A NEW METHOD FOR THE VISUALIZATION AND MEASUREMENT OF ULTRASONIC FIELDS

by

Grant S. Bennett

A THESIS

Submitted to the School of Graduate Studies of Michigan State College of Agriculture and Applied Science in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Department of Physics and Astronomy

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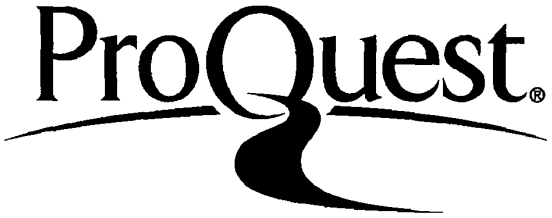

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AN ABSTRACT

Submitted to the School of Graduate Studies of Michigan State College of Agriculture and Applied Science in partial fulfillment of the requirements for the degree of

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Approved E. A. Hiedemann
Major Professor

Existing methods of observing ultrasonic wave fields are discussed and the limitations of each pointed out, together with an indication of why such measurements are of interest. A new method is described which uses starch coated plates in a dilute aqueous solution of iodine in a manner analogous to the use of photographic emulsions for the observation of electromagnetic wave fields. The process depends on the acceleration of the starch-iodine reaction under the action of ultrasonics, and evidence is put forth to suggest that the mechanism of the acceleration is a transport phenomenon. Applications of the new technique are indicated by several near-field diffraction patterns of circular sources at different frequencies and distances, by an edge diffraction pattern, and by a sound shadow picture of a lead plate. Properties of the starch "emulsion" are described by a typical H and D curve as is done photographically. Two existing techniques - the use of phosphors, and the Pohlman cell - are examined in detail, and it is shown that the starch plate method is much more flexible and simple to use, and produces good quality pictures.

The author wishes to acknowledge his indebtedness and express his appreciation to Dr. E.A. Hiedemann who came as head of the Physics Department while this work was in progress, and who has made many suggestions, particularly with respect to the literature, supplying from his own voluminous collection many reprints of papers otherwise difficult of access; to Dr. T.H. Osgood, head of the department when this work was originally undertaken, for encouragement; to Dr. C.D. Hause and Dr. R.D. Spence for their continued interest, many helpful discussions, and the original inspiration for this particular field of investigation.

Grant S. Bennett

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A New Method for the Visualization and Measurement of Ultrasonic Fields

INTRODUCTION

One of the important applications of ultrasonics lies in their use for the investigation of wave behavior on a laboratory scale, made possible by the short wave lengths attainable. This same feature of extremely short wave length, however, introduces problems in measuring techniques. For example, in the range of audible frequencies microphones are used to detect and measure sound characteristics, and the usual rule of thumb is that the detecting device should be of dimensions less than one-tenth the wave length in order that the measuring device should not by its presence distort and destroy the very effect to be measured. Quite obviously at wave lengths of a millimeter or less, as will be attained with sound frequencies in the megacycle range produced in water, such detecting devices are ruled out by sheer size considerations. Even apart from these diffraction effects, for detailed studies of field patterns it is apparent that an instrument large compared with the wave length would not be suitable, since the microphone signal is determined by the average of the measured sound characteristic over the sensitive area. Further, such a technique gives values for points, and a point-by-point

plot is necessary for the determination of the complete field. Keck, Heller and Williams (19) have developed a method in which a pulsed source is rotated about its axis and the signal produced by a stationary microphone is displayed on a cathode ray oscilloscope, giving the directivity pattern of the source. The method is specialized to this one type of measurement, obviously. Such considerations as indicated above have lead to the development of different techniques for the observation of ultrasonic fields, taking advantage of effects peculiar to the high frequency range. In general, these methods give a picture of the entire field, in much the same sense that a photographic plate gives a picture of the electromagnetic wave field, in which relative magnitudes are discernible readily, and absolute magnitudes are usually somewhat difficult to obtain. Some of these methods will be discussed below, classified as to the effect of the ultrasonic wave utilized, and particular attention will be given to the limitations of each. The latter part of the paper will describe a new method for such observations which avoids many of these difficulties, and which is applicable for the visualization of ultrasonic fields in liquids - in particular, water or aqueous solutions.

Optical Methods

Optical methods for the observation of ultrasonic fields have been very extensively developed, one advantage being that the measuring instrument - a light ray - most certainly will have no perturbing influence on the sound wave. All optical methods depend for their operation on the changes in the index of refraction of the medium resulting from the variations of density in the sound wave. Perhaps the simplest of the methods is the spark shadowgraph arrangement, in which light from a short duration spark is rendered parallel and passes transversely through the sound wave. The light is deviated from the regions of low index, and there results what appears to be an instantaneous shadow picture of the ultrasonic wave. Hubbard, Zartmann and Larkin (18) have used this technique to study diffraction in air, and it is also applicable to liquids. One of the experimental difficulties lies in the production of a sufficiently intense, sufficiently short duration spark source. The class of optical methods known generally as schlieren techniques is subject to many variations experimentally, but depends on the fact that the periodic variations of index of refraction in the sound wave constitute a phase grating, and the light in the diffraction orders is a function of the diffractor. For example, in the case of a simple, thin grating the light in the nth order represents the

grating characteristics in a manner peculiar to it, and differently than the other orders, such that if the diffracted light be allowed to recombine, one obtains an image of the diffractor. The sound wave is not a thin grating, and furthermore it is moving, so that the simple theory does not apply; still it is represented by the diffracted light. Hiedemann and coworkers (15, 16, 17, 24) and at about the same time Bär (1) have investigated and developed this type of measurement extensively, using a variety of techniques, The zeroth order may be blocked out, the zeroth order only may be used to form an image, single orders may be used to view the field, or various combinations of orders, each arrangement resulting in a slightly different aspect of the sound field. Hiedemann's "method of isochromats" utilizes white light and a single order to produce a colored image of the field in which areas of the same color correspond to areas of constant amplitude, hence the name. The Mach-Zehnder interferometer is used for the observation of shock waves, and has been used by Timbrell (30) for the absolute measurement of pressure in a plane wave, but seems less well adapted to the visualization of the complete sound field. These optical effects can be classified in terms of the acoustical quantity operative - the interferometer measures pressure directly, the <u>schlieren</u> method responds to pressure gradient, and the shadowgraph depends on the

second space derivative of pressure.

All the above methods suffer from a common disadvantage- namely, the light traverses the cell in a direction transverse to the direction of the sound wave, and the region of optical effect is one of considerable depth. Hence if the sound field is not completely uniform laterally there is serious question as to just what the image represents. Since the usual case corresponds approximately to axial symmetry, these techniques can be only indicative of the field pattern. Hiedemann and Osterhammel (16, 17, 24) have avoided this situation by use of a quartz source which is long and narrow, corresponding to a slit source, the field of which was observed by means of light travelling parallel to the long dimension of the quartz bar. The same technique could, of course, be applied to the other methods, but they do not represent general procedures for obtaining field patterns. Schaafs (29) has used the schlieren method for observation of the vibration of crystals, sending the light through the quartz in the direction of the sound wave, but the same lack of homogeneity of index variation in the direction of light travel renders this technique difficult of interpretation in terms of the sound field.

Other Methods

Optically, diffraction patterns are obtained as the transverse section of the beam, rather than as longitudinal

sections. For this reason, as well as the desirability of of examination of shadows cast by obstacles, one is lead to seek methods for observing the transverse section of the sound field. Ultrasonic waves have long been known to exhibit certain effects peculiar to the high frequency range as well as the phenomena of audible sound. Among these are a dynamical [illegible] or Rayleigh disk effect, the acceleration or initiation of certain chemical reactions, thermal effects resulting from the high intensities readily attainable at high frequencies or from the absorption of short wave length sound, and certain other effects whose origins are difficult to catalogue. All of these types of effect have been used to indicate ultrasonic wave field distributions.

