APPLICATIONS OF ULTRASONIC VIBRATIONS*

E. G. RICHARDSON

Professor of Acoustics, University of Durham, England

THESE vibrations though possessing the same physical characteristics as sounds have frequencies so high that they fall outside the range of pitch to which the human ear is susceptible. It is well known that as the pitch of a sound goes up it eventually becomes inaudible when its frequency is about 20,000 vibrations per second. There is no theoretical upper limit to the ultrasonic frequency though with existing means, experiments are limited to the range 20 kilocycles to 50 megacycles per second.

Most of the applications to which I shall refer make use of sources working on the piezo-electric or the magneto-striction principle. The former is an adaptation of an effect discovered by the brothers Curie, *i.e.*, that certain crystals, when compressed along one of their axes, develop charges on these or other faces and *vice versa*. If now an alternating potential difference is applied across one pair of faces, compressions and contractions of the crystal follow at the same frequency. The effect will be most manifest when the exciting frequency corresponds to one of the natural frequencies of vibration of the crystal, determined by its length in the particular direction of expansion and contraction, and the velocity of sound in the material. Such a piezo-electric resonator was first realised by Langevin in 1917; he used slabs of quartz and applied the necessary potential difference through a thermionic valve oscillator.

The substances most commonly used as sources in this way are quartz, Rochelle salt and tourmaline. They are cut into discs or slabs in such directions that electrodes may be applied to carry potential in the direction of one of their crystalline axes. In the case of the slabs, the electrodes are cemented to the top and bottom and the extensions and contractions take place along the greatest dimension. The discs are usually cut so that the motion takes place in the same direction as the applied alternating potential, namely, perpendicular to the flat face (in concertina fashion). The natural frequency is inversely related to the thickness of the disc, about 2·5 cm. for 100,000 c./sec.; 2·5 mm. for 1,000,000 c./sec. in quartz.

* Based on lectures given at a number of Indian Universities in December 1957 and January 1958.

The magneto-striction oscillation is induced by a current of the requisite frequency through a coil wrapped round an iron or nickel rod, causing variations in length as the magnetic field strength alternates.

Either of these latter types of source is capable of sending out ultrasonic waves into the fluid medium in which it is placed, of sufficient energy for most laboratory experiments. In certain applications, however, a larger radiating surface is required than can be obtained from the face of a single crystal or nickel rod. In order to achieve this, Langevin constructed a sort of sandwich consisting of a large number of little slabs side-by-side and all having their axes of vibration parallel between two metal slabs to act as electrodes. By the concourse of crystals vibrating together the lower plate was made to move relative to the top one, and thus a large radiating area was added to the source, when working into water. It is also possible to construct a bowl-shaped oscillator made of a mosaic of crystals so that a large ultrasonic intensity is produced at the focus (Fig. 1).

