the altitude at which the rockets explode. Hence, he deduced that the action of the explosion on the hail must be instantaneous and proposed that shock-induced cavitations of air bubbles within the hailstones are responsible for the weakening of the latter's structure. The aim of the present paper is to report a laboratory investigation on the effect of shock waves on a hailstone model carried out at the Explosives Research Laboratory of Canadian Industries Limited.

2. Simulated hailstones

The internal structure of a hailstone is not completely known. However, most recent theories suggest that it consists of an ice shell containing water pockets, e.g., List (1961, 1963). Since formation of the stone takes place in air, it can be assumed that the water is well aerated.

To simulate such hailstones, ice cubes 1 cm×1 cm×1 cm were prepared by freezing tap water in plastic trays. The water used was previously exposed to the air for several hours so that it should be thoroughly aerated. In the middle of the cube was inserted a fine brown copper wire, as shown in Fig. 1. Thus, by shining a strong beam of light on the cube, a column of water formed around the wire due to the greater absorption of light energy by the dark wire than by the transparent ice. The melting of the ice around the wire was observed with a microscope and stopped when the column of liquid around the wire was about 1.5 mm in diameter. This working model simulated hailstones insofar as both are made up of water pockets surrounded by ice shells; the water in both cases is well aerated.[5]

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[3] Defence against hail in Italy during 1956. Report of the Italian Technical Bureau Against Hail.

[4] Vittori, O., 1959: Preliminary report on a study of the effects of explosions upon hailstones. Italian Ministry of Agriculture.

[5] More recent work revealed that a foreign body (such as the fine copper wire) facilitates the cavitation of bulk water under shock. This observation, which will be discussed in detail in a further publication, raises some doubts on the applicability to natural hailstones of the threshold value of overpressure determined in this study. However, the presence of insoluble material generally found in hailstones could equally favor cavitation at relatively low shock wave overpressures.

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3. Exposure to shock

Such ice cubes were exposed to explosively generated shock waves of various intensities. The larger part of the investigation used a $\frac{1}{3}$ lb stick of high explosive held 3 ft away from the cube, as shown in Fig. 2. Charges tried ranged from $\frac{1}{3}$ lb down to a single detonator (0.0014 lb). The experiments were carried out in a steel tank built especially for explosive research. A suitable container was designed for holding the ice cubes. It consisted of a heavy wooden frame whose floor and four walls were lined with 2-inch thick foam rubber; the roof consisted simply of a copper screen to allow passage of the shock. This frame was placed on the floor of the tank with the ice cube on the foam rubber floor and the charge hung vertically above the screen (see Fig. 2). The foam rubber lining prevented damage to the cube by impact against the walls while the screen insured the cube from being ejected out of the enclosure. Thus, any damage observed could be attributed to the direct effect of the shock.

The procedure adopted was as follows. An ice cube was removed from cold storage and put in a refrigerated (−78C) polythene tent where it was exposed to a light beam; a microscope was used to observe the melting taking place around the copper wire. The cube was then transferred to a portable cold box (−78C) and brought to the firing tank. It was placed in the foam rubber lined container and the explosive charge detonated. The cube was next returned to the refrigerated tent for examination or for impact tests. The whole procedure lasted around 5 min, of which about 2 min were spent in the firing tank.

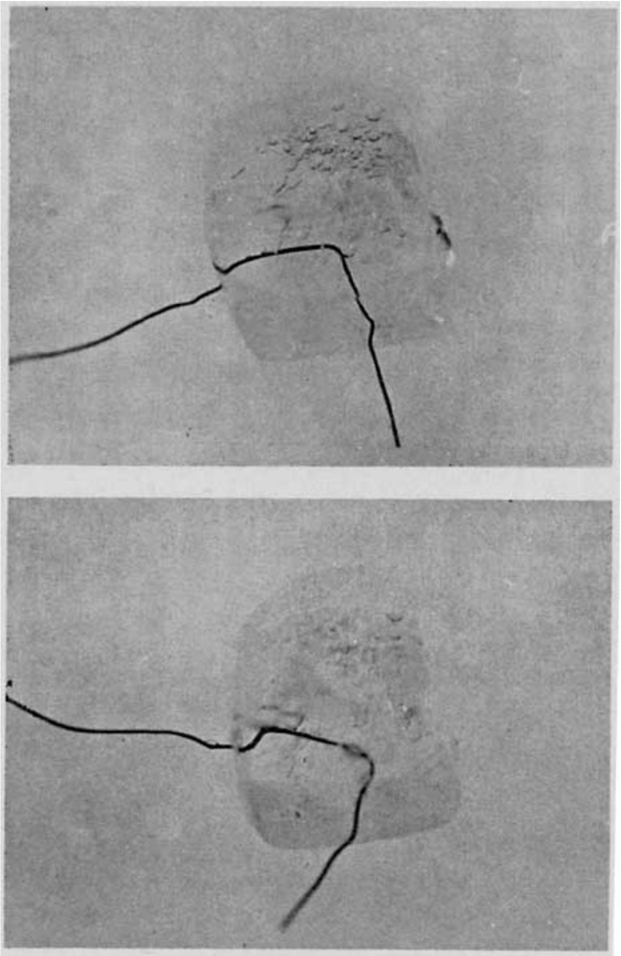

FIG. 1. Ice cube, top, before exposure to shock; bottom, after exposure to shock.