The Rayleigh disk effect, long used for the absolute measurement of sound intensities, is manifest as the property of a small, flat disk to align itself normal th the direction of the sound wave. Pohlman (26, 27, 28) has taken advantage of this property in his image converter cell, a thin circular cell having a back of thin metal, a front of glass, and containing a suspension of fine aluminum flakes in xylene. The cell is illuminated from the front, and because of the random orientation of the Al flakes the light is reflected diffusely. If, now, a sound wave enters the cell through the thin metal back, the flakes in the field

are oriented normal to the direction of sound travel, and specular reflection takes place. The sound field is thus made visible, and the pattern appearing in the cell can be photographed. This method will be discussed in more detail below, as it is one of the techniques scrutinized in this work.

Marinesco, observing that the light sensitive Eder reaction was equally well initiated by ultrasonic waves took the logical step of studying the action of ultrasonics on photographic plates, and found that a latent, developable image was produced. Ernst (9) and Bennett (2) have applied this phenomenon to the observation of sound fields, Ernst using the longitudinal section and Bennett the transverse section. The basic causes for the ultrasonic image production are not yet completely understood. Pinoir and Pouradier (25) are of the opinion that the exposure is due to the luminescence of bubbles of dissolved gas, although this opinion is not universally held. Marinesco originally attributed the effect to the activation of the silver atoms by collision. This method requires sound waves of relatively high intensity, and long exposure times - of the order of an hour - are necessary. Further, the customary photographic precautions must be observed. The long exposure to the sound beam produces thermal effects in the gelatin, in some cases resulting in an actual melting, and in the writer's opinion having to do with the formation of the image.

Schreiber and Degner (30) and almost simultaneously Eckardt and Lindig (8) have used phosphors for the visualization of the ultrasonic wave. The technique is essentially identical with that of infra-red phosphors - the phosphor (e.g, ZnS with Cu as activator) is excited with ultraviolet light and after a short decay period is subjected to the ultrasonic beam. The acoustic energy absorbed by the phosphor and s supporting film appears as heat and accelerates the phosphorescent decay, so that the areas upon which the sound is incident appear bright against a less brilliant ground. If, now, the sound be turned off before the decay is complete, the previously bright areas appear darker than their surroundings as a result of the "unloading"of the stored-up energy. The patterns may be photographed in the conventional manner, or a contact "print" may be made on a piece of cut film applied directly against the phosphor. This method will also be discussed in more detail below. Ernst and Hoffmann (10) have reported the use of various thermally sensitive substances for the observation of sound fields. For example, they have used pigments which change color at a given temperature, etc, as well as phosphors. Most of the changes are apparently reversible, so that photography is necessary to obtain a permanent record. Dognon and Simonot (5, 6, 7) have investigated thermal effects, although none of their results appear to be directly applicable to the present problem.

Many direct chemical effects of ultrasonic waves have

long been known (see Bergmann, ref. 3, chap. V) and there has been continued interest in the underlying principles of such action. Typical reactions are the production of free iodine from KI, the liberation of Cl_2 from aqueous solutions of CCl_4, the formation of MnO_2 from $KMnO_4$, etc. In every case the effect is as if the ultrasonic wave were an oxidizing agent. Investigators agree that intensities of cavitation magnitudes are required, and the reactions take place only when certain gases are present in solution. A. Kling and R. Kling (20) have shown the presence of hydrogen peroxide in previously pure, oxygen saturated water after ultrasonic irradiation, and evidence of ozone. If air be the dissolved gas rather than oxygen, one obtains oxygen-containing compounds of nitrogen. Grabar and Prudhomme have reported (12) similar researches with similar results. Weissler, Cooper and Snyder (33) have investigated the liberation from KI of free iodine in a solution containing CCl_4, and conclude that the liberated I is primarily an indicator of the free chlorine produced. Frenkel (11) has proposed a theory for the chemical action of ultrasonic waves based on the electric charge that may result when a bubble is formed due to the statistical fluctuations in the distribution of ions. He concludes that a sufficiently strong electric field may be produced in the bubble to result in a discharge through the vapor, producing active radicals either directly, or indirectly

through the action of the light accompanying the discharge. The difference in behavior of different dissolved gases results, then, from the differences in vapor pressure and and electrical properties of the vapor in the bubble. Bresler (4) has reported experiments which he feels confirm completely the theory of Frenkel. Griffing (13) on the other hand, has proposed a theory for the chemical action predicated on the very high temperatures possible in the bubble. These temperatures, possibly of the order of several hundred degrees Centigrade, give rise to large thermal gradients in the liquid in the immediate vicinity of the bubble, thereby producing the chemical reaction. According to this theory the action depends on the thermodynamical properties of the gas, the temperature being determined by the ratio of the specific heats through the term $(\gamma-1)$ and the thermal gradient in the liquid depending on the thermal conductivity of the vapor. Weissler (32) has pointed out, however, that certain effects are not explained by this theory, and suggests that the rate of collapse of the bubbles has some influence. To the writer's knowledge, such direct, irreversible chemical changes have not been applied for the observation of ultrasonic field patterns, although the liberation of free iodine sounds interesting because of its positive effect on starch. Haul, Studt and Rust(14) have used a plate carrying a grid in which was imbedded

starch for the measurement of the quantity of iodine liberated, and have investigated the action in various solutions.

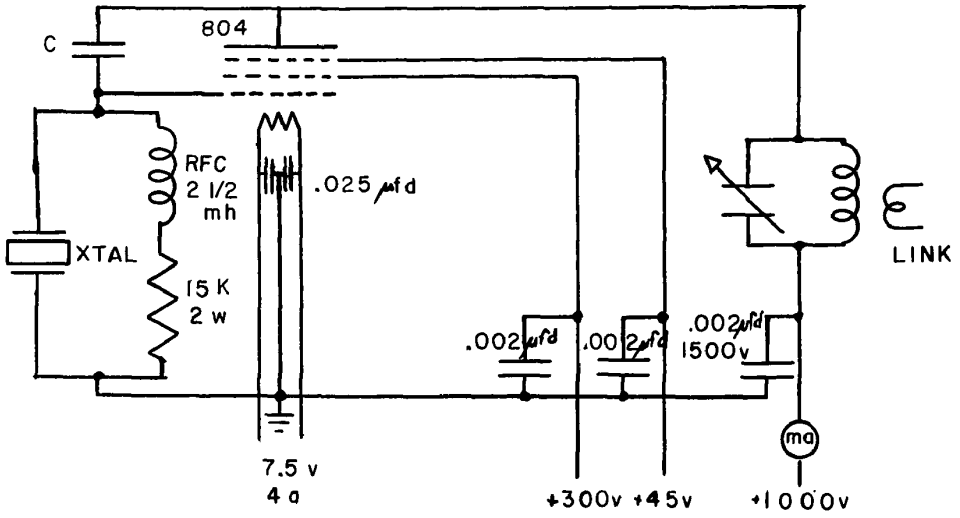
An ultrasonic wave of less than cavitation intensity may influence the rate of reaction, as has been known for the starch-iodine reaction, which is accelerated in the presence of the sound wave. This effect immediately suggested itself in the search for an acoustic analogue to the photographic process, and it is with the techniques and results of the development of such an analogy using the starch-iodine reaction that this report will be concerned. Comparisons will be made with other methods, specifically the Pohlman cell and the phosphor technique, from the standpoint of ease of obtaining results, possibilities, and quality of records. The technique to be described will be shown to be much simpler and flexible in manipulation than either of the methods mentioned, and to result in pictures as good as or better than the phosphor technique at somewhat lower sound intensities. The near-field, or Fresnel, diffraction patterns of transducers will be used as a basis of comparison, and certain other applications will be indicated.