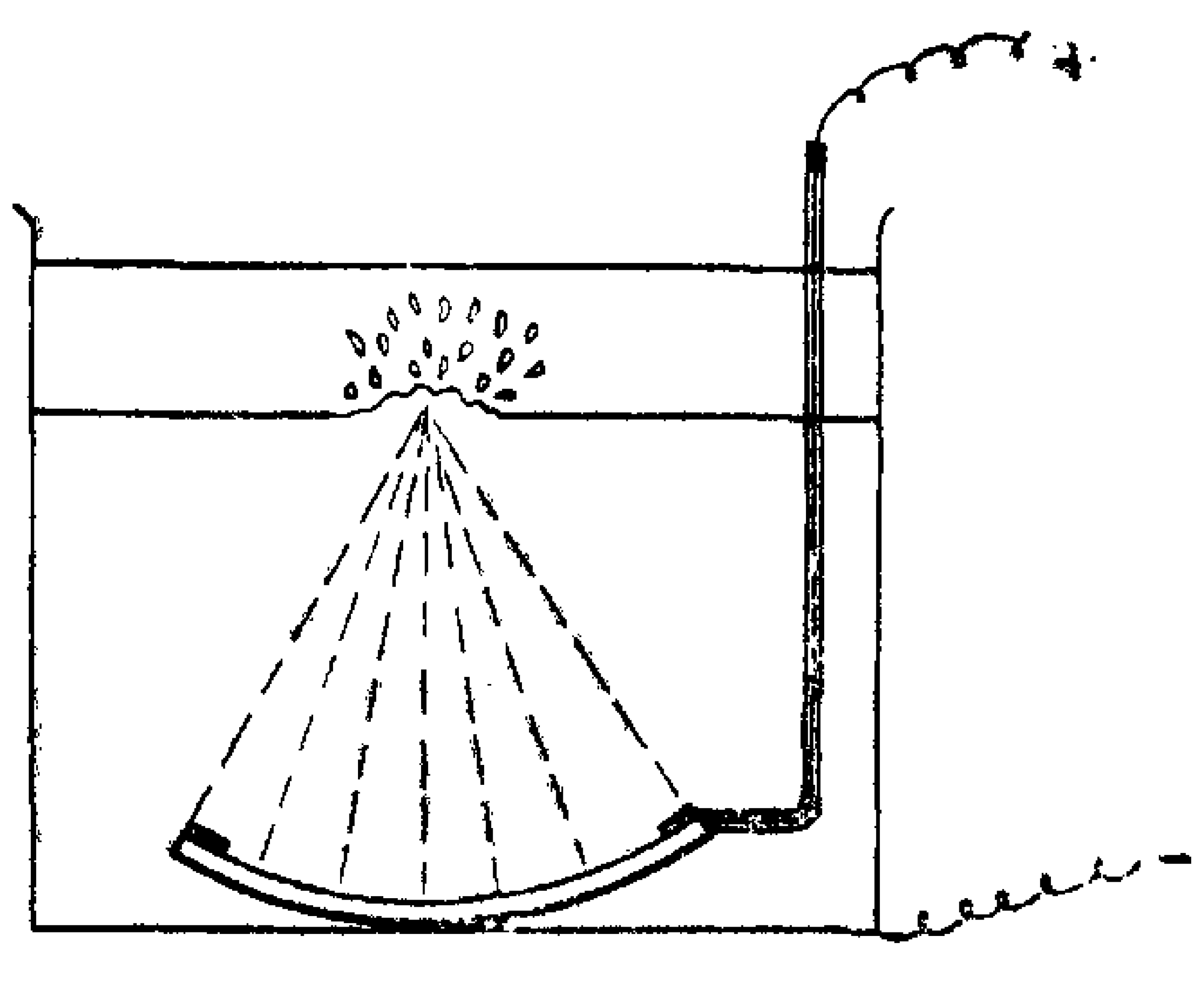

FIG. 1. Bowl type of ultrasonic source focussing sound energy at the surface of a liquid.

In the case of the magneto-striction oscillators a number of rings threaded together have coils wrapped round them so that they all expand and contract round their circumferences in unison. The energy is received on the surface of a metal horn, so that the radial oscillations are turned through a right angle and sent out from the horn in the form of a beam (Fig. 2).