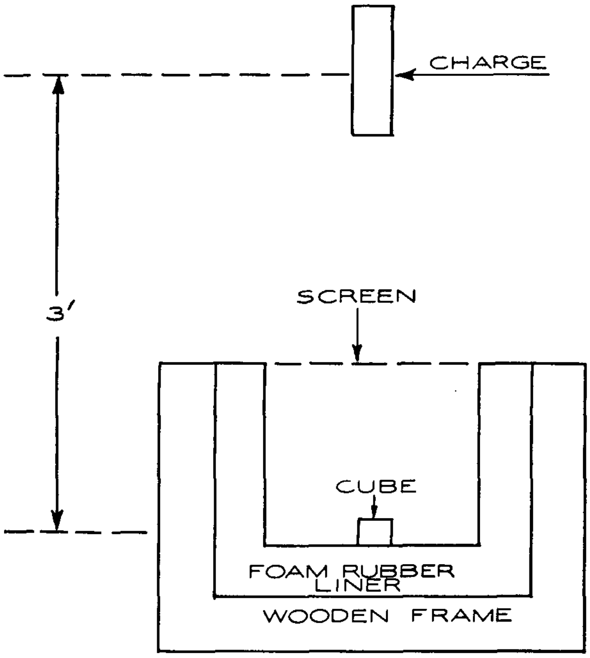

FIG. 2. Experimental arrangement for exposing simulated hailstones to explosive shocks.

4. Impact tests

To determine quantitatively the weakening of the ice cubes resulting from the shock waves, a series of impact tests was carried out with an impact apparatus (Fig. 3) consisting of a platform on which the ice cube was placed, a cylinder and piston above the cube, and an 88-gm weight which could be dropped on the piston from known heights. In Fig. 3 it can be seen that the weight, piston and ice cube are in a vertical line, the cylinder restricting the piston's motion to this line. The entire apparatus was placed in a refrigerated tent (−78C). Before impact the lower end of the piston rested on the upper face of the cube. The weight was then dropped from a predetermined height and the cube examined; it was rated as broken or unbroken. In the former case the height of drop was decreased for the test with the next cube while in the latter case it was increased, i.e., the Bruceton method was applied. The results for a series of such tests could be used to determine the height of fall at which 50 per cent of the cubes broke.

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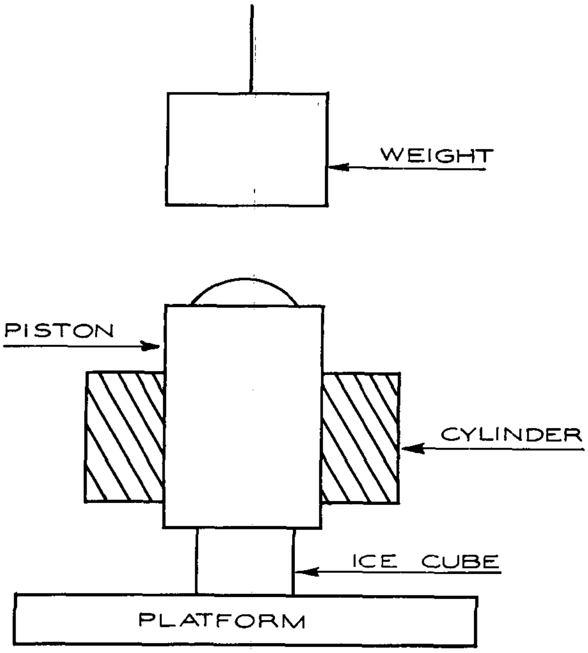

FIG. 3. Impact apparatus for crushing tests.

Using the technique just described and a large number of initially identical ice cubes, four series of impact tests were carried out. Each series involved about 20 cubes. For the first series, ordinary cubes were used, i.e., cubes containing a copper wire but not exposed to a light beam or a shock. The second series dealt with cubes exposed to the light beam until they contained a column of water 1.5 mm in diameter. The third series used cubes exposed not only to light but also to an explosive shock. The fourth series dealt with cubes which had been exposed to a shock but without prior exposure to light, i.e., not containing a water column. In all four series a constant interval of time was maintained from the moment the cube left the freezer to the moment it was set in the crushing apparatus. Thus, the heights for 50 per cent breakage of the ice cubes, as listed in Table 1, represent separately the weakening effect of exposure to light, exposure to shock, and exposure to both.

TABLE 1. Strength of ice cubes for various treatments.

Treatment	Height for 50 per cent break (cm)	Standard deviation (cm)	Kinetic energy (ergs)	No. of cubes tested
Unexposed cubes	20.2	±0.8	1,740,000	50
Cubes exposed to shock only	19.9	±0.9	1,510,000	20
Cubes exposed to light only	18.4	±0.9	1,410,000	16
Cubes exposed to both light and shock	12.7	±0.8	1,100,000	20

The following conclusions can be drawn from Table 1:

a) Exposure to light alone reduces the height for 50 per cent break by 1.8 cm.
b) Exposure to both light and shock reduces the height by 7.5 cm; hence, the net effect of the shock when a water pocket is present amounts to 5.7 cm.
c) Exposure to shock alone reduces the height by only 0.3 cm; hence, the net weakening effect of the shock on a cube containing a water column is many times as great as that of the shock on a solid ice cube. This increased effect would moreover be expected to be greater still in a real hailstone since the latter contains several water pockets, whereas the ice cubes used in the present work contained only 2.6 per cent water (a 1.5 mm diameter by about 1.5 cm long water column for a cube 1 cm×1 cm×1 cm).

