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Ultrahigh-Frequency Acoustic Waves in Liquids and Their Interaction with Biological Structures

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Introduction by Dr. Carstensen

One of the outstanding characteristics of the ultrasound symposia held at the University of Illinois is the opportunity to have a relaxed discussion about current progress in research. Consequently, we have the opportunity of learning some possible new approaches to problems, or occasionally, we may hear about some recent research results that look very promising. I know that Dr. Floyd Dunn has recently been doing work with biological materials in the several-hundred-megacycle frequency region, and although he did not plan to give a talk on this topic during the symposium, I have persuaded him to discuss his recent experiments in this field.

A. INTRODUCTION

Research recently carried out at this laboratory has produced methods for generating and detecting acoustic waves in liquids in the kilomegacycle frequency region. Associated studies of the interaction of these ultrahigh-frequency sound waves with biological systems are just beginning. This paper discusses the techniques for generating and detecting uhf acoustic waves in liquids and includes a brief description of an experiment illustrating that interesting possibilities lie ahead.

B. METHODS OF GENERATING UHF SOUND IN LIQUIDS

Two methods of exciting quartz plates to propagate uhf sound in liquids have been employed (1).

The first method can be described as standard as far as the transducer is concerned in that the piezoelectric radiator, a thin X-cut quartz plate electroded on both major faces, is supported by clamping on the periphery. The radiating face is in contact with the liquid medium under investigation and the opposite face is terminated by a material of low characteristic acoustic impedance. The radiating face is held at ground potential and the opposite face is electrically connected to the oscillator via one or more inserted short sections of coaxial transmission line and 50-ohm cable, as illustrated in Figure 1. The inserted sections are designed to produce an impedance match between the 50-ohm line and the quartz plate assembly. For example, in the case of a single insert, the characteristic impedance of the coaxial section is designed, as is common practice, to be the root-mean-square of the input impedance of the transducer assembly, and that of the 50-ohm line and its length is chosen as an odd multiple of a quarter wavelength of the wave in the section.

Quartz plates having fundamental thickness modes of vibration of 4, 12, 15, 18, and 30 Mc, with diameters ranging from ¼ to ¾ in, have been employed. These have been operated at the odd harmonics to nearly 2 kMc. That is, for the 4-Mc plate operated at 1948 Mc, the highest operating frequency attempted thus far, the 487th harmonic is excited. The pulse lengths employed,

