APPLICATION OF ULTRASONICS TO PARTICLE SEDIMENTATION IN WATER

by

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CHAPTER I

INTRODUCTION

Water Treatment

A 1958 inventory of water supply facilities in the United States, based on communities with populations of 25,000 or more, indicated that nearly 99 per cent of this population is drinking from treated water supplies. The provision of an adequate water supply for industries and all but the very smallest communities almost invariably requires some water treatment process. The objectives of this treatment may be: disinfection; taste and odor control /1; demineralization; removal of suspended matter, turbidity, iron and manganese compounds; water softening; corrosion control; or any combination of these.

Sedimentation

Various processes are used to accomplish these objectives. Nearly all involve sedimentation, "the retention of water in a basin so that the suspended particles may settle as a result of the action of

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/1 Disinfection and taste and odor control are not major objectives when the water is for industrial use only.

gravity and other forces."/1 This sedimentation process takes time -- time that is provided by giving the basin such dimensions that, while flowing through the basin, the settling particles will reach the bottom before reaching the outlet. Resulting detention periods of 6 to 8 hours for plain sedimentation basins are not unusual. The ideal particle settling velocity is described by Stoke's law in the form:

$$V_s = \frac{g}{18} (p_1 - p_w) \frac{d^2}{u}$$

where: V_s = Particle settling velocity, cm/sec

g = Gravitational constant, 981 cm/sec^2

p_1 = Particle density, gm/cc.

p_w = Water density, approximately unity

d = Particle diameter, cm

u = Viscosity coefficient of water, gm/cm-sec

There are so many other factors involved (wind, density currents, etc.) that Stoke's law must be tempered with certain experience factors before its application to field conditions. It can be seen however, that the particle settling velocity is a funtion of the particle size and density and of the effective viscosity of the water.

Chemical coagulation, which precedes sedimentation,

/1 "Water Supply Engineering," Babbitt & Doland, p. 411. 5th Edition.

increases the particle size. This may reduce the necessary sedimentation basin detention time to 1.5 to 3 hours. Still, a city of 25,000 might easily have water treatment facilities for 10 million gallons per day, requiring at best a sedimtentation basin capacity of a million gallons. For a relatively small city, this represents an impressive structure. A simplified diagram of a typical municipal water treatment facility is shown in Fig. I. The treatment process as well as the relative physical size of the major components is illustrated.

Purpose

Sedimentation basin dimensions have been successfully reduced by using chemical coagulation to increase particle settling velocities. It can be seen from the Stoke's relationship that further improvement may be obtained by reducing the viscous or shear drag on these coagulated particles. An investigation into the field of ultrasonics was begun with the thought that high frequency sound vibrations, possibly through increased molecular activity, might produce a reduction in the apparent viscosity of water.

As this investigation progressed, a growing awareness of certain acoustical phenomena led to the belief that a really major research program involving the

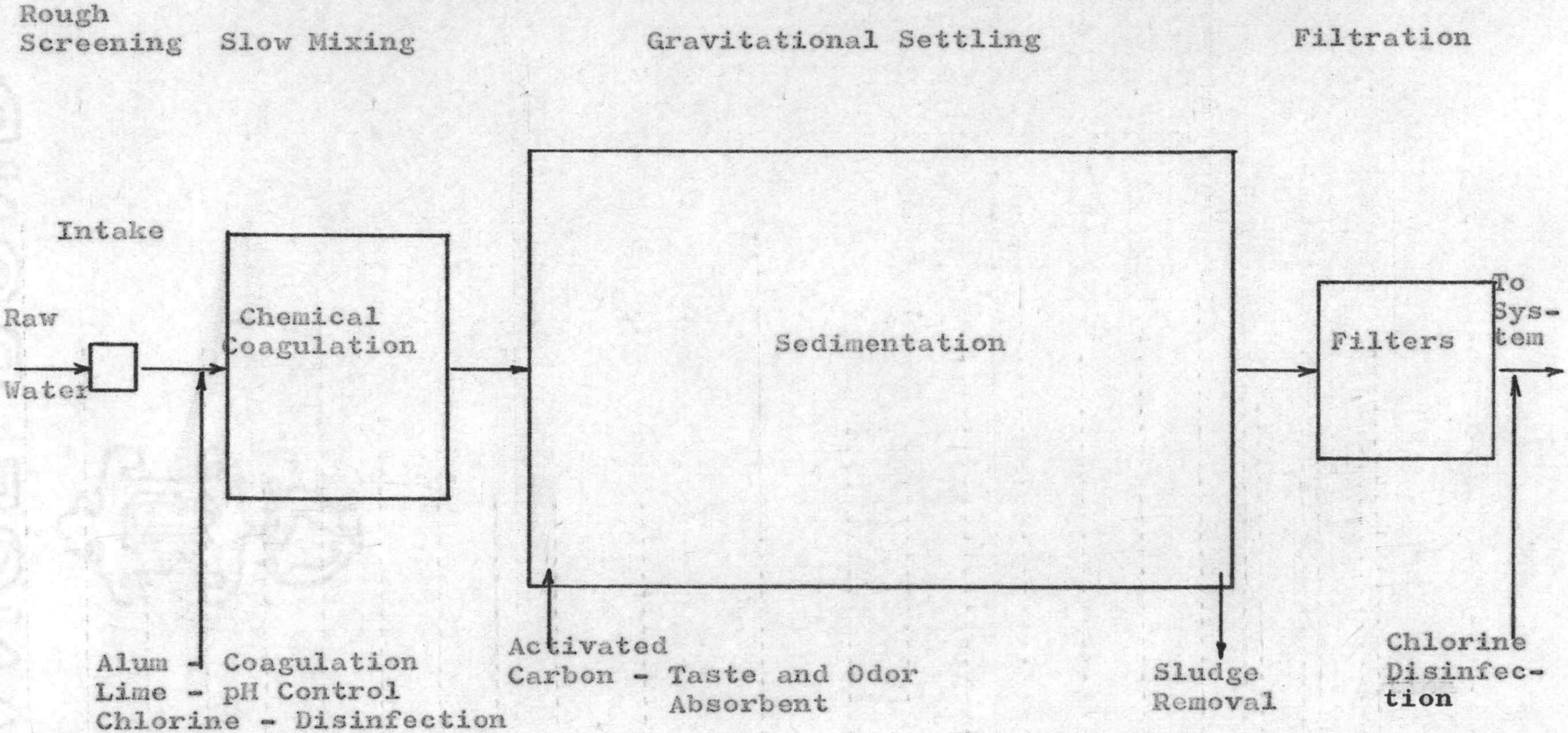


Figure I. Typical Municipal Water Treatment Process application of ultrasonics to water treatment processes might well yield a significant change in these processes. In the light of this new possibility, an exploration of existing information in the ultrasonics field was initiated for the purpose of developing the background and methods for an advanced research program.

CHAPTER II

ULTRASONICS

Historical

"Ultrasonics" has long been an acoustical term describing those frequencies beyond the range of human audibility or, practically, above about 16,000 cycles per second. Within the last 15 years however, it has come to denote a new and individual science which has found application from dentistry to submarine detection.

It had long been realized that bats were able to navigate in utter darkness by emitting ultrasonic waves and listening for the echo from obstructions in their path. In 1917, a French scientist developed an apparatus for bouncing ultrasonic waves off underwater objects. The navigational feat of the bats was duplicated and ultrasonics had found its first application. Until the second world war, the ultrasonics industry consisted of these underwater echo-ranging, or sonar, applications.

In the 1930's cavitation was produced in liquids with high power ultrasonic energy. Then during the second world war, with the tremendous advances in electronics, the ultrasonics industry began to move into the diverse areas it now occupies.

