United States
Environmental Protection
Agency

Industrial Environmental
Research Laboratory
Research Triangle Park NC 27711

Research and Development

EPA-600/S7-84-062 Aug. 1984

EPA

# Project Summary

# Feasibility of Ultrasonic and Other Methods for Direct Measurement of Condenser Biofouling

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**This project involved a literature review and laboratory studies of the potential of ultrasonic and other methods for *in-situ* measurement of biofouling on heat transfer surfaces (e.g., tubes) of electric utility steam condensers. Detection of the presence of biofouling in steam condensers is important for maintaining maximum heat transfer efficiency and minimizing the addition of chlorine (used to control biofouling) to meet discharge regulations. Literature relating to current industrial practices and research underway was searched to develop indirect and *in-situ* methods of biofouling measurement. Most methods are not sensitive enough to detect biofouling in its early stages, when it is easiest to control. A preliminary assessment indicated that this shortcoming might be avoided, using ultrasonics. An evaluation of the sensitivity of ultrasonic methods for this application confirmed the possible feasibility of this approach, but a number of questions were raised because of the lack of testing with the specific equipment needed, as well as the lack of acoustic property data on biofouling material. Samples of biofouling material, obtained from an operating commercial condenser, were "grown" in the laboratory. The acoustic properties of the material were measured as being close to those of water, but sufficiently different than biofouling measurement via ultrasonics might be feasible with further equipment improvements.**

***This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).***

## Introduction

Steam/electric power plants utilize steam/water condensers to remove heat from and condense low pressure steam following expansion in a steam turbine. The cooling-water side of the condenser can be operated in either a once-through or recirculating mode. In either case, a large quantity of cooling water is pumped through the condensers. Cooling waters may contain various materials that can form inorganic and/or organic deposits (referred to as "fouling") on condenser tube walls and water boxes. There are four general types of fouling: (1) scale formation resulting from precipitation of inorganic salts (e.g., calcium carbonate, calcium sulfate, silicates); (2) corrosion when insulating layers of metal oxides are formed on tubes; (3) adherence of particulate matter (e.g., silt) on tube surfaces; and (4) development of biological growth (biofouling) on tube surfaces.

The accumulation of biofouling accelerates corrosion of metal surfaces and/or impairs heat transfer from the condensing steam to the cooling water flowing through the condenser tubes. The inability to remove heat from the condensing steam results in higher condensing steam temperature and a correspondingly higher turbine back-pressure. Higher

turbine backpressure limits the steam flow through the turbine and directly results in a loss of generating capacity.

Cooling water systems, especially in the heat transfer tubes and inlet, outlet, and turning heads of the condenser, provide microbial organisms with a warm, oxygenated, nutrient-rich environment in which to grow. When this growth is uncontrolled, severe plugging of the tubes occurs, reducing heat transfer. If this situation persists, a generating unit may have to reduce load or be shut down to clean the condenser, resulting in a costly reduction in generating unit availability and reliability.

To protect the condenser from biofouling, a number of methods are commonly used to either retard biological growth or mechanically remove it before it reaches a critical condition. Mechanical cleaning methods have been used at a number of plants and have met with some success; however, most plants use a method involving the addition of chlorine into the condenser cooling water inlet to control biofouling. High concentrations of residual chlorine are toxic to biofouling and other aquatic organisms. The proper doses of total residual chlorine can usually control biofouling within tolerable limits.

To protect other aquatic life, the EPA has limited the chlorination period and the chlorine concentrations in the discharge from an individual generating unit. Regulations allow a free residual chlorine concentration of 0.1 mg/L (average) and a maximum instantaneous concentration of 0.5 mg/L for one 2-hour period per day. Proposed New Source Performance Standards require zero discharge of total residual chlorine, except where it is demonstrated that biofouling cannot be controlled under these conditions. In these cases, a maximum total residual chlorine concentration of 0.14 mg/L is allowed and limited to 2 hours per day per discharge point. These regulations emphasize the need to minimize the use of chlorine by close control of chlorine additions and enhancement of the effectiveness of each application.