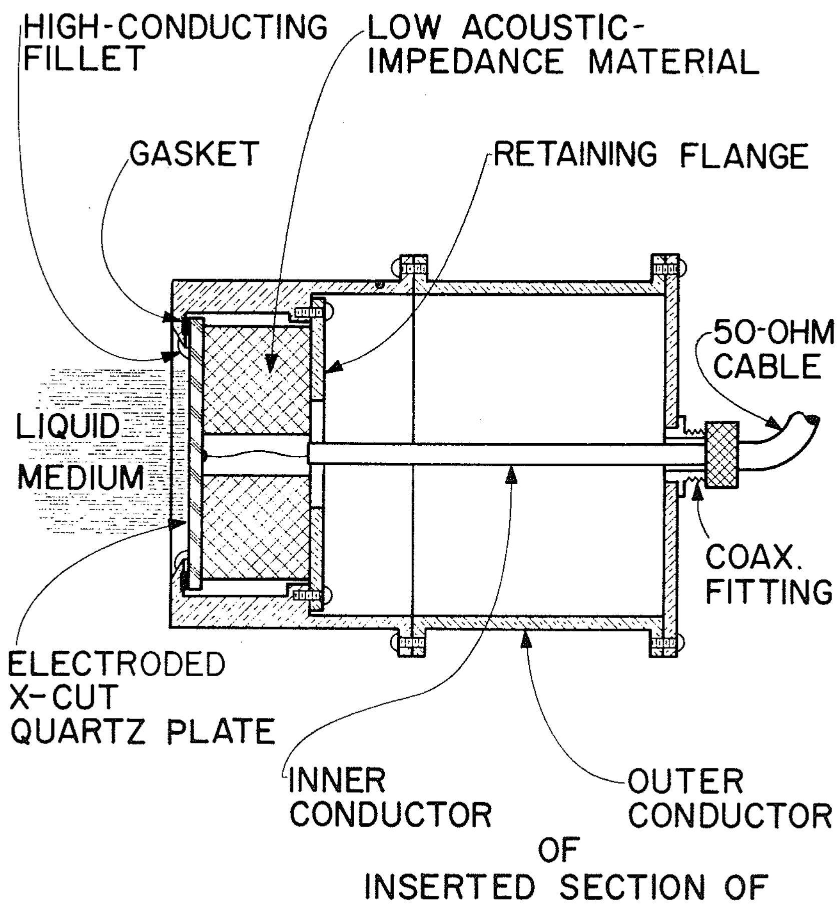

FIGURE 1. Schematic diagram of transmission line coupling method of exciting X-cut quartz plate.

namely, 0.1 sec, result in the establishment of steady-state conditions in the vibrating element.

A second method of exciting the quartz plate utilizes a resonant electromagnetic cavity. Here, the electroded quartz plate is placed in the reentrant structure of a cylindrical cavity, as shown in Figure 2. The design of the cavity follows from established engineering principles (2), taking due account of the fact that the relative dielectric constant of the piezoelectric material is considerably greater than unity. Accordingly, a cavity transducer was designed and fabricated to resonate at 820 Mc, the 205th harmonic of the 4-Mc quartz plate. Excitation was accomplished by coupling the 50-ohm rf transmission line to the fundamental mode of the magnetic field of the

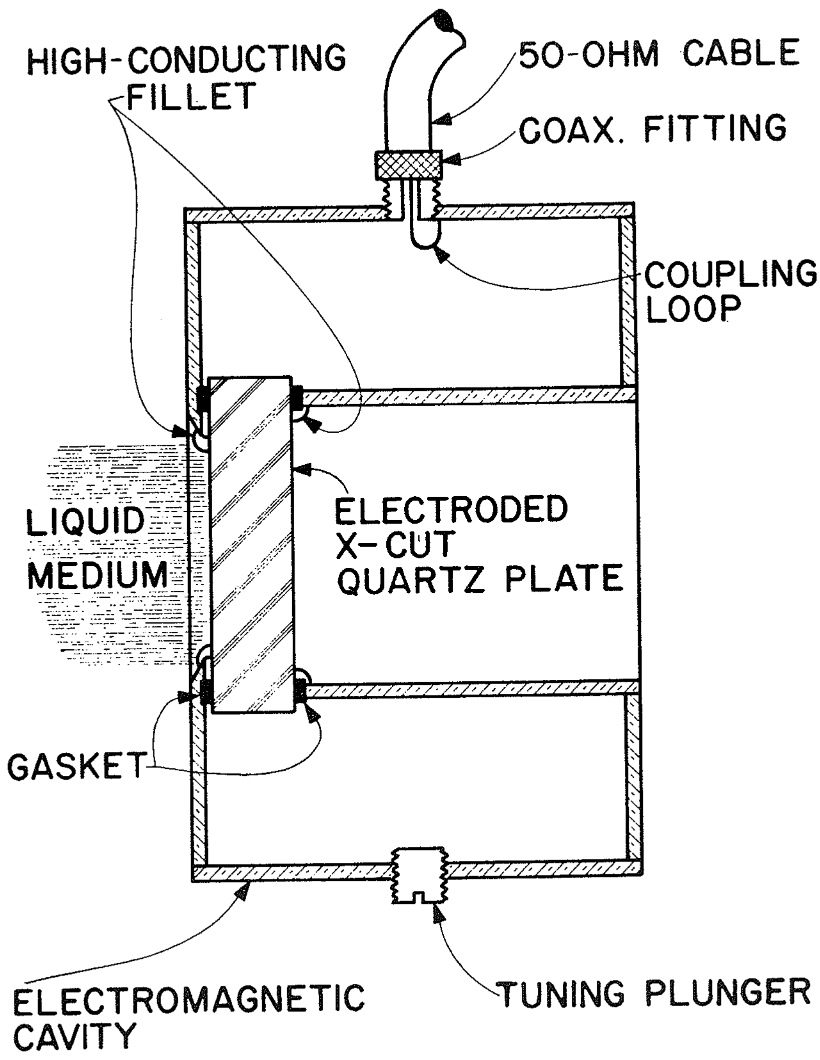

FIGURE 2. Schematic diagram of resonant electromagnetic cavity transducer.

cavity via a small wire loop from the center conductor of the transmission line to ground. A threaded plug was provided, enabling alteration of the cavity volume, for final tuning adjustment. The Q of the cavity, when the quartz plate radiates acoustic waves into a liquid having a value of $\rho C \simeq 1.5 \times 10^5$ g/cm^2 sec, is approximately forty implying a half-power frequency width of approximately 20 Mc. Thus only a few odd harmonic frequencies of the 4-Mc quartz plate can be excited to generate appreciable acoustic power in the liquid by the fixed-dimension cavity employed here.