Today, the original echo-ranging principles are used in device for detecting submarines, icebergs, schools of fish, for surveying the ocean bottom, for non-destructive testing and thickness gauging of metals and other materials. Cavitation production is the basis for many ultrasonic cleaners, emulsifiers, drills, welders, etc. in operation today. Strong ultrasonic energy fields are used for the destruction of bacteria and insects, for breaking down cell structures, for cold-boiling and degassification of liquids. Ultrasonic liquid-level switches and indicators, flow metering devices, burglar alarms, etc. are in existence. Water and waste water treatment processes, in fact, appear to be among the very few areas of modern technology where ultrasonics has not found some application.

General

Ultrasonics is essentially a combination of acoustics and electronics. It utilizes also, concepts from mathematics, thermodynamics, fluid and solid state mechanics, chemistry and various other sciences. Certainly the field is far too vast to be even perfunctorily covered here; however, certain basic mechanisms and relationships do exist, the understanding of which will be essential to the investigation of any application to water or waste water treatment processes.

Ultrasonic waves propagated in liquids are longitudinal waves. The individual liquid particles oscillate back and forth along the line of propagation of a wave, causing zones of compression and rarefaction to move along this line. This concept is illustrated in Fig. II.

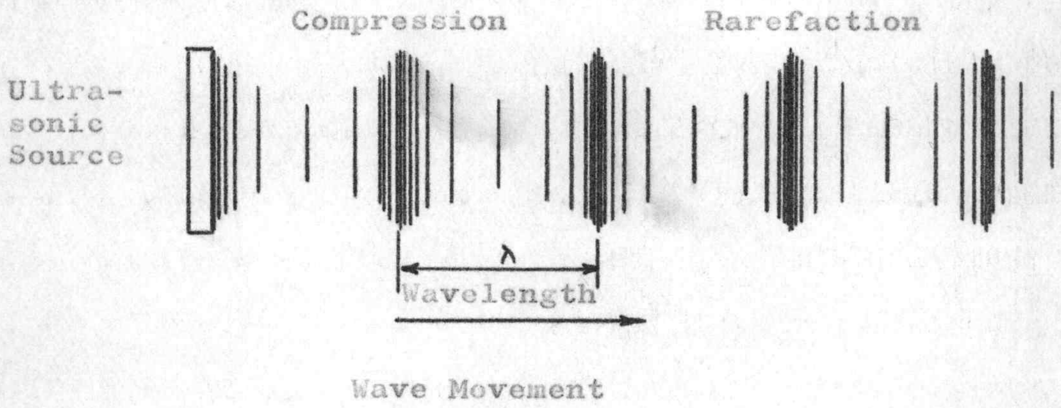


Figure II. Ultrasonic Waves

The distance between two consecutive compressions or rarefactions is the wavelength, λ. These compressions and rarefactions move through the liquid at the acoustic velocity, c, which is about 1.4×10^5 cm/sec in water. The basic relationship then exists:

$$\lambda = c/f$$

where: λ = wavelength, cm

c = acoustic velocity, cm/sec

f = frequency, cycles per second.

Assuming an ultrasonic wave propagated in a tank or container of some size, the wave must eventually strike some boundary of this container. The portion of energy then reflected back into the water is determined by the respective specific acoustic impedances of the water and of the boundary material:

$$\frac{E_r}{E_o} = \left(\frac{p_w c_w - p_b c_b}{p_w c_w + p_b c_b}\right)^2$$

where: E_r = Energy reflected from boundary

E_o = Energy incident on boundary

p_w = Density of water, gm/cm^3

p_b = Density of boundary material, gm/cm^3

c_w = Acoustic velocity in water, cm/sec

c_b = Acoustic velocity in boundary material, cm/sec

pc = Specific acoustic impedance

The specific acoustic impedance of water at 17°C is 1.43×10^5 gm/cm^2 sec. Table I indicates the specific acoustic impedance of various other substances and the relative amounts of energy that may be expected to be reflected back into water from these substances.

A wave is reflected from a boundary at the same angle as its approach or incidence. The portion of

Table I. Energy Reflections at Boundaries.

	Specific Acoustic Impedance gm/cm^2 - sec	% Energy Reflected Back into Water
Water	1.43×10^5	0
Wood (Oak)	0.3×10^6	13
Granite	1.1×10^6	59
Slate	1.2×10^6	62
Aluminum	1.4×10^6	66
Glass	1.5×10^6	68
Tin	2.0×10^6	75
Brass	2.9×10^6	82
Steel	3.9×10^6	86
Iron	4.1×10^6	87
Iridium	10.7×10^6	95
Gas (Air)	41.3	100

Note: These values vary with temperature, surface characteristics, etc. and are tabulated only to present an idea of the magnitudes to be expected.

the wave that is not reflected but is refracted into the boundary material, however, is not transmitted through any such similar angle. The relationship between the angle of incidence and the angle of refraction is:

$$\frac{\sin i}{\sin t} = \frac{c_w}{c_b}$$

where: i = Angle of incidence

t = Angle of refraction

c_w = Acoustic velocity in water

c_b = Acoustic velocity in boundary material

The relationships between the angles of incidence, reflection and refraction are illustrated in Fig. III.

Reflection and refraction have been discussed in relation to container boundaries. It should be pointed out that for water containing suspended particles, both reflection and refraction of energy will occur to some extent between the water and the particles in suspension. This will result in some scattering of the ultrasonic beam and some energy losses.

Some energy is also lost by absorption as the wave passes through the water. The classical Stokes-Kirchhoff description of these losses is:

$$I = I_o e^{-2ax}$$

where: $$2a = \frac{4\pi^2 f^2}{c^3 p}\left[\frac{4}{3}u + \frac{(k-1)}{C_p}K\right]$$

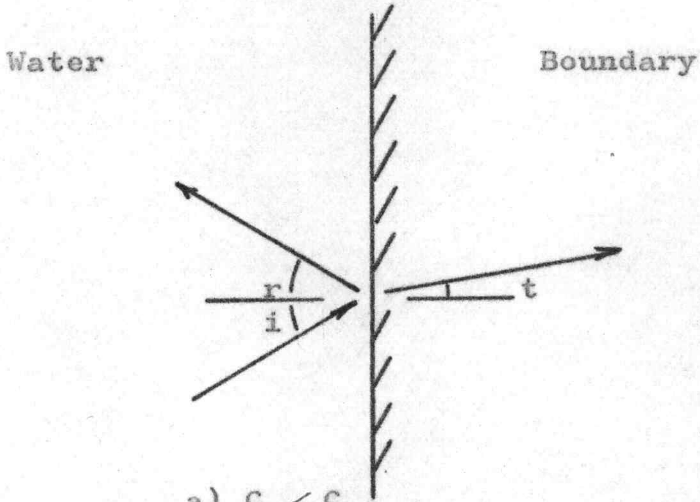
and: I_o = Initial energy intensity, watts/cm^2

I = Intensity after traversing a distance, x

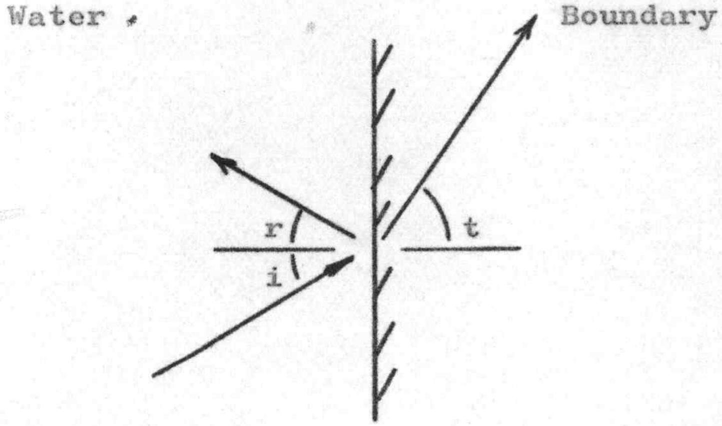
f = Frequency, cps

c = Acoustic velocity in water, cm/sec

p = Density (mean) of water, gm/cm^3



a) $C_b < C_w$



b) $C_b > C_w$

i = angle of incidence
r = angle of reflection ; r = i
t = angle of refraction

Figure III. Reflection and Refraction

u = Viscosity of water, gm/cm-sec

k = Ratio of specific heats

K = Thermal conductivity of water

C_p = Specific heat at constant pressure

According to this relationship, it would require a distance of about 150 feet in water before half the energy of 1 megacycle wave was absorbed. Experimental results do not conform to this value, perhaps because heat radiation between the compression and rarefaction areas is not considered in the Stokes-Kirchhoff equation. Nevertheless, energy losses by absorption do not appear to present any serious obstacle.