5. Possible explanation

The experimental results of the impact tests indicate that the passage of a shock wave has nearly negligible effect on solid ice cubes; however, it substantially weakens cubes which contain a water column. An attempt was made to find a plausible explanation for this phenomenon by closer examination of cubes before and after exposure to shock.

First, it was noted that the *external* appearance of the cubes, whether containing a water column or not, was never appreciably altered by the explosion. This is demonstrated in the photographs of Fig. 1 showing the same cube before and after exposure to shock. In fact, very little external damage was caused to ice cubes even when placed almost in contact with an explosive charge. A discernible weakening effect was made evident *only by the impact tests*, in which a large amount of additional energy is supplied to the cubes, an amount far in excess of the small quantity of energy already imparted by the passage of the shock itself. This suggests that the passage of the shock merely causes a weakening of the *internal structure of the cubes containing a water column*, predisposing them to shatter more easily when more energy is subsequently imparted to them. In the case of actual hailstones, this additional energy comes from impact with the ground.

In order to investigate the ideas of the last paragraph, the internal structure of cubes was scanned, before and after exposure to shock, using a high power microscope which could be focussed on a small region inside a cube. Typical results are reproduced in Fig. 4, displaying microscope photographs of a region near the center of a cube, taken before and after exposure to shock. The magnification is 30×. The slender copper wire is clearly visible; it has a sharp corner in the photographs of Fig. 4 with the water column surrounding it.

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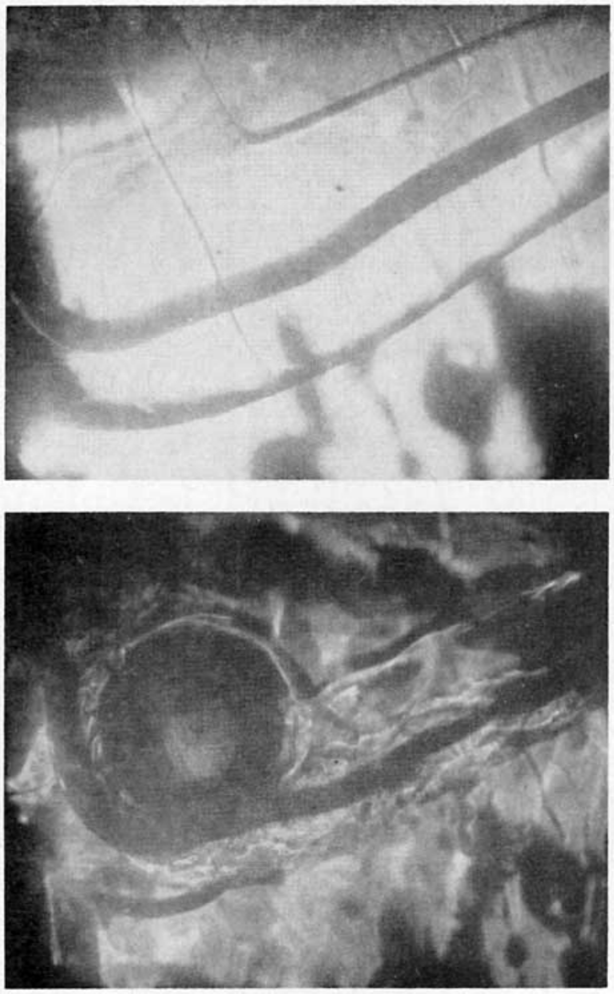

Fig. 4. Microscope photographs of water column, top, before exposure to shock; bottom, after exposure to shock.

From observations such as those of Fig. 4, it can be surmised that the internal structure of the ice "appears" more stressed after exposure to shock. However, a more tangible observation involves the appearance of gas bubbles inside the previously clear water column, apparently produced by the explosion. In Fig. 4, for example, a large gas bubble of 1.2 mm diameter is seen to have formed inside the water. Such bubbles were observed for *all* the tests provided that the shock intensity was above a certain threshold. As discussed below, the production of these gas bubbles is compatible with the hypothesis that shock-triggered cavitations occur inside the water column. In order to demonstrate the link, the phenomenon of cavitation must be briefly reviewed.

6. Cavitation

Broadly speaking, cavitation occurs whenever tension forces in a liquid produce cavities or bubbles. If the liquid medium is aerated water, then such cavities usually contain air. When the tension stress which produced an air bubble is removed, the latter contracts radially. This contraction generates a disturbance which travels throughout the liquid medium surrounding it. However, when the stress system which led to the production of the bubble is repetitive, the latter undergoes successive expansions and contractions, i.e., the bubble oscillates radially.