Both methods are capable of producing sound amplitudes of sufficient intensity in liquids to be detected with ease. The fixed-dimension cavity method, however, has the inherent disadvantage of being restricted by the electromagnetic Q of the unit to a narrow frequency range of operation.

It is possible to solder the quartz plate, having vacuum-deposited gold or silver electrodes on the major faces, directly to the metallic members of either type of transducer, thereby eliminating the gaskets and electrically conducting fillets illustrated in the figures.

C. METHOD OF DETECTING UHF SOUND IN LIQUIDS

A miniature copper-constantan thermocouple probe is employed to detect the uhf acoustic waves (1). The probe, illustrated in Figure 3, is made by etching commercially available 0.0005-in-diameter wire in acid in the vicinity of the junction (to reduce the original diameter), and fabricating the thermocouple by a welding technique in which a condenser is discharged through a circuit containing the thermocouple elements (3).

The structure of the assembled unit is such that little distortion occurs in translation through viscous fluids. A particular advantage of the detector lies in the microscopic volume occupied by the junction. Thermocouples with a maximum dimension of the junction of 5 μ (approximately 10-Ω resistance) are readily constructed. This does not represent the minimum size for such probes, and procedures for fabricating smaller junctions are currently being developed.

For the determination of acoustic absorption coefficients at ultrahigh frequencies, the following procedure is used (4-6): The quartz plate, in contact with the liquid, is excited electrically, at an odd harmonic, to produce a single acoustic pulse with rectangular envelope of 0.1-sec duration. As a result of this relatively short acoustic pulse, the action of the viscous forces brought into play by the relative motion between the thermocouple wires and the imbedding liquid produces a transient temperature rise in the immediate neighborhood of the thermocouple junction. The resulting transient thermal emf produced in the thermocouple circuit is a measure of the acoustic intensity in a plane wave field in the neighborhood of the junction. The transient thermal emf is fed into a DC amplifier which in turn is fed to the vertical deflection plates of an oscilloscope. The thermocouple response, which is directly proportional to the acoustic intensity in the neighborhood of the junction, is observed as the deflection of the electron beam spot from its initial equilibrium position. The deflection of the oscilloscope beam spot is observed for varying distances between the source and probe (this measurement being made with a micrometer having a least count of 0.00001 in). The points are plotted on semilog paper and a straight line of best fit is drawn through the set of points. The acoustic intensity absorption coefficient per unit path length is then readily computed from a knowledge of the slope of this line, assuming that the intensity decreases exponentially with increasing distance from the source.