In addition to an accurate chlorine metering system, two critical measurements are needed to properly control biofouling at these reduced chlorine concentrations: (1) accurate measurement of residual chlorine, both at the point of addition and at the condenser outlet; and (2) accurate measurement of condenser performance relative to the chlorine dosage and biofouling. While some problems still exist with the long term reliability of continuous chlorine analyzers, accurate measurement of condenser performance is a more significant problem.

Calculating condenser performance is complex, requiring the input of data from both the water and steam sides of the condenser. The calculation can be modified to allow calculating an overall heat transfer coefficient and its component resistances to heat flow (e.g., the fouling factor). Many plants automatically monitor and calculate fouling factor continuously with process computers. However, the accuracy of this method is highly dependent on the reliability and sensitivity of the monitoring instruments and upon plant maintenance practices. Changes in load, steam flow rate, cooling water and ambient temperatures, and many other factors vary the calculated fouling factor. This variation makes fouling factor data difficult to interpret and masks many of the subtle changes during the initial stages of the biofouling process.

More direct and simpler approaches to monitoring of fouling are now being developed. More accurate and reliable detection methods could result in improved generating unit availability. These methods could greatly enhance the effectiveness of low-level chlorination as well as aid in meeting discharge regulations. This project evaluated the feasibility of some of these methods, with emphasis on ultrasonics. The project consisted of: Task 1, a literature search of current industrial practices used to detect biofouling in condensers and to identify potential methods that appear promising based on research results; Task 2, a determination of the sensitivity of ultrasonics for detecting biofouling and the feasibility of this approach; and Task 3, a laboratory study to determine the acoustic characteristics of biofouling materials.

## Task 1—Literature Review

Biofouling detection methods evaluated and compared under this task are shown in Table 1, along with information on the development status and sensitivity of each. Condenser cooling water pressure drop, turbine backpressure monitoring, and overall heat transfer efficiency are the most common methods used for detecting condenser tube fouling. However, the complexity of the factors involved in their computation or measurement results in very low sensitivity to the early growth phase of biofilm development. These methods indicate only severe fouling accumulations and are, therefore, of limited value to a chlorine minimization program.

Three detection methods that are potentially applicable to the detection of biofouling were found during the survey:

1. The Monirex Fouling Device—This is used to detect nonbiological fouling of petroleum fractions in various refining processes by a heat transfer measurement. Its application to biofouling would require additional development, and sensitivity would be limited as in other heat transfer techniques.
2. Standard Plate Counts—These are made from bacterial colonies that develop under accelerated growth conditions on a media that has been exposed to the cooling water, thereby indicating the presence of biofouling organisms. Because correlating the development of bacterial colonies with biofouling accumulations in condenser tubes would be difficult, its usefulness is limited to supporting other techniques.
3. Chemical/Biological Monitoring Techniques - These utilize total organic carbon (TOC) and adenosine triphosphate (ATP) as indicators of biological growth. ATP, found only in living cells, is released to the cooling water rapidly upon death. Monitoring of ATP and TOC at the condenser cooling water inlet and outlet is a way to estimate biomass accumulation in the condenser. The specialized analytical equipment required to monitor these parameters and the batch nature of the analysis make this method of biofouling detection impractical at this time.

The new methods currently under active development are sidestream reactors, heat transfer resistance methods, and ultrasonics. Sidestream reactors consist of tubular and annular reactors that attempt to simulate heat exchanger conditions and are limited by their ability to duplicate these conditions. These techniques are in the early developmental stage and require supplemental microscopic and manual biomass accumulation analysis to determine biofouling accumulation thickness.

Heat transfer resistance methods have been developed for detection of biofouling of heat exchangers in Ocean Thermal Energy Conversion (OTEC) systems. These devices require highly skilled technicians to operate and interpret measurements. These devices are also sidestream simulators, and their usefulness is limited by their ability to duplicate

condenser operating conditions. Their sensitivity to the early growth phase of biofilm development is not well defined, but appears to be effective in measuring thickness in the 35-50 μm range.