The most common manner of exciting gas bubbles to oscillate is by feeding ultrasonic radiation into the liquid containing the bubbles. The phenomena which occur when this is done have been studied by Blake (1949), Willard (1953), Crawford (1955), Briggs *et al.* (1947), and others. These researchers have observed that if an ultrasonic field is applied for some duration, microscopic bubbles (presumably already present in the liquid; it is believed that such microscopic bubbles exist in all aerated water) grow to visible sizes. This growth can be explained on the basis that gas dissolved in the liquid diffuses through the liquid-gas boundary of the bubble. During the positive pressure half-cycle of the applied ultrasonic vibration the liquid-gas solution is undersaturated so that gas dissolves out of the bubble, and vice versa during the negative half-cycle. However, the average surface area of the bubble is less during the positive half-cycle than during the negative one. Hence, the bubble gains a net quantity of gas with each full cycle so that it tends to grow. Moreover, like most other oscillatory systems, the oscillating bubble can be at resonance with the frequency of the applied ultrasonic field. Smith (1935) has deduced that, for a given applied field of frequency f_0, resonance will occur when the average bubble radius r_0 has grown to a value given by

$$r_0=\frac{K}{f_0}, \tag{1}$$

where K depends on the liquid medium, the gas in the bubble, and the ambient pressure. For example, if f_0 is 330 kcs, resonance will be reached when r_0 grows to 0.01 mm, if f_0 is 33 kcs, resonance will be reached at an r_0 of 0.1 mm, while if f_0 is 3.3 kcs, resonance will be reached at an r_0 of 1 mm. In practice, ultrasonic frequencies ranging between 50 and 3000 kcs are employed.

Consider a bubble of initial average radius r oscillating under the effect of a pressure field varying at frequency f_0. If r is less than r_0, where r_0 corresponds to f_0 in Eq. (1), then the bubble will grow until r approaches r_0. At such time as this occurs the amplitude of the oscillations will increase very rapidly and become non-sinusoidal. This continues until r has grown beyond r_0, after which the amplitude of oscillations becomes smaller again. Usually r is by then so large that the buoyancy of the bubble forces it upward. Crawford (1955), Briggs *et al.* (1947), Willard (1953) and others have observed large bubbles rising to the top of the liquid after ultrasonic induced cavitations had occurred;

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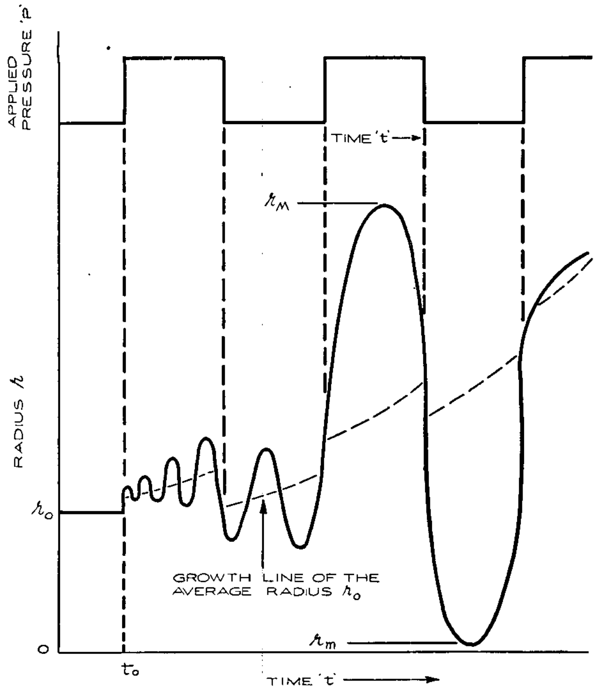

FIG. 5. Growth of an oscillating bubble to resonance with the applied pressure field.

experimental evidence indicated that such bubbles were made up by coalescence of several post-cavitation bubbles. Fig. 5 displays the approximate radius vs. time relationship for an oscillating bubble growing to resonance under the influence of an applied pressure field. In Fig. 5 the latter is not sinusoidal but rather it consists of a series of square waves. As discussed below this makes no difference on the process whereby r grows to the resonance value r_0.

According to Willard (1953) a time of the order of 0.3 msec is required for a microscopic air bubble in water to grow to resonance size. During the oscillations close to resonance the pressure disturbances produced by the contractions, or collapses, of the bubble are of very high intensity. They are in fact shock waves; for bubbles of the order of 0.01 cm in diameter, calculations by Silver (1942) have shown that the shock pressure generated is of the order of 1000 atmospheres. This is, of course, a much higher pressure than that which originally triggered the cavitation. The resultant shocks are, in fact, of such high intensity that they can trigger further cavitations, resulting in what might be described as a "chain reaction." This last phenomenon has been extensively observed by Willard (1953) and Crawford (1955) in aerated water. The various secondary shocks emitted, after numerous collapsing bubbles are formed, are, of course, highly damaging to the walls containing the water. In terms of the present paper, the term "cavitation" will usually refer to the case where oscillating bubbles grow to the resonant frequency and trigger further bubble growth.

