LBL-21403
Preprint c.2

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

RECEIVED
LAWRENCE
BERKELEY LABORATORY

AUG 12 1986

LIBRARY AND
DOCUMENTS SECTION

Engineering Division

Submitted to IEEE Transactions on Ultrasonics,
Ferroelectrics and Frequency Control

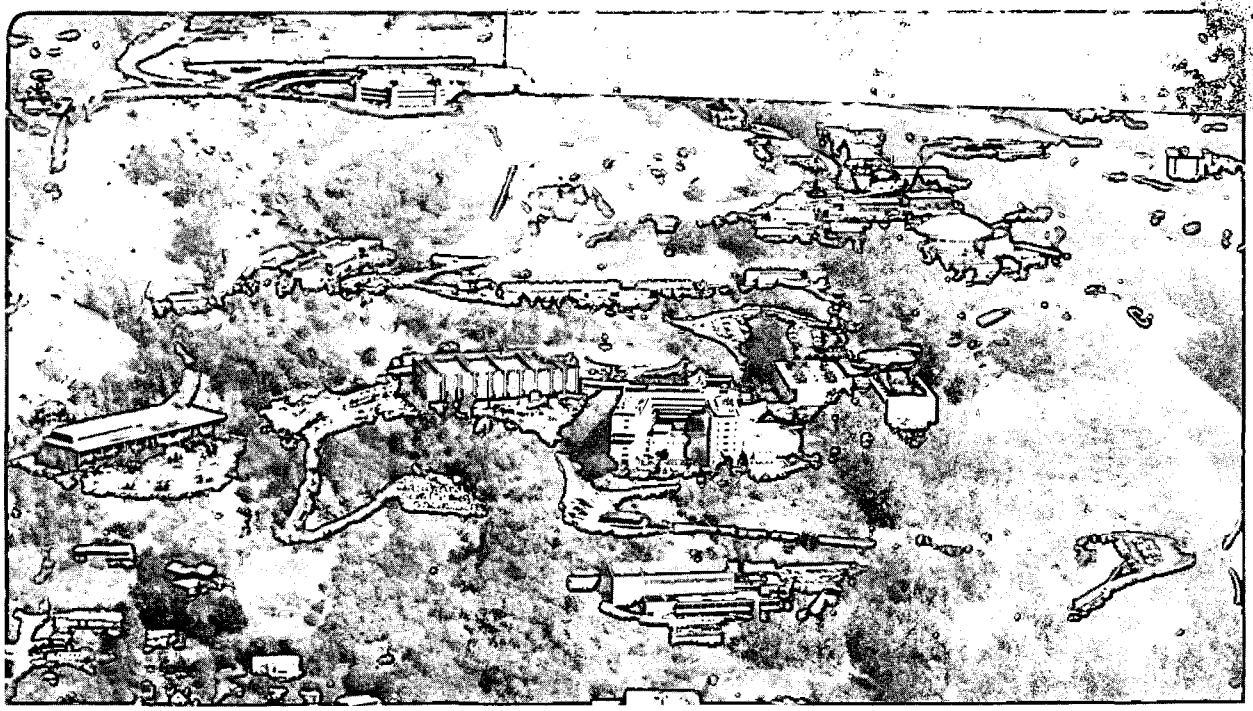
ACOUSTIC CHARACTERIZATION OF COAL AND GLASS BEAD SLURRIES THROUGH OPTICALLY NON-TRANSPARENT MEDIA

W.F. Kolbe, B.T. Turko, and B. Leskovar

September 1985

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks.



LBL-21403 c.2

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

LBL-21403
PUB-5149

ACOUSTIC CHARACTERIZATION OF COAL AND GLASS BEAD SLURRIES THROUGH OPTICALLY NON-TRANSPARENT MEDIA

W.F. Kolbe, B.T. Turko and B. Leskovar

Electronics Research and Development Group
Department of Instrument Science and Engineering
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720 U.S.A.

September 15, 1985

Prepared for the U.S. Department of Energy under contract No. DE-AC03-76SF00098.

ABSTRACT

A preliminary investigation of the feasibility of acoustic characterization of coal and glass bead slurries through optically non-transparent process lines is described. Specifically, studies were made of the frequency dependent properties of a coal slurry mixture in order to determine the particle size. Measurements were made of the propagations of acoustic pulses between two ultrasonic transducers mounted on opposite sides of a pipe containing the slurry. The detected signal was then Fourier analyzed to obtain the frequency spectrum relative to that of pure water. The calculations yielded both the absorption as a function of frequency and velocity dispersion of sound waves as they propagate through the mixture. Furthermore, on-line imaging of slurries were made under simulated dynamic conditions using an array of 10 acoustic transmitter-receiver pairs mounted circumferentially around a steel pipe. Time-of-flight of the acoustic wave was used to characterize slurry flow conditions along the pipe.

INTRODUCTION

In coal conversion processing plants it is important to measure the mass flow[1,2] of coal slurries in process lines in order to provide for the efficient, economic and safe operation of the plants. In addition to the total mass flow, a knowledge of the coal particle size distribution is also of interest[2] in optimizing a plant's performance. The particle sizes in such facilities range from a few microns to several hundred microns, and are transported at concentrations up to about 50% in water or various organic liquids. Because of the corrosive, abrasive and sludge-like nature of the slurry mixture, it is difficult, if not impossible, to use monitoring instrumentation which pene-

trates the walls of the process lines. Ultrasonic transducers offer a promising alternative to conventional instrumentation since they are non-invasive.

In the search for non-invasive instrumentation for the process lines, the use of acoustic flowmeters[2-4] has been investigated by several authors. These devices consist of one or more pairs of acoustic transducers mounted on opposite sides of the pipe in such a way that acoustic signals are propagated through the slurry medium. If the acoustic path is at an angle to the flow direction, the flow velocity can be measured[5] by means of the doppler frequency shift. Alternatively, with two pairs of transducers, the velocity can be determined[3] from the cross correlation signal between two pairs, the correlation resulting from acoustic disturbances which propagate down the pipe at the flow velocity. For a given particle size distribution, the acoustic absorption at a particular frequency is found[3] to be linearly dependent on the coal concentration and thus provides a measure of the actual coal concentration. Taken together, the concentration and flow velocity measurements can be used to determine the coal mass flow in the slurry.

A number of investigators[6-8] have also studied the acoustic absorption of small particles suspended in a fluid. These studies show the frequency dependence of the absorption is a function of the particle size and various theoretical models have been developed to calculate this dependence. For this reason, a measurement of the frequency dependence of the absorption offers promise as a method of characterizing the particle size distribution within the pipe.

In this paper we describe a preliminary study of the frequency dependent properties of a coal slurry mixture in order to investigate the possibility of making a particle size determination by acoustic methods. With our apparatus, acoustic pulses are propagated between two ultrasonic transducers mounted on

opposite sides of a pipe containing the slurry. The detected signal is then processed by Fourier analysis to obtain the frequency spectrum relative to that of pure water. The calculation yields both the absorption as a function of frequency and the velocity dispersion of sound waves as they propagate through the mixture. Since the extraction of a size distribution from the data is a difficult problem, the availability of as much information as possible will facilitate the solution. Our initial studies of this problem are described.

The analytical methods for characterization of coal slurries require a relatively long time for data processing before the results are known. An attempt was made for on-line imaging of slurries under simulated dynamic conditions resembling those in the real pipe flow. An array of acoustic transmitter-receiver pairs was arranged around the circumference of a steel pipe. The transmitting transducers were fired one at a time in a sequence. The receiving transducer on the opposite side of the pipe detects the acoustic signal travelling across the pipe. The time-of-flight of the acoustic wave is a function of the slurry concentration and the distribution of the particle sizes.

Although time-of-flight data alone cannot yield definitive information about both the particle size and the concentration of the slurry, it still may prove useful in monitoring slurry flow conditions at any point along the pipe. Turbulences in the flow, change in slurry concentration and the amount of sediment at the pipe bottom can be easily observed and measured on-line.

An apparatus, originally designed for acoustic imaging of air bubbles in the interior of water filled steel pipes,[9,10] was modified for the slurry flow measurements. The modifications included the addition of a motor driven slurry agitator to the existing section of the test pipe. The pipe already had an ar-

ray of acoustic transducers mounted around the circumference. (See Fig. 9.) Also, appropriate changes of the electronic circuits were made and the computer software rewritten for this new application.

STUDY OF ACOUSTICAL PROPERTIES OF COAL AND BEAD SLURRIES

Experimental Apparatus

For our first study of the acoustical properties of the coal slurry, the apparatus shown in Fig. 1 was constructed. A lucite pipe with an inside diameter of 57 mm and length of 150 mm is provided with removable caps at each end. Two acoustical delay lines 13 mm in length and 25 mm in diameter, also made of lucite, are mounted facing each other through holes drilled in the walls of the pipe. The inner surfaces of the delay lines are separated by 50 mm. Ultrasonic transducers are mounted on the outer surfaces of each delay line. The transducers (Panametrics model V106) are 13 mm in diameter with a resonant frequency of 2.25 MHz and are heavily damped to produce a broadband response.

A commercial pulse generator (HP model 8082A) is used to excite the transmitting transducer. It was adjusted to provide as short a rise time as possible and a sufficiently long pulse length to separate, in time, the transducer responses from the rising and falling portions. In order to simulate an impulse excitation, only the data resulting from the rising portion of the pulse was recorded. The two acoustic delay lines serve to couple the acoustic signal to the slurry medium and to eliminate the effects of reflections at the interface boundaries.

The output signal from the receiving transducer is amplified by an HP model 8447F amplifier. A Transiac model 2001 8-bit transient digitizer with a maximum sampling rate of 100 MHz and a capacity of 8000 channels is used to capture

the acoustic signal. The digitizer is provided with a Transiac model 4100 signal averager to permit the rapid acquisition and averaging of the acoustic signals. A pulse sequencer, constructed according to Ref. 11 is used to trigger the pulse generator and the digitizer. The pulse sequencer, transient digitizer and averager are mounted in a CAMAC crate which is interfaced to a PDP 11/34 computer.

The data is acquired by placing the desired coal slurry mixture in the pipe, agitating it to produce a uniform suspension and then averaging a number of digitized acoustic pulses. A second, reference signal, is then generated by replacing the slurry with pure water or allowing the coal mixture to settle below the transducer plane and repeating the measurement. The two data sets are then processed by Fourier analysis as described below to obtain the frequency dependent absorption and velocity dispersion.

Fourier Analysis of Acoustic Signals

As described above, the measuring system consists of an acoustic transmitter excited by an electrical impulse, an acoustic medium of path length z, and a receiving transducer which converts the acoustic energy back into an electrical signal. If we assume this system to be linear, then the total transfer function[12] can be written as a product of a set of individual transfer functions in the frequency domain:

$$S(f) = E(f)I_T(f)I_R(f)H_M(f)D_M(f) \qquad (1)$$

where S is the received electrical signal, E is the excitation signal, I_T and I_R are the acoustoelectric transfer functions for the transducers, H_M is the transfer function for the medium and D_M is the diffraction transfer function.