Ultrasonics is currently the only technique for direct measurement of biofouling film thickness under consideration. Its application to thickness measurement of materials is used extensively. Its high accuracy in metal thickness measurement in the 50 μm range closely correlates to the 35-50 μm detection range of other biofouling detection methods. Previous studies of the acoustic properties of biofouling have indicated that detection of biofilms less than 50 μm in thickness may be feasible.

## Task 2 — Sensitivity of Ultrasonics

This task involved a search of available literature for: (1) sensitivity of ultrasonic techniques in the detection of biofilm; (2) determination of the acoustic properties of biofouling materials; and (3) correlation of chlorine effectiveness, biofilm thickness, and ultrasonic detection.

The goal of this task was to determine from available literature the feasibility of ultrasonic technology for the detection of biofouling and the advisability of continuing the program with laboratory studies. The information was grouped into four categories: thickness measurements and general applications, biofilm thickness measurement, acoustic properties of biomass, and probability of industrial application.

### *Present Measurements by Ultrasonic Techniques*

Thickness measurement of metals is one of the most common applications of ultrasonic technologies in industry. Both resonance and pulse-echo methods of detection are utilized to measure metal thicknesses and detect flaws. The most common applications of the resonance method for thickness measurement are in the 0.05-in. (1270 μm) to 0.175-in. (4445-μm) range with an accuracy of ±1.0 percent. Instruments using the pulse-echo method of detection are commercially available which measure thicknesses of 0.1 in. (2540 μm) to 10 in. ($2.5 \times 10^5$ μm) inch with a ±10 percent accuracy. Most of these resonance and pulse-echo instruments use frequencies in the 1-5 MHz range.

Measurement of thicknesses in the 50 μm-range requires the use of ultrasonic waves with frequencies in the 10-30 MHz range. A metal thickness of 50 μm has been measured with an accuracy of ±1 percent by the resonance method. This is the smallest metal thickness measurement recorded in the literature surveyed. Details of the specific equipment used to make this measurement were not found, but it appears that measurements in this range are within the measurement limits of ultrasonic technology.

### *Biofilm Measurement by Ultrasonic Techniques*

Only one research paper was found on measuring biofilm thickness ultrasonically: it discussed the theoretical analysis of the potential of resonance and pulse-echo methods for biofilm thickness measurement. It concludes that measurement of biofilms in the 10-30-μm thickness range is possible by pulse-echo and resonance methods at frequencies in the 20-30 MHz range. However, the accuracy of measurements in this range had not been verified by laboratory testing.

***Table 1.*** *Summary of Biofouling Detection Methods*

| *Detection Method* | *Developmental Status of Method for Biofouling Detection* | *Sensitivity to Biological Growth Phase*[a] | *Accuracy* | *Comments* |
|---|---|---|---|---|
| *Ultrasonics* | *R&D* | *I, E* | *±1% @ 50 μm* | *Direct measurement* |
| *Condenser Pressure Drop* | *Commercial* | *E, P* | *N/A*[b] | *Common indirect detection method* |
| *Tubular Reactor* | *R&D* | *N/A* | *N/A* | *Sidestream simulator* |
| *Annular Reactor* | *R&D* | *N/A* | *N/A* | *Sidestream simulator* |
| *Heat Transfer Resistance Methods* | | | | |
| *Overall Heat Transfer Efficiency* | *Commercial* | *E, P* | *±4%* | *Common indirect detection method* |
| *Turbine Backpressure* | *Commercial* | *E, P* | *N/A* | *Most common indirect detection method* |
| *Carnegie-Mellon University Device* | *R&D* | *E*[c] | *±10% and ±12%*[d] | *Developed for ocean thermal energy conversion biofouling applications* |
| *Lockheed Missile and Space Company Device* | *R&D* | *E*[c] | *$3 \times 10^{-5}$ (hr-°F-ft²)/Btu*[e] | *Developed for ocean thermal energy conversion biofouling detection* |
| *Monirex Fouling Device* | *Potential* | *E, P* | *N/A* | *Developed for petroleum process fouling detection* |
| *Standard Plate Counts* | *Potential* | *N/A* | *N/A* | *Commonly used in evaluating biofouling control agent effectiveness; used for detection in cooling tower systems* |
| *Chemical/Biological Monitoring* | *Potential* | *N/A* | *N/A* | *Commonly used in evaluating biofouling control agent effectiveness* |

