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IN SITU HEAT EXCHANGER TUBE FOULING THICKNESS MEASUREMENTS USING ULTRASONICS

Final Report on a Laboratory Feasibility Study

Jules Hirshman and Robert S. C. Munier

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Final Report on a
Laboratory Feasibility Study

by

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September 1980

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TABLE OF CONTENTS

1.0 EXECUTIVE SUMMARY

The growth of fouling layers on heat exchanger surfaces and the corrosion of heat exchanger materials exposed to seawater have been recognized since the beginning of OTEC research as basic problems which could render the concept uneconomical. Consequently, a significant effort has been directed toward predicting, measuring, identifying, explaining and solving potential biofouling and corrosion phenomena. Of particular importance is a better understanding of the relationship between heat transfer degradation and fouling growth on heat exchanger surfaces in order to optimize methods of tube cleaning. Film characterization studies (microbiological, biochemical, SEM, etc.) can only be conducted on pipe or other samples after they are removed from the system and the films are significantly altered (dehydrated, fixed, cultured, etc.) in the course of the analysis. There is no justifiable means by which these laboratory analyses can be correlated back to some film characteristics, such as thickness as they exist in situ, which in turn is related to heat transfer rate changes.

To address this problem, the feasibility of establishing a practical microacoustic technique to measure fouling film thickness in situ on typical OTEC heat exchanger tasks was studied. Seven techniques were studied for this application, including velocity measurements, acoustic diffraction, acoustic interferometer, doppler flow velocity, pulse echo, critical angle, and surface (shear) wave effects. Of these, the latter five were laboratory tested using conventional microacoustic system components in various configurations.

Only the pulse echo technique yielded promising results. On fouled aluminum plates, thin film layers of 40μm and greater were measured using a focused 30MHz ceramic transducer operated at 25MHz; this represents a resolution of about 2/3 wavelength. Measurements made on the inside of fouled 1" aluminum pipes yielded film thicknesses of 75 to 125μm. The thinnest layer resolved was approximately 1-1/4 wavelength.

The resolution of slime layer thicknesses in the magnitudes of OTEC interest (5 to 30μM) using pulse echo microacoustics will require transducer development. In particular, a higher operating frequency (150-200MHz) and advanced material construction is recommended for further research.

2.0 INTRODUCTION

This is the final report of a short laboratory study conducted by Tracor Marine, Inc. and the New York Institute of Technology (NYIT) Research Center. The purpose of the study was to establish through laboratory testing the feasibility of a practical microacoustic technique to measure the fouling film thickness in situ on OTEC heat exchanger tubes.

The experimental work was conducted at NYIT. Tracor Marine provided fouled aluminum pipe samples to NYIT for the ultrasonic tests (see Section 3.0). Verification of candidate ultrasonic technique was to be made by comparing film measurements with light section microscope data (see Section 4.0). These comparative measurements, however, were unsuccessful.

The results of the microacoustic tests are described in the NYIT report which has been included herein (Section 5.0) in its entirety.

3.0 SAMPLES

Fouled samples (aluminum 6061 T6) for ultrasonic tests were generated under the following conditions:

1) One-inch internal diameter, 4-foot-long pipes in a PVC manifold system. The pipes were upstream of a jacuzzi centrifugal pump and subject to flow rates of 6' per second. The system was pierside and utilized seawater from the nearby intracoastal waterway. After prescribed periods of exposure, selected pipes were removed from the system and cut into 6" sections for insertion into the ultrasonic test apparatus at the NYIT Laboratory. The vacated position in the manifold system was filled with a new 4-foot test pipe.

2) One-inch internal diameter, 6-inch-long pipes and flat plate coupons were suspended from a pier into natural seawater for selected time periods for quiescent exposure conditions.

Transfer of all samples from their exposure location to the NYIT lab was made in natural seawater. The duration of transfer periods was usually less than 2 hours.

The quality (thickness, continuity) of the fouling films produced under the conditions described above varied considerably from exposure to exposure. In particular, the summer samples yielded thicker and more uniform films than did those samples exposed during the winter.

4.0 LIGHT SECTION MICROSCOPE

A Gaertner D-10142 light sectioning microscope was obtained to provide a secondary method of measuring thin film thicknesses which could serve to verify the validity of the ultrasonic measurement techniques under study. Loeb (unpublished manuscripts, also Little and Lavoie, 1979) has successfully used this method on OTEC samples from the Gulf of Mexico buoy experiment.

Unfortunately, the particular unit obtained for this work was configured for observation of samples immersed in water, i.e., the objective lens was water-proofed and the angle between the slit assembly and viewing microscope was calibrated to account for the angle of refraction of water. The setup worked fine for measuring the thickness of lacquer test films. The thickness of slime produced on samples exposed to natural environments, however, could not be resolved, probably because those slimes are predominantly water. For the method to produce satisfactory results, the refractive index of the sample must be substantially different from that of the medium in which the sample is viewed.