In the time domain, the equivalent relationship is the convolution:

$$s(t) = e(t)*i_T(t)*i_R(t)*h_M(t)*d_M(t) \tag{2}$$

where the symbol, * denotes convolution.

If we consider two different media, water and the coal slurry, then in each case the signal is:

$$S_W(f) = E(f)I_T(f)I_R(f)D_W(f)H_W(f) \tag{3}$$

and

$$S_C(f) = E(f)I_T(f)I_R(f)D_C(f)H_C(f) \tag{4}$$

Taking the ratio:

$$\frac{S_C(f)}{S_W(f)} = \frac{H_C(f)D_C(f)}{H_W(f)D_W(f)} \tag{5}$$

Since the water medium is essentially loss free and non-dispersive, we take $H_W(f) = 1$ and we have:

$$H_C(f) = \left[\frac{D_W(f)}{D_C(f)}\right] * \left[\frac{S_C(f)}{S_W(f)}\right] \tag{6}$$

If we express $H_C(f)$ in polar coordinates

$$H_C(f) = \left|H_C(f)\right| \exp\left[i\phi_C(f)\right] \tag{7}$$

then the magnitude $H_C(f)$ yields the frequency dependent losses of the medium. For a path length, z, the loss in dB/unit path length can be expressed as

$$\alpha(f) = -[20 \log \left|H_C(f)\right|]/z \tag{8}$$

The phase portion of $H_C(f)$ is responsible for velocity dispersion in the medium. According to the time shift theorem[12] of Fourier transform theory, a shift, τ , in the arrival time of the acoustic pulse is manifested in the frequency domain by a phase shift

$$\phi(f) = 2\pi f\tau \tag{9}$$

If v(f) is the acoustic velocity in the medium and v_o is the velocity in pure water, then

$$v(f) = v_o + \Delta v(f) \tag{10}$$

where $\Delta v(f)$ is the velocity change due to dispersion and other effects contrib-

uted by the medium. The corresponding expression for the frequency dependent arrival time of the acoustic signal is

$$t(f) = t_o + \tau(f) \tag{11}$$

where (f) is given by Eq. 9 above.

For the given acoustic path length, z, we have $v(f) = z/t(f)$ enabling us to write

$$v_o + \Delta v(f) = 1/[1/v_o + \tau(f)/z]. \tag{12}$$

As a result, the velocity dispersion, $\Delta v(f)$ becomes

$$\Delta v(f) = v_o \{[1 + v_o \phi(f)/(2\pi f z)]^{-1} - 1\}. \tag{13}$$

Before proceeding to examine the experimental results, we note that in Eq. 6 the factor $D_W(f)/D_C(f)$ is not determined. The quantity, D(f) accounts for the loss in the detected signal as the divergent acoustic beam propagates through the medium. Papadakis[13] has examined this contribution to the signal loss and has presented graphical results for the loss and phase shift for a piston transducer such as used in the present study. D(f) is a function of the path length, the transducer diameter and the wavelength of the sound. Of these three quantities, the first two are the same for both (water and slurry) media. On the other hand, the wavelength is velocity dependent. If the velocity dif-

ference between the two media is large, then a correction such as that provided by Papadakis[13] should be applied. In our measurements, the difference in velocities is quite small and we have taken the ratio D_W/D_C to be unity.

In summary, time spectra $s_C(t)$ and $s_W(t)$ are obtained for the coal slurry and water reference signals respectively. These spectra are then Fourier transformed and $H_C(f)$ is computed according to Eq. 6. After conversion of the result to polar coordinates, the frequency dependent absorption and velocity dispersion are computed using Eqs. 8 and 13. A computer program in FORTRAN was written to accomplish the necessary transformations.

Experimental Results

Samples of coal were prepared by grinding lumps of the material in a blender and separating the resulting powder into different size ranges using calibrated sieves. Weighed samples from each group were then mixed with water to form a slurry. The slurry was washed several times by shaking the container and, after settling, replacing the liquid fraction with clean water. After cleaning, the fluid above the settled coal particles was nearly transparent. The settling time, which varied with particle size, was on the order of 10 s in each case, more than adequate for the measurements to be described below.

The acoustic properties of the coal slurry mixtures were measured according to the following procedure: First the mixture was allowed to settle to a point below the transducer plane. Then the acoustic time spectrum of the essentially pure water residue was digitized. After storing this data in the computer, the mixture was agitated enough to yield a uniform suspension of the coal particles. The measurement was then repeated before the mixture could settle. In each case an average of 5000 samples were obtained to enhance the accuracy and

signal-to-noise ratio of the data. The data was digitized at a sampling rate of 50 ns/sample and stored in 512 channels. The total sampling time in each case was ~0.5 s. The two data sets were then processed by Fourier analysis.

Coal samples were prepared with particle sizes in three ranges, 106-125 μm, 150-180 μm and 180-300 μm. Figure 2 illustrates the typical time spectra obtained. In the figure, curve (a) corresponds to pure water, curve (b) was obtained with coal particles of size 180-300 μm at a concentration of 18% by weight and in (c), a 15% concentration of 106-125 μm coal particles was used. As can be seen, the effect of adding the coal is to reduce the peak amplitude and broaden the width of the signal, with the larger particles producing more broadening than small particles.

For each of the three particle size ranges, three different slurry concentrations were prepared. The data from these was Fourier analyzed and processed as described above. The results are shown in Figs. 3-5 with the various particle sizes and concentrations used identified in the figure captions. In the upper figures of each set the computed acoustic absorption is shown and in the lower figures the velocity dispersion is given.

The data was further analyzed by assuming both the absorption and dispersion to be linearly proportional to the concentration. This is a reasonable assumption for the relatively low concentrations used in this study. By scaling all the concentrations to 10% it is possible to plot all the data on a single pair of graphs. In Fig. 6 the results of this scaling are shown. The data for each particle size range is seen to correspond reasonably well, indicating the validity of the scaling assumption. The observed deviations may be, in part, a result of errors in generating precise concentrations due to incomplete

mixing of the slurry. In Fig. 7 we present the same data averaged into single curves with the uncertainties visible in the previous figure indicated by error brackets.

In order to illustrate the possibility of characterizing a composite mixture of different particle sizes, we combined two of the above size groups. A mixture containing 50% of the size range 150-180 μm and 50% of the larger 180-300 μm size was diluted in water to a concentration of 17% by weight. The frequency dependent absorption and velocity dispersion of this slurry was then measured with the results plotted in Fig. 8 (solid line). The data previously obtained (Fig. 7) for the individual size ranges was then combined by summing the two curves (b) and (c) and scaling the result to 17%. These calculated curves are also shown in Fig. 8 as a dashed line. The agreement for the absorption portion of the data is very good. In the case of the velocity dispersion, the two curves are parallel but slightly displaced, by an amount comparable to that previously observed in Fig. 6. It should be noted that the separation of the two curves corresponds to a velocity difference of less than 0.004 mm/μs, about 0.25% of the velocity (1.5 mm/μs) of sound in water.

If we compute the difference in arrival time for an acoustic pulse travelling over the 50 mm path length of this experiment for the two velocities, 1.500 mm/μs and 1.504 mm/μs corresponding to the above velocity difference, we find the time difference to be only 88 ns. This time difference is approx. equal to the 50 ns sampling intervals at which all of the above data was sampled. It is therefore possible that the present data is inherently subject to errors of this magnitude. If so, the problem could easily be solved by sampling at a higher rate. With the present digitizer, the sampling time can be reduced to 10 ns and future data should be acquired at a rate of 100 MHz.

CHARACTERIZATION OF THE COAL SLURRY BY ACOUSTIC IMAGING TECHNIQUES

Experimental Apparatus

A block diagram of the apparatus for acoustic imaging of slurries in a steel pipe is shown in Fig. 9. A length of steel pipe (57.5 mm diameter and 3 mm wall thickness) has an array of 10 pairs of acoustic transducers mounted around its midsection. To each transmitting transducer (T10-T19), the corresponding receiving transducer (R0-R9) is mounted on the opposite side of the pipe. The transmitters are fired one at a time, producing an acoustic pulse which travels through the slurry-filled pipe to the receiver. The time the sound takes to reach the receiver is a function of the concentration and the particle size distribution of the slurry.

The control logic is programmed to fire the next transmitter after the reverberations from the preceding pulse have subsided. The sequence of pulses that fires all 10 transmitters is called a frame. Consequently, each pulse, traversing the pipe at a different angle, is called a line of the frame. The magnitude and shape of the signal detected by the receiver is a complex function of the acoustic wave interaction with the slurry particles. A typical signal received through the pipe filled with water is shown in Fig. 10. A discriminator following the signal amplifier fires each time the negative transition of the waveform exceeds the preset threshold. Each pulse, depending on the magnitude and shape, can trigger the discriminator more than once. The arrival time at each discriminator pulse is digitized (Data Processing block in Fig. 9) and stored in the computer.

Along with the time information of each pulse, data relevant to the frame and line number is also stored. Any desired number of digitized frames can be either displayed or printed out in a form shown in Fig. 11. Each frame con-

sists of 10 lines with a cross printed each time the acoustic signal edge fired the discriminator. The horizontal axis shows real time in clock pulses elapsed from the firing of the transmitter at the beginning of each line. The frequency of the clock pulses is known and selected to scale properly the desired portion of the line time.

Each line in a frame of Fig. 11 shows a signal with three lobes of sufficient magnitude to trigger the discriminator. Since the travel distance across the pipe is the same for each line, the three columns of data should lie on a straight line if the medium inside the pipe were homogenous. The pipe containing a mixture of glass beads and water in 3:5 volume ratio was rocked about the axis normal to the pipe length when the frames in Fig. 11 were taken. Consequently, a substantial change of bead concentration in the pipe cross section is "seen" by the tranducers. Also, the concentration changes from frame to frame as the beads shift in lumps as the pipe is being rocked.

The data can be also displayed on-line on the oscilloscope as they are passed to the computer in the same format as in Fig. 11. A trained observer can thus "see" the slurry flow live on the screen.

In order to simulate a slurry flow, the test pipe section in Fig. 9 was sealed at the bottom. A motor driven rotating blade was inserted into the pipe through a leakproof bearing. The motor speed can be controlled by a variable transformer. The pipe was filled with a mixture of water and glass beads. The beads were a kind used for industrial sand blasting, the mixture of round to irregular shapes range in sizes from 50-300 μm.

The pipe was first filled up with water. The concentration was further controlled by replacing a known volume of water by the same volume of beads.

The top of the pipe was sealed and residual air pockets eliminated through a valve. This is because the air broken into bubbles by the blade might alter acoustic properties of the mixture.

The bead concentration along the pipe is a function of the blade velocity. The beads slowly settle to the bottom when the motor is cut off. This process can be easily observed by shooting the frames continously at a given rate.

Experimental Results

Several experiments are presented here in order to demonstrate that this method can be useful in the live monitoring of slurry flow in pipes. Figure 12 shows a long sequence of frame compiled from a printout similar to that on Fig. 11. A ratio 5:4 of glass beads to water was selected to make sure that the depth of the settled beads was above the transducer plane. The frames were recorded at the ratio of 2/s from the beginning of the settling period immediately after the motor was turned off. The horizontal axis in Fig. 12 represents about 20 s of real time, the vertical axis, the propagation time of sound waves across the pipe (i.e. the concentration of glass beads in water) and the z axis (at 45° angle) the individual lines of a frame.