[a] *I - Induction phase or primary biofilm formation (biofilm thickness 0 to 40-50 μm).*
*E - Exponential accumulation phase (biofilm thickness greater than 35-45 μm).*
*P - Plateau or steady-state phase.*
[b] *Data not available.*
[c] *Overlap of induction and exponential phases may allow these methods to detect growth during the induction phase.*
[d] *From two different sources.*
[e] *To convert to metric equivalents, please use the following: 1°F = 9/5(°C + 32); 1 ft² = 0.093 m²; and 1 Btu = 1.055 kJ*

## *Acoustic Properties of Biofouling Materials*

Many of the acoustic properties of a microbial slime (biomass), obtained from a condenser using Chesapeake Bay water for cooling, have also been determined, using an ultrasonic interferometer which uses the pulse-echo technique. Table 2 summarizes acoustic and other physical properties of biofouling materials. Of the acoustic properties presented, acoustic impedance is of great importance when considering the use of the pulse-echo method for biofouling detection. The acoustic impedance value in Table 2 is in the same range as other biological tissues of comparable specific gravity, as shown in Table 3. Biofouling materials, like other biological tissues, are composed of up to 98 percent water. The high water content strongly influences the acoustic impedance of the materials and tends to make acoustic impedance vary over a small range. This correlation also confirms the validity of the biomass impedance experimental measurement technique.

The acoustic impedance of biofouling materials is only slightly higher (<5 percent) than that of water. This small impedance difference could make it difficult to distinguish a biofilm/water interface from a metal/water interface because of the weak wave reflection from the interface. This is confirmed by the relative amplitude values of the reflected signals from the biofilm/metal and biofilm/water interfaces shown in Table 2. The large difference in the amplitudes of the two interfaces makes resolution of the weaker signal difficult. The poorer the resolution, the more difficult it becomes to measure the time interval between the reflections. Measurement of this time interval is crucial to accurate thickness measurement.

The initial ultrasonic pulse can be separated from the reflections by increasing the transducer metal thickness and, therefore, adding a time delay. However, the reflected signals cannot be separated and will result in a superimposed and distorted signal curve, as shown in Figure 1. To measure the thickness of the biofilm, the time between the reflected signal amplitude peaks, $\tau$ (see Figure 1), must be discernible.

Other acoustic properties important to ultrasonic thickness measurements by the pulse-echo method are the attenuation coefficient and the speed of sound through the biofouling material Attenuation is the measure of the sound energy dissipated as it passes through a material. The attenuation coefficient of biofouling materials at 10 MHz is 1.3 dB/cm as compared to 0.3 dB/cm for water. Unfortunately, this higher attenuation adds to the problem of detecting the biofilm/water interface. The higher the attenuation coefficient, the weaker the reflected signal from an interface will be. The speed of sound is only slightly higher in biofouling materials than in water and will not significantly impact the measurement of biofilm thickness.

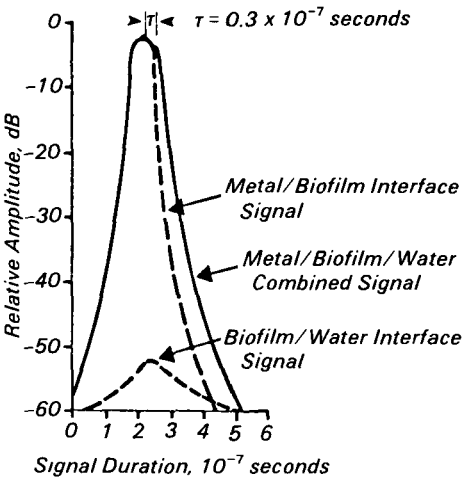



***Figure 1.*** *Predicted distortion caused by the overlap of the time duration of the reflections from metal/biofilm and biofilm/water interfaces (theoretical signal curves shown with dashes; τ is the time lapse between interface reflections that must be measured in order to detect the biofilm).*

The pulse-echo method of thickness measurement is very dependent on the acoustic impedance of metal and biofouling materials and the ultrasonic wave length. The resonance method of thickness measurement correlates biofilm thickness with the shift in the tube metal resonance frequency. Therefore, the resonance method of biofouling is much less dependent on the individual acoustic properties than is the pulse-echo method.