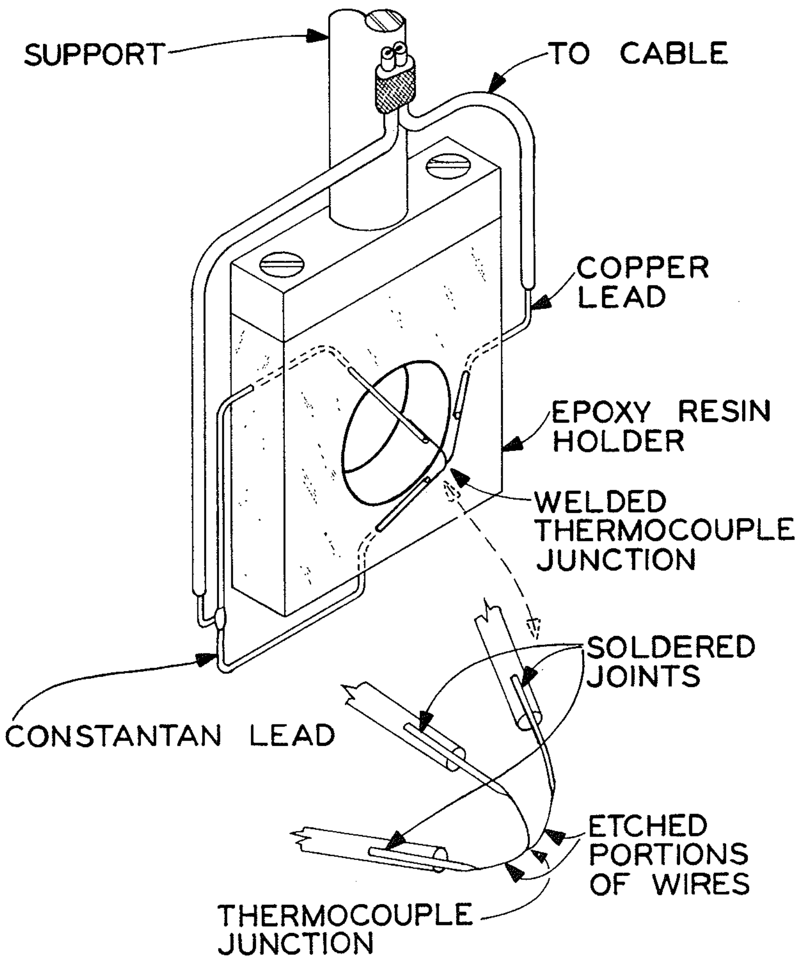

FIGURE 3. Schematic diagram of miniature thermocouple for detecting uhf acoustic waves in liquids.

D. ULTRAHIGH-FREQUENCY ACOUSTIC ABSORPTION MEASUREMENTS

The transient thermoelectric method has been used to study the uhf behavior of the acoustic absorption coefficient of several liquids. For all of the measurements reported below, the acoustic intensity ranges from the 10^{-3} to 10^{-2} w/cm^2 and the temperature rise in the liquid varies from 10^{-2} to 10^{-1}°C.

Figure 4 shows the absorption data obtained by the method described above for castor oil at 30°C together with data obtained by other methods (7–10). It is seen that the agreement between the five independent investigations is generally good. The curve drawn through the plotted points has a slope of 1.66. The dashed line is the computed Stokes viscous absorption for castor oil. The measured values lie below the Stokes values throughout the frequency range above 1 Mc. Figure 5 shows the absorption data for cottonseed oil at 26°C obtained by the method discussed in this paper and by the pulse method (8). It is seen that cottonseed oil behaves as a true Stokes liquid in the frequency range of measurement from 3 to 100 Mc. Figure 6 shows absorption data for Dow-Corning silicone fluid 710 at 26°C to nearly 2 kMc determined by the transient thermoelectric method. The point at 1 Mc was also determined by another method (11). The dashed curve is the Stokes absorption. Assuming negligible velocity dispersion, the data fits very closely a single relaxation process centered at approximately 40 Mc.