At time zero, coincident with the first frame, the frame shot earlier in pure water is superimposed for reference (100% water). Following the propagation time for line No. 0 for instance, a gradual decrease in the propagation delay is noticeable, as the density of glass beads increases due to the settling (i.e. the velocity of sound increases accordingly).

A sudden decrease in propagation time can be seen, after about 6 s, the point where the beads touch and no longer stay separated by water. It is interesting that this jump occurs simultaneously in all lines and fast. Even at much higher frame rates, the jump occurred during a single frame period.

After the touch-up point, the settling process continues for several more seconds. A jump in the steady state can be made by tapping the pipe, which packs the beads tighter with a corresponding drop in propagation delay. Other lines in the frame track each other, indicating the expected uniform settling of the beads throughout the pipe cross section.

Periodic changes in slurry density were simulated by rocking the test pipe, filled with glass beads in water (3:5 ratio by volume), back and forth about the vertical axis. The results, shown in Fig. 13, show accordingly the periodic fluctuation of bead concentration. Although the lines follow the same periodic pattern as expected, there is a noticeable difference among individual lines, indicating nonuniformity in bead concentration. The vertical scale is calibrated in relative concentration of beads in water. For line No. 0, the concentration varies from about 5% (almost pure water) to 50%.

A somewhat different presentation of glass bead distribution over the pipe cross section as a function of time is shown in Fig. 14. A sequence of frames shows a substantial fluctuation as the beads shifted during the time the pipe was moved off its vertical axis.

The acoustic imaging of the cross section of the pipe in a horizontal position was also done. The pipe was filled with 3 parts glass beads and 6 parts water and left in a horizontal position to let the beads settle evenly on the bottom. A single frame was taken in this position and shown in Fig. 15a (dotted line) along with two reference frames taken earlier with the pipe in the vertical position. One of the two frames was taken through the glass beads filling the entire cross section of the pipe (left column) and the other frame through pure water (right column). The lines of the frame shot in the pipe

horizontal position lie obviously between the two reference frames. In particular, the lines R1-R3 coalesce with the lines of the reference frame, indicating that there were no beads along those acoustic paths.

An image of the pipe cross section can be built by transforming the data of Fig. 15a into cylindrical coordinates.(Fig. 15b) The fraction, d_b of the inner pipe diameter d filled with beads can be calculated for each line from

$$\frac{d_b}{d} = \frac{(t_{wd} - t)}{(t_{wd} - t_{bd})} \tag{14}$$

where t_{wd}, t_{bd} and t are propagation times measured for 100% water, 100% beads and the bead-water mixture respectively, read out from Fig. 15a.

The results shown in Fig. 15b match quite accurately the actual ratio of beads to total pipe volume of 3/9 = 0.33. The shaded bead area (2590 mm^2), found by the graphic integration, divided by the pipe cross section (7854 mm^2) results in the same ratio of 0.33.

Results obtained by the acoustic imaging technique show that the real time acoustic imaging of slurries flowing through steel pipes is possible, along with the measurements of their concentrations. However, further efforts are necessary to discriminate the size of certain categories of glass beads used for slurry simulations.

DISCUSSION

We have examined the application of acoustic techniques to the problem of coal slurry characterization from two different points of view. On the one hand, we have measured the frequency dependent absorption and velocity disper-

sion of coal slurry samples using Fourier analysis. The information gained from these measurements offers promise as a method for the characterization of particle size distributions in the slurry. We have also examined the application of acoustical imaging techniques in characterizing the coal slurry. The information to be gained from this approach is different in that it provides a gross "picture" of the larger structures present within the slurry containment vessel.

Summarizing the spectral analysis first, we find that one can, in fact, determine both the absorption and velocity dispersion with reasonable accuracy by Fourier analysis of acoustic pulses propagated through the slurry. In addition, we have shown that both of these components are proportional to the slurry concentration, at least within the range of concentrations considered. The shape of the curves, as expected, is a pronounced function of the particle size and therefore can yield information about the size distribution.

By combining two fractions of coal containing particles from different size ranges, and measuring the frequency spectra of the composite sample, we were able to show good agreement with the frequency spectra predicted from a linear combination of the individual groups. While this is a crude characterization of particle size, it may suffice in many practical situations. It would be a considerably more difficult problem to completely characterize an arbitrary distribution. To achieve this end it is desirable to obtain as much information as possible about the acoustic properties of the slurry. For this reason we believe that a measurement of the velocity dispersion in addition to the absorption spectrum (the latter can be measured by other, perhaps simpler methods) can offer additional useful information appropriate to a more complete characterization.

One should point out at this juncture that there exists a very general formalism originally derived by Kramers and Kronig[14] which relates the real and imaginary parts of any measurable property of a physical system obeying causality. The application of the Kramers-Kronig relationships to the case of acoustics has been discussed by O'Donnell et al.[15] As these authors point out, the acoustic absorption and velocity can be related through the real and imaginary parts of the complex dynamic compressibility of the fluid and hence can also be linked through the Kramer-Kronig relationships. The problem in applying these relationships is that to compute one quantity at a given frequency it is necessary to know the other at all frequencies. If the spectral information is incomplete, as in this case, the calculation cannot, in general, be performed. For the case of weak absorption, O'Donnell et al have derived a quasi-local relationship for which the calculation can be performed. We do not get good agreement when this calculation is applied to our data. In fact, the calculation predicts an increase in velocity with frequency whereas our data shows a decrease. Clearly the problem should be investigated further.

Sayers[16] has investigated theoretically the propagation of ultrasound in concentrated mixtures and suspensions. He finds for his model calculation, a decrease in velocity with frequency which becomes more pronounced as the concentration is increased. This effect is a strong function of the particle size and, as he points out, it may be useful as a technique for particle sizing.

In order to determine if an arbitrary particle size distribution can be fit to the absorption and dispersion data, more precise measurements are needed. A number of such improvements have already been described above and these will be incorporated in future measurements. Improved calculations of the scattering

of acoustic waves by the slurry particles, especially at high concentrations, is also needed to establish a secure theoretical basis for understanding the measured results.

With the apparatus just above, we are able to investigate, in some detail, the acoustic properties of the slurry mixture along a single path extending across the pipe. In order to detemine the variation in media properties in different cross sections of the pipe, it is necessary to employ an array of transducers, as in the case of the imaging described above. Such a system should be explored as a means of obtaining valuable information needed in the transport and utilization of slurries.

ACKNOWLEDGEMENT

This work was performed as part of the program of the Electronics Research and Development Group of the Department of Instrument Science and Engineering, Lawrence Berkeley Laboratory and supported by the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

REFERENCES

1. R.W. Doering, Ed., The Proceedings of the 1980 Symposium on Instrumentation and Control for Fossil Energy Processes, Argonne National Laboratory Report, ANL-80-62, CONF-800602 (1980).

2. S.K. Kawatra, M.J. Laurila and J. Keck, On-line Characterization of Coal Slurries, Proc. of the 1980 Symposium on Instrumentation and Control for Fossil Energy Processes, 133-149, Virginia Beach, VA (1980)

3. A.C. Raptis and S-H Sheen, Ultrasonic Properties of Coal Slurries and Flow Measurements by Cross Correlation, IEEE Trans. on Sonics and Ultrasonics, SU-28, 248-256 (1981).

4. A.C. Raptis, Instrumentation and Control for Fossil Energy, Quarterly Technical Progress Report, Argonne National Lab ANL/FE-84-14 (1984).

5. L.C. Lynnworth, Ultrasonic Flowmeters, in Physical Acoustics, XIV, 407-525, Academic Press, N.Y. (1979).

6. J.R. Allegra and S.A. Hawley, Attenuation of Sound in Suspensions and Emulsions: Theory and Experiments, J. Acoust. Soc. Am., 51, 1545 (1972).

7. R.J. Urick, The Absorption of Sound in Suspensions of Irregular Particles, J. Acoust. Soc Am., 20, 283 (1948).

8. M.C. Davis, Coal Slurry Diagnostics by Ultrasound Transmission, J. Acoust. Soc. Am., 64, 406 (1978).

9. W.F. Kolbe, B.T. Turko and B. Leskovar, Acoustic Imaging of Vapor Bubbles Through Optically Non-Transparent Media, IEEE Trans. Nucl. Sci., NS-31, No. 1, 726-732 (1984).

10. W.F. Kolbe, B.T. Turko and B. Leskovar, Acoustic Imaging in a Water-Filled Metallic Pipe, IEEE Trans. Nucl. Sci., NS-32, No. 1, 1016-1024 (1985).

11. H. Saint-Jalmes and Y. Barjhoux, Rev. Sci. Instrum., 53, 1 (1982).

12. A. Papoulis, The Fourier Integral and its Applications, McGraw-Hill, N.Y., 1962.

13. E.P. Papadakis, Physical Acoustics (W.P. Mason and R.N. Thurston, Eds), V11, 151-211, Academic Press, N.Y., 1975.

14. R. Kronig and H.A. Kramers, Absorption and Dispersion in X-Ray Spectra, Zeits. f. Phys. 48, 174 (1928).

15. M. O'Donnell, E.T. Jaynes and J.G. Miller, General Relationships between Ultrasonic Attenuation and Dispersion, J. Acoust. Soc. Am., 63, 1935 (1978).

16. C.M. Sayers, On the Propagation of Ultrasound in Highly Concentrated Mixtures and Suspensions, J. Phys. D: Appl. Phys., 13, 179 (1980).

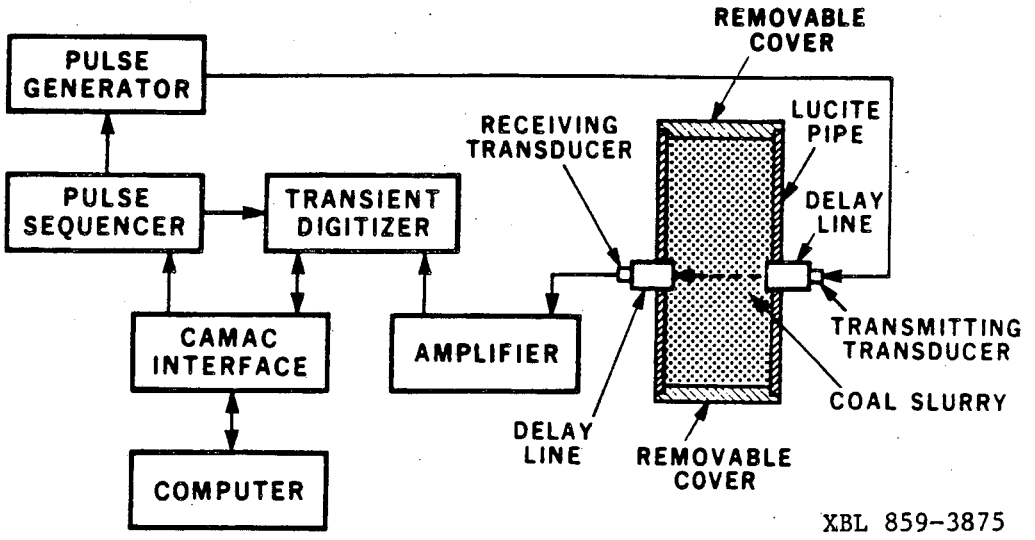


Fig. 1 Block diagram of apparatus for measuring frequency dependent acoustic properties of coal slurry.