7. Conditions for cavitation in ice cubes

As seen in the last section, cavitations triggered in a body of liquid by means of an ultrasonic pressure field lead to the production of large gas bubbles which rise to the top of the liquid. If the conditions necessary for cavitation can be shown to be present inside an ice cube exposed to a shock wave, then it will not be unreasonable to suggest that the gas bubbles observed by the authors inside the water column in cubes exposed to

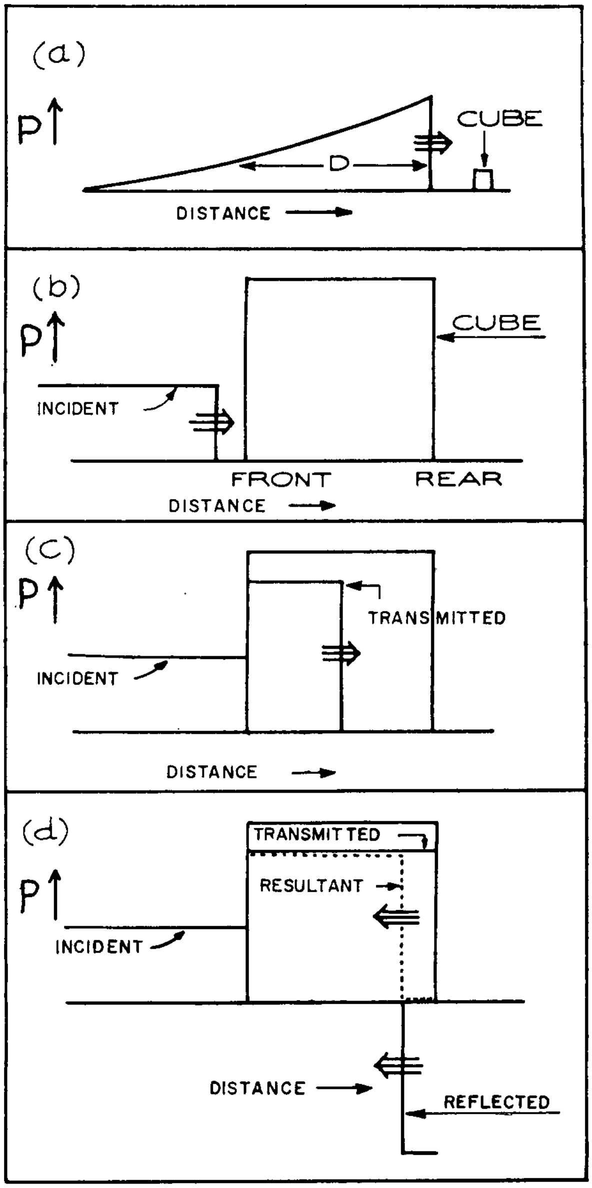

FIG. 6. Pressure outline at various instants: a, b; pressure step just approaching the cube face; c, just after incidence on the front face; d, just after reflection from the rear face.

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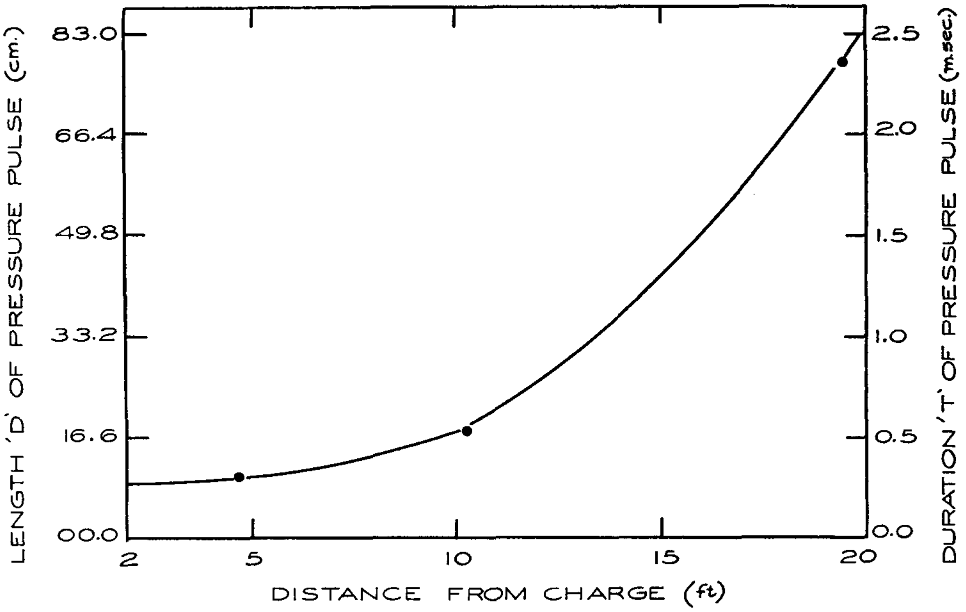

Fig. 7. Length D and duration T of the pressure pulse from 1/3 lb of high explosive as a function of distance from the charge.

shocks also result from cavitations therein. These conditions are as follows:

a) The water in the column must contain dissolved air.
b) An oscillating pressure field must be set up inside the ice cube.
c) This oscillating field must be applied long enough to cause cavitations; according to Willard (1953) about 0.3 msec is necessary.

Consider first condition a). The ice cubes were made with well aerated water; during freezing some of the air previously dissolved in this water dissolved out to form air pockets dispersed throughout the cube (see Fig. 1). However ice retains some dissolved air in it (e.g., 2 per cent air in ice at 0C); moreover, those air pockets originally in the area of the water column redissolved in the water of the latter. Thus condition a) is satisfied.