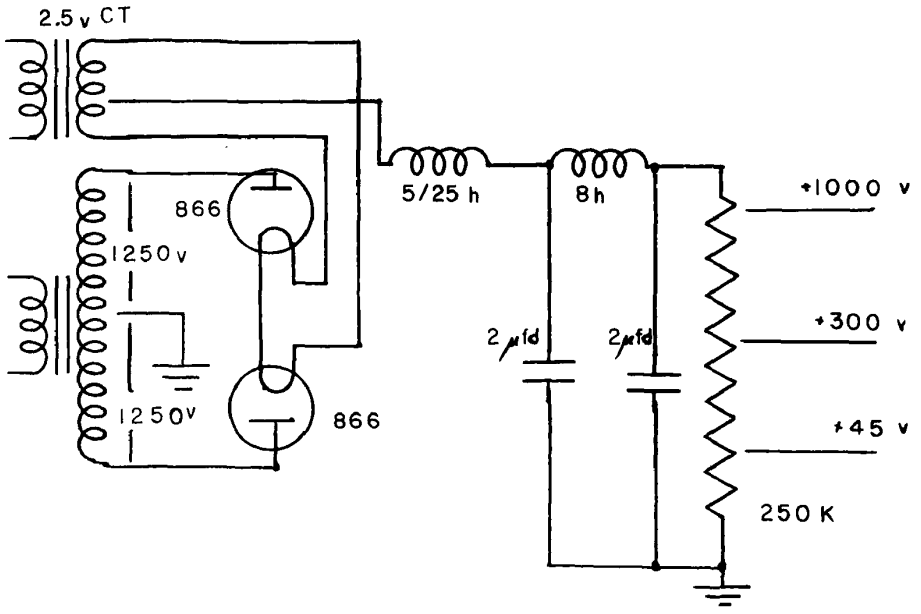
THE STARCH PLATE TECHNIQUE

Apparatus

Barium titanate ceramic disks were used for this work. These transducers are commercially available in several frequencies and sizes with electrodes and leads attached. This type of transducer is of low electrical impedance, has a rather broad resonance, and the electromechanical coupling factor is higher than for most piezoelectric materials. For these reasons the ceramic transducer is somewhat simpler to handle circuitwise, and makes available higher acoustic intensities than a quartz source operated from the same circuit. The transducer was driven by a crystal controlled oscillator using a type 804 pentode tube. The nominal output power of this circuit is about 50 watts. An assortment of control crystals and tank coils makes available frequencies in the range 0.5 - 9 megacycles per second. The circuit diagram is shown in Fig. 1. The transducer proper is coupled to the tank circuit of the oscillator by means of a link coupling and appropriate matching circuit. A high impedance transducer such as quartz must be connected in parallel with a resonant circuit terminating the link, while the barium titanate requires only a parallel capacitance in place of the second tuned circuit. The very high Q of quartz requires a very careful match between control crystal and transducer with respect to resonant frequencies, while the

Fig. 1
OSCILLATOR CIRCUIT





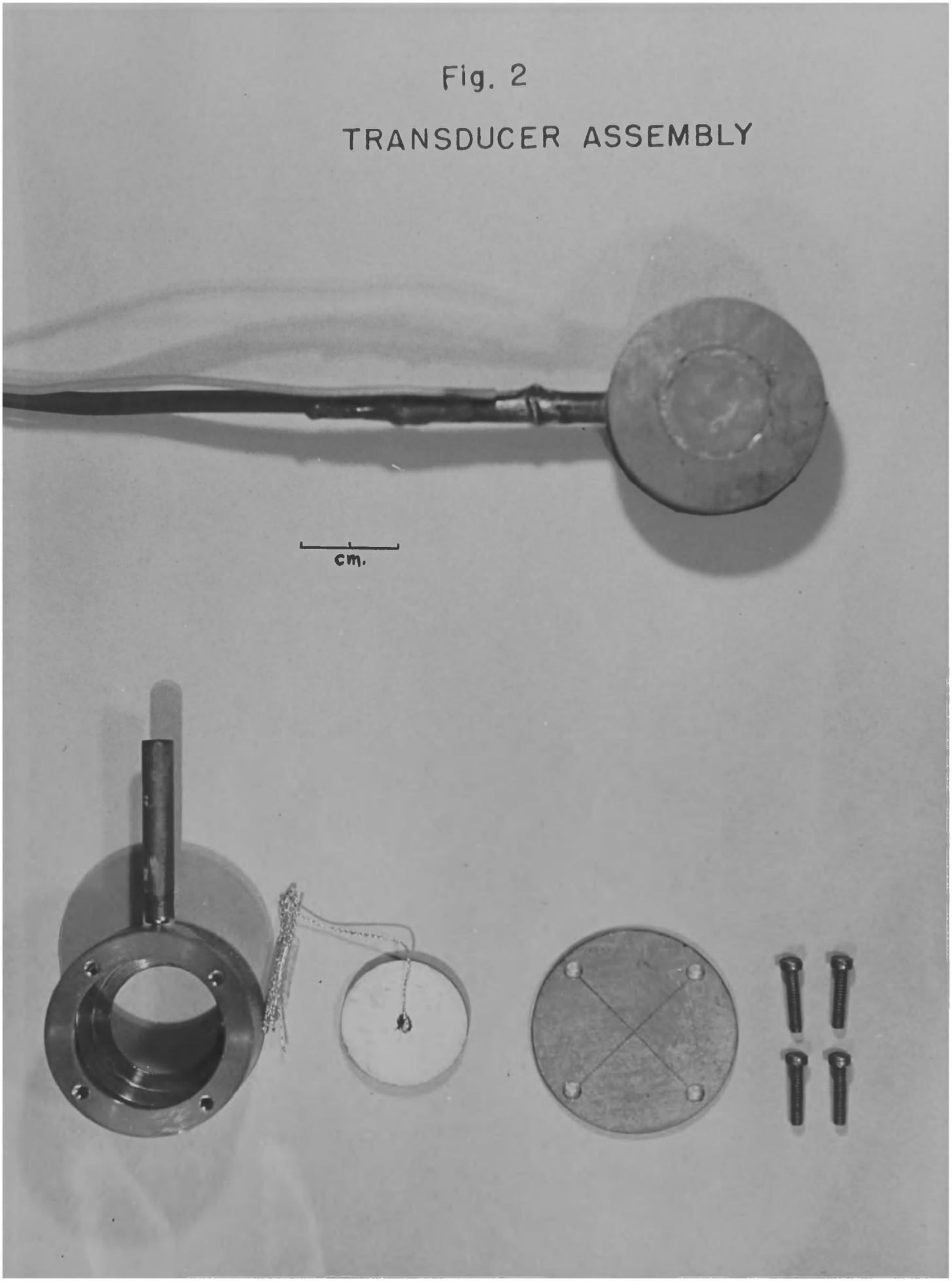
resonance curve for the titanate ceramic is sufficiently broad that this careful match is not required, Ceramics used here were of nominal frequencies 1, 2.5, and 5 mcy/sec, and were driven at 1.073, 2.390, and 4.970 mcy/sec. respectively, representing the frequencies of control crystals closest to the nominal transducer frequencies.