Cavitation

Though, as shall be explained later, the production of cavitation in the proposed application should probably be avoided, its importance in so many other applications demands some discussion of the phenomenon. Cavitation is the formation and collapse of vapor bubbles in a liquid when pressures are reduced to those necessary for vaporization. Destructive cavitation occurs as the result of excessive velocities in hydraulic systems and around propellors and pump impellers.

As the intensity of an ultrasonic wave increases, the pressure differential between the compression and rarefaction areas also increases. When the pressures in the rarefaction areas approach the vaporization pressure of the liquid vapor bubbles begin to form.

Apparently there are two distinct types of bubbles involved in ultrasonic cavitation. The first is composed of the dissolved gases present in the liquid, such as air and dissolved oxygen in aerated water. Bubbles of this type grow to visible size and eventually rise to the surface of the liquid. Cavitation of this type is used in liquid degassification processes.

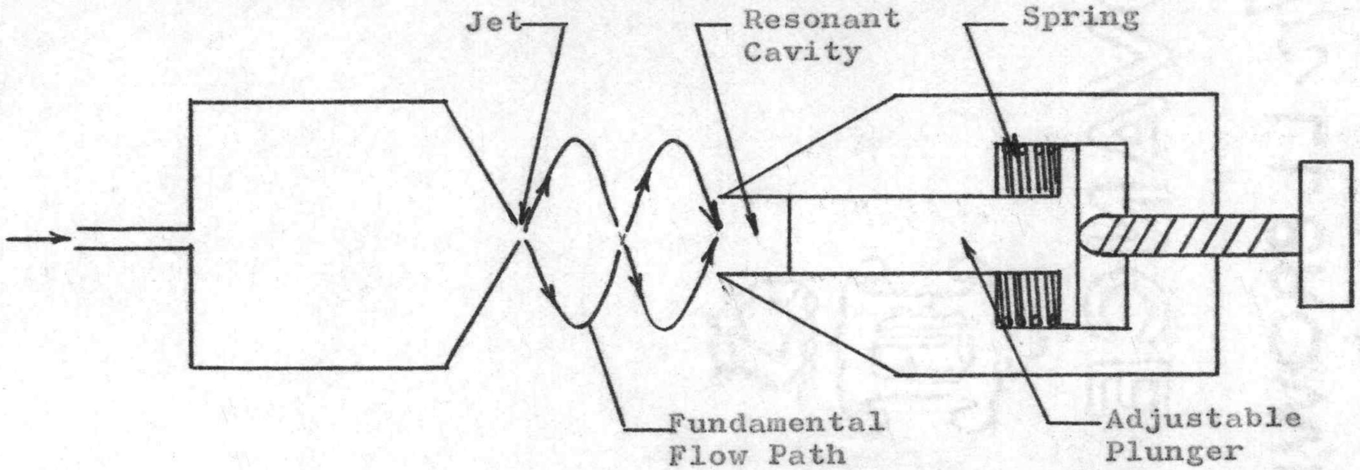
The second type of bubble is of microscopic dimensions and is composed of the vaporized liquid. The formation and collapse of these bubbles is a most violent and explosive reaction, involving pressures of several hundred atmospheres. Cavitation of this type is used in ultrasonic cleaners, the destruction of water borne organisms, the production of dispersions and emulsions, and in initiating many types of chemical reaction. It is accompanied by a hissing and crackling and, at very high energy levels, a loud steady roaring sound.

Water at atmospheric pressure and room temperature will tend to cavitate at energy intensities of about one-third watt per square centimeter. Temperature increases of the order of 0.5°C/minute have been observed under such conditions.

Wave Generation

Ultrasonic waves are generated by either jet or electrical methods. The jet generators convert air of liquid pressure directly to ultrasonic energy. One of the main advantages of these generators is the simplicity of their power source. Power is usually supplied by a compressor pump or a high velocity rotor. Resonant cavity whistles, pulsating jets, vortex whistles, and sirens are all examples of jet generators. A Hartmann type resonant cavity whistle is illustrated in Fig. IV. This type of generator requires some sort of reflector or horn to properly beam the ultrasonic energy. Other forms of jet generators, such as sirens, depend upon gas or liquid streams being emitted in "pulses" at a certain frequency.

Electrical methods of ultrasonic wave generation all depend upon some form of transducer for converting electrical energy to mechanical vibrations. The electrical energy may be generated by an electro-mechanical system composed of an electric motor driving an electric generator. Frequencies so generated range from about 10 to 20 kcs. The more common method utilizes electronic oscillators composed of vacuum tube or



Gas or liquid flows at high velocity through the jet. A resonant cavity positioned into this jet stream at a point of flow instability will result in the gas or liquid in the cavity being excited into resonance.

Figure IV. Fundamentals of the Hartmann Whistle.

transistor circuits which act as automatic a-c voltage generators. The circuitry of such an oscillator depends upon the transducer to be used and upon the particular application involved.

Transducers fall into three categories: piezoelectric, magnetostrictive, and electromagnetic. Certain crystals, when mechanically distorted, generate an electrical potential. Conversely, when an electric potential is applied to such a crystal, it will physically distort. The application of an alternating potential will result in a periodic vibration of the crystal at the frequency of the alternating potential. This property is known as the piezoelectric effect and is widely utilized in ultrasonic wave generation. Crystals used in this manner as transducers are cut to a specific thickness so that they will be mechanically resonant at the desired frequency. Mechanical or natural resonance occurs when the crystal thickness is equal to a half wave length.