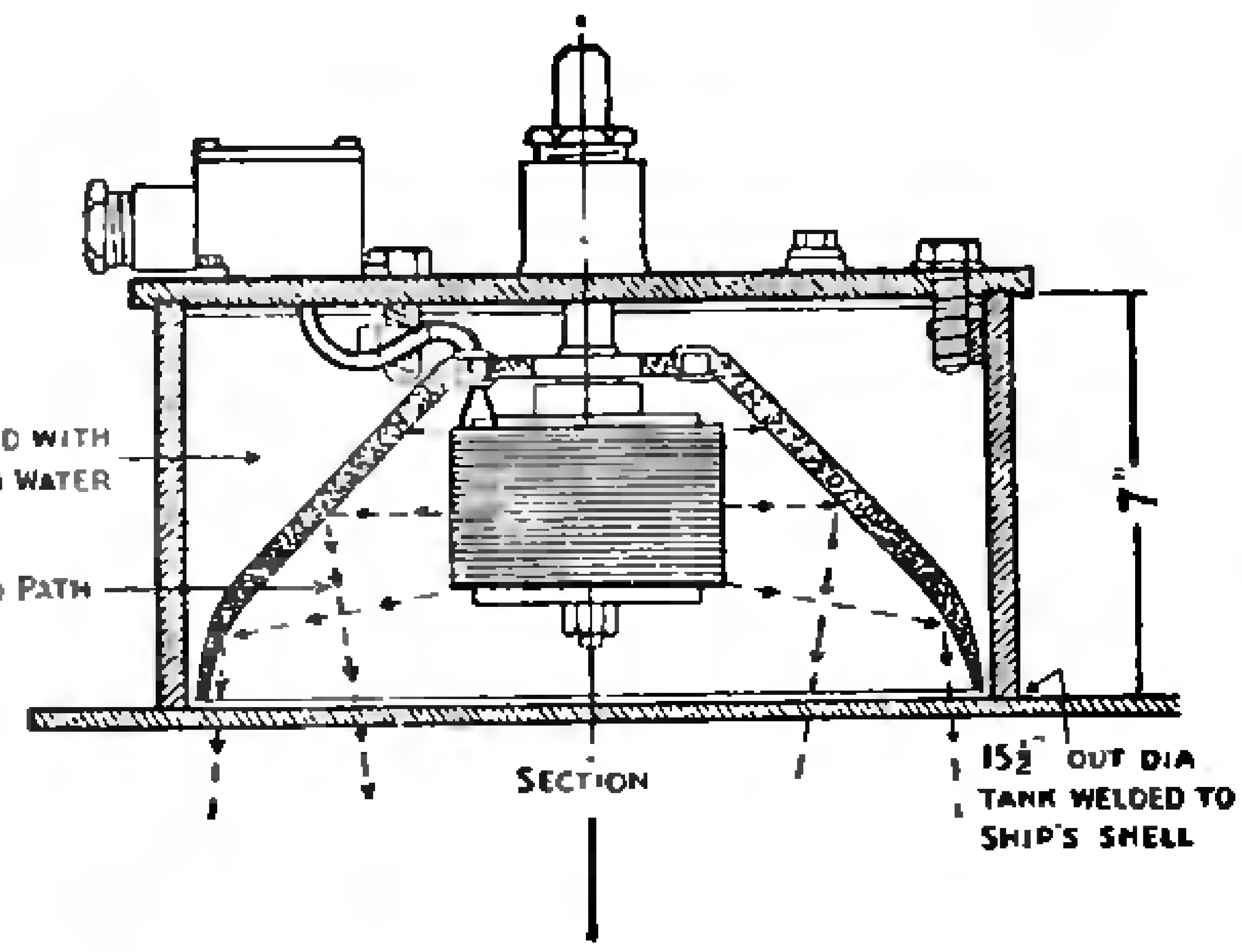

FIG. 2. Magneto-striction source reflecting energy from a metal horn into a liquid.

The applications of ultrasonics on a larger scale fall under two heads. There are those which make use of the energy of the high frequency vibration which can be induced by their aid to agitate various materials, both inorganic and organic. Others use the principle of echo-detection by which a beam of ultrasonics is made to pulse towards a suspected obstacle, to be reflected there and caught on a suitably-tuned receiver. In this latter use a source of high frequency is essential, as we shall see, but many of the perturbation methods could be equally well carried out with a source of lower frequency. The advantage here of the ultrasonic source is in its compactness and the fact that the intense vibrational energy can be concentrated into a small region, a thing which would be difficult to do with a source of lower frequency. On the other hand, this feature prevents many successful small-scale experiments being copied on an industrial scale, except with much duplication of the apparatus and at considerable expense.

Of industrial applications in the first class, I shall mention the formation of emulsions, the coagulation of smokes and the degassing of melts. It is readily observed that when a quartz oscillator is set in intense vibration under oil the liquid, particularly at the surface, is set into violent agitation; in fact, the liquid may rise above the surface in a fountain which disperses fine oil drops as a foam above it (Fig. 3). Place a lighter liquid above the one in which the oscillator is working and you disperse one into the other as an emulsion. This process is sometimes used in the manufacture of photographic emulsions, as it is found that a finer grain results. If an ultrasonic emitter is placed at the base of a glass chimney to which tobacco smoke or a water mist has been disseminated, the particles are agitated and brought into collision more frequently than otherwise. This causes coalescence and the larger particles so formed soon drop to the floor of the chimney. It is necessary that the final resting place of the liquid or solid forming the smoke shall be screened from the radiation, otherwise a certain amount of re-dispersal results.