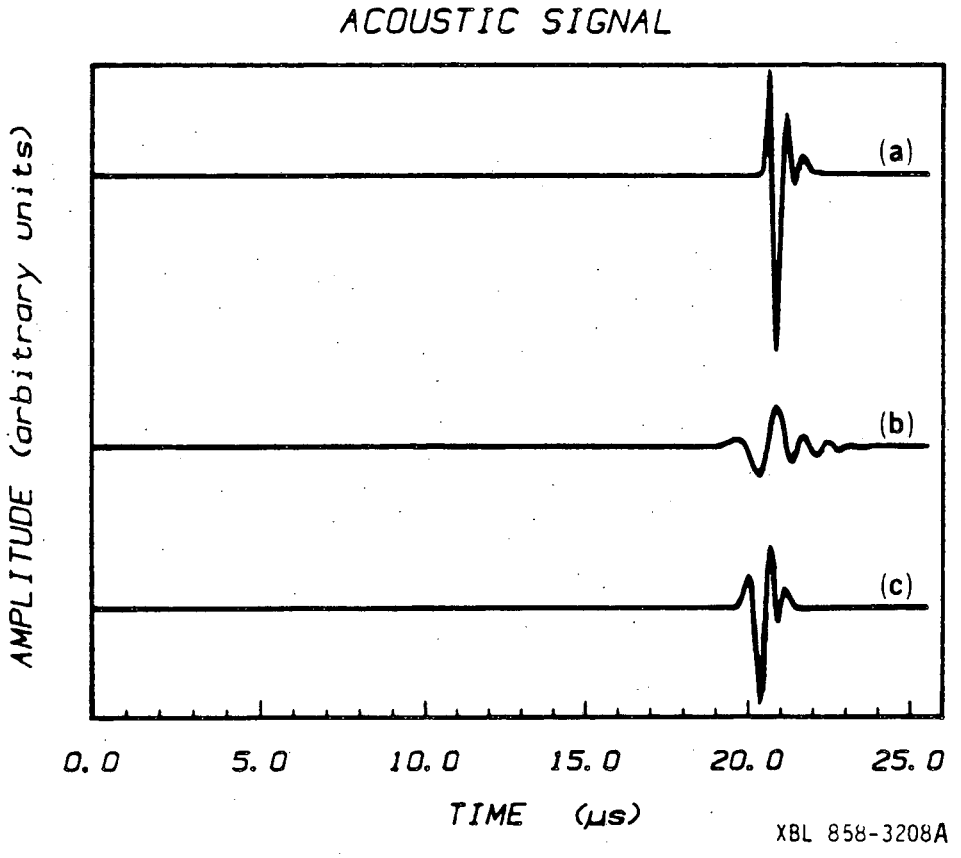
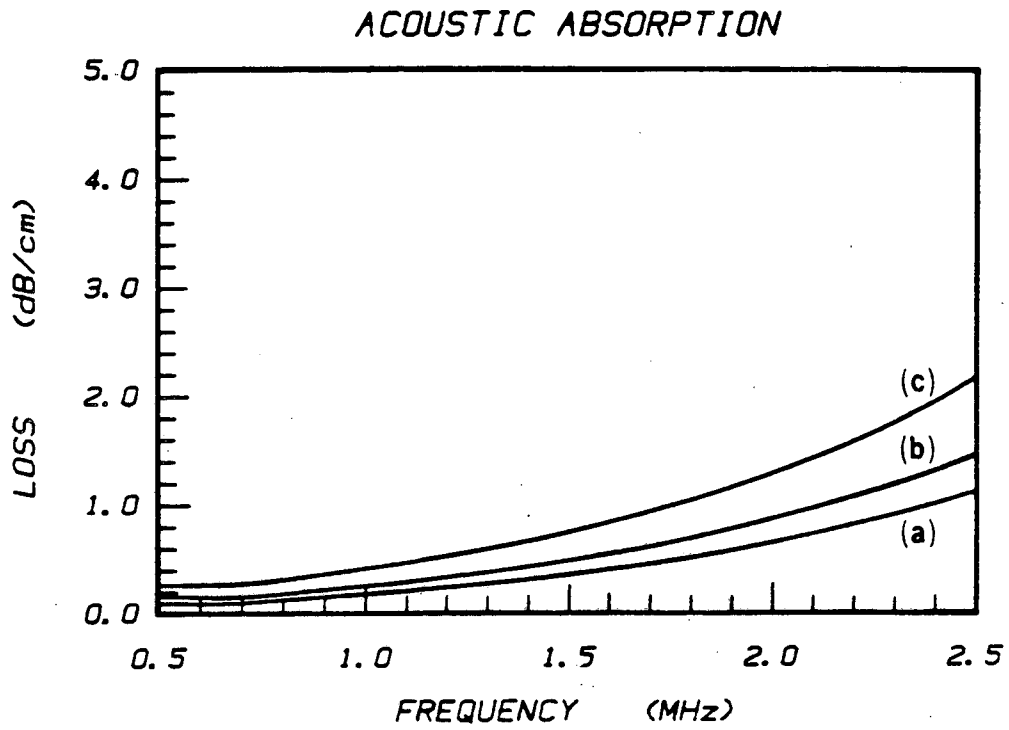
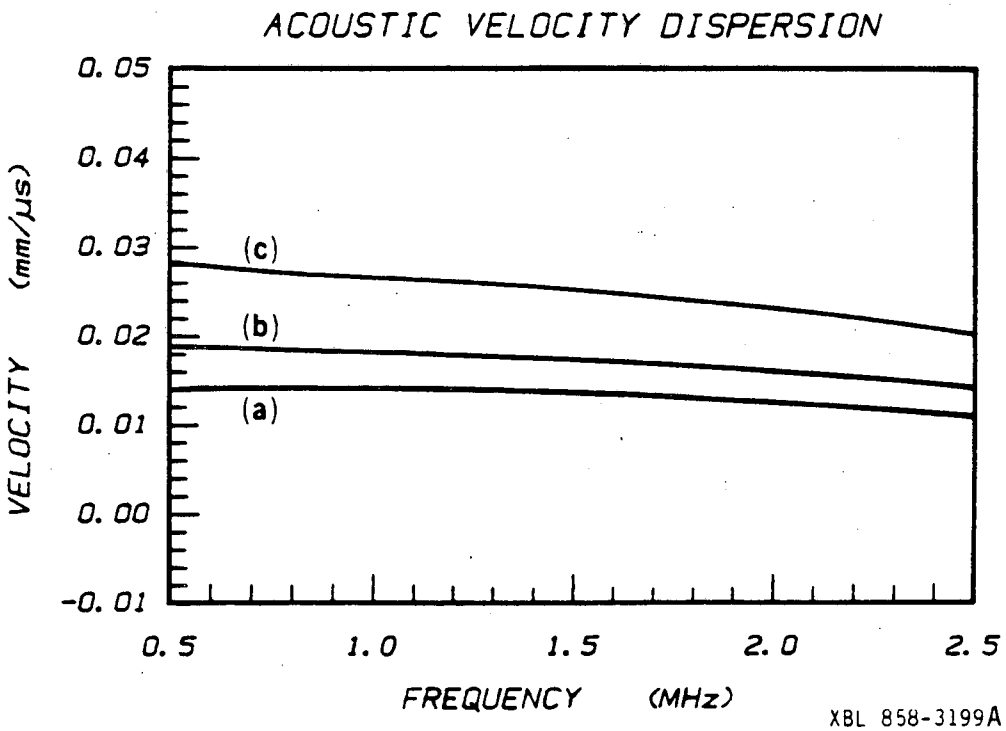


Fig. 2 Acoustic time signals for (a) pure water, (b) 18% by weight concentration of 180-300 μm coal particles, (c) 15% concentration 106-125 μm coal particles.

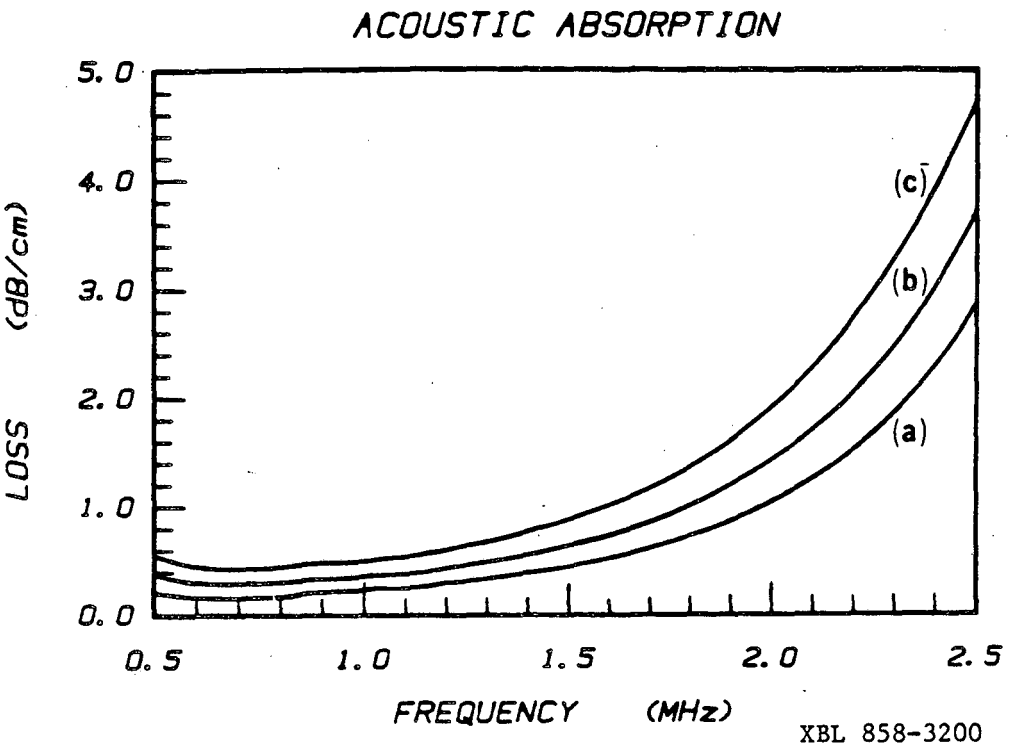


XBL 858-3198



XBL 858-3199A

Fig. 3 Acoustic absorption and velocity dispersion for 106-125 μm coal slurry for (a) 7.0%, (b) 9.6% and (c) 15% concentration.