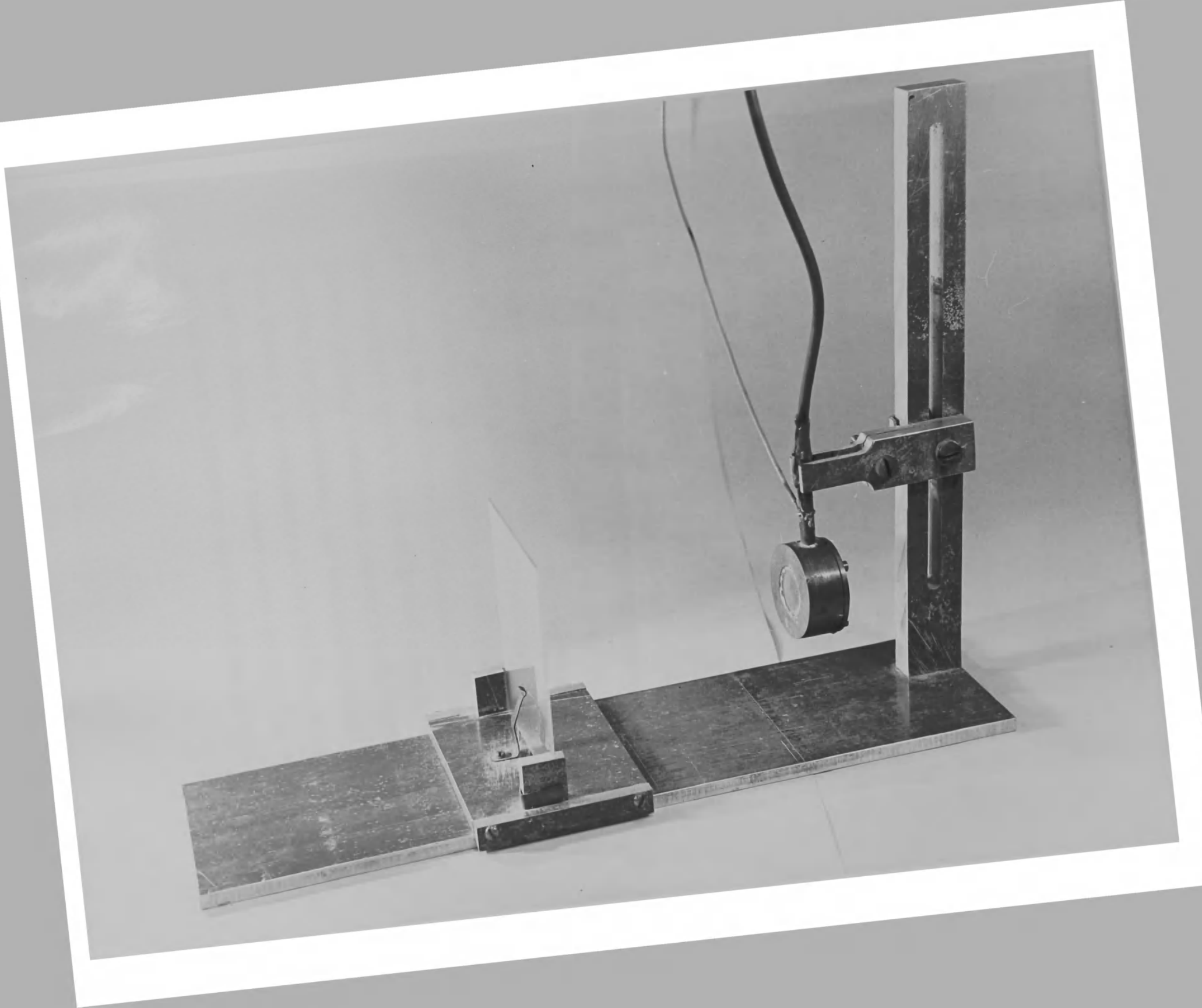
Since the work was to be done in water, and since it is desirable to have as much of the acoustic energy as possible in a single beam, the transducers were mounted so that one face was in contact with the water, and the other with air. Because the acoustic impedance of the water is much closer to that of barium titanate than is the case for air, by far the greatest part of the energy goes into the liquid. Fig. 2 shows the details of the transducer mounting. The transducer disk proper was cemented into the recess provided with Amphenol liquid polystyrene coil dope, which, of the various methods tried, proved to be simple and satisfactory. The brass shell and the water serve as the ground connection, and the high potential lead is brought in to the rear face of the disk through the stem, which is sealed with red wax or other material.

The transducer unit was mounted in a holder as shown in Fig. 3, which also provided a holder for the plate which could continuously be adjusted for distances from less than one centimeter to about 40 centimeters from the transducer. The complete

Fig. 2

TRANSDUCER ASSEMBLY





mounting was adjusted outside, then immersed in a tank containing about five gallons of water for the exposure.

Preparation of Plates

In the first attempts to make starch plates it was thought necessary or desirable to provide a carrier for the starch. For this reason a gelatin solution was prepared, to which was added the dissolved starch. Many different combinations of proportions were tried, with no particular differences in results. Shortly it was found that the gelatin was not necessary, the cooked starch forming a satisfactory "emulsion" itself. As a matter of fact the gelatin showed a strong tendency to dry out hard and brittle, cracking and peeling off the glass plate. The starch originally used was reagent grade, obtained from the Chemistry Department, and made very satisfactory plates. This particular bottle was exhausted, and the next starch obtained, although meeting the same general specifications, was found to be unsatisfactory. In almost every case the starch layer did not adhere to the glass, and cracked. Many varieties of starches were tried - reagent grade, corn starch, household laundry starch, commercial laundry starch having a fat additive for smoothness, and household liquid starch * and none formed a satisfactory plate. The liquid starch did not crack on drying, but formed large grains. The final mixture adopted uses a little of the liquid starch together with

the cooked starch to take advantage of the preservative in the liquid starch, and the combination produces very satisfactory plates. It was found that if the starch mixture were irradiated with ultrasonics before heating the entrained air was driven out, and the starch more finely dispersed, resulting in smooth, uniform plates.

While there seems to be nothing critical about the kind of starch, proportions, or treatment, current practice is as follows: 10 g. of starch (dry) is mixed into 200ml of water to which is added 10ml of liquid starch; the mixture is irradiated with 5 mcy/sec. ultrasonics for about four minutes, after which the mixture is heated over hot water to 78°C; the hot solution is poured onto clean glass plates and allowed to cool, after which the plates are ready for use. Lantern slide cover glass plates were used, and of course they must be kept level until the starch has hardened.

Preparation of Solution

A stock solution of iodine was prepared by dissolving 30g. of iodine crystals in methyl alcohol to make one liter, and appropriate amounts of this solution added to the five gallons of water normally used in the tank. For most of the work reported 100ml of iodine solution was used, although again the amount is not critical. The more iodine in the tank, the more the plate as a whole darkens. Except for the extreme case where the whole plate darkens completely, there seems

to be little variation in contrast with the quantity of iodine used.

General Discussion of Technique

The mounting shown in Fig. 3 was designed to facilitate pictures of the transverse section of the sound field. In typical operation the whole mounting was removed from the tank, the necessary adjustments made, the plate inserted in the plate holder, and the complete system replaced in the tank. The transducer is energized for the proper length of time - usually of the order of one to three minutes - the mounting removed and the plate extracted. The only treatment of the plate required is that it be washed off and allowed to dry.

Plates made and exposed in the manner described show a tendency to fade in time. It has not been possible to correlate the time of fading with any other variable, although on the whole the more intense the darkening the longer the plate lasts. In general the plates are usable for a matter of weeks after exposure, although some lightly exposed plates have faded in a day. For most purposes the time is sufficient, but a truly permanent record can be easily made by contact printing onto photographic paper. Since the starch plates show somewhat less contrast than photographic emulsions, it is frequently desirable to use

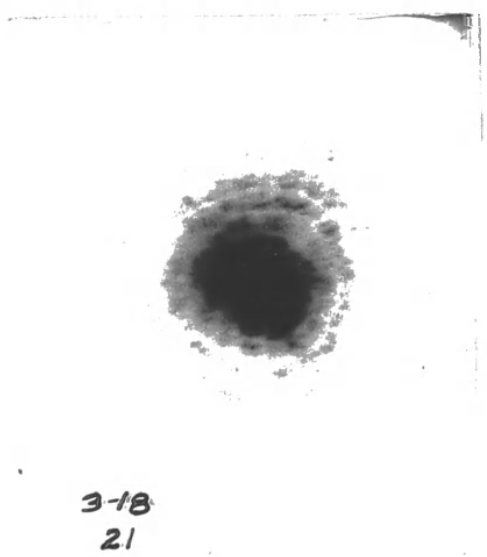
#4 or #5 paper for the prints. These first prints can then be used in turn for second prints, which are then positives with respect to the original plate. Of course, a certain amount of detail is lost in the reproduction process, so that quantitative measurements should be made on the starch plate. Fig. 4 shows the three types of record photographed together. It should be pointed out that the loss of detail in the second print is usually not as severe as indicated here - in this case the copy work was done to bring out detail in the original plate. Succeeding figures show positive prints of the sound field under various conditions, with pertinent information given for each. Fig 6d is the second print used for the photograph of Fig. 4.