***Table 2.*** *Acoustic and Other Physical Properties of Biofouling Materials*

| | |
|---|---|
| *Acoustic Impedance of Biofouling Material* | *3% Higher than seawater @ 10 MHz or approximately 1.57 x $10^5$ g/$cm^2$-sec* |
| *Attenuation Coefficient* | *1 3 dB/cm @ 10 MHz* |
| *Relative Sound Speed of Biofouling Material (Ratio of the speed of sound in biomass to speed of sound in water)* | *1.011 @ 10 MHz* |
| *Relative Density (specific gravity) of Biofouling Material* | *1.02* |

*Relative Amplitudes of Ultrasonic Echoes from Metal/Slime and Slime/Liquid Interface for the following Metals·*

| *Metal* | *Metal/Biofilm Interface Relative Amplitude* | *Biofilm/Liquid Interface Relative Amplitude* |
|---|---|---|
| *Aluminum* | *0.837* | *4.6 x $10^{-3}$* |
| *Titanium* | *0.895* | *3.1 x $10^{-3}$* |
| *Stainless Steel* | *0.937* | *1.9 x $10^{-3}$* |

***Table 3.*** *Acoustic Impedance of Biological Materials and Water @ 10 MHz*

| *Material* | *Acoustic Impedance g/$cm^2$-sec* | *Specific Gravity* |
|---|---|---|
| *Water* | *1.52 x $10^5$* | *1.00* |
| *Biofouling* | *1.57 x $10^5$* | *1.02* |
| *Blood* | *1.62 x $10^5$* | *1.06* |
| *Brain Tissue* | *1.55-1.66 x $10^5$* | *1.03* |
| *Kidney* | *1.62 x $10^5$* | *1.04* |
| *Liver* | *1.64-1 68 x $10^5$* | *1.06* |

## Task 3 — Measurement of Acoustic Properties of Biofouling Material

To determine the feasibility of ultrasonic detection of biofouling, laboratory determinations of the acoustic impedance of biofouling material were undertaken. Since the acoustic properties of biofouling material and water are very similar, the test work performed in this task represents a worst case condition for ultrasonic detection of biofilms. The complex biofouling encountered in industrial condensers may be more easily detected than pure biological material

due to the acoustic properties of contaminants trapped in the biomass. The investigations were designed to determine if a reflection from the biofouling/water interface can be detected with state-of-the-art ultrasonic equipment.

## Sample Collection and Biofouling Growth

To conduct the acoustic characterization study on representative fresh water biofouling materials, samples from an operating power plant condenser were obtained from Public Service Electric and Gas Company's Mercer Generating Station, which uses Delaware River water for cooling. This station has been the site of testing of pilot-scale condensers for biofouling measurement and control by the Electric Power Research Institute (EPRI). The station experiences severe biofouling during the summer months.

The samples were collected by plant personnel during a unit outage. About 2 qt (1.9 liters) of biofouling sample was collected and frozen prior to shipment. The samples were a conglomeration of biological materials and silt. Since there was not enough biological material in the sample that could be isolated for the laboratory study, sufficient biomass had to be grown. To do this, 10 gal. (37.9 liters) of Delaware River water was also shipped to Radian to ensure that the laboratory growth and nutrient availability were comparable to the power plant cooling water.