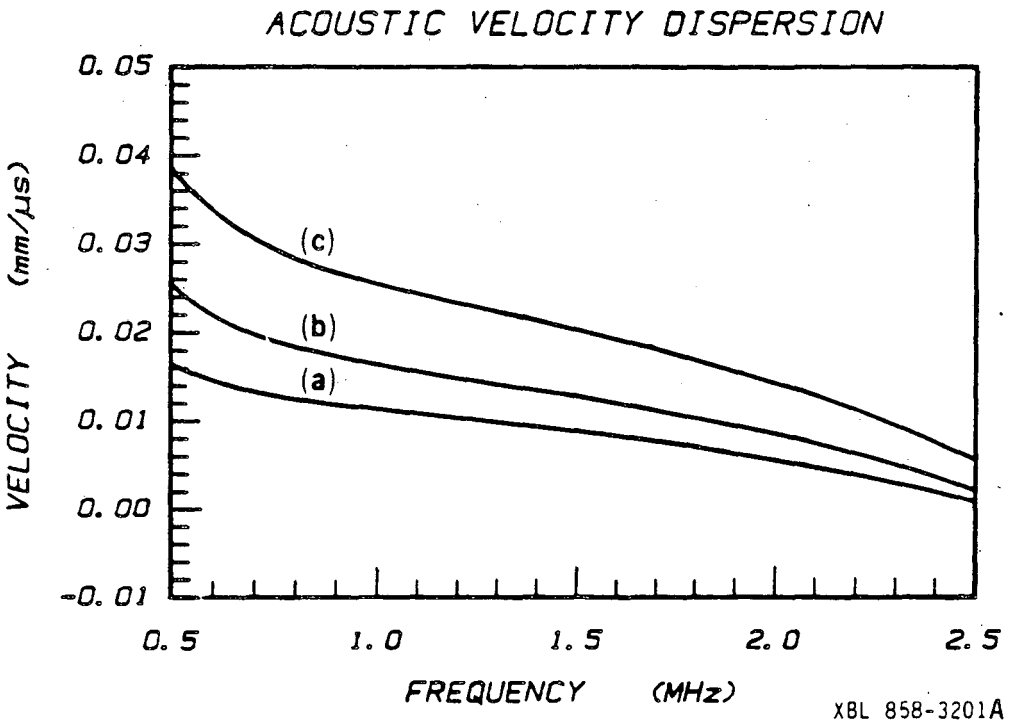
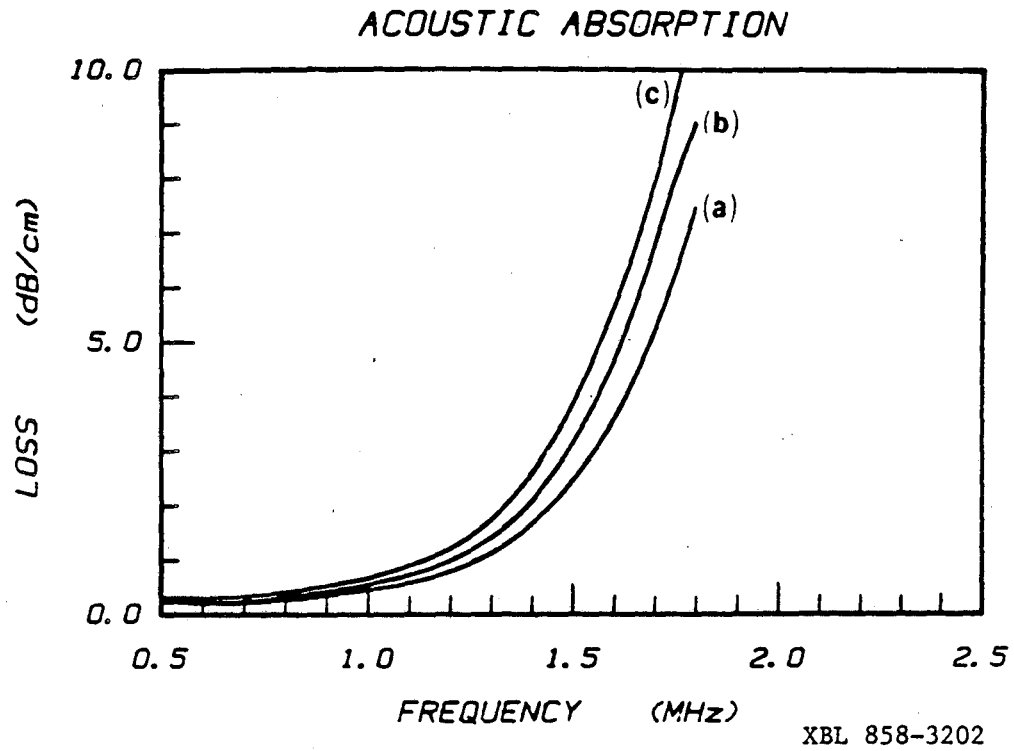


Fig. 4 Acoustic absorption and velocity dispersion for 150-180 μm coal slurry for (a) 6.6%, (b) 9.0% and (c) 14.2% concentration.



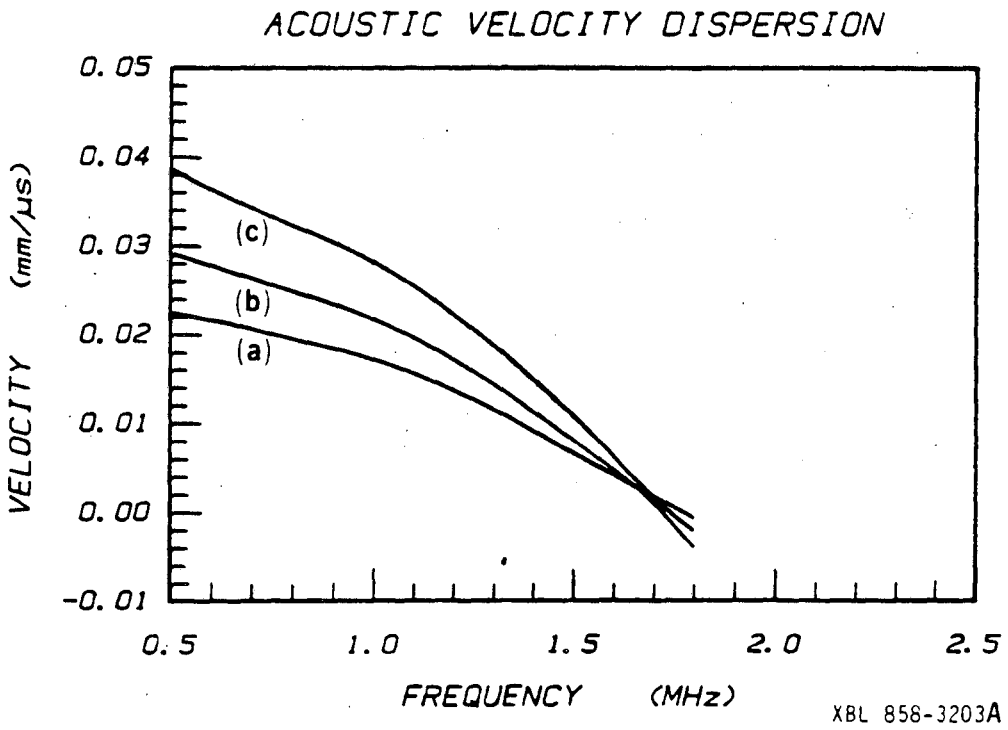
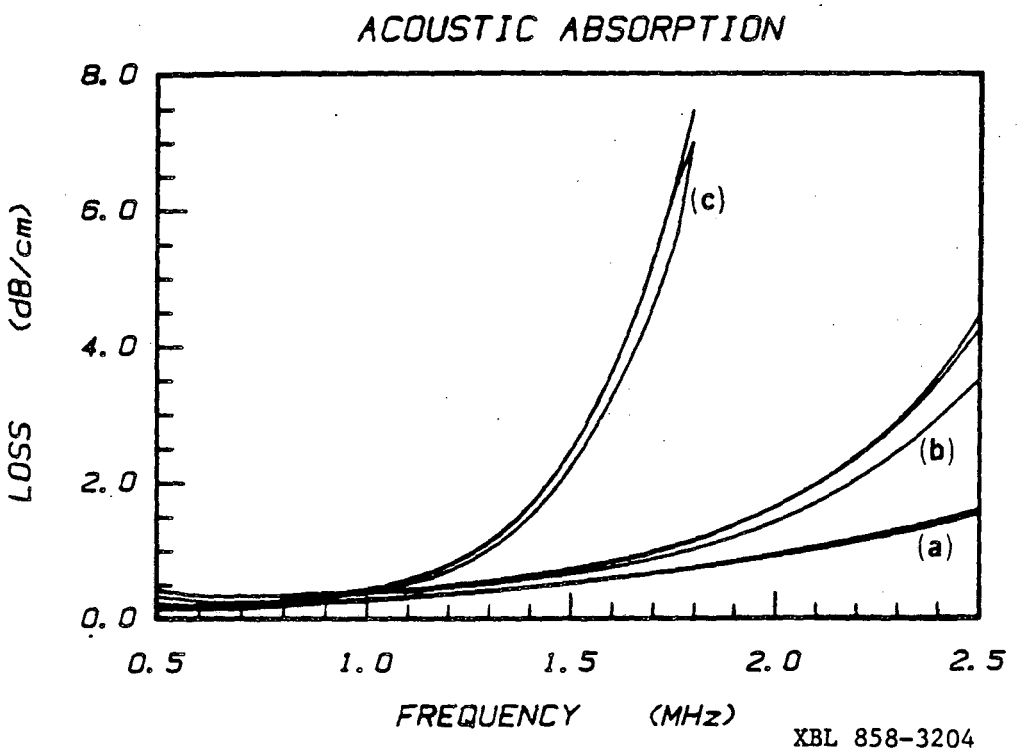


Fig. 5 Acoustic absorption and velocity dispersion for 180-300 μm coal slurry for (a) 10%, (b) 12.9% and (c) 18.1% concentration.