Discussion of Results

The photosensitive properties of photographic emulsions are described by Hurter and Driffield curves, in which the density is plotted as a function of the logarithm of the exposure. Exposure is defined as the product of light intensity and exposure time, and density is defined as the logarithm of the ratio of the incident light intensity to the light intensity transmitted by the emulsion. In each case the logarithm to the base ten is used. The resulting typically sigmoidal curves indicate the range of exposure

Fig. 4

STARCH PLATE and PRINTS



STARCH PLATE

FIRST PRINT

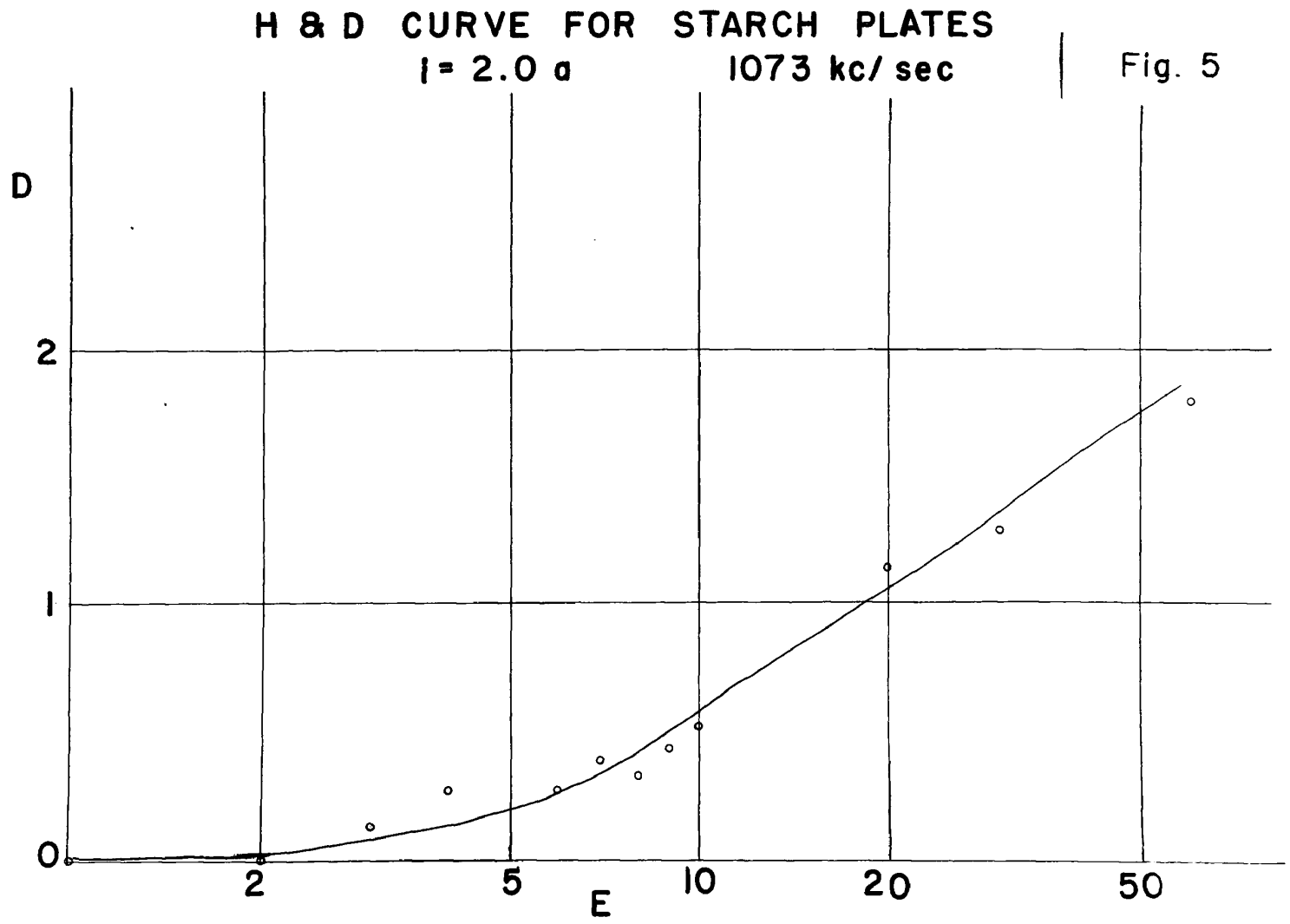
SECOND PRINT

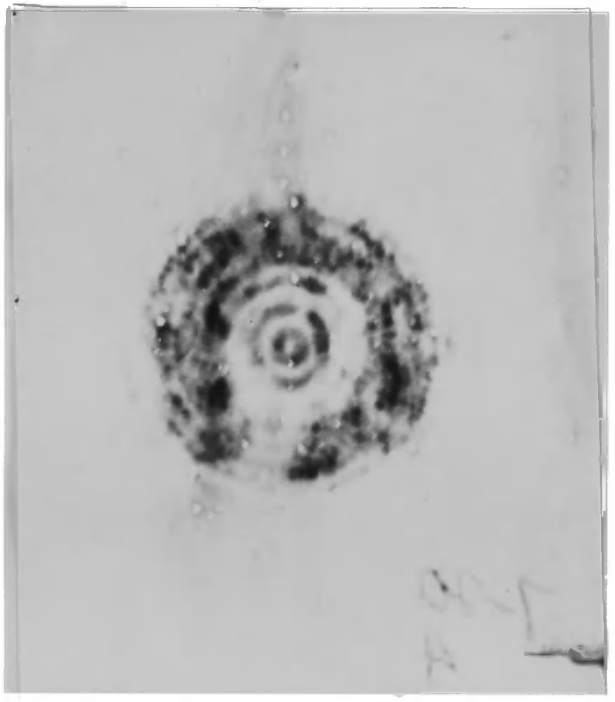
for the emulsion by the position of the steeply ascending portion, and the slope of the approximately linear portion gives the contrast index, or "gamma". Marinesco and coworkers used a large aperture densitometer in their work with photographic emulsions in the sound field, and showed that the average densities so obtained exhibited the same general relationship to ultrasonic exposure as to light exposure when a dilute solution of developer was used as the sound transmission medium in which the plate was immersed. They even observed the phenomenon of reversal, or solarization, for very long exposures.

It seemed obvious, then, to investigate the characteristics of the starch plates in the same fashion. In the absence of precise information as to the sound intensities the exposure was taken as the product of transducer current and exposure time. Under similar conditions of position and transducer current plates were exposed for varying times, and the density of each read on the Ansco-Sweet densitometer at some convenient common position, usually the central dark spot. In each case an average or typical background density was determined and subtracted from the value for the point in question. Such readings were made on plates of different batches, on the same plates over an extended time to determine the effect of fading, for different transducers, and for different transducer currents. While the position of the curves along the abcissa varied

for each set of conditions because the sound intensities were not known quantitatively, all curves showed about the same shape, and all gave a gamma of about two. No curve was carried so far as to show the shoulder, since the starch "emulsion" showed a tendency to break up under prolonged exposure. One would certainly expect a saturation effect to exist, and perhaps if higher intensities were available, allowing of a large exposure at short times, this part of the curve could be shown. Fig. 5 gives a typical curve for starch plates.

Figs. 6a-6h show a variety of near-field or Fresnel diffraction patterns for different transducers and frequencies. It is not to be expected that these patterns be interpretable in terms of a piston source, since no attempt was made in the design of the transducer shell to obtain such behavior. The patterns do, however, look like what might be expected for a circular source. It should be noted that these figures represent fields much closer to the source than are possible optically - in certain cases the pictures were made at distances of 6-7 wave lengths. The theory of such very near field patterns is currently of interest, and such pictures as shown here should be of assistance in verifying such calculations.


H & D CURVE FOR STARCH PLATES
I = 2.0 a
1073 kc/ sec
Fig. 5
D
2
1
0
2
5
10
20
50
E

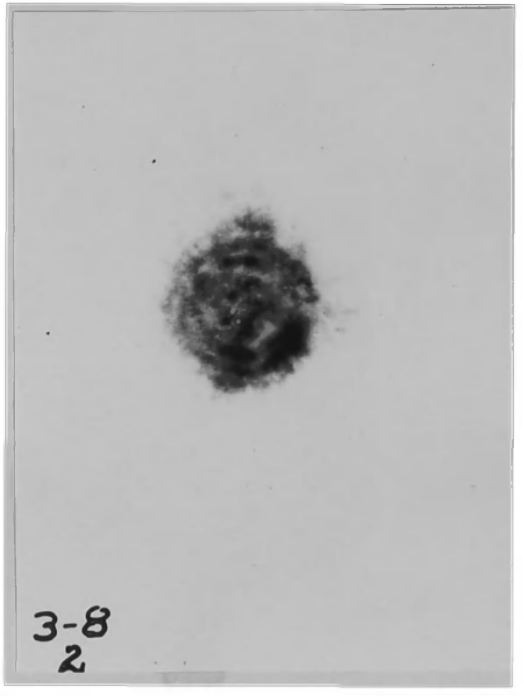


(a)

1073 kc/sec. 100ml iodine sol'n

4 cm. from 4.81 cm. diameter transducer

Exposure time 1 min. at 1.55 amp.