Consider secondly condition b). Although a single shock wave is generated by the explosion, it will now be demonstrated that internal reflections within the ice cube turn this shock into an oscillating field. Fig. 6a shows the exponential spatial outline of an explosive generated pressure shock, at the instant the steep leading edge approaches the ice cube. Let D be the "length" of the pulse, i.e., D is the distance over which the pressure is greater than P_m/e, where P_m is the peak pressure and e is the base of natural logarithms. The length D depends on the size of the charge and on the distance between the charge and the leading edge. For $\frac{1}{3}$ lb of high explosive in air, D is plotted in Fig. 7 (left hand scale) as a function of distance from the charge. It can be seen that 3 ft away from the explosive D is about 10 cm, i.e., 10 times longer than an edge of the ice cube. Hence, in comparison with the cube, the shock appears like a step pressure discontinuity, as shown in Fig. 6b. Consider now what happens when this step discontinuity arrives at the cube face. Figs. 6b, 6c and 6d show the pressure outline at various subsequent times. In 6b the pressure step is just approaching the cube face. In 6c it has entered the cube and the amplitude of the transmitted pressure step is twice that of the incident one. This doubling effect at an air-solid boundary is well known; it is discussed, for example, in Chapter 2 of Cole (1948). Fig. 6d displays the pressure outline a short time after the transmitted wave has arrived at the second cube face; the shock wave reflected in the ice at this second face equals in amplitude the transmitted shock which has just crossed the cube but now is a tension wave. The resultant pressure to the right of the reflected wave is therefore zero. When the reflected wave in the cube reaches the first face it is once more reflected but as a compression wave; this reversal of a wave reflected from a solid-air boundary is also discussed by Cole. Hence, the result is that compression waves and decompression waves alternately sweep across the ice cube. At a given point within the latter, the pressure outline as a function of *time* looks like that shown in the upper part of Fig. 5. The effect of the cube boundaries is therefore to "chop up" the long lasting incident shock wave into a series of square pressure pulses. Thus, an oscillating pressure field is set up in the cube and condition b) is fulfilled. The duration of each pulse can be obtained by dividing the dimension of the cube (1 cm) by the velocity of sound in ice (380,000 cm sec^{-1}). It

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turns out to be 2.6 μsec. This corresponds to a repetition frequency of 190 kcs, i.e., a frequency of the same order of magnitude as the ultrasonic field used by Willard and others to study cavitation in water.

The analysis just outlined is only approximate. Since the pressure behind the leading edge slowly drops, as shown in Fig. 6a, the amplitude of the pulses in the upper part of Fig. 5 actually decreases slowly. Moreover, the presence of the ice-water boundaries between the water pocket and ice shell has been neglected. This is justified by the fact that water and ice have comparable acoustic impedance. Taking into consideration the decrease in pressure behind the leading edge, as well as the presence of internal ice-water boundaries, does not appreciably alter the conclusions arrived at, namely that an oscillating pressure field is set up; on the other hand, it renders the details of the analysis substantially more complicated. A further discrepancy, which does not apply to the experiments with ice cubes but would apply to actual hailstones, is the fact that the latter are more spherical than cubic. In the case of a shock wave passing through an ice sphere, the oscillating pressure field which would be set up is not as easy to visualize as that in the case of a cube. However, there is no doubt that normal modes of reflection exist for all cases and that the pressure at a given point within the hailstone would oscillate with time in a manner similar to that shown in the upper part of Fig. 5. It should, moreover, be noted that the applied field in the upper part of Fig. 5 consists of a series of square pressure waves, whereas the studies of ultrasonic-induced cavitations were carried out using sinusoidal waves. However, calculations carried out by the authors on the response of a simple harmonic oscillator (the gas bubble) under the action of square waves showed that the latter produce twice the amplitude of oscillation as compared with sine waves of the same intensity. Hence, a train of square waves should be twice as efficient in triggering cavitations as ultrasonic sinusoidal waves.

In Fig. 7 the length of pulse D can be converted to duration T if D be divided by the velocity of sound in air. The right hand scale in Fig. 7 shows this conversion. Thus, it can be seen that 3 ft away from a $\frac{1}{3}$ lb charge of high explosive, the duration of the pressure pulse is about 0.3 msec. This is of the same order of magnitude as the time which Willard found was necessary for cavitations to occur. Hence, an oscillating pressure field was applied to the ice cubes for a sufficiently long duration to cause cavitations and condition c) required above is fulfilled in the present experiments.

Since conditions a), b) and c) have been shown to be present when a shock wave passes through an ice cube containing a water pocket, the authors suggest the possibility that the bubbles observed during their experiments result from shock-induced cavitations in the water column around the wire, that is, bubbles such as that of Fig. 4b correspond to the bubbles observed to rise to the surface in the work of Crawford, Briggs *et al.* and Willard on ultrasonic induced cavitations.

8. Threshold for the production of bubbles

All the results presented so far were obtained for ice cubes exposed to a shock generated by the detonation of $\frac{1}{3}$ lb of high explosive 3 ft away from the cube. It is well known that the peak shock pressure varies with the weight of the charge. The peak pressure 3 ft from the end of a $\frac{1}{3}$ lb cylinder of high explosive was experimentally measured to be 25 psi. Studies with ultrasonic energy, on the other hand, showed that there is a minimum intensity of the pressure field below which cavitation cannot be triggered. Crawford (1955) found that this threshold is about $\frac{1}{4}$ atmosphere, i.e., 3.7 psi.