$$t = \frac{1}{2}\lambda$$

and since $\lambda = c/f$,

$$t = c/2f$$

where: t = Crystal thickness, cm

c = Acoustic velocity in crystal, cm/sec

f = Desired frequency, cps

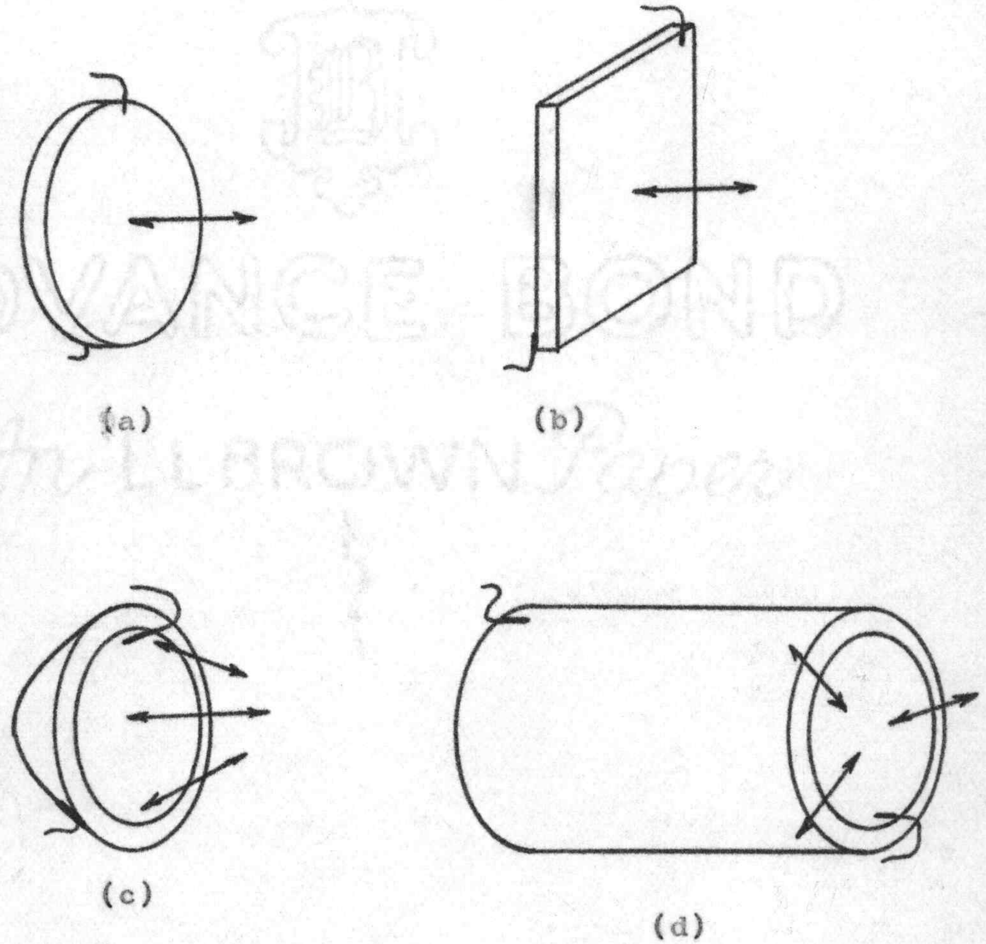
For example, the acoustic velocity in quartz is 540×10^3 cm/sec. The resonant frequency of a quartz crystal will then be:

$$f\ (\text{kcs}) = \frac{270}{t}$$ /1

Crystals other than quartz which are commonly used as transducers include Rochelle salt, ammonium dihydrogen phosphate, lithium sulfate, dipotassium tartrate, potassium dihydrogen phosphate, and tourmaline. Some polycrystalline ceramics also exhibit properties similar to the piezoelectric effect. Barium titanate ceramic transducers are finding increasingly wider use and offer many advantages in liquid applications. They have very good chemical stability, possess a high resistance to mechanical vibration and shock, can be operated at relatively high temperatures and, probably most important, can be shaped in nearly any desired form or size. Several piezoelectric transducers are illustrated in Fig. V.

Another form of transducer is based upon the magnetostrictive properties of certain ferromagnetic metals. The atomic structure of these metals is a somewhat random arrangement. When magnetized, the atoms are realigned into an orderly arrangement.

/1 In practice, this value more nearly approaches $\frac{283}{t}$ because of induced shear stresses in the quartz.



All electrical contact surfaces are coated with a conductive film.

(a) Circular cut crystal
(b) Rectangular cut crystal
(c) Focusing bowl
(d) Hollow flow-through cylinder

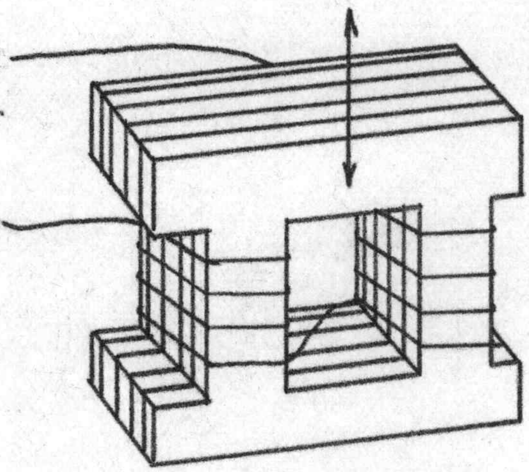
(c) and (d) are possible with ceramics (Barium Titanate)

Figure V. Piezoelectric Transducers

This results in a change in the physical size of the metal and this action is called magnetostriction. A coil wound around a ferromagnetic metal core is the usual form taken by a magnetostrictive transducer. The most common metals are nickel and permendur (an iron-cobalt alloy). When a-c voltage is applied to the coil, the metal core vibrates along the axis of the coil. A common example of magnetostrictive vibration results in the 60 cycle hum emitted from standard power transformers.

Heat losses from large eddy currents are reduced by using a built up laminated stack as a core, however most applications will still require air or water cooling to dissipate the heat losses. A typical window type laminated core magnetostrictive transducer is illustrated in Fig. VI. The core dimensions shrink /1 whenever the metal is magnetized, regardless of the polarity of this magnetism. Consequently, the core will vibrate at twice the frequency of the applied a-c voltage. However, if a bias is applied, either by a permanent magnet or a direct current bias, so that the polarity of the core does not change, the core will vibrate at the same frequency as the applied voltage. The amplitude of vibration, though, will be twice as great.

/1 Iron expands upon magnetization.



Transducer core is a built up window type laminated stack.
This is the most common method of utilizing the magnetostrictive effect.

Figure VI. Magnetostrictive Transducer

Such a bias is often applied to increase the power output of a magnetostrictive transducer.

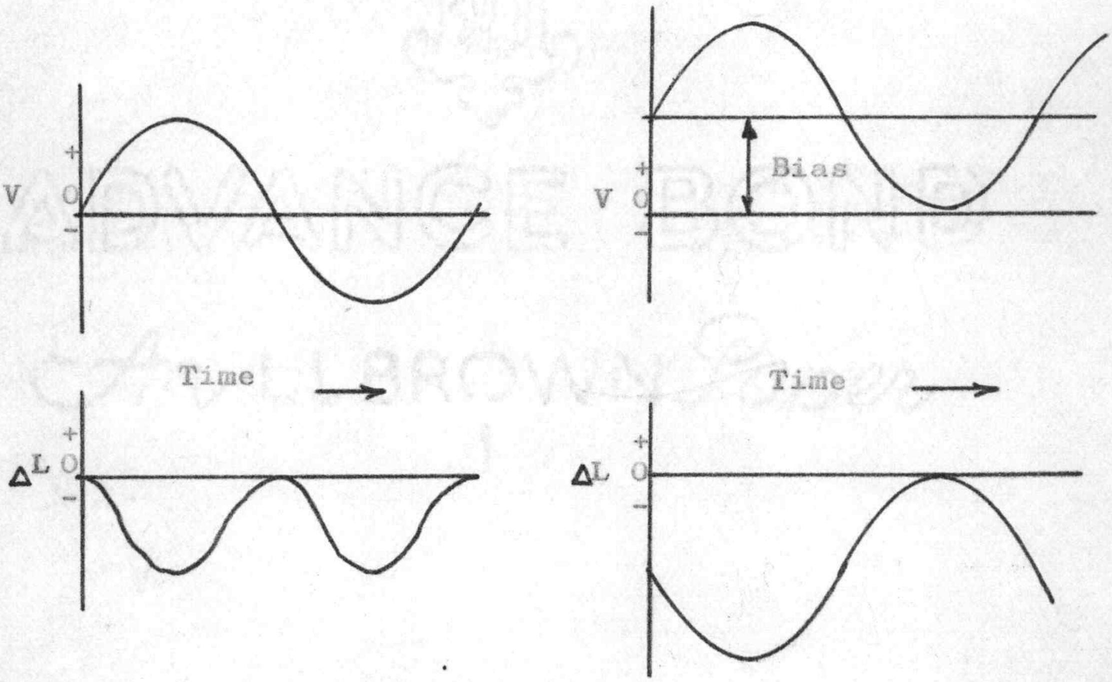


Figure VII. Bias Effect of Magnetostriction

Magnetostriction transducers, like piezoelectric transducers, are designed to vibrate at their natural resonant frequency.