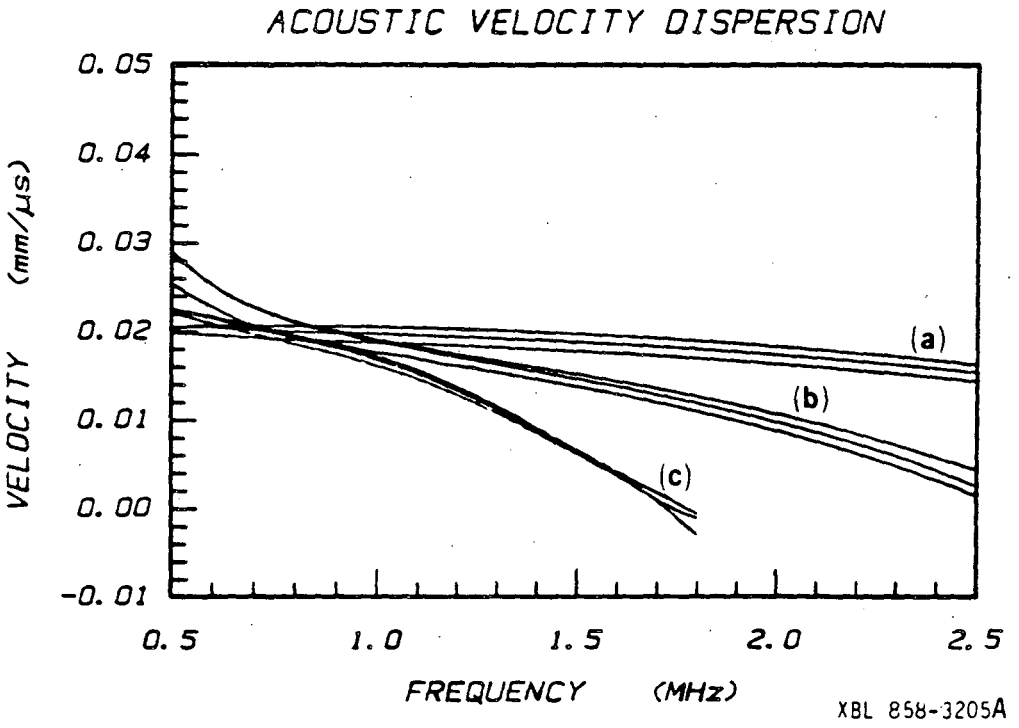
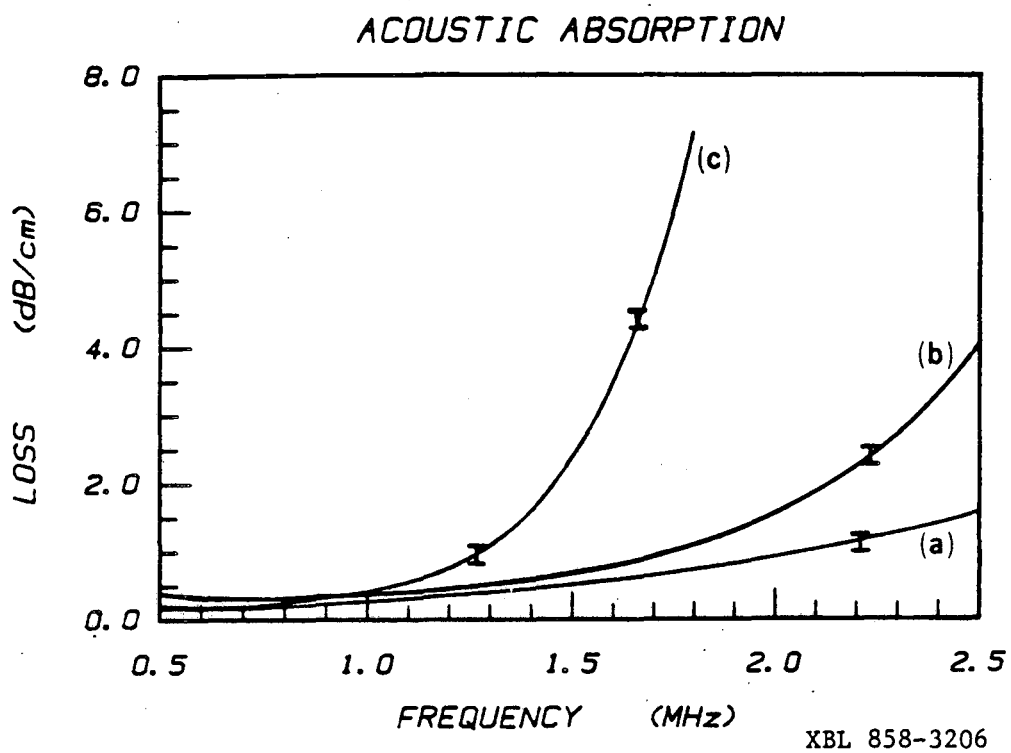


Fig. 6 Superposition of all data linearly scaled to a concentration of 10 (a) 106-125 μm, (b) 150-180 μm and (c) 180-300 μm.



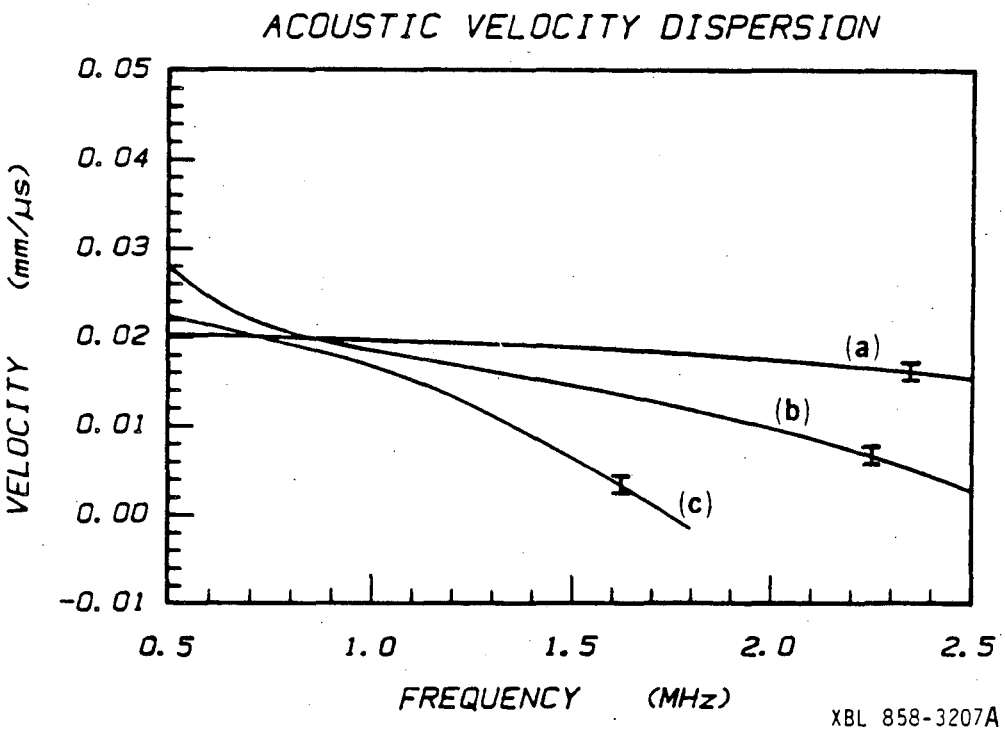
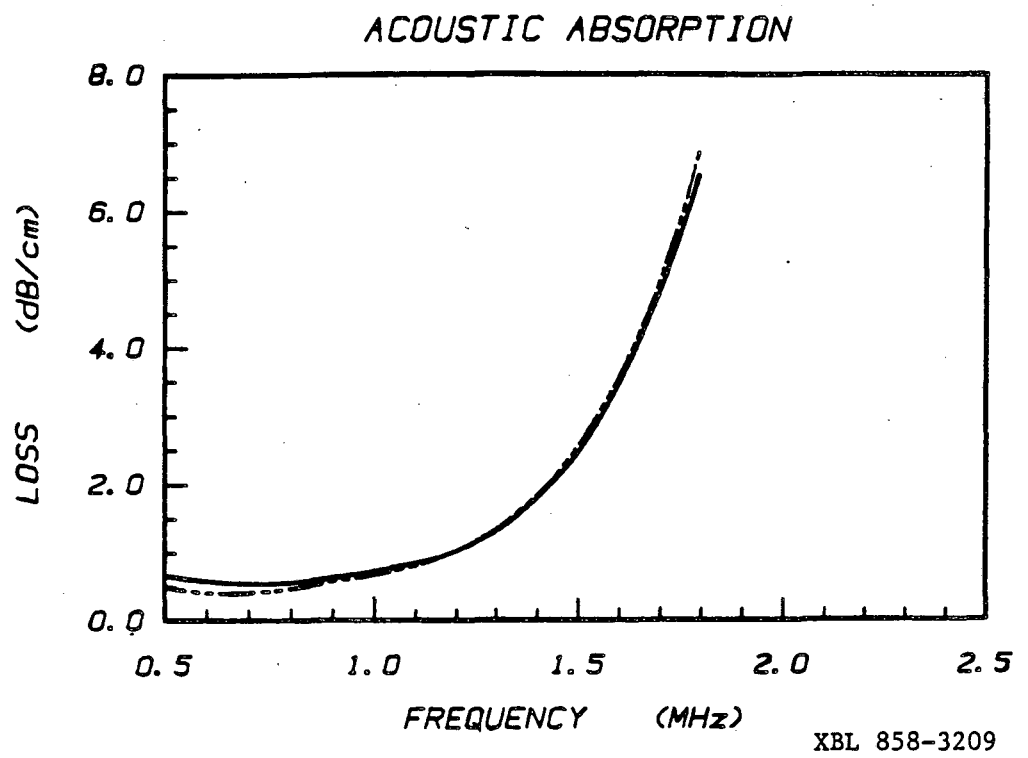


Fig. 7 Acoustic absorption and velocity dispersion for 10% concentration coal slurry of particle size (a) 106-125 μm, (b) 150-180 μm and (c) 180-300 μm.



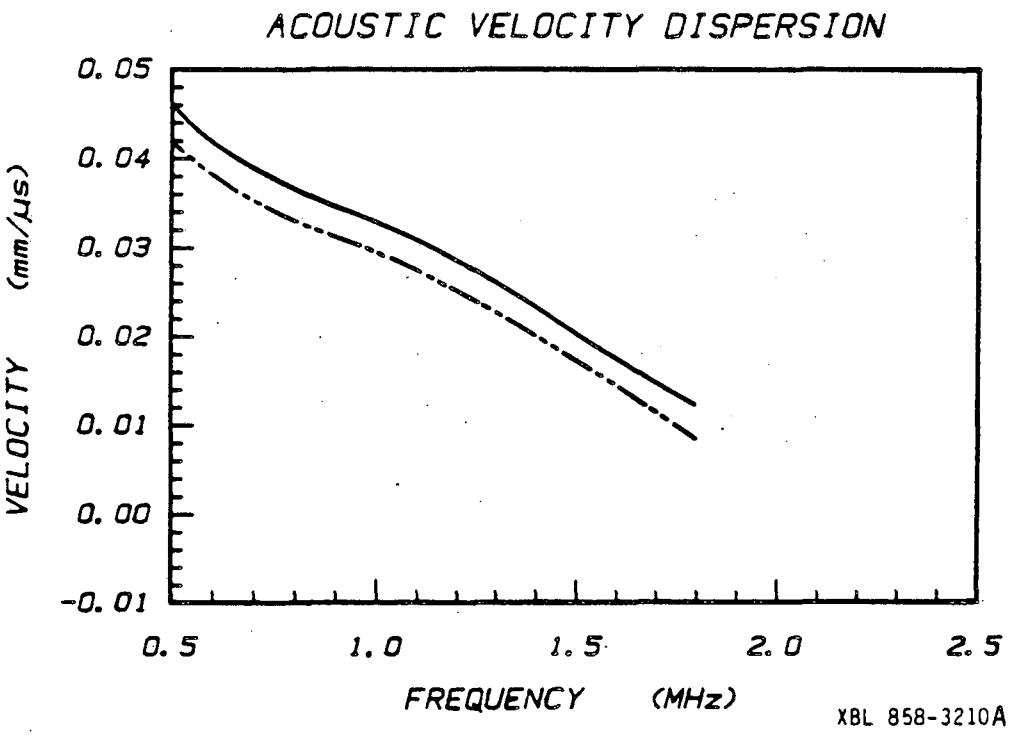


Fig. 8 Acoustic absorption and velocity dispersion for coal slurry mixture containing equal amounts of 150-180 μm and 180-300 μm coal, solid line measured data and (b) dashed line calculated from Fig. 7.