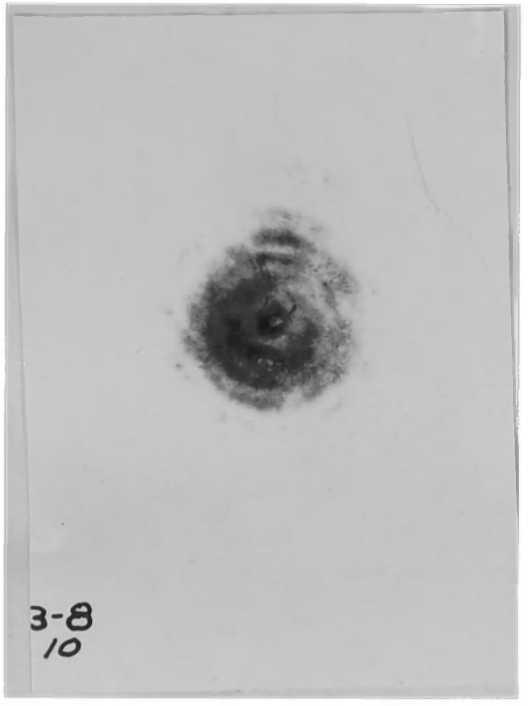
(b)

1073 kc/sec. 50ml. iodine sol'n

2 cm. from 2.88 cm. diameter transducer

Exposure time 2 min. at 1.25 amp.

Fig. 6

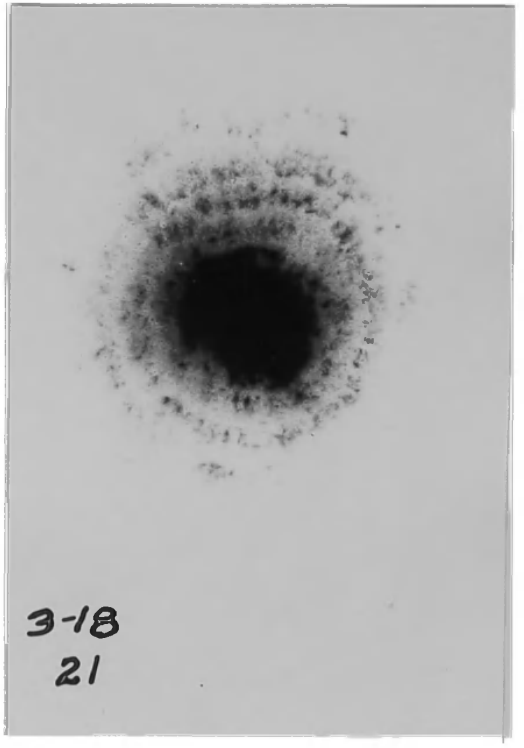


(c)

1073 kc/sec. 50ml. iodine sol'n.

3 cm. from 2.88 cm. diameter transducer

Exposure time 2 min. at 1.25 amp.



(d)

1073 kc/sec. 50ml. iodine sol'n

5 cm. from 2.88 cm. diameter transducer

Exposure time 10 min. at 0.65 amp.

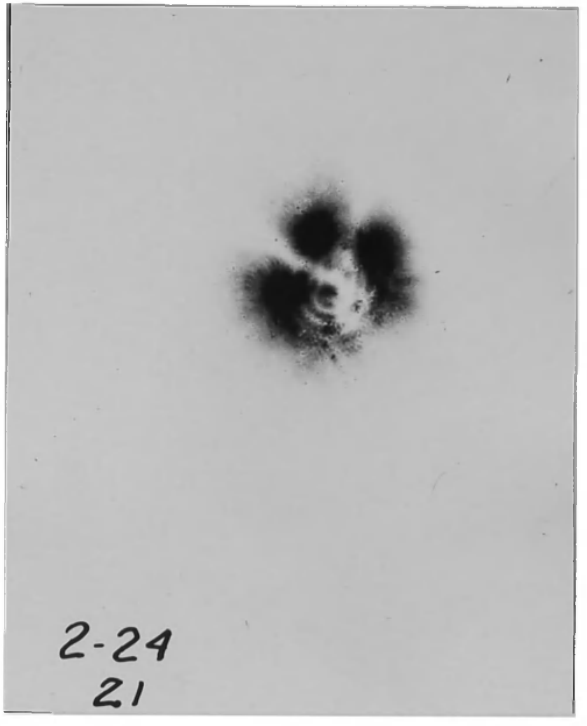
Fig. 6 (con.)

(e)

2390 kc/sec. 100ml. iodine sol'n.

3 cm. from 1.99 cm. diameter transducer

Exposure time 3 min. at 2.0 amp.



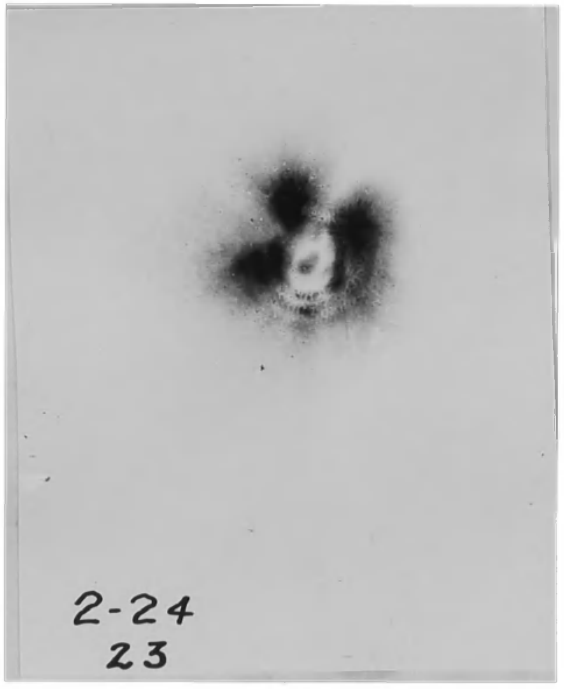
(f)

2390 kc/sec. 100ml. iodine sol'n.

3.8 cm. from 1.99 cm. diameter transducer

Exposure time 3 min. at 2.0 amp.

Fig. 6 (con.)

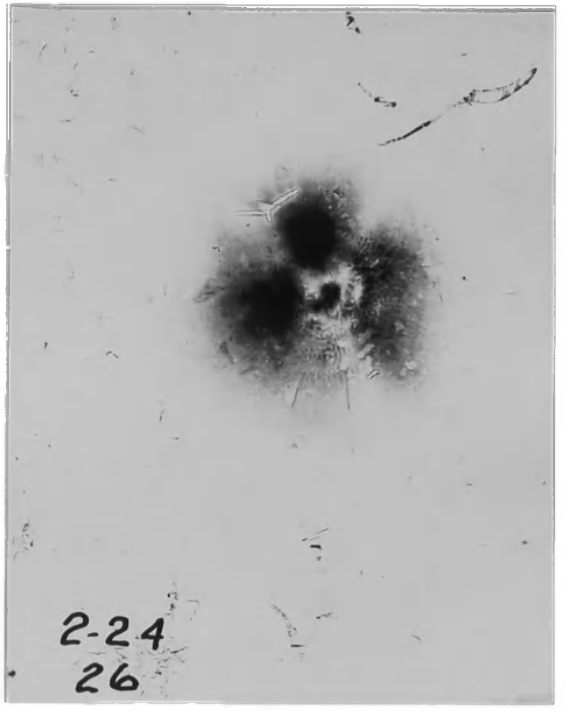


(g)

2390 kc/sec. 100ml. iodine sol'n.

4.5 cm. from 1.99 cm. diameter transducer

Exposure time 3 min. at 2.0 amp.



(h)

2390 kc/sec. 100ml. iodine sol'n.

5.5 cm. from 1.99 cm. diameter transducer

Exposure time 3 min. at 2.0 amp.