The third transducer type, electromagnetic, has found some use in the lower frequency ranges. These tranduscers are either moving coil or moving iron systems. An ultrasonic moving coil vibrator is simply a modification of a standard dynamic loudspeaker, the normal loudspeaker cone being replaced by a resonant bar. A moving iron vibrator is a modification of a headphone or telephone earpiece. An ultrasonic clothes washing machine has been developed using a moving iron to force streams of water through the garments.

Electromagnetic transducers have very low natural resonant frequencies and are not normally operated at resonance. For this reason, their power output decays rapidly at high frequencies and they are not usually operated above about 10 kcs.

Standing Waves

Consider a plane ultrasonic wave propagated in a water filled chamber, and a plane boundary of some sort placed in the path of this wave to act as a reflector. With this reflector spaced an integral number of half wavelengths from the source of vibration and maintained parallel to the source, the reflected wave and the incident wave would be in phase. The system between ultrasonic source and reflector would be in state of resonance. The power input necessary to maintain a desired energy intensity in this system would be appreciably reduced. More important, the combination of the incident and reflected waves would result in compression and rarefaction areas that remain stationary. This is called a standing wave pattern.

In the classical Kundt tube experiment, fine powder is sprinkled in a horizontal glass tube. A tuning fork is struck at the open end of the tube and a piston is adjusted at the other end of the tube until resonance occurs. When this condition is obtained, the powder moves to the nodal positions of the resulting standing wave. The object of this experiment was the visualization of a standing wave pattern and the measurement of wavelength as the distance between the observed nodal points.

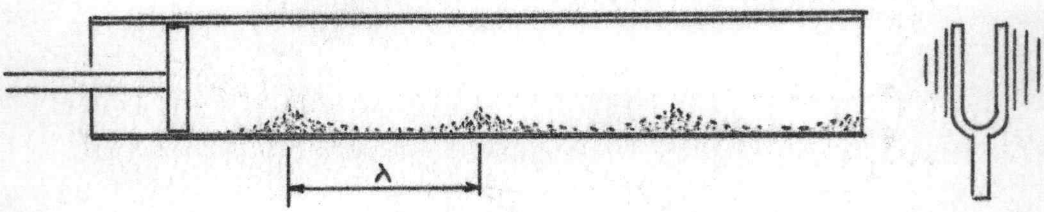


Figure VIII. Kundt Tube Experiment

The significance of the experiment is in revealing how a sound wave, in a resonant situation, might cause agglomeration of particles.

From this premise, considerable work was done exploring the mechanisms of precipitation by sonic and ultrasonic waves of smokes, mists, and other gaseous suspensions. The early work of Brandt, Freund, and

Hiedmann was particularly important. Several industrial precipitators based on the principles outlined by these men are in use today.

The various relationships describing precipitation of gaseous suspensions, or aerosols, involve density and viscosity terms so their extrapolation to hydrosols does not seem illogical. Their application to water or waste water indicates some fascinating possibilities.

CHAPTER III

APPLICATION TO PARTICLE SEDIMENTATION IN WATER

Coagulation in Standing Wave Pattern

Imagine a standing wave of proper frequency and sufficient intensity set up in a tank or tube containing a suspension of solids in water. It is expected that these solids would readily coagulate. Those solids heavier than water should accumulate at the antinodes of the wave, coagulate, and settle to the bottom of the container; those lighter than water should accumulate at the nodes of the wave and rise to the surface. Moreover, it is suspected that the time required for this to occur would be of the order of a few seconds.

This phenomenom, called agglomeration, would result from a combination of three distinct actions:

1. Particle vibration
2. Repulsion and attraction between adjacent particles.
3. Radiation pressures.

Particle Vibration

In a fluid subjected to a periodic vibration, a suspended particle realizes an amount of drag due to its size and the viscosity of the fluid. Also, it tends to resist this drag due to its own inertia. The amplitude of vibration of a particle will be a function of its size, its density, the viscosity of the fluid, the frequency of the vibration, and the energy intensity or applied power. It can be seen that, with very small particles and low frequencies, the amplitude of the particle vibration will be the same as the fluid's. As the frequency is increased, the particle inertia becomes more influential and its amplitude decreases. At very high frequencies, then, large dense particles would be expected to remain stationary while the fluid oscillates back and forth past them. The ratio of particle amplitude to fluid amplitude is described by the equation:

$$\frac{A_p}{A_f} = \frac{1}{\left[1 + (\pi p f d^2/9u)^2 \right]^{1/2}}$$

also: $$\phi = \tan^{-1} (\pi p f d^2/9u)$$

where: A_p = Amplitude of particle vibration

A_f = Amplitude of fluid particle vibration

ϕ = Phase angle between fluid and particle vibrations

p = Particle density, gm/cm^3

f = Frequency of applied vibration, cps

d = Particle size, cm

u = Fluid viscosity, gm/cm-sec

Ortho-kinetic coagulation of particles occurs when the particles are forced together at such velocities that the ionic repulsive forces between them are overcome. Inducing as much relative motion between particles as possible will increase the probability of their coming into contact with each other at sufficient relative velocities to coagulate. In an isodisperse suspension, most of the particles will be influenced when the ratio of amplitudes is maintained between 0.2 and 0.8. At ratios greater than 0.8, particle vibration will be in phase with the fluid and at ratios less then 0.2, particle movements will be negligible. This at least has been the experience with aerosols and should be equally true with suspensions in water. For any particular amplitude ratio, it is seen that the frequency is an inverse function of particle size and density. This function is illustrated in Fig. IX. The figure indicates the size range of particles suspended in water which a particular frequency may expect most to influence.

Repulsion and Attraction Between Adjacent Particles

When particles are separated by only a few diameters, fluid vibrations induce certain hydrodynamic forces between the particles. Fluid vibrating between two particles whose common axis is perpendicular to the direction of vibration causes a reduction in pressure between the particles. The two particles are hence