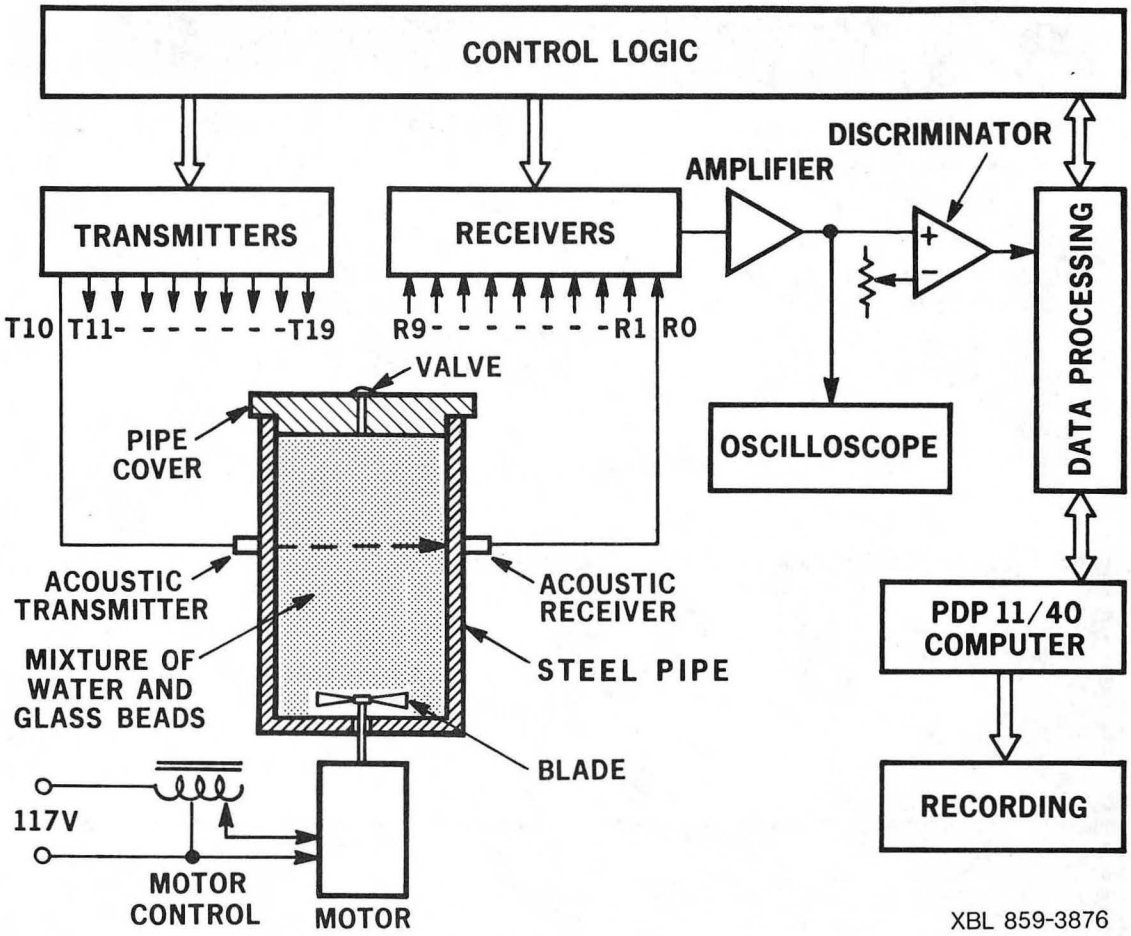


Fig. 9 Apparatus for acoustic imaging of slurries in a steel pipe.

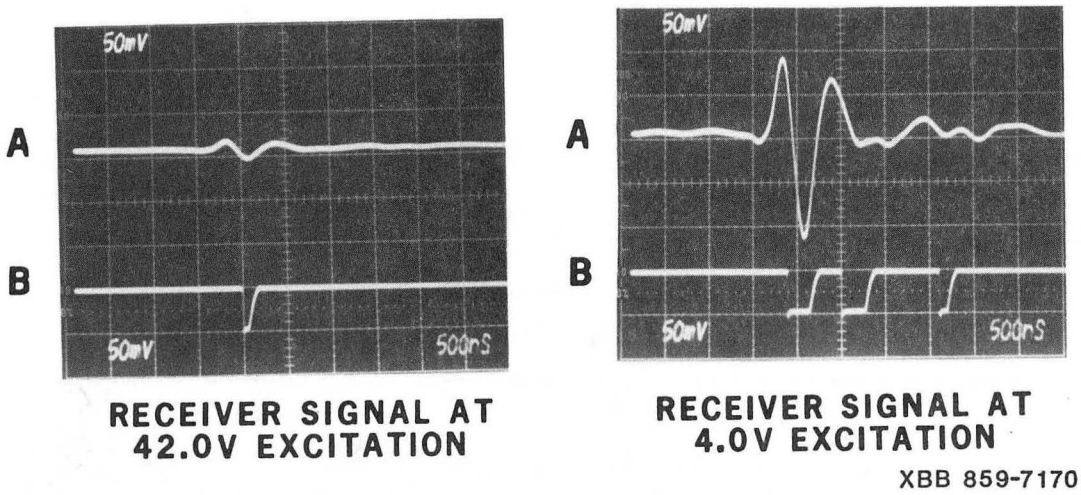


Fig. 10 Typical receiver signals from acoustic wave crossing water filled pipe at two excitation levels seen at the amplifier output (A). The discriminator fires each time the edge of waveform exceeds a preset threshold (B).

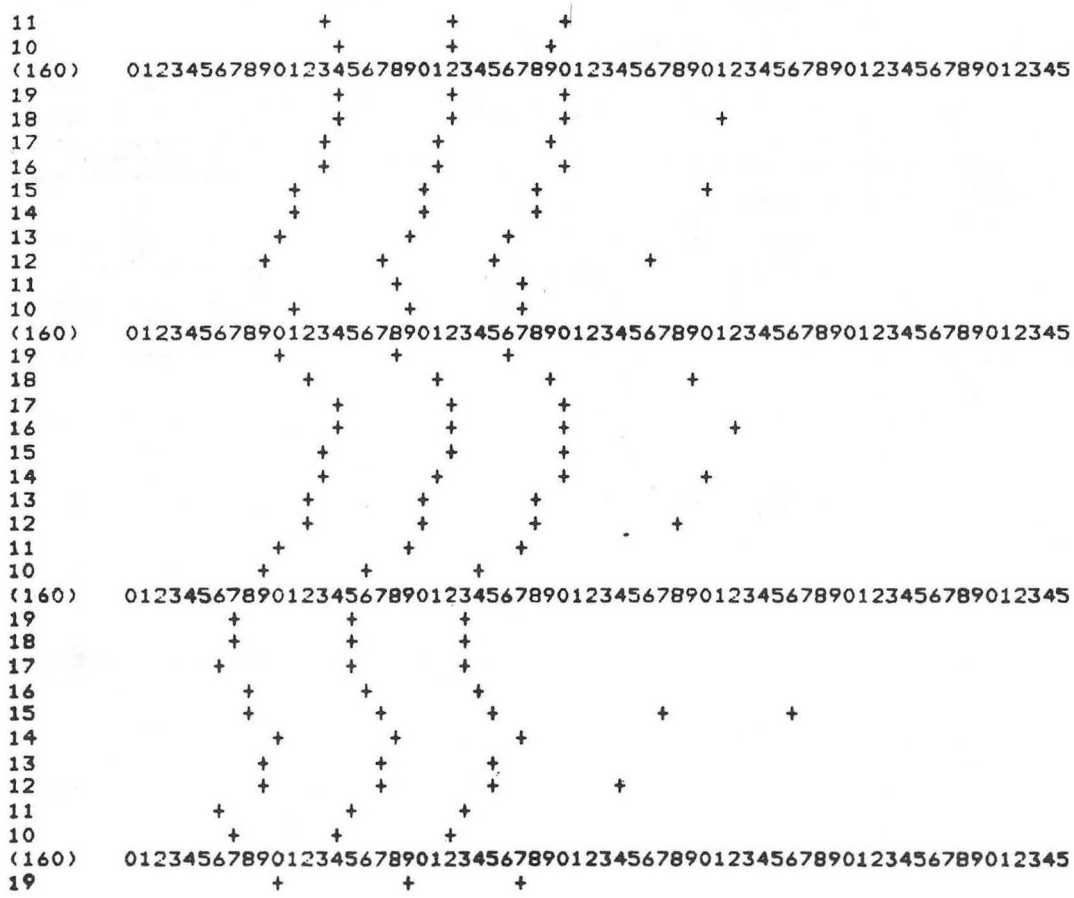


Fig. 11 Printout of a sequence of several consecutive frames of glass beads and water (ratio 3:5) mixture in steel pipe rocked perpendicularly to the pipe axis.

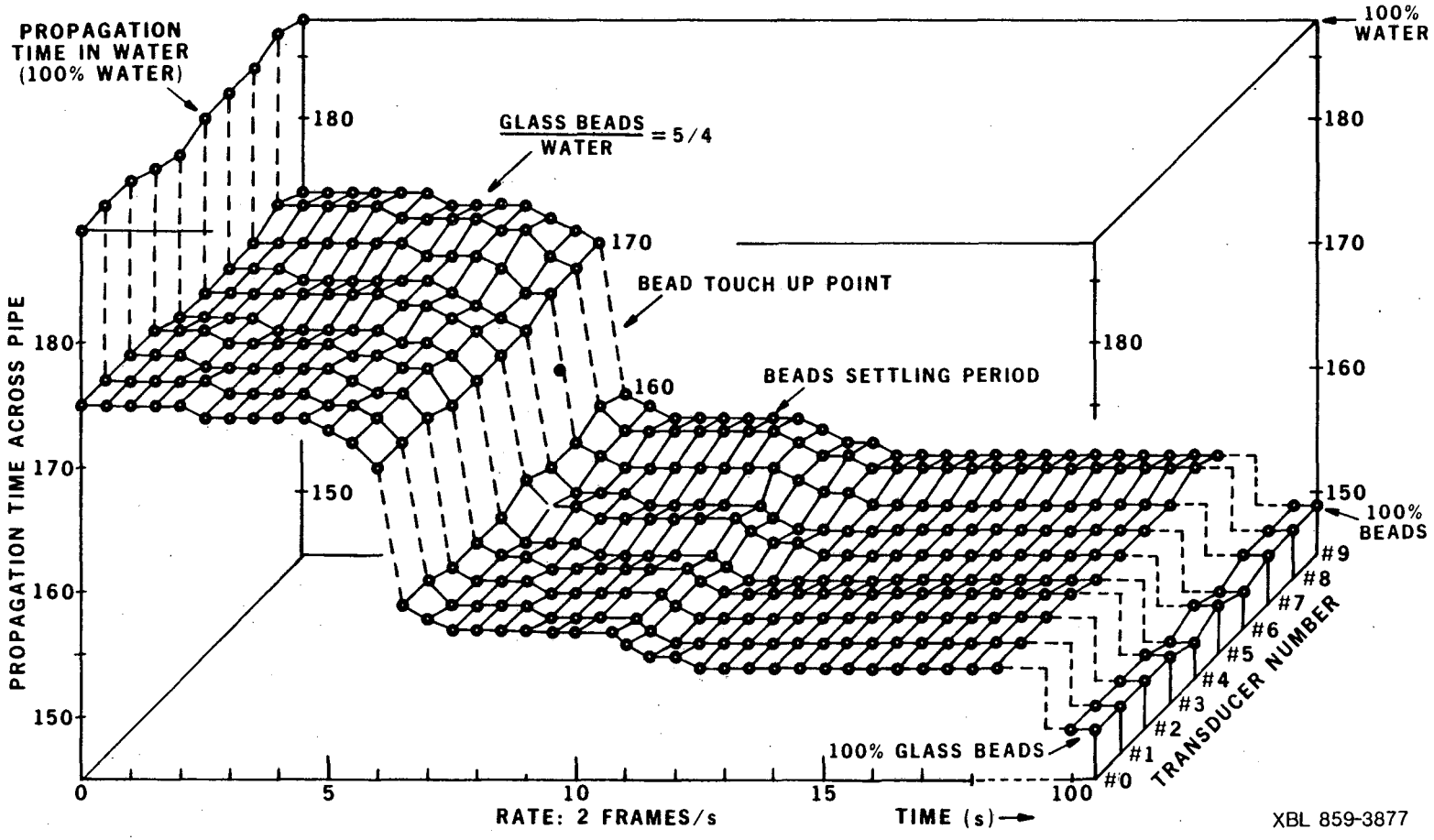


Fig. 12 Sequence of frames showing settling transient of a mixture of glass beads in water.