Fig. 6 (con)

Because of the small diameter of the main beams produced by the sources used the observation of such phenomena as diffraction by obstacles and apertures is somewhat difficult. Fig. 7 shows an edge diffraction pattern, where a lead plate about 2mm. thick served as the diffractor. Fig. 8 shows the image of a similar lead plate with holes of different diameters drilled in it. To avoid both the near-field diffraction and diffraction at the holes, and because the sound beam was not extensive enough to irradiate the whole plate, the transducer was moved about behind the lead sheet, which was placed close to the starch plate. This gives, then, essentially a shadow picture of the sample. Obviously, in order to get the proper exposure time of, say, two minutes on a given portion of the plate the total exposure time must be much longer, depending on the relative size of beam and sample.

Rather simple experiments indicate that the acceleration of the starch-iodine reaction, and the mechanics of image formation as used here, is a transport phenomenon, the sound field serving to carry fresh iodine to the plate and thus maintain the process. For example, a screen of sound transparent material was placed in front of the plate to shield it from the unidirectional liquid flow associated with the sound wave. The action on the starch was much less

Figure 7

Vertical lead plate edge 20.5 cm. from 2390 kc/sec. source. Exposure time 8 min. at 1.95 amp

Figure 8

Lead plate with holes .093", .136", .213" and . 328" diameter from left to right. Irradiated total of 5 min. at 0.85 amp, 1073 kc/sec. 160ml. iodine, source moved.

marked than without the screen, and if the solution were stirred relatively gently by hand during the exposure the whole plate darkened and the area of sound incidence could not be distinguished. Without the screen and in a stronger sound field, stirring did not obliterate the pattern, but the plate was darkened and the lines of the pattern tended to be smeared out.

All of the evidence indicates that the technique described, using starch plates in a weak solution of iodine, provides a new, convenient, and valuable method for the study of ultrasonic field patterns in the laboratory. For purposes of comparison with other methods similarly applicable, the phosphor technique and the Pohlman cell were investigated, as described below.

THE PHOSPHOR TECHNIQUE

Experimental Arrangement

The procedure followed was essentially that described by Eckardt and Lindig (8). Although Schreiber and Degner (30) exhibited somewhat better pictures, their description of experimental details is scanty; however, it appears that the methods of the two groups were similar. In this work, the phosphor in the dry form was mixed with a suitable carrier and laid down on a thin diaphragm to form the sonosensitive element. Duco cement thinned proved very

satisfactory as the carrier, and thin phodphor bronze was used as the backing. The metal apparently served as well as the photographic film base originally used, and had the advantage of not softening under the action of the acetone. This phosphorescent screen formed a boundary of the liquid container, or was placed at the surface of the water in the large tank, so that the phosphor was outermost and the sound was incident on the backing. The phosphor was irradiated with the unfiltered light from a laboratory high pressure mercury arc, allowed to decay for 20-30 seconds, and the sound turned on. In a few seconds the areas of sound incidence were made apparent by the increase in brightness as the release of the stored up energy was accelerated by the heating effect of the sound wave. If the sound is removed before the decay is complete, those areas which were bright appear darker than their surroundings since their energy has been depleted. In principle the patterns can be photographed in the usual way, or contact "prints" can be made by application of a piece of cut film directly to the phosphor. The writer was unable to obtain photographs with the modified Polaroid-hand camera used because of the very low light intensities. The camera modification consisted of the attachment of an

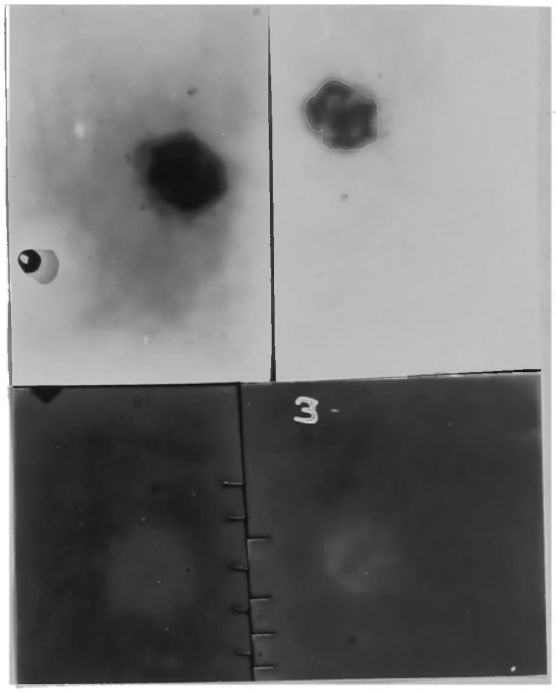
auxiliary lens for closer work than allowed for on the camera alone.

Discussion of Results

Fig. 9 shows records obtained by the contact process. These are similar to those published by Eckardt and Lindig, no structure being apparent. Schreiber and Degner exhibit results similar but inferior to those of Fig. 6 by the starch plate method, but give no indication of the sound intensities required. Eckardt and Lindig report the use of 70 watts input, which is a little higher than used here. It might be presumed that at sufficiently high intensities the secondary lobes would show up. The writer has also observed at times a "growth" of the pattern, as might be anticipated for a thermal effect. For fairly high beam energies a self-reversal of the pattern has also been produced.

It has been the writer's experience that the time of irradiation by the ultraviolet light is not at all critical, but that the longer the phosphorescence is allowed to decay before application of the sound the better is the contrast. Several commercially available phosphors were tried, the only ones suitable from the standpoint of decay time and intensity of effect being the green and yellow luminescing sulphides of zinc, activated with copper and manganese

(a)



(b)

(c)

(d)

Phosphor Technique

1073 kc/sec.

(a) and (b) are exposures made after the sound field was turned off, and the beam is indicated by the dark areas. (c) and (d) are exposures made during sound irradiation, and the beam is indicated by the light areas. Eastman Super-Panchro press type B film was placed in immediate contact with the luminescent screen

Figure 9

respectively.

This method requires that the phosphorescent screen be optically accessible from outside the tank, requires initial excitation of the phosphor, and photographic techniques must be used at the time of observation for the production of a permanent record. The method has not been shown to produce results of quality comparable to those obtained with the starch plates, and apparently somewhat higher intensities are required for any semblance of a pattern.