A laboratory apparatus was set up to grow and maintain a healthy population of biofouling microorganisms. It consisted of a 10-gal. (37.9 liter) aquarium tank, a plate glass sheet, a circulating pump, aluminum test coupons, and an immersion heater. The glass sheet was placed in the aquarium at about a 30° angle. Water in the aquarium was pumped and distributed uniformly over the surface of the inclined glass plate to provide a flowing water film on the glass plate. Test coupons were attached to the surface of the glass plate to provide the growth and accumulation points for the biofouling materials. An immersion heater was placed in the aquarium tank to maintain the water at 76°F (24°C), which is comparable to the cooling water outlet temperature at the Mercer Station. To simulate the utility condenser environment, the entire apparatus was enclosed to exclude light. This system was designed to encourage the growth of the microorganisms that thrive under the condenser temperature and nutrient conditions.

To compare acoustic properties of biofouling material grown in the tank and pure biofouling (slime) material, several petri dishes containing an agar substrate were innoculated with water from the growth tank. Relatively pure cultures of biofouling microorganisms were grown in this manner. During the acoustic characterization studies, both the pure microorganisms grown in petri dishes and tank-grown biofouling materials, which used an agglomeration of living materials with traces of silt, were evaluated.

The time required to accumulate sufficient biofouling materials (approx. 100 ml) for the acoustic characterization studies was approximately 3 months. Growth on the aluminum test coupons was extremely slow and had to be abandoned. These coupons were to fit directly into the ultrasonic testing assembly. As a result, samples were scraped from the inclined glass plate and aquarium walls. The attachment of microorganisms to a tube surface may have a significant impact on the detection of a biofilm, but has negligible impact on the acoustic impedance measurements of this task.

Three samples were used in acoustic characterization: (1) a water/biofouling mixture from the growth tank (about 50 wt percent water), (2) a filtered biofouling sample from the growth tank, and (3) a pure bacterial sample from the petri dish cultures. These three samples provided a wide range of sample characteristics for which acoustic properties could be determined.

## Summary of Results

Three test fixtures were used to measure the relative sound speeds in three samples of biofouling material (1) a water/biomass mixture (approx. 50 percent free water) grown in a tank; (2) dewatered biomass similar to the first sample, except that most of the water was removed by filtering; and (3) cultured bacteria grown in a petri dish.

Each sample was tested in a different test fixture. Although the fixtures were all nominally of the same dimensions, they were not identical: the slight differences caused easily measurable differences in the pulse transmit times. Consequently, the transit times between different test fixtures are not directly comparable. However, the relative transit time of each sample in a given test fixture with respect to water in that same test fixture is a valid comparison of the samples. Each fixture was filled with water and tested to obtain the reference for each sample.

The test results are summarized in Table 4, which shows the measured delay times ($\Delta t$) between the first and fifth received pulses for each of the three samples and for water in the test fixtures. The temperatures at which the measurements were made are also recorded because sound speed in water is sensitive to temperature. The uncompensated time delay ratios and sound speed ratios are computed first. A temperature correction for the sound speed ratio is then computed on the basis of 0.0016/°C temperature difference between the water and biofouling samples. This correction is derived from the sonic velocity correction for water at room temperature of 2.4 m/sec-°C divided by the sonic velocity of 1500 m/sec. Since the temperature of the water and biofouling samples were very close during the testing, this temperature correction factor has little effect on the sound speed ratio, as shown in the last column.

The computed results are that the sound speeds in the first two samples are 99.98 percent of the sound speed in water. Since the experimental accuracy is no better than 0.02 percent, it may be concluded that the sound speed in these two samples is indistinguishable from the speed of sound in water. However, the third sample (consisting of cultured bacteria) had a sound speed 2.4 percent greater than the sound speed in water. This is much larger than the experimental uncertainty, so the measured sound speed difference is significant.

The acoustic impedance of the biofouling material is the product of its sound speed and density. Similarly, the relative acoustic impedance of the biofouling material with respect to water is the product of the relative sound speed and relative density. This relative acoustic impedance is important because it determines the detectability of the biofouling layer in contact with water by ultrasonic inspection techniques.

The relative sound speed of the biofouling material was measured to be in the range of 1.0 to 1.024, depending on the sample composition and preparation. The density was measured using a picnometer to be in the range of 1.0 for water/biomass to 1.04 for dewatered biomass. There was insufficient cultured bacteria for a density determination. The relative acoustic impedance of the material is the product of the relative density (specific gravity) and relative sound speed.