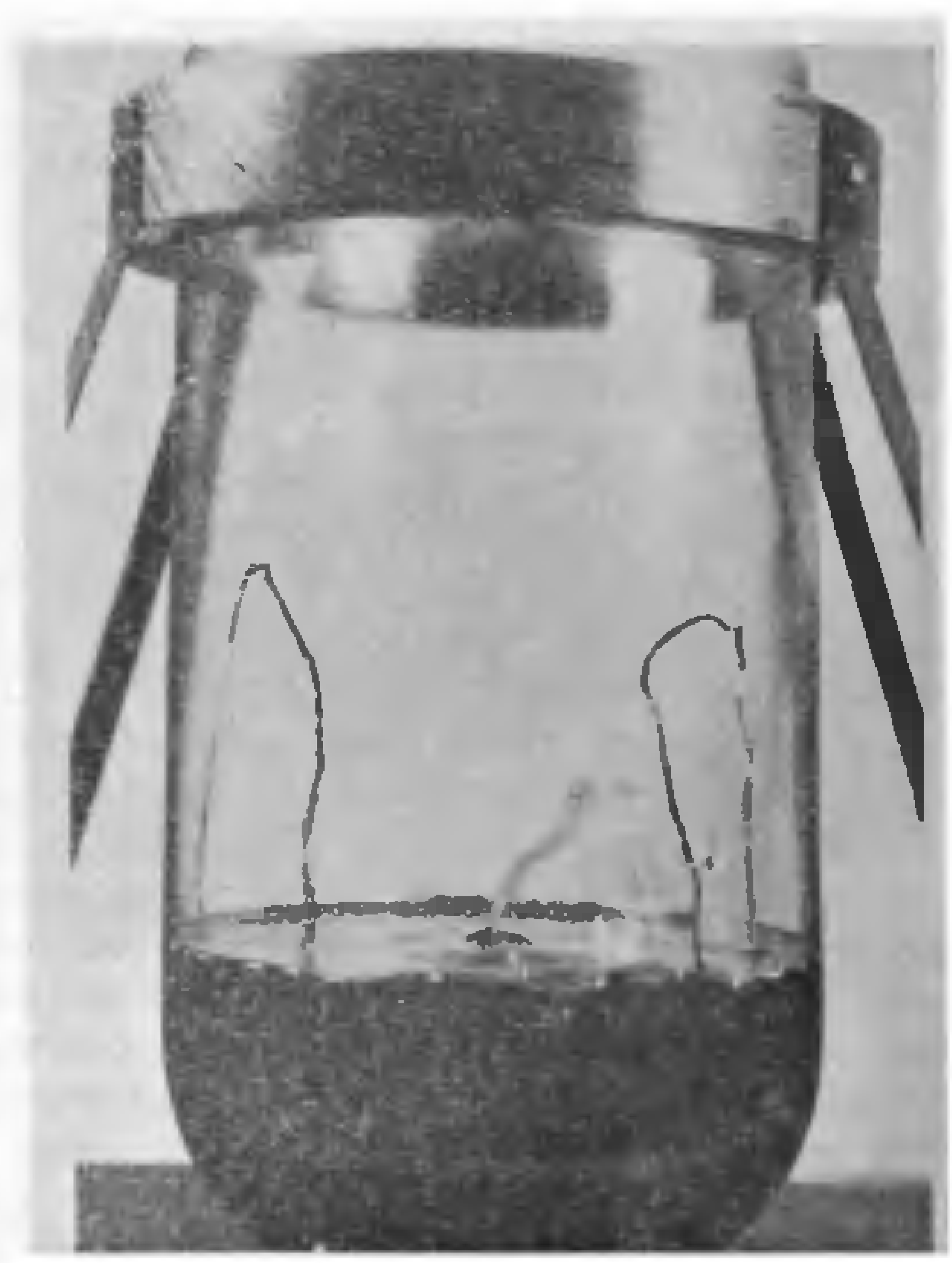

FIG. 3. Bowl type of source producing a fountain at the surface of a liquid.

Gas bubbles suspended in molten metals may similarly be brought to the top and out of suspension. In casting molten metal, such bubbles may be occluded and serve to weaken the structure after solidification. It is also possible to clean textiles immersed in water, as in laundering, by agitating the water ultrasonically. This removes dirt and fat.

For some years it has been known that it is possible to tin aluminium and its alloys by subjecting their surface to the action of intense ultrasonic vibration at the same time as molten solder is applied. It is now established that the process is one of removing the oxide skin by cavitation erosion. When, however, the experiment was repeated with an ambient pressure of 4 atmospheres, tinning was completely prevented. Since the increased pressure can have had only a negligible effect on any factor other than cavitation, this seems convincing evidence of the essential part played by the latter.

Aluminium is known to have a low resistance to cavitation erosion, even in water, so it is not surprising that collapsing voids in molten solder will be able to disrupt the surface, exposing the aluminium underneath for alloying with the metal which is impinging violently against it in the very action of cavitation. We can expect, moreover, that the usefulness of the ultrasonic technique for tinning different 'difficult' metals will be related to their susceptibility to cavitation erosion.

The detection of underwater obstructions by the echoes which they send back to a ship was the first application of ultrasonics and the *raison d'être* of the Langevin quartz 'sandwich'. Although too late for much use in the First World War, the apparatus under the name of Asdic was of great service for detecting submarines in the Second. It is well known that between the two wars, a device on the same principle using electromagnetic waves was developed, under the name of radio-location or radar, to detect obstacles in the air. Owing to the great absorption, which the latter suffer in water, ultrasonic waves must be used in the sea. It is interesting to note that high-frequency sound waves were suggested in a patent by Dr. L. F. Richardson for the detection of the submerged portion of icebergs after the *Titanic* disaster, but the means of producing them in sufficient power were wanting until Langevin's invention.

Unfortunately, the similar elastic properties of ice and water prevent a good echo being obtained off an iceberg, but the ultrasonic echo-sounder has now become a common piece of equipment for hydrographic surveying, both for delineating the bed of the sea when pointed downwards from the survey ship, or pointing upwards from the harbour bed to measure tidal-height or even wave height. With the former arrangement even a shoal of fishes can be detected.

Another factor which must be reckoned with is the increasing absorption which sound waves suffer in a fluid as the frequency is pushed up. This can be noticed by anyone who has used underwater listening equipment. When a hydrophone is laid at some distance from a ship the low-frequency engine noises and hull vibrations predominate. This factor combined with the diffraction we have already noted sets the optimum frequency for under-water echo sounding at about 20 kc./sec., just above the audible limit.

In use the magneto-strictive oscillator in its horn-like housing is turned either vertically downwards, if it is the sea-bed which is to be detected or roughly horizontally and scanned round in a circle by rotating the housing if, *e.g.*, submarines are being looked for, just as a radar beam is scanned round the horizon from the transmitter-*cum*-receiver aerial.