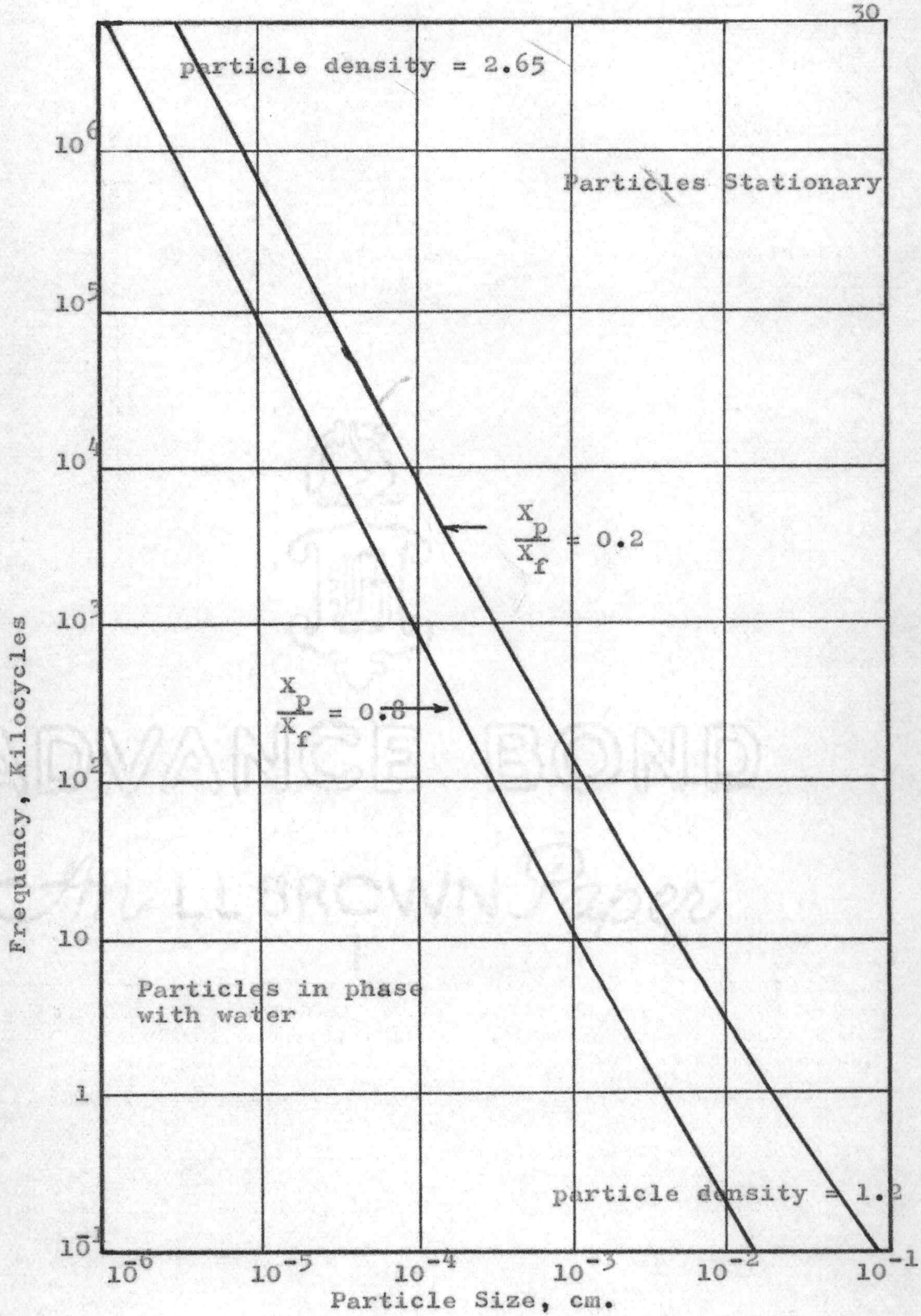


Figure IX. Frequency and Particle Size Relationship for Amplitude Ratios of 0.2 and 0.8 in Water at 10°C.

attracted to each other. If the common axis of the two particles is parallel to the direction of fluid vibration, so that one particle lies in the "shadow" of the other, pressure is built up between the particles and a repulsive force exists between them.

Radiation Pressure

A strong pressure acts in the direction of propagation of an ultrasonic wave. In a standing wave system, this pressure results in a force which urges the suspended particles towards the nodes or antinodes of the wave. This force is zero at the nodes and antinodes and reaches a maximum value midway between these points. This maximum force is described by the equation:

$$F = \frac{10}{3} \frac{\pi^2 d^2}{\lambda} E$$

$$= \frac{10^8}{3} \frac{\pi^2 d^2 f}{c^2} I$$

where: F = Maximum force, dynes

d = Particle size, cm

λ = Wavelength, cm

f = Frequency, cps

c = Acoustic velocity in the fluid, cm/sec

E = Energy density, ergs/cm^3

I = Energy intensity, watts/cm^2

As an illustration of the magnitudes of this radiation pressure, it has been observed that, under the influence of a sound wave imposing an amplitude of 50 microns at a frequency of 20 kcs, a sphere of the density of water can be suspended in air against the force of gravity.

Agglomeration Rate

The rate of agglomeration is a function of the ultrasonic energy density. The energy density and intensity are described by the equations:

$$E = 2\pi^2 p f^2 A^2$$

$$I = 2\pi^2 p c f^2 A^2 \times 10^{-7}$$

$$I = cE \times 10^{-7}$$

where: E = Energy density, ergs/cm^3

I = Energy intensity, watts/cm^2

p = Fluid density, gm/cm^3

f = Frequency, cps

A = Amplitude of vibration, cm

There is an energy threshold below which no effective agglomeration will occur. It has been the experience with aerosols that this threshold level lies around 50 ergs/cm^3. Moreover, really fast agglomeration does not occur below about 100 ergs/cm^3.

Experimental

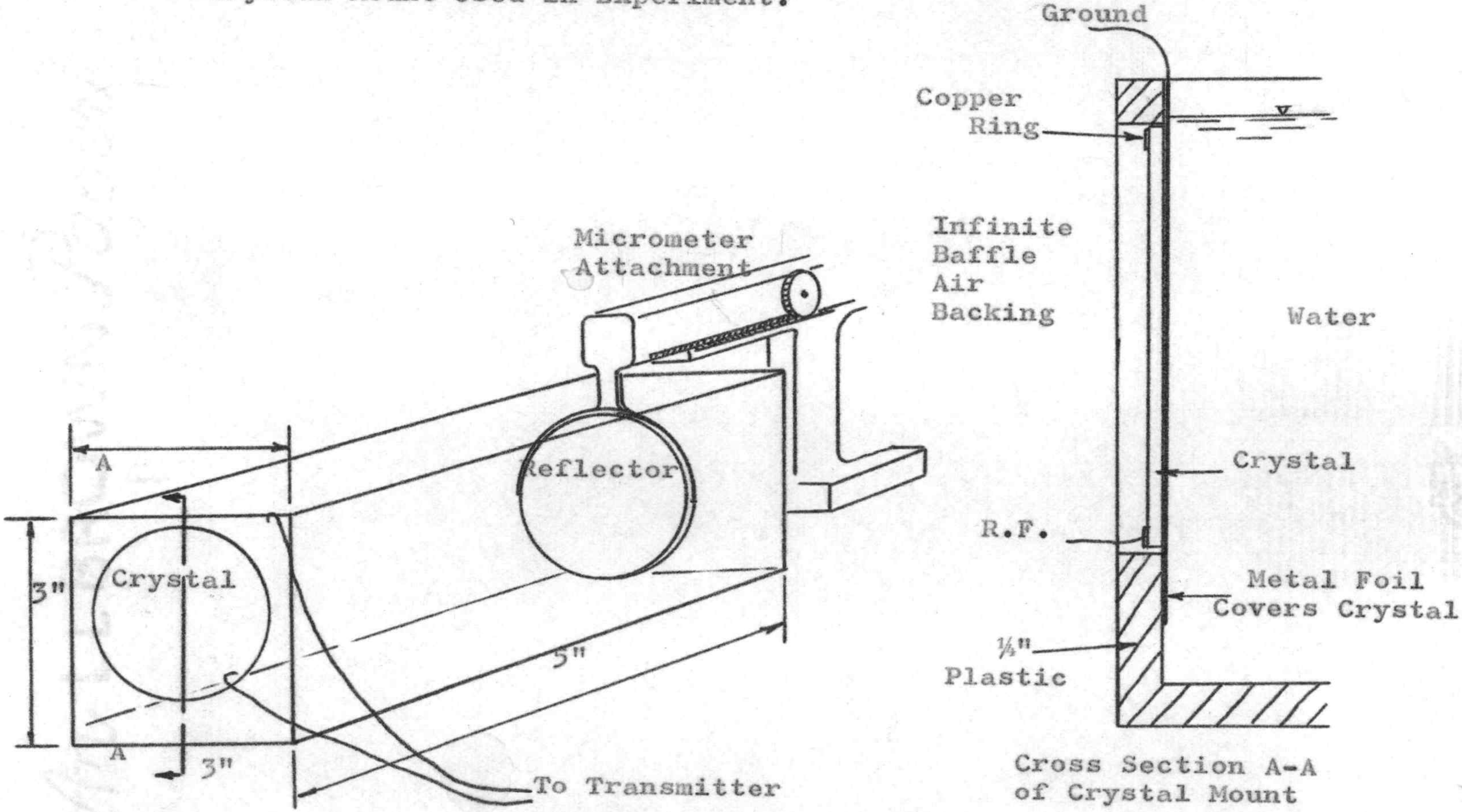
An attempt was made to produce a standing wave system a 7 megacycle 2½ inch diameter quartz crystal as a transducer. The crystal was driven by a Heathkit Model DX-40 radio transmitter operated at the 7 megacycle frequency. A clear plastic rectangular cell was constructed in which the standing wave system was to be produced. A micrometer attachment, borrowed from an AO Spencer microscope, was mounted above the cell. This attachment was to position a glass reflector suspended in the path of the ultrasonic wave. The apparatus is diagrammed in Fig. X.