If bubbles like that of Fig. 4b are to be associated with cavitations, then their production also is expected to occur only for shocks of intensity above a threshold value. To investigate this, experiments were carried out as follows. Ice cubes containing a water column were exposed, at a constant distance of 3 ft, to shocks from progressively smaller charges ranging from $\frac{1}{3}$ lb down to 0.0014 lb of explosive. Each cube was examined under the microscope before and after exposure and the total volume of bubbles produced was measured. In some cases a single bubble resulted while in other cases two or more bubbles appeared. No special meaning is attached to this difference since it is believed that all the bubbles observed were made up by coalescence of a great number of smaller cavitation bubbles. In all cases, therefore, it was the total volume of the bubbles which was considered as a meaningful quantity. Fig. 8 shows a log-log

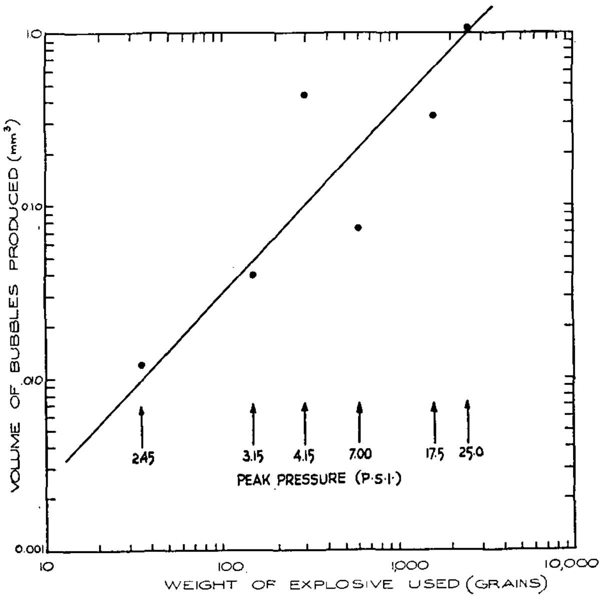

FIG. 8. Volume of cavitation bubbles produced as a function of weight of explosive. The peak pressure at the ice cube is indicated for each weight of explosive used.

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plot of bubble volume against weight of explosive in grains, 7000 grains corresponding to one pound. Most points are the average of several trials. It is seen that the bubble volume produced decreases with decreasing charge weight. No explanation is available for the peak around 300 grains and so a straight line has been drawn freely through all the points. The results in Fig. 8 are in agreement with Willard's (1953) work; the latter observed that the number of bubbles resulting from cavitations in a liquid exposed to ultrasonic energy rose as the pressure field intensity was increased. The experimental evidence in Fig. 8, displaying a similar result, strengthens the hypothesis that shock-induced cavitations took place in the simulated hailstones exposed to detonations.

The existence of a threshold pressure for the production of bubbles is evident from the data of Fig. 8. The peak pressure corresponding to each weight of explosive used is shown on the abscissa. With 10 grains of explosive (1.97 psi peak pressure at a distance of 3 ft from the charge) no bubbles were observed in 2 trials. With 35 grains (2.45 psi peak pressure) bubbles were observed in each of 2 trials. An approximate threshold value can be estimated by extrapolating the data of Fig. 8 to zero bubble volume on a linear plot of the latter against shock pressure; the results give 2.2 psi incident on the cube, i.e., 4.4 psi inside it, which is in rather good agreement with Crawford's estimate of 3.7 psi as the threshold for ultrasonic induced cavitations in aerated water. Thus, it becomes even more plausible that the bubbles produced in the shock-exposed cubes are of the same nature as those observed by Crawford and others.

9. Range of effect

The results presented in Table 1 above indicate that explosive shock waves do weaken substantially the strength of ice cubes containing a water column. The discussion of Sections 5, 6, 7 and 8 suggest that the shock wave triggers cavitation inside the water column. If it is correct to surmise that there exists a cause-effect relationship between the occurrence of cavitation and the weakening of the ice structure, then the effective range for a given explosive charge might be estimated. The threshold for the production of bubbles has been determined above to be about 4 psi inside the cube, that is 2 psi at the face of the cube. Fig. 9 indicates the peak pressure produced at various distances from the detonation of 1 kg of TNT in air; this charge corresponds to that carried by the rockets used in Europe. A peak pressure of 2 psi occurs at about 30 ft from the explosion. This estimated range of action, calculated on the basis of the threshold for the production of bubbles in ice cubes, is much lower than the 1400 ft range allotted to each rocket by the Italians in their field operations (Italian Technical Bureau Against Hail, 1956). The discrepancy might be due to one or several of the following reasons:

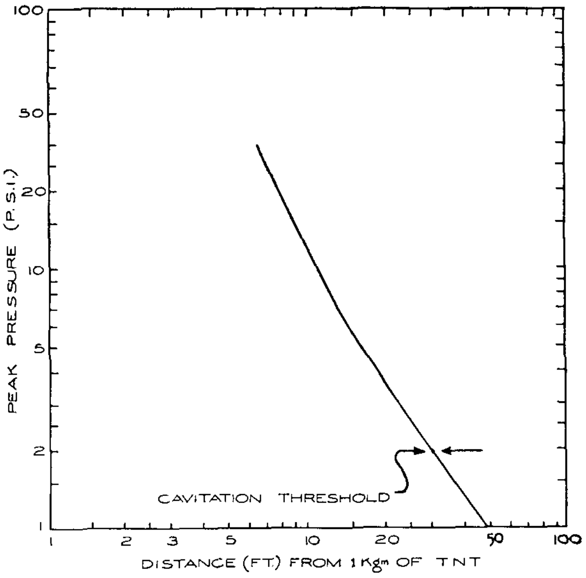

Fig. 9. Peak pressure as a function of distance from 1 kg of TNT in air.