For the detection of flaws in the form of hairline cracks in metals, a system has been developed by the firm of Hughes in England in which a short train of waves is sent out and its wave form, as recorded by the receiver, noted on a cathode-ray oscillograph. They use quartz oscillators sometimes one at each end of an ingot (transmission method); sometimes on two facets of a prismatic specimen (reflection or echo-sounding method). The presence of hair-line cracks is shown in the latter method by a number of secondary echoes which reach the second quartz before the main reflection from the base of the prism (Fig. 4). Whereas

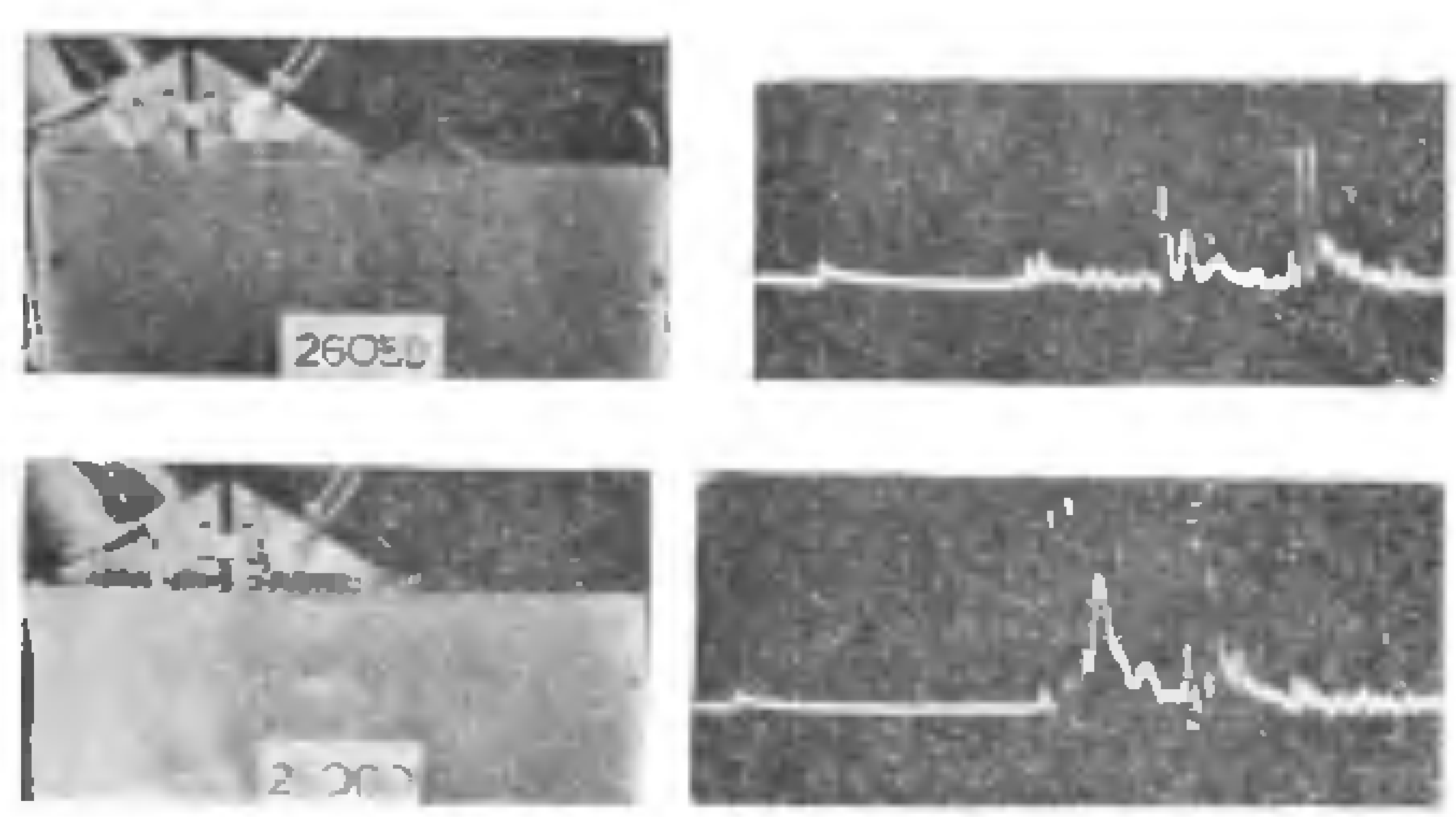

FIG. 4. Detection of flaws in a metal ingot. The echoes from these and from the base of the ingot are shown in the cathode-ray oscillograph displays on the right.

large fissures may be more readily detected by X-rays, the ultrasonic method is better for spotting these tiny cracks since it needs but the narrowest break in the continuity of the metal to give rise to a secondary reflection.