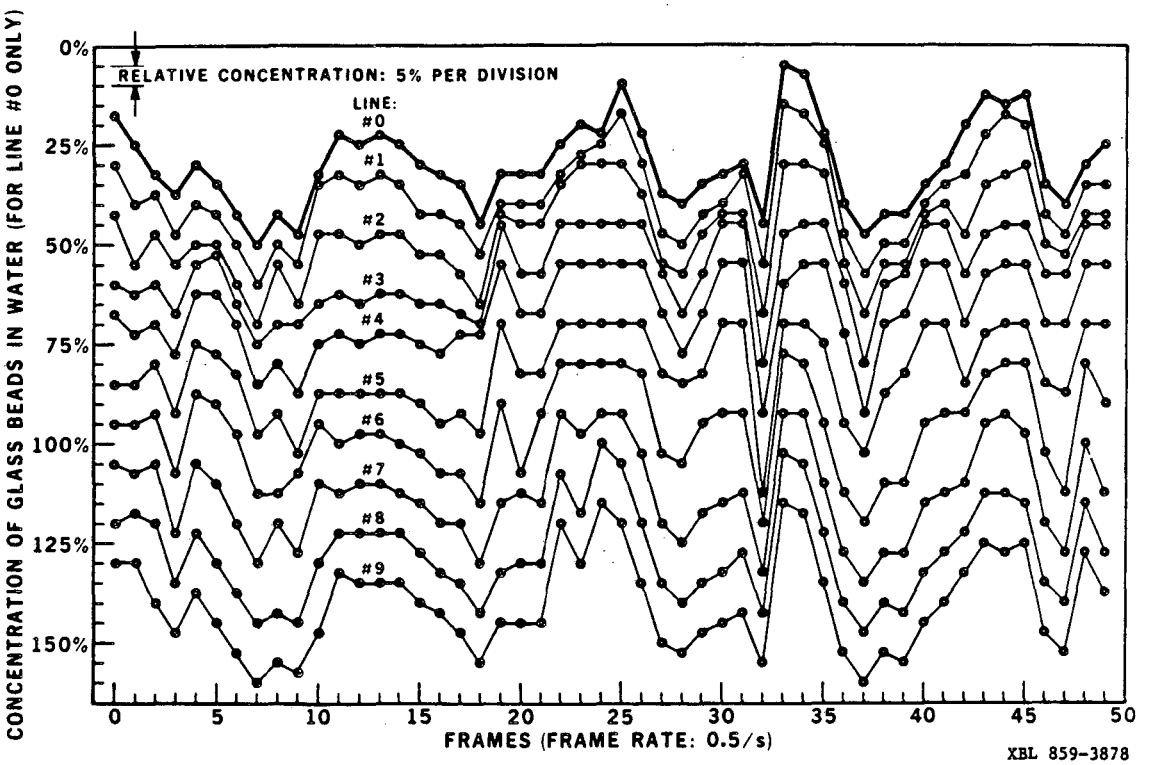


Fig. 13 Monitoring periodic changes in simulated slurry flow by rocking test pipe about vertical axis.

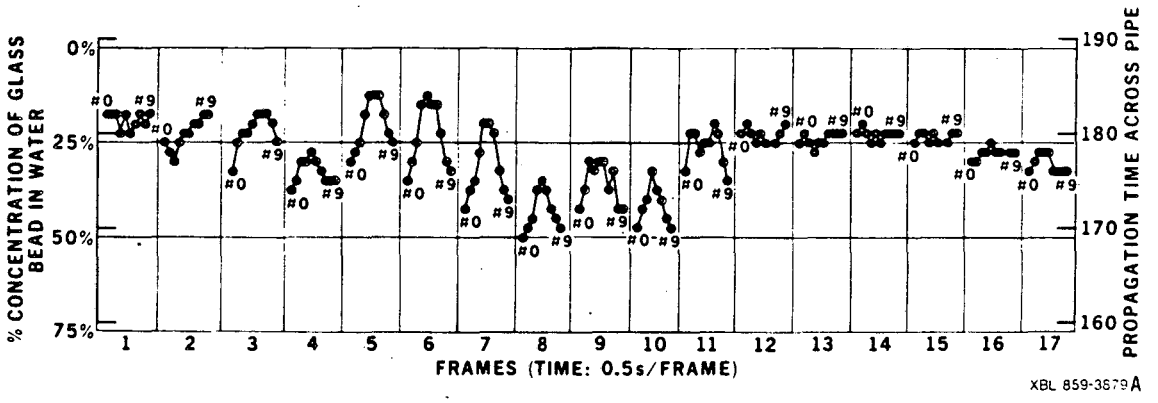
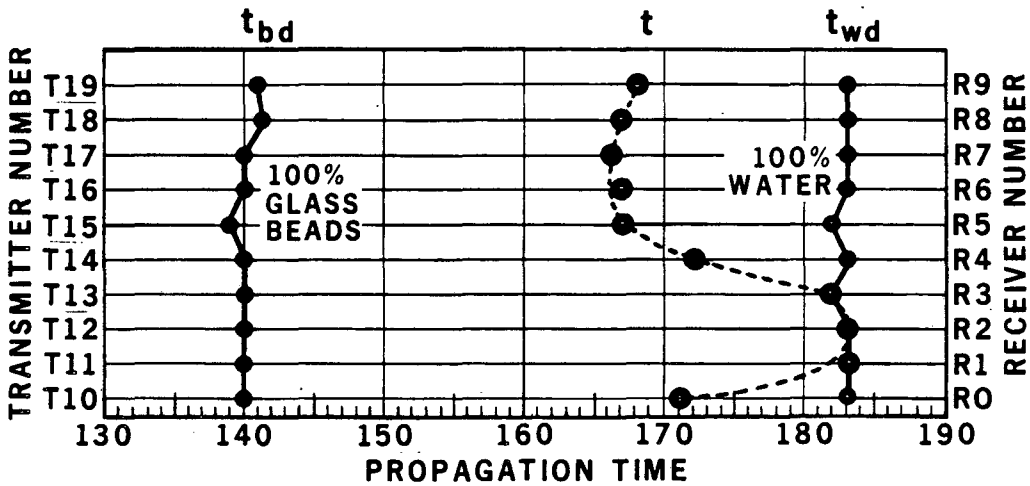


Fig. 14 Fluctuation of glass bead distribution over pipe cross-section as function of time (3:6 average bead to water ratio).

15a



15b

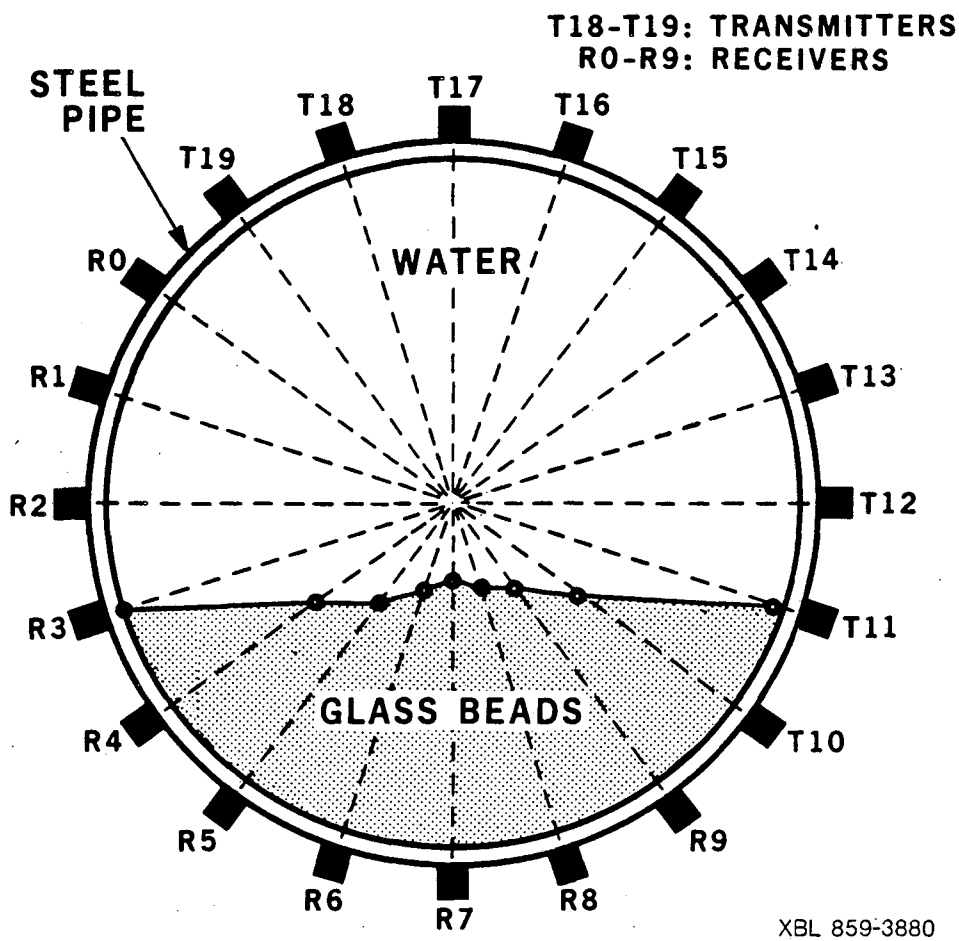


Fig. 15 Imaging the cross-section of a horizontal pipe with glass beads settled at the bottom. (A): 3 super-imposed single frames (100% water, 100% glass beads and mixture of 3 parts beads and 6 parts water); (B): reconstructed image of the pipe cross-section.

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720