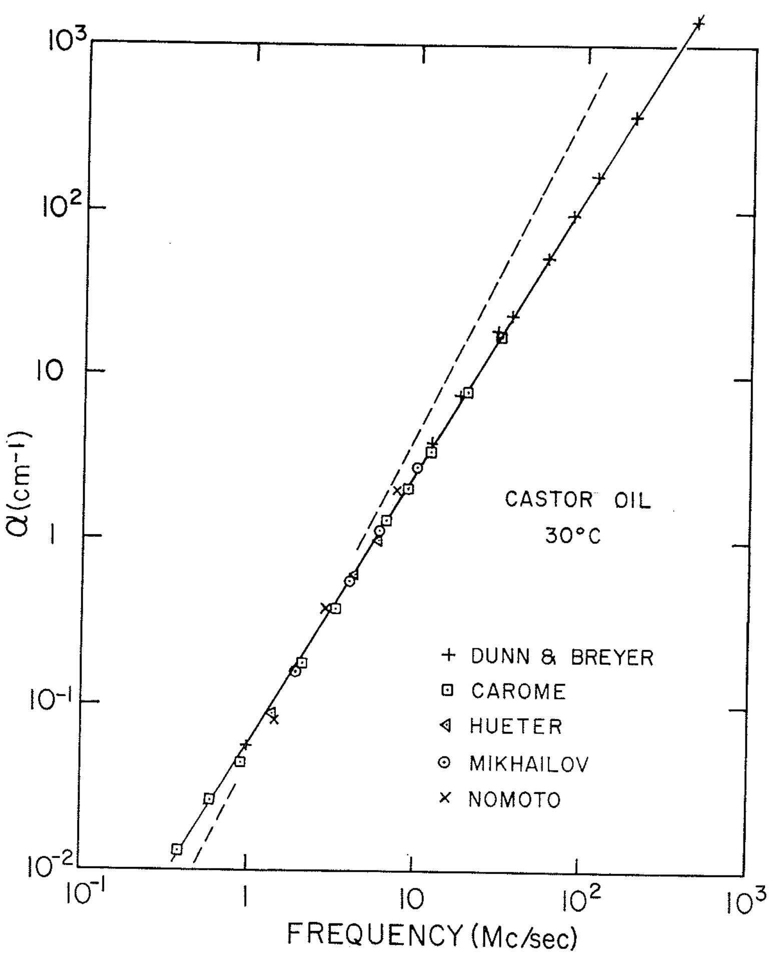

FIGURE 4. Acoustic amplitude absorption coefficient of castor oil vs frequency at 30°C.

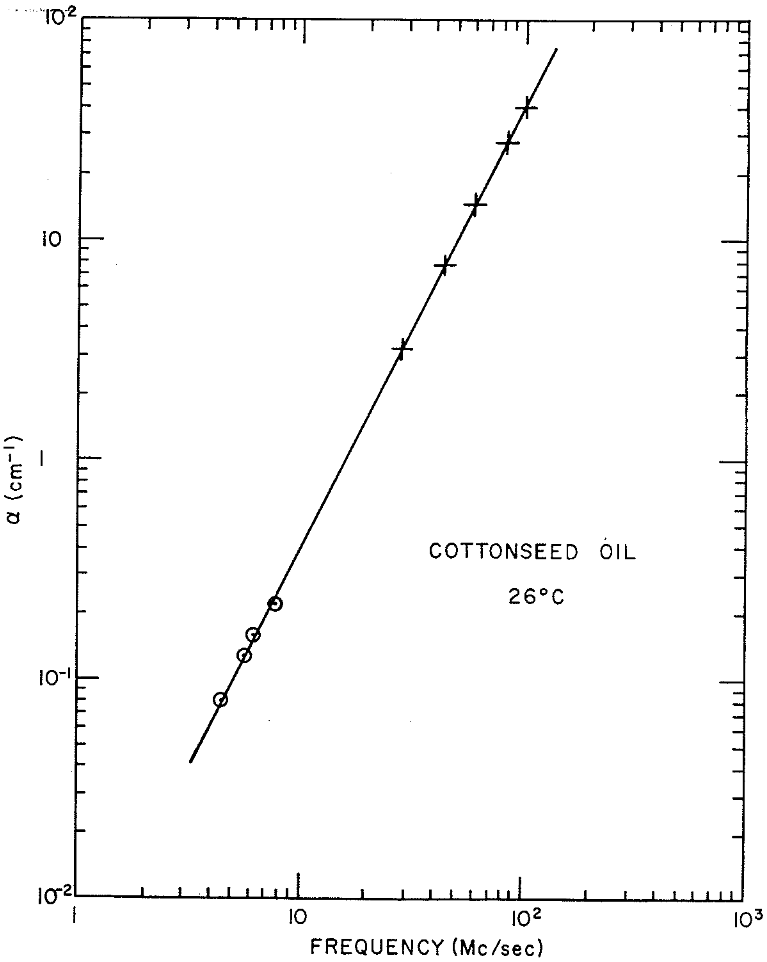

FIGURE 5. Acoustic amplitude absorption coefficient of cottonseed oil vs frequency at 26°C. +, Dunn and Breyer; O, Mikhailov (7).