Formerly the velocity of sound in a gas was thought to be independent of frequency, the fact that the music of an open-air band is not distorted by distance being cited as proof. Soon after the discovery of ultrasonic quartz sources by P. Langevin, however, G. W. Pierce noted that at a frequency of about 100 kc./s. a rise of velocity occurred in carbon dioxide, accompanied by a considerable absorption of the energy. Following an idea which Debye had already pursued with success in explanation of the variation of dielectric constant with frequency, Herzfeld and Rice suggested that this was an acoustic relaxation involving the transfer of translational into vibrational energy and taking time in the process. In other words, above a certain frequency there is not time for this transfer to take place and the molecules become effectively stiffer, hence the rise in velocity of propagation and the change in phase between pressure and particle velocity which results in the attenuation of the ultrasonic signal as it passed through the gas. This behaviour is characteristic of a system which possesses a single relaxation time for the transfer of translational into vibrational energy.

In the succeeding twenty-five years, similar relaxations have been discovered in other gases, though none so pronounced as in carbon dioxide. Fig. 5, for example, shows a vapour in which this rise in velocity of sound accompanied by enhanced absorption occurs at a certain value of the parameter (frequency/pressure), for it is found that the relaxation time is inversely proportional to the pressure on the gas.

The subject has received attention in recent years from workers in aerodynamics who are looking for vapours capable of being substituted for the air in supersonic wind tunnels. These should have a low velocity of sound in order that high Mach numbers may be reached without excessive tunnel speeds. Possible vapours for this purpose are the freons and the hexafluorides, and work is going on in the author's laboratory on these vapours, with such aerodynamic applications in view (cf. Fig. 5).

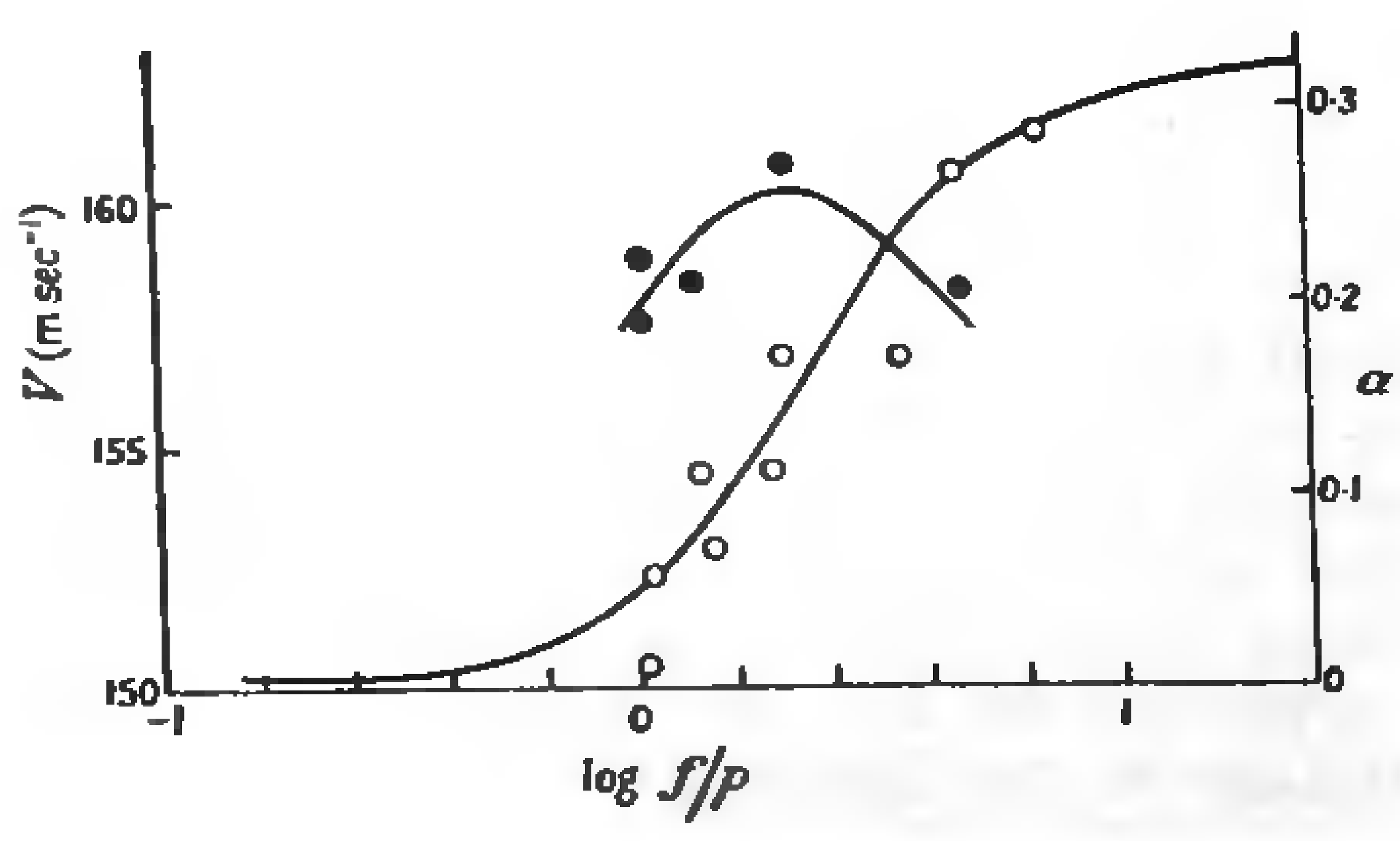

FIG. 5. Variation of velocity of sound V (*o*) and absorption *α* (*o*) in freon exhibited in terms of frequency/pressure.