THE POHLMAN IMAGE-CONVERTER CELL

Experimental Arrangement

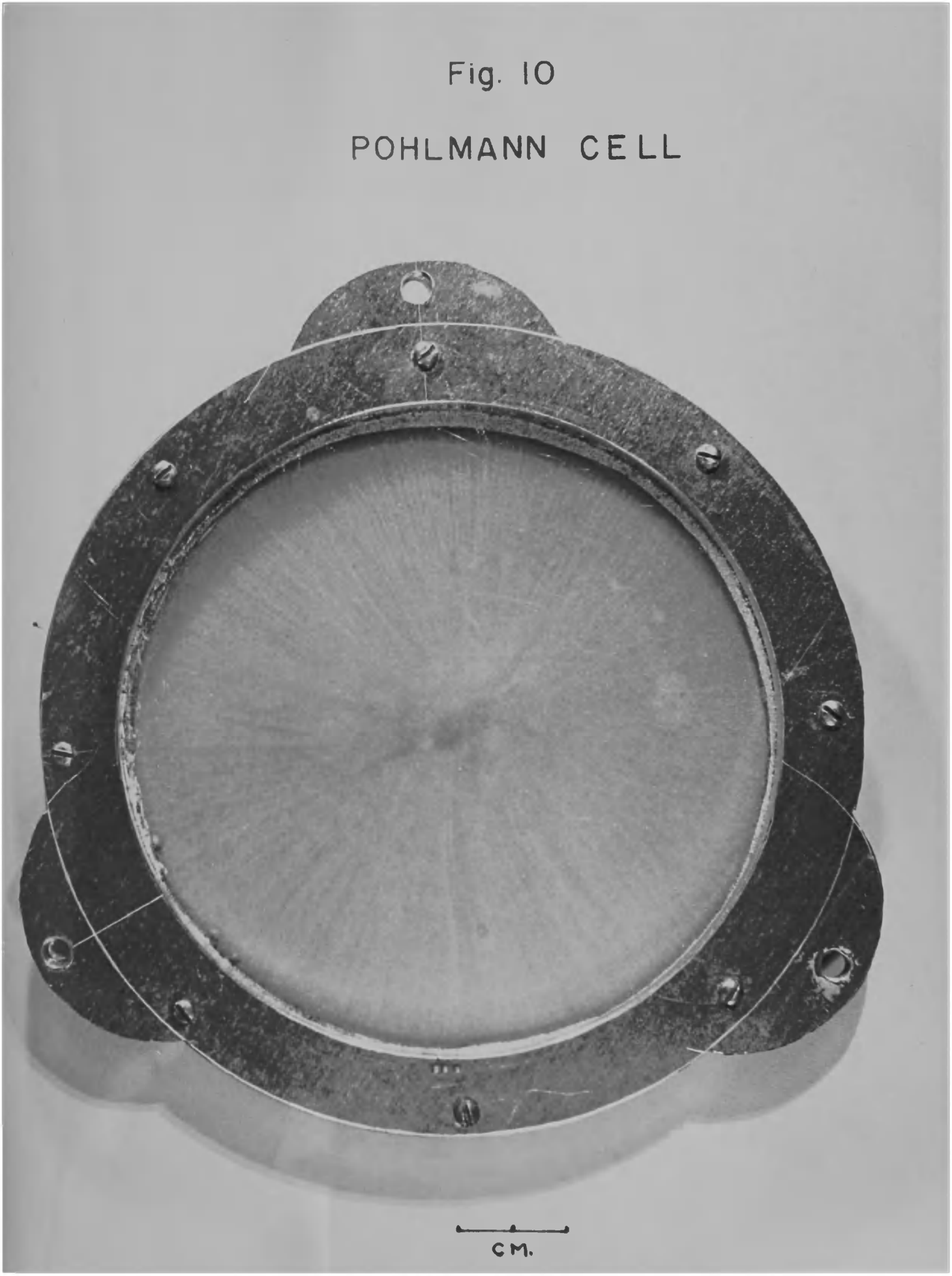
As noted in the introduction, Pohlman (26, 27, 28) has developed a method for the visualization of sound fields consisting essentially of a great many minute Rayleigh disks, so that incident light is regularly reflected in the areas where the disks are oriented by the sound beam, and diffusely reflected in other areas. Using this device together with acoustic lenses, he has constructed acoustical analogues of optical devices, and in particular has developed a method for flaw detection in solid objects. While his description of the actual cell is sketchy, the following information is given: thin metal foil (thickness given as 0.01 mm) forms the back of the cell, and glass the front; in

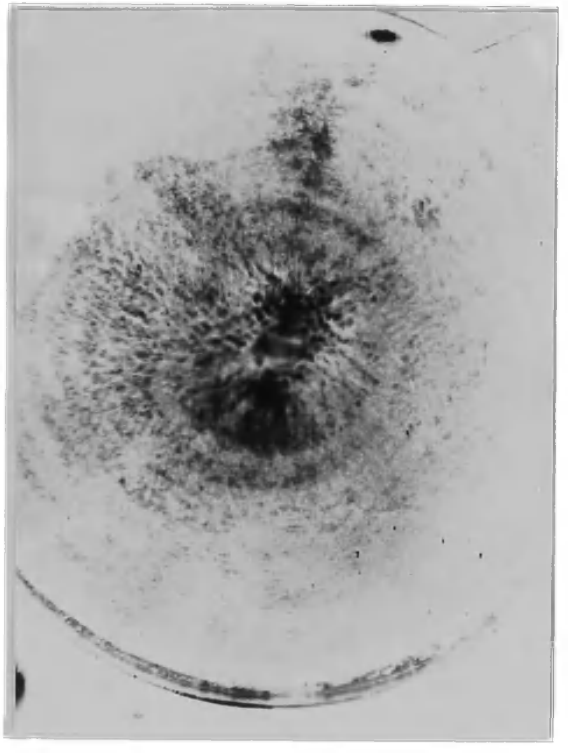
the cell is a suspension of aluminum flakes in xylene. The flakes are described as being of about 20 microns diameter, and about 1.5 microns thick, there being about $4 \times 10^6/cm^3$. Pohlman shows that the contrast is greatest for low sound intensities, and calculates that the pattern visibility threshhold corresponds to about $3 \times 10^{-7} w/cm^2$ sound intensity, which is very much lower than is required for most of the other methods.

Several cells answering the general description were built, the one finally used being 12 cm. in diameter, about 2 mm. thick, with a back of 0.08 mm. phosphor bronze and the front of 1/8" Lucite. The aluminum flakes used were the powder sold commercially for use in aluminum paint, and xylene was used for the suspension. Stereographic electron microscope studies indicate that these flakes range in size down from about 30 microns, and that they are thinner than this, although thickness measurements were not feasible. The writer is indebted to Dr. H. Bendler for these data from the electron microscope. The cell is shown in Fig. 10, and was supported horizontally in the large tank so that it could be viewed or photographed from the top. Because the suspension settles out, the cell must be periodically agitated to obtain a reasonably uniform suspension. The modified Polaroid-Land camera was used to produce the permanent record.

Fig. 10

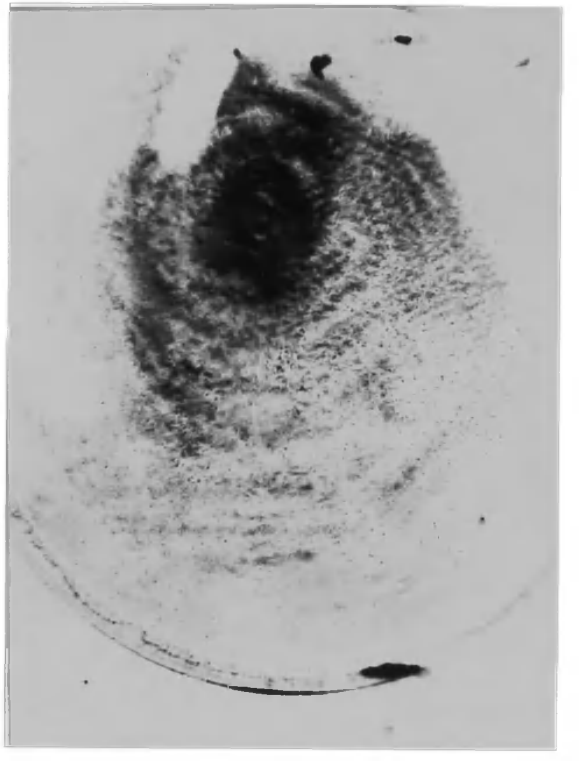
POHLMANN CELL





(a)

Beam centered in cell



(b)

Beam at one side of cell

Pohlman Cell Method

1073 kc/sec, cell about 7.5 cm. from 2.88cm. diameter transducer. Polaroid-Land camera setting 1, pictures taken immediately after sound turned on. Scale approximately 3/4.

Figure 11

Discussion of Results

The type of picture obtained is shown in Fig. 11, where it is seen that the patterns resemble those obtained with the starch plates. These patterns are about two-thirds actual size. The original picture from the camera was used to make contact prints, and it is these prints which are shown in Fig. 11, so that the black portions represent the sound beam. Fig. 11b is of particular interest in that the cell was deliberately placed off center with respect to the beam, and structure is apparent which is more nearly concentric with the cell than with the sound beam. This would imply that the cell boundaries have an influence which would have to be taken into account in the interpretation of the pattern. Such effects are to be expected since the suspension is agitated by the sound wave, and flow results. It would be expected that at very small intensities this difficulty would be minimized. Pohlman has published no results in the way of near-field patterns, but has concentrated on geometrical acoustics. The writer has been unable to produce pictures of the near-field using the Pohlman cell of quality comparable to that obtained with the starch plates.

This method again requires optical accessibility, photographic procedures, and the cell must be periodically

agitated in order to maintain the homogeneity of the suspension.

CONCLUSIONS

The use of starch plates in a dilute solution of iodine provides a method for the visualization and measurement of ultrasonic fields which appears to be superior to existing methods from the standpoint of quality of record, ease of obtaining the record, and simplicity of experimental arrangements. Because of these advantages the method should prove valuable in the study of source patterns, diffraction effects, and other investigations where an acoustical analogue to photography would be desirable.

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