E. EXAMPLE OF THE INTERACTION OF UHF ACOUSTIC WAVES WITH BIOLOGICAL STRUCTURES

Rotifers (12), small polynucleated aquatic animals several hundred microns in length, were suspended in physiological saline on the surface of the quartz plate of the type of transducer illustrated in Figure 1 (that is, the transducer was arranged to radiate vertically upward). At room temperature, and with no sound present, the specimens attach their (lower) extremity to the surface of the quartz plate and adopt a nearly vertical posture undergoing undulating-like dances in an approximately 60° conical volume. The animals were exposed to single ultrasonic pulses ranging from 0.1-sec to several minutes duration at acoustic intensities of the order of 10^{-3} w/cm² in the frequency range from 200 to 600 Mc. It was observed that only in relatively narrow frequency bands in the neighborhoods of 270 and 510 Mc were these

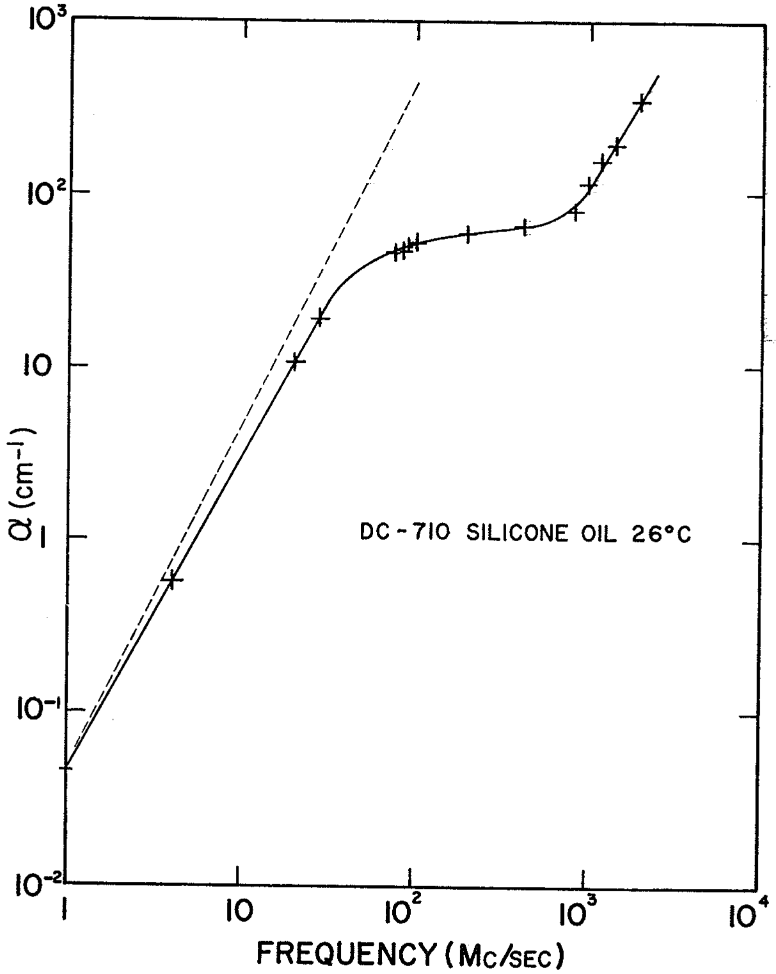

FIGURE 6. Acoustic amplitude absorption coefficient of Dow-Corning silicone fluid vs frequency at 26°C.

characteristic activities altered. The nature of the change in activity was virtually complete cessation of all movement. The animal, still attached to the quartz plate, assumed a globular configuration and remained dormant. Upon cessation of short acoustic pulses (3 to 30 sec), the specimen recovered the characteristic activity. Numerous rotifers were studied in this manner and any single specimen could be carried through repeated acoustic cycles, throughout the frequency range investigated, without apparent damage. Pulse durations of the order of several minutes led to apparent irreversible damage as viability did not return.