After the cell was filled with water, the transmitter was loaded and power applied to the crystal. The reflector was then moved slowly back and forth through several wavelengths in an attempt to locate a position of resonance where a standing wave pattern might appear.

The experiment evidently required a greater precision than the apparatus provided, for all such attempts were unsuccessful. The acoustic wavelength at 7 megacycles is about 0.02 cm in water. While the micrometer arrangement for moving the reflector along the line of wave propagation was probably sufficient, it was very difficult to position the reflector parallel to the crystal face with adequate precision.

A strong radiation pressure was noted which

Figure X. Diagram of Plastic Cell and Crystal Mount Used in Experiment.



resulted in rapid circulating currents in the water. Boundary effects due to the relatively small size of the cell were probably responsible in large part for this circulation. Small granules of sponge and cork were dropped into the water near the crystal. They were hurled instantly against the reflector, 5 inches away, and held there by the radiation pressure.

The reflector was tilted at an angle of 45° to direct the wave upwards. A liquid fountain, 2½ inches in diameter, was lifted about ¼ inch above the normal water surface. Assuming a 65% energy reflection from the glass reflector, this would indicate a radiation pressure of about 1 gm/cm^2. Although no energy density measurements were obtained, the level was assumed to be less than ⅓ watt/cm^2 since no cavitation was observed.

A solution of Fuller's earth and water was prepared and placed in the cell for observation of particle settling velocities under the influence of ultrasonic vibrations. Sedimentation did appear to be accelerated after a few seconds of vibration during the preliminary trials with the system. While developing a technique for timing and measurement, though, a short circuit developed across the crystal mounting and the fragile crystal was shattered.

Certainly none of the problems encountered appeared to be insurmountable. The conviction was, if anything, strengthened that a real improvement in particle sedimentation may be realized through the application of ultrasonic energy.

Some interesting data has been collected by Lyon, the results of which were published in 1951 in the Sewage and Industrial Wastes Journal. He observed improved settling characteristics of activated return sludge after exposure to ultrasonic vibrations. He used a war surplus BC-375-E radio transmitter with a TU-26-B tuning unit to drive a quartz crystal transducer at 240 kcs. The crystal mounting that was used is shown in Fig. XI.

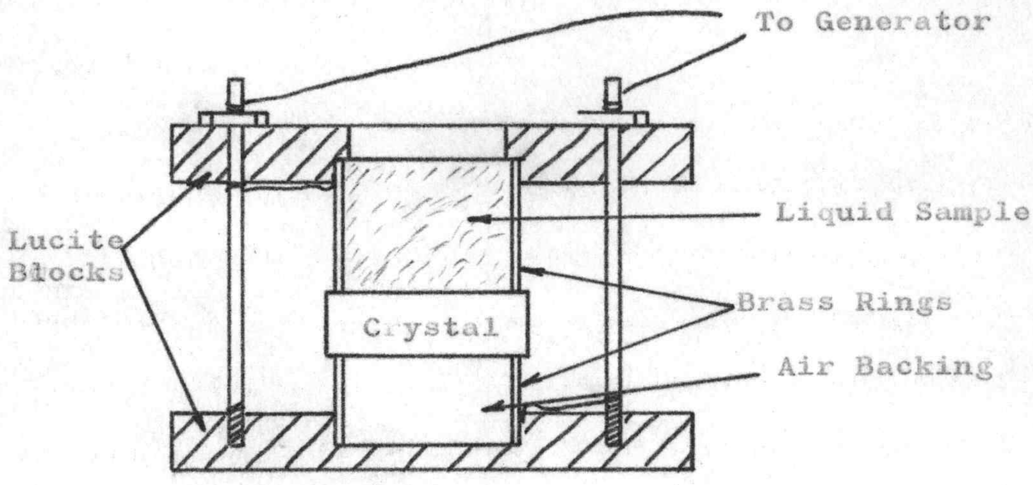


Figure XI. Crystal Mount Used by Lyon

A 7 ml sample of activated return sludge was placed in the cavity above the crystal and irradiated with ultrasonic energy for a measured length of time. The sludge was thereupon removed from the cavity and transferred to a test tube where it was permitted to settle, After 30 minutes of settling, the height of sediment, d, and the total height, h, of liquid in the test tube were measured.

These values, recorded as d/h ratios, were determined for various periods of vibration exposure. Observations at various power inputs were also recorded. Temperature increases of 0.5°C/min were noted during the vibration, as was a slow stirring of the sludge. Control samples were subjected to these same temperature and stirring conditions.

It was found that the sludge settled twice as fast after 10 minutes of vibration and three times as fast after 15 minutes of vibration as did the control samples. Although no absolute power or energy density values were obtained, an increase in the power output of the generator showed a similar increase in the amount of settling.

Observations and calculations indicate that ultrasonic energy, particularly in a standing wave system will greatly accelerate particle sedimentation in water. It is apparent that nowhere in the described experimentation was a standing wave system obtained. Still, some definite improvement in sedimentation was noted. It can only be concluded that a real need exists for more research, and more advanced research, in this area of sedimentation acceleration, both in standing wave and in moving wave systems.

CHAPTER IV

SUGGESTED STUDY

Purpose

This preliminary exploration has resulted in the belief that a judicious and controlled application of ultrasonic energy to water borne suspensions of solid particles will greatly accelerate the removal of these particles by sedimentation. The existing information, however, is much in the form of qualitative observations and estimations.

It may be noted that the ultrasonic relationships discussed were based on the assumption of homogeneous, spherical particles in suspension. Also, the hypothetical system discussed was a standing wave system. While this would certainly be the ideal situation, obtaining such a system on a large scale, with very short wavelengths, may present some serious difficulties.

Extrapolation of energy threshold levels from aerosols to suspensions in water indicates that intensities around 0.75 watt/cm^2 would be required for effective coagulation /1 and around 1.4 watt/cm^2

/1 Improved sedimentation has been observed at lower energy levels.

would be necessary for a really high speed process. Since water has been found to cavitate at around 0.3 watt/cm^2 at atmospheric pressure, and since the violent dispersive action of cavitation does not appear to be conducive to coagulation, some means of obtaining higher intensities without initiating cavitation will have to be sought. A solution that comes readily to mind is pressurizing the system.

Of the three mechanisms involved in agglomeration, it is not apparent which has the greater influence on the process. Perhaps each has a greater effect in certain ranges of particle size or frequency.

All these facets, and certainly many others, make necessary a program of testing and analysis organized to determine and evaluate those effects of ultrasonic energy which are pertinent to the removal of water borne suspensions.

Testing Procedure

Suspensions of various kinds and under various conditions should be exposed to ultrasonic vibrations. Suspensions should be of known particle size and density ranges. Concentrations, or turbidities, should be varied as should temperatures. Samples of several different river waters, raw and partially treated sewages, and different types of industrial wastes should be examined.

All test samples should be exposed to several frequencies over the ultrasonic range. Sonic and sub-sonic frequencies should not be overlooked. These frequencies should be applied at various energy intensities as well as various periods of exposure. Both a standing wave pattern and a non-resonant moving wave should be tried, as should different directions or axes of vibration.

Each test should result in both a quantitative and qualitative description of coagulation and sedimentation effects associated with ultrasonic vibration. Changes in chemical and physical characteristics of the sample (pH, hardness, alkalinity, acidity, etc.) should be noted. An attempt should be made to evaluate any energy losses or beam scattering effects. Observations or estimations of boundary effects in the test apparatus should be noted.

The testing should occur under continuous flow rather than static conditions. The vibration exposure period could be adjusted by changing the flow rate through the treatment area.