If, as is apparent, their molecules can relax at lower frequencies than those of oxygen or nitrogen of the atmosphere (which scarcely show relaxation within yet attainable ultrasonic frequencies), then shock waves initiated in them may not properly reproduce conditions in the atmosphere. When a shock wave passes through a relaxing gas, the density does not immediately take up its new value. A photograph taken with an optical interferometer will then show (in the interference bands) the gas adjusting itself exponentially to the new conditions, instead of instantaneously (*cf.* Fig. 6, which refers to carbon dioxide).

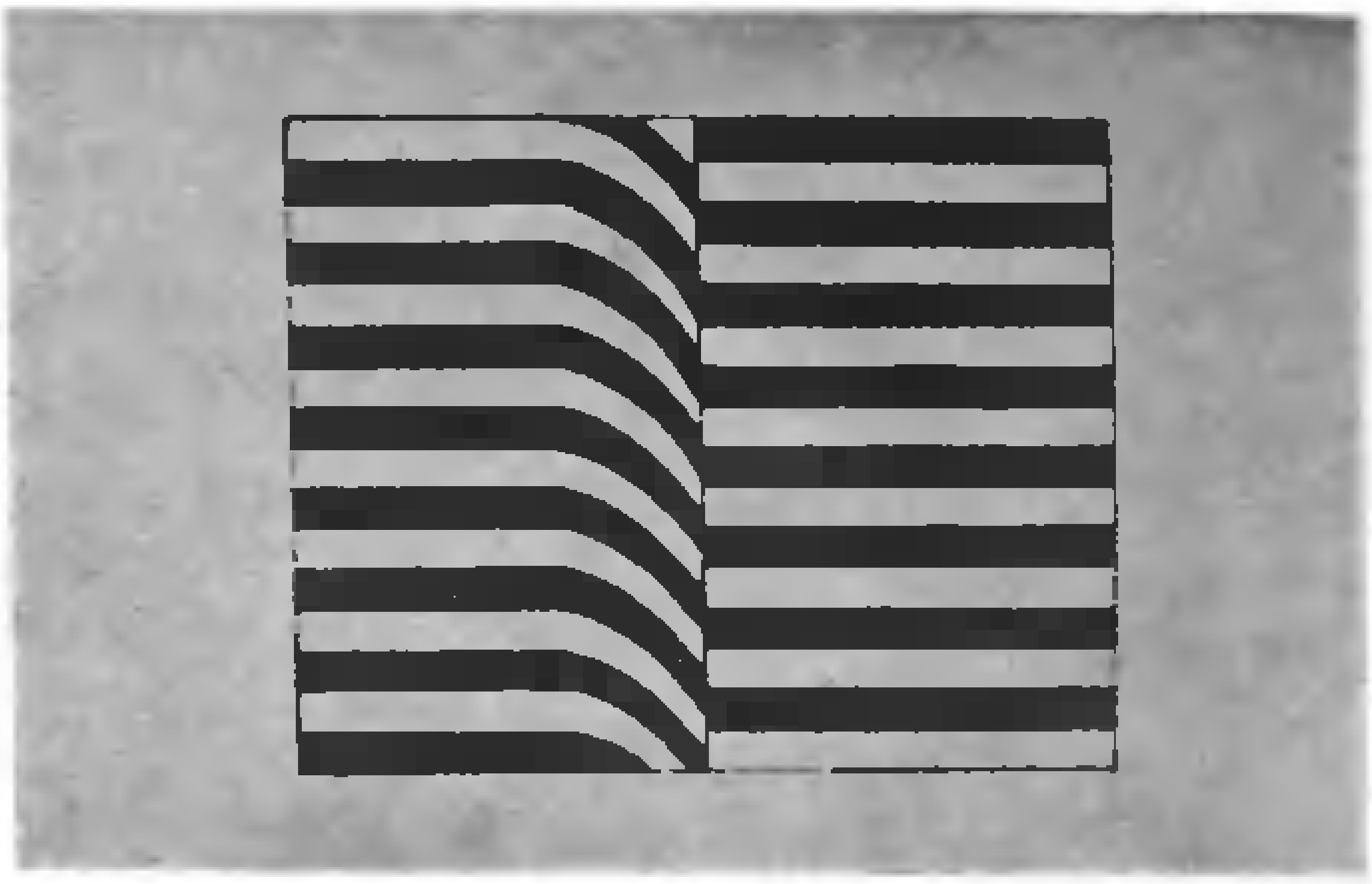

FIG. 6. Passage of shock front in carbon dioxide. The black lines are the diffraction bands seen in an optical interferometer.