These observations illustrate a unique interaction between sound waves at approximately 270 and 510 Mc and the in vivo rotifer. Although the nature of the interaction is at present unknown, the following statements can be made. Injury produced in rotifers (and other biological structures) at lower frequencies (below 1 Mc) has been attributed to cavitation present during ultrasonic exposure (13). However, the thresholds of cavitation at the frequencies employed in the present study are considerably in excess of the sound intensities produced, namely, in the vicinity of 10^5 w/cm^2 (5). This fact, together with the finding that the suppression of rotifer activity occurs in particular frequency bands, should eliminate cavitation as the mechanism of interaction. In the absence of more specific information, let it be assumed that the acoustic intensity absorption coefficient per unit path length in the rotifer is the same as the average value observed for the mammalian central nervous system, namely, approximately 0.2 cm^{-1} at 1 Mc, and that it increases linearly with frequency. This leads to an estimate of the time rate of temperature rise in the rotifer of approximately 3×10^{-2}°C/sec. It is seen that for acoustic exposure durations as long as 10^2 sec, the maximum temperature developed in the animal, in the absence of thermal conduction, is but several degrees above room temperature and this is not sufficient to be considered seriously, for the rotifer thrives at temperatures in excess of 35°C (14). The greatest temperature developed in the saline containing the specimen was of the order of 30°C, that is, a temperature increase of approximately 5°C. The absorption of sound in the imbedding liquid is sufficiently great, as is the path length in the chamber, such that standing waves of large amplitude are not produced. That this is not important in the alteration of the activity of the rotifer was verified by the observation that changing the acoustic path length had no observable effect upon the experimental results.

As the observed effect appears in the neighborhood of 270 and 510 Mc, two frequency regions nearly integrally related, it is tempting to consider a resonance phenomenon as playing a role in the interaction. However, considerably more work will have to be accomplished before the verity of this suggestion can be established.

F. CONCLUDING REMARKS

The techniques for generating and detecting uhf acoustic waves in liquids appear to have reached a degree of sophistication enabling them to be employed in investigations of biological systems. However, such applications are currently in a very early and primitive stage. This laboratory plans to conduct additional experiments in this area. The experiment described in the previous section illustrates that interesting results may be forthcoming.

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DISCUSSION

DR. VON GIERKE: Have you tried focusing the sound waves at these very high frequencies?

DR. DUNN: We have not attempted to focus since all materials, including any materials from which lenses could be fabricated, absorb sound energy at a very high rate at these microwave frequencies. However, at these frequencies a very interesting situation occurs. Consider the sound source to be approximately 1 cm in diameter. Since the absorption coefficient of all liquids is very high at these frequencies, the measurements are always made with the probe a very short distance from the quartz plate; that is, the distance from the probe to the sound source is very small by comparison with the diameter of the source. With the probe on the axis of the quartz plate, contributions to the intensity at the probe position from the periphery of the sound source are negligible by comparison with those from the axial region. Thus, we have, possibly for the first time, what may be described as an infinite acoustic source, as viewed by the probe positioned on or near the axis of the source.

DR. VON GIERKE: You have, then, a solid acoustical transmission line between two electrical surfaces.

DR. DUNN: Yes. I should point out that while our work has resulted in the generation and detection of the highest frequency acoustic waves in liquids attained thus far, namely, up to 2 kMc, other investigators have measured the absorption and speed of sound in quartz bars at frequencies as high as 24 kMc (see for example E. H. Jacobson, in "Quantum Electronics," C. H. Townes, ed. [Columbia University Press, New York, 1960], p. 468).

DR. HERRICK: Why do you use a thermocouple in preference to a very fine thermistor as the acoustic detector?

DR. DUNN: Primarily because we have the technology for fabricating thermocouple detectors as small as 5 μ and the possibility of fabricating them as small as 1 μ. The smallest thermistor elements currently available are larger than 50 μ. In principle, they could be made smaller, but there are many technical problems involved. Your suggestion is a good one since the thermistor should provide an acoustic detector of considerably greater sensitivity than that of the thermocouple.

DR. BELL: Do you anticipate problems associated with heating the biological materials at these high frequencies?

DR. DUNN: We do not anticipate any great problems because of the following. If we assume a value 0.2 cm^{-1} as an average value for the acoustic intensity absorption coefficient per unit path length of biological materials at 1 Mc and assume further that this increases linearly with frequency, then at 1000 Mc the absorption coefficient has a value of 200 cm^{-1}. The highest acoustic intensities that we have been able to produce thus far are approximately 0.1 w/cm^2; however, the rotifer experiments were carried out at intensities of the order of 10^{-3} w/cm^2. For the highest intensities currently available, at 1000 Mc, this implies a time rate of temperature rise, in the absence of thermal conduction processes, of less than 10°C/sec. Since thermal conduction would serve to limit the temperature rise and the rotifer experiments indicate that events occur within time intervals less than 1 sec, it appears that results of more than routine interest are produced without appreciable heating of the biological specimen.