The relative acoustic impedances determined for each sample are presented in Table 5.

*Table 4.* *Sound Speed Measurement Results*

| Sample | Δt Sample μ sec | Δt Water[a] μ sec | Δt Ratio Sample/Water[b] | Sound Speed Ratio Sample/Water[b] | Temperature Correction for Sound Speed Ratio | Temperature Corrected Sound Speed Ratio |
|---|---|---|---|---|---|---|
| Water and Biomass | 5.55 @ 24.5°C | 5.54 @ 25.5°C | 1.002 | 0.998 | 0.0016 | 0.999 |
| Dewatered Biomass | 5.66 @ 23.5°C | 5.65 @ 24.5°C | 1.002 | 0.998 | 0.0016 | 0.999 |
| Cultured Bacteria | 5.56 @ 25.0°C | 5.70 @ 24.7°C | 1.0975 | 1.025 | -0.0005 | 1.024 |

[a] *Δt is the measured time delay between the first and fifth pulses. Three different test fixtures were used to test the three biofouling samples. Each water Δt at value is for the test fixture used with the sample in the same row of the table.*
[b] *No temperature correction factor applied.*

The results compare favorably with those of another study that determined an acoustic impedance of biomass relative to sea water of 1.03.

## Detection of Biofouling by Ultrasonic Techniques

Ultrasonic techniques under consideration for the detection of biofouling inside a water-filled metal tube depend on the biofouling material's having a different acoustic impedance than water. The interface between the biofouling material and the water must present a distinct change in impedance to the acoustic signal to make this interface reflective.

A pulse-echo technique for detecting biofouling is shown in Figure 2. A short pulse is transmitted by a transducer into the metal pipe wall. If biofouling is present, as shown in the figure, the pulse is reflected by the pipe/biofilm interface ($r_{pb}$) and by the biofilm/water interface ($r_{bw}$). The biofilm is detected and its thickness measured by observing the reflections of the pulse from the pipe wall/water interface.

The relative amounts of energy, reflected (r) and at an interface transmitted (t) past it, are defined by the power coefficients ($\propto$) as follows:

$$\left[\propto r_{pb} = \frac{\rho_b c_b - \rho_p c_p}{\rho_p c_p + \rho_b c_b}\right]^2 \quad (1)$$

$$\left[\propto r_{bw} = \frac{\rho_w c_w - \rho_b c_b}{\rho_b c_b + \rho_w c_w}\right]^2 \quad (2)$$

$$\left[\propto t_{bp} = \frac{\rho_p c_p}{\rho_b c_b}\,\frac{2\rho_b c_b}{\rho_p c_p + \rho_b c_b}\right]^2 = 1 - \propto r_{pb} \quad (3)$$

$$\left[\propto t_{bw} = \frac{\rho_w c_w}{\rho_b c_b}\,\frac{2\rho_w c_w}{\rho_w c_w + \rho_b c_b}\right]^2 = 1 - \propto r_{bw} \quad (4)$$

*Table 5.* *Relative Acoustic Impedance of Biofouling Materials*

| Sample | Specific Gravity | Relative Sound Speed | Relative Acoustic Impedance |
|---|---|---|---|
| Water Biomass | 1.00 | 0.999 | 1.00 |
| Dewatered Biomass | 1.04 | 0.999 | 1.04 |
| Cultured Bacteria | 1.00[a] | 1.024 | 1.02 |

[a] *Assumed to be the same as for water.*

where $\rho$ is the density of the material; c is the speed of sound through the material; their product, $\rho c$, is the acoustic impedance of the material; and p (pipe), b (biofilm), and w (water) indicate the materials at the interface.

The flexibility of detecting biofilms by the pulse-echo technique is determined by the strengths of the $r_{pb}$ and $r_{bw}$ reflections and the time delay between them. The strengths of the reflections are calculated by first calculating the power reflection and transmission coefficients at the interfaces using Equations (1) - (4). An example is presented below using the dewatered biomass from Table 5 and the properties of a stainless steel pipe (tubing).