In liquids, relaxations in the sense of anomalous absorption accompanied by a rise in velocity of propagation have not been definitely established since, within the limits of precision of present experimental technique, no dispersion of velocity with frequency has been established (except in acetic acid). This is not to say that the attenuation of the wave is normal in the sense that it is proportional to the kinematic viscosity of the liquid in the way that the 'classical' formula of Stokes would have it be. In fact, although in many liquids the quotient; (absorption coefficient)/(frequency)^2 is a constant as it should be (and which precludes relaxation on the simple theory), this constant is in very few cases the Stokesian one, for instance, in benzene it is 600 and in carbon disulphide 1,000 times the expected value on the basis of shear viscosity. It has been suggested by the author that this effect is connected with the ease of formation of cavitation nuclei in these liquids which have high vapour pressures. Others ascribe it to a form of compressional viscosity, peculiar to the propagation of ultrasonic energy.

The molecules of solid bodies, being more restricted in their movements, show usually a spectrum of relaxation times spread over the whole gamut. The disentanglement of these and their ascription to various causes is a major problem to the physical metallurgist and his fellow worker in high polymer studies.

This molecular friction must be related to things which can be directly measured. These are (a) the decrement of amplitude of forced vibrations, and (b) the reciprocal width of a resonance peak under forced vibration. In a number of materials available in the form of cylinders, transverse oscillations may be excited by clamping one end and attaching an iron inertia bar to the other which is then set in motion by external magnets. As the range of frequency of the experiments is raised, the investigator usually replaces flexural vibrations by torsional vibrations. It is often more convenient to vary the temperature than the frequency. In general the internal friction will fall as the temperature rises, though it rises in glass. If there is a relaxation peak in the infrasonic range it will usually shift with temperature, so that at a given temperature the substance will have a loss which represents some point on the peak.

ROCKET-FIRING CONTRIBUTION TO GEOPHYSICAL YEAR

COMPARED with the amount of attention given to satellites, the firing of 120 or so rockets as contributions to the International Geophysical Year has passed largely unnoticed. Yet a preliminary review of the scientific information obtained from 81 research rockets launched by the U.S.A. between July 1, when the I.G.Y. began, and November 30 shows that much of interest has been learnt, especially from northern and Arctic firings.

The American northern firings have been from a rocket base set up by Canada at Fort Churchill on Hudson's Bay. This is more favourably placed than might be supposed. Although no farther north than John O'Groats it is only some 900 miles from the North Magnetic Pole. It is therefore well placed for the study of those effects which are produced on the earth by the arrival of electrically charged particles from the sun ; since, influenced by the magnetic field of the earth, they follow spiral paths towards the regions of the two magnetic poles. Firings within the Arctic circle were made from shipboard, using the "rockoon" method, in which the rocket is fired by radio signals from below a balloon.

Rockoon

A result of the "rockoon" firings was that "an excellent survey was made for the first time of auroral particles"—which are known to include protons, otherwise hydrogen nuclei, ejected from the sun—"and their association with actual auroræ". This is one of several points about auroræ on which there have been gaps in knowledge. In principle it should be possible to correlate the forms and development of auroræ with the distribution of incoming particles. But to do this completely, even for one area, would require a very large number of rockets.

A total of 18 "rockoons" was fired during the American Arctic cruise, and 36 in a similar operation which was carried southwards from the Pacific into Antarctic waters. The southern cruise was, however, completed too late for the present summary.

One object of firings from Fort Churchill was to explore conditions in the ionosphere during a polar radio black-out—an effect which was first established during the International Polar Year of 1932-33 through an expedition led by Prof. Sir Edward Appleton to Tromso, in Norway. Rocket measurements, made apparently by two different methods, have now confirmed that the cause of such sudden lowering of the D-region of the ionosphere—the lowest of the (normally) radio-reflecting regions of the atmosphere.

Other firings had as their object the collection of information about the pressure, temperature and density of the air above Fort Churchill. They were carried out in different months, by night as well as by day, and at heights of up to 125 miles. A general effect was to show that the density of the air at the greatest heights was much more strongly controlled by the sun than above New Mexico, where most previous research rockets have been fired. "There appear to be a latitude effect, a seasonal effect, and a strong diurnal effect; none of these effects appears at lower altitudes at Fort Churchill or at lower latitudes." Temperatures in the stratosphere were found to continue rising up to greater heights—37 miles, compared with about 30 miles—than in lower latitudes.

Another experiment is thought, provisionally, to provide the first evidence of the beginning of a sorting out of the gases of the atmosphere on the basis of density, as height is increased.