Apparatus

An effective test apparatus for the suggested research should fulfill several requirements. It must be capable of producing easily standing wave and moving wave situations. It must also be capable of producing these situations at various energy levels, along different axes of the system, and over a wide range of frequencies. Pressurization of the treatment chamber, probably tp about 10 psig, should be possible, as should reasonable precise control of the flow rate through the treatment area.

The treatment chamber should be of sufficient size to reduce undesirable boundary effects and to permit complete sedimentation of the particles. Facilities for removal of sediment and treated supernatant should be provided at several positions along the length of flow.

Instrumentation for measurement of frequency, power output, pressure, temperature, and flow rate will be required. Also, a method for detecting resonance in the system (standing wave) will have to be devised, possibly through the use of an oscillograph.

Miscellaneous standard laboratory equipment for measurement of turbidities, alkalinity, acidity, hardness, etc. should be available.

Several ultrasonic generators and transducers are commercially available which should be adequate for this program. Ultrasonics, Inc. has developed a variable frequency amplifier which will produce frequencies ranging from 20 kc to 2 mc with powers ranging up to 1 kw. Transducers for this particular application could be provided with the amplifier unit. Brush Electronics Co. has a generator, Model BU-204, which has a variable frequency range from 100 kc to 1 mc with power variable to 250 watts. Barium titanate transducers should probably be used and they could be provided with both the generators mentioned.

A proposed treatment chamber design is outlined in Fig. XII. Certainly there are other methods as satisfactory, but the simplicity of the illustrated design does offer several advantages. It is easily portable, readily assembled and dismantled, and it offers a variation in the length of the treatment area. Circular transducers are used because this shape is most easily mounted. Also since the flow through the chamber will be laminar, with a parabolic velocity distribution, the treatment period will be more nearly equal for all particles if a circular transducer is used. The transducer and reflector will be mounted in a sleeve-type assembly which will be inserted in the vibration chamber.

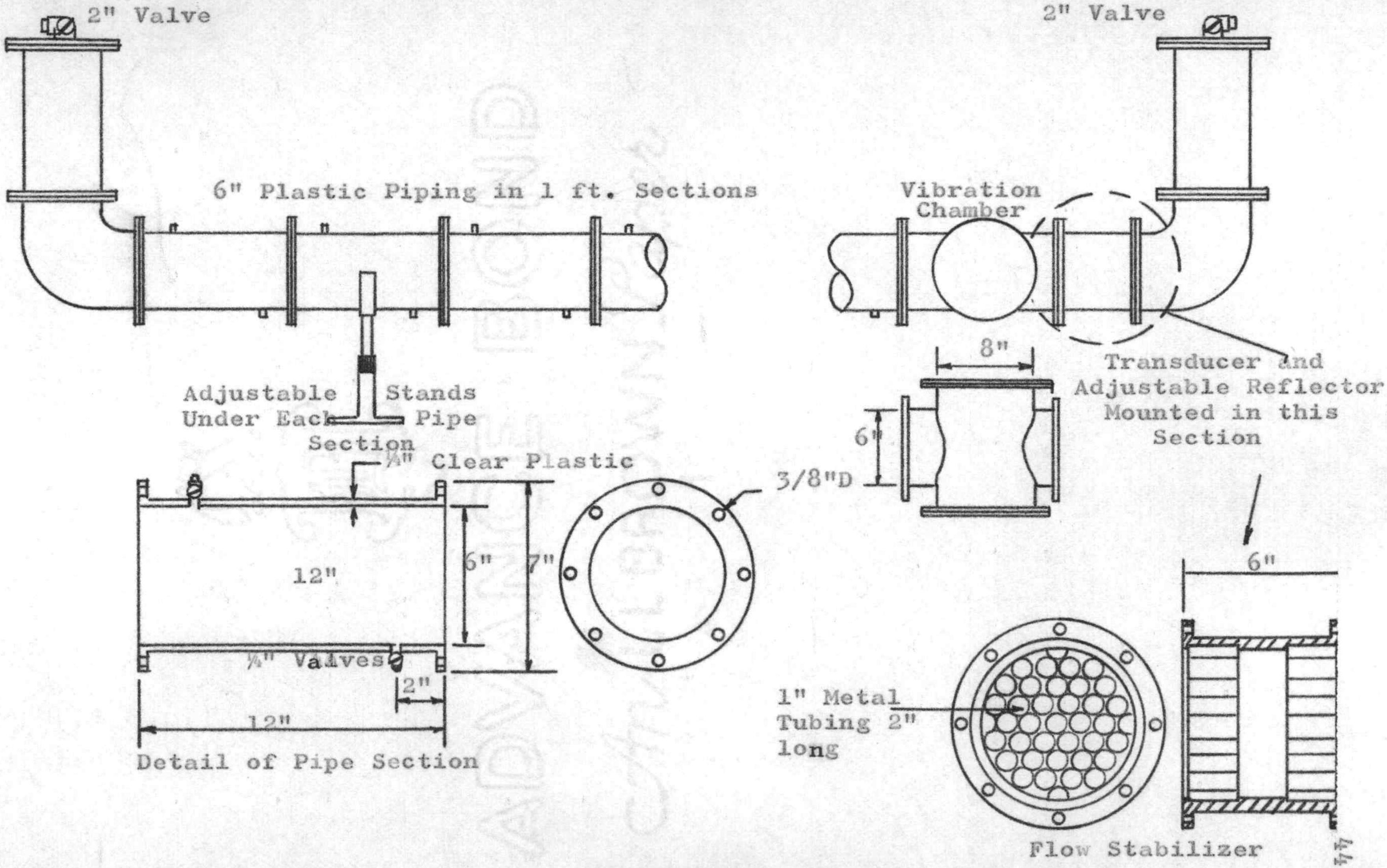


Figure XII. Treatment Chamber Design Details

Cost and Time Estimate

A cost estimate breakdown for the suggested apparatus is as follows:

Item		Cost
1. Generator and Transducers		$ 7,500
2. Treatment Chamber		600
3. Instrumentation		
Pressure Gauge	25	
Flow Rate Indicator	75	
Absorption Wavemeter	200	
Oscillograph	200	
Total Instrumentation		500
4. Laboratory Equipment		
Turbidimeter		
Titration Burettes	Contingencies not charged to the program	
pH Meter		
Thermometers		
Miscellaneous		
5. Compressor (10 psi)		150
6. Pump		300
7. Miscellaneous containers, tubing, etc.		100
8. Maintenance and Replacements		200
Apparatus Cost Estimate:		$ 9,350

It would be difficult to predict the amount of time necessary to do justice to the study. Quite possibly during the early experimentation, some of the factors mentioned will prove to have a negligible effect upon the process and may be eliminated from the test process. Assuming the study to be conducted as a graduate research program or in conjunction with a teaching position, at least a year would be required for the collection of data. Analysis and evaluation of this data, with mathematical and graphical formulation, and reporting on the entire study would demand an additional minimum of six months.

CHAPTER V

CONCLUSIONS

An exploration of the existing information in the field of ultrasonics has disclosed the necessity for further research into the effects of ultrasonic vibrations on particles suspended in water. The experience with aerosol coagulation, in particular, is indicative of the potentialities of these effects.

In so far as can be determined, very little experience exists in ultrasonic coagulation and settling of suspensions in water. Moreover, the experience that does exist has been on a very small scale laboratory basis. The apparatus that has been used has left much to be desired in effective control.

The conviction persists that an exhaustive program of testing, using equipment designed to yield reproducable data, is needed and is definitely worth while. Such a program would require considerable time and considerable expenses. A year and a half has been estimated as the time necessary to complete the study, and this may be a little optimistic. The equipment costs have been estimated at about $10,000.00, and it is difficult to imagine an effective apparatus costing much less.

The possibility does exist, though, that the suggested study may result in the development of an entirely new concept in the water and waste water treatment processes. The possibility of reducing treatment periods from several hours to several minutes is a tremendous idea, and one that may very well be conceivable. The value of such a concept cannot be estimated.

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