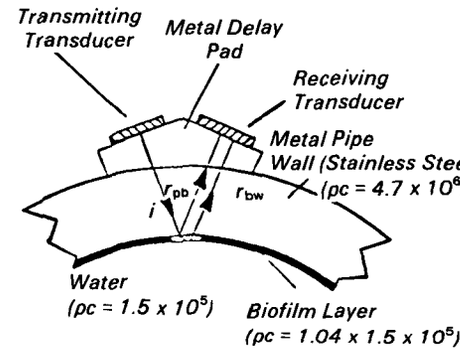
$$\propto r_{pb} = \frac{1.04 \times 1.5 \times 10^5 - 4.7 \times 10^{6^2}}{1.04 \times 1.5 \times 10^5 + 4.7 \times 10^6} = 0.88$$

$$\propto r_{bw} = \frac{1.5 \times 10^5 - 1.04 \times 1.5 \times 10^{5^2}}{1.5 \times 10^5 + 1.04 \times 1.5 \times 10^5} = 3.8 \times 10^{-4}$$

$$\propto t_{pb} = 1 - \propto r_{pb} = 0.12$$

$$\propto t_{bw} = 1 - \propto r_{bw} = 0.9996$$

These coefficients indicate that at the pipe/biofilm interface, 88 percent of the pulse energy is reflected and 12 percent is transmitted across the interface. At the biofilm/water interface, only 0.004 percent of the energy is reflected.




*i* – *ultrasonic energy pulse*
$r_{pb}$ – *reflection from pipe/biofilm interface*
$r_{bw}$ – *reflection from biofilm/water interface*
$\rho c$ – *acoustic impedance of the material*

*Figure 2.* *Detection of biofouling by reflection from biofilm layer interfaces (pulse-echo method).*

By tracing the paths of the $r_{pb}$ and $r_{bw}$ reflected signals in Figure 2, the received signal levels can be calculated. Assuming the incident signal (i in Figure 2) to have a unity signal level in the metal pipe wall, the $r_{pb}$ and $r_{bw}$ signal levels are:

$$S_{r_{pb}} = 0.88$$

$$S_{r_{bw}} = t_{pb}\,(\propto r_{bw})\,(\propto t_{pb}) =$$

$$0.12\,(0.0004)\,(0.12) = 5.5 \times 10^{-6}$$

The $^{S}r_{pb}/^{S}r_{bw}$ power ratio is $1.6 \times 10^5$ or 52 dB, where dB = 10 log (power ratio). The times of arrival at the receiving transducer of signals $r_{pb}$ and $r_{bw}$ differ by the flight time through the biofilm layer, $\tau$, which is determined by:

$$\tau = 2x/\rho c$$

$$\tau = 2x/(1.04)(1.5 \times 10^5)$$

where x is the thickness of the biofilm layer in centimeters. For example, if x = 0.005 cm (50 $\mu$m), which is the biofilm thickness above which condenser heat transfer is impeded, then x = 64 nanoseconds.

The feasibility of ultrasonic detection of biofouling materials is confirmed by the laboratory evaluations performed for this study. The processing of ultrasonic signals in the frequency and dynamic ranges required are within the capability of current technology. However, hardware has not been specifically developed to meet all requirements of biofouling. A program to develop an acoustic system specifically designed for biofouling detection would be of value. This program could emphasize the use of off-the-shelf ultrasonic equipment to augment the capability of the equipment used in the current program.

A program for continuing the development of an ultrasonic detection device could include: (1) a survey of available manufactured hardware; (2) hardware acquisition/modification/design, as appropriate, and acoustic characterization of additional biofouling samples; (3) laboratory tests in a simulated condenser environment; and (4) field tests in a utility condenser.

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*The complete report, entitled "Feasibility of Ultrasonic and Other Methods for Direct Measurement of Condenser Biofouling," (Order No. PB 84-207 067; Cost: $11.50, subject to change) will be available only from:*

*National Technical Information Service*
*5285 Port Royal Road*
*Springfield, VA 22161*
*Telephone: 703-487-4650*

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☆U. S. GOVERNMENT PRINTING OFFICE: 1984/759-102/10630

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