a) Cavitation might explain only a part of the weakening effect measured in the present studies (see Table 1).
b) The threshold for the generation of visible bubbles is associated with "catastrophic" cavitation, that is the situation where minute oscillating bubbles grow to the resonant frequency and trigger further bubble growth. It is possible that even the earlier stage of cavitation, where the oscillating bubbles have not sufficiently grown to coalesce into visible bubbles, magnifies the incident shock intensity sufficiently to account for the turning of solid hail stones into "mushy" ones up to a distance of 1400 ft from a 1 kg charge.
c) The present work dealt with ice cubes containing a single water column. Actual hailstones are spherical and contain many water pockets. It is possible that the spherical shape of hailstones, or of water pockets in them, act so as to focus the incident shock wave; thus, the pressure intensity at certain points within the stone might be substantially greater than that of the incident shock.

It appears that a more direct way of determining the range of the weakening effect reported in Table 1 would be to actually measure this effect, in the manner described in Section 4, for decreasing levels of shock intensity.

10. Refreezing

A continuous source of worry during this work was the effects to be attributed to refreezing of the water

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column inside the ice cube. As the temperature in the refrigerated tent and in the cube carrier was below zero, refreezing started on removal of the light beam used to form the column. For example, the water column diameters in the photographs of Fig. 4 are 1.5 mm before and 1.1 mm after exposure to shock, indicating 50 per cent refreezing. This was exceptional, however, in that the cube of Fig. 4 was driven back and forth a half mile from the firing tank to the special microscope equipped with a camera. In regular tests with an ordinary microscope located in the same building as the firing tank, refreezing was only 5–10 per cent. Nevertheless, it can be argued that even this small amount of refreezing could account for at least some of the weakening effect observed on the cubes. However, the following arguments suggest that the fraction of weakening to be attributed to refreezing is minor compared with that to be attributed to the shock:

i) The results of Table 1 show that the net weakening effect of the shock on cubes containing a water column ($18.4-12.7=5.7$ cm) is three times greater than the net weakening effect of exposure to light ($20.2-18.4=1.8$ cm). As this 1.8 cm must also include weakening due to refreezing, this latter effect is evidently less than that of the shock.

ii) The wire around which the column was melted extended outside the cube; thus, the water column was opened at its ends allowing for pressure release as refreezing took place.

Another consideration again suggests that refreezing played a minor role. This involves the fact that the production of air bubbles inside the water column seems to be intimately connected with the weakening effect observed, in that they were observed together. Now, the results of Fig. 8 show that the volume of bubbles produced varies strongly with shock intensity, for tests carried out at constant refreezing; thus, shock intensity has more bearing than refreezing.

For these reasons, the authors feel that the phenomena investigated in the present work are attributable to the passage of the shock wave rather than to refreezing.

11. Conclusions

The use of rocketborne explosive charges to combat hailstorms is already a fairly common practice in Italy, Austria, France and Kenya. Field observers report that shortly after rockets have begun to be fired, the falling hailstones appear to become "mushy" or "slushy," so that they shatter more easily on impacting the ground. If the field observations are correct, and if it is reasonable to surmise that the explosions did indeed lead to the observed effect, then the results of the present work show that the phenomenon of weakening the structure of ice by explosively generated shock waves can be reproduced in the laboratory. The authors found that the strength of simulated hailstones, as measured by a simple crushing test, was substantially less after exposure to a shock. In this test the kinetic energy of the impacting mass corresponds to that of the falling hailstones.

The crushing test results demonstrate that a weakening occurs; however, they do not by themselves explain the mechanism whereby this weakening takes place. The following evidence, when taken together, suggests that at least a part of the weakening effect might be explained by cavitation:

a) Weakening only occurs when an ice cube contains a water column.
b) The passage of the shock sets up an oscillating field in the ice cube; the frequency of these oscillations is in the range known to cause cavitations.
c) The oscillating field lasts for the 0.3 msec known to be necessary to cause cavitations.
d) The passage of the shock produces gas bubbles in the water column. Such bubbles are observed when cavitation occurs.
e) The threshold for the production of bubbles is about 4.4 psi; this is of the same order of magnitude as the threshold of 3.7 psi for ultrasonically-induced cavitation.
f) The volume of bubbles produced increases with the intensity of the shock; a similar result is observed for ultrasonically-induced cavitation.

Thus, insofar as an ice cube with a water column in it crudely simulates a hailstone, the "softening" of hailstones by explosions might, at least partially, be explained in terms of cavitations in the water layers inside hailstones. These cavitations are presumably triggered by the oscillating pressure field set up inside the stone by the passage of the explosive shock. Once triggered, the cavitations generate, within the stone, secondary shocks of intensity greater than that of the original incident one; such secondary shocks would have a severe weakening effect on the internal structure of the hailstone. On impact with the ground, the stone would consequently shatter more easily than one which has not been exposed to shock. The presence of the wire raises some doubts on the threshold overpressure intensity in natural hailstones, but does not alter the conclusion that a measurable weakening of the ice structure is produced when cavitation is triggered in a volume of water contained by ice.

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