Because of the short-term nature of the project and the secondary importance of the light section measurements, the light section measurements were discontinued.

IN SITU HEAT EXCHANGER TUBE FOULING THICKNESS MEASUREMENTS USING ULTRASONICS.

FINAL REPORT ON A LABORATORY FEASIBILITY STUDY

by

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CONTENTS

List of Figures

ABSTRACT

The NYIT Research Center (NYITRC) provided subcontract services in the area of ultrasonics to Tracor Marine Inc. (TM), for the Department of Energy's OTEC biofouling program. Our task was to quickly determine, in the laboratory, whether any of several micro-acoustic techniques could be used to directly measure the thickness of thin bacterial slime layers on the seawater side (inside) of simulated heat exchanger tubes, in situ; and whether development of a prototype instrument was warranted based on the results of this task. No direct methods of measuring slime thickness, in heat exchanger tubes in place, exists at this time.

This work utilized ultrasonic equipment available at NYITRC, and was performed on fouled field samples provided by TM. TM acquired a light-sectioning microscope to provide an independent measure (optical) of film thickness on cut samples.

I. Literature Search

The only reference to the use of microacoustic techniques to measure the thickness of fouling films in heat exchanger tubes found in the literature is (1). Useful measurements of microbial slime velocity, density and absorption coefficients (all compared to water) were made; and several possible techniques for measuring slime thickness from the outside (working fluid side) of the heat exchanger tube were suggested.

II. Experimental Measurements

A. General

The development and use of a system for directly measuring the thickness of bacterial fouling layers on the surface of heat exchanger tubes while in use, would have practical benefits in the evaluation and design of tube cleaning systems, and in the determination of operational cleaning procedures and fouling prevention measures, for OTEC heat exchangers.

The need for this experimental phase of research requires some explanation, since several of the techniques proposed are presently used successfully (at other acoustic frequencies) for thickness measurements in other materials. Non-destructive testing (NDT) for quality control of materials and products is one example. In addition, this laboratory has used some of these techniques in developing equipment for medical tests and experiments.

In the present project, both the acoustic velocity and the density of the bacterial slime layer have been thought to be very close to those of water because of the large amount of water trapped in a "glycocalyx" (polysaccharide matrix) (2). The close value of these physical properties to those of water has been recently confirmed by measurement (1). Based on this information, the ability of acoustic signals to distinguish between water and bacterial slimes seemed certain to be difficult; if at all practical. Testing this possibility was the purpose of this research.

B. Approach

1. Frequencies lower than those required to "see" a 10μm layer (a prototype objective) were to be used in this experimental phase, with thicker slime layers (50μm and up) to determine whether particular acoustic

techniques could produce a usable signal or not. This permitted us to perform this first phase at low cost, by utilizing equipment available at our laboratory. The results, if successful, could then be used in the design of a prototype system by scaling frequencies up; slime thickness and wavelength down. (The minimum ability of various sonar, radar, and laser devices to detect objects, requires, among other things, that the object to be detected be of the same general order of size as a wavelength of the detection signal.)

2. Measurements were made from the inside of the simulated heat exchanger tube because:

a. it was believed to be easier to make measurements of slime thickness on the seawater/slime side of the tubing,

b. the shell and tube heat exchangers then being considered by DOE for OTEC had provisions (end caps) for access to the inside of the tubes, and

c. this procedure would require neither special access to the outside of the tubes (through the shell), nor exposure of the sensors to the working fluid (ammonia) when in use.

C. Methods

A number of acoustic techniques were tested on stainless steel plates, aluminum plates and aluminum tubes. At first these were coated with known thicknesses of lacquer, from which a good reflection could be obtained, and compared to clean surfaces to assure that the equipment was functioning properly. Then biologically fouled aluminum substrates were used. An independent measure of slime thickness was to be provided by the prime contractor (TM) utilizing a light-sectioning microscope; following the method of Loeb (NRL) as described by Little (3), however, no suitable measurements of this type were obtained.

The basic test system and the various apparatus set-ups used are described and illustrated in Section III, Instrument System Description, of this report. A brief description of the basic methods follows.

1. Pulse-Echo Effects

At an interface of two materials, a mismatch of acoustic impedance (a function of acoustic velocity and material density) and a sufficient layer thickness with respect to acoustic wavelength, permits an impinged acoustic beam to produce a reflection at the interface. To compute the thickness of a bacterial slime layer on a metal substrate, in seawater (SW), with an acoustic beam at normal incidence, we:

a) require a reflection from the SW/Slime interface, and from the slime/metal interface,

b) require the time interval between the two reflections above, and the value of the velocity of sound in the slime.

The close match of the acoustic impedance of SW and slime will produce an extremely weak reflection from this interface, while the large slime/aluminum mismatch will produce an extremely strong reflection. A -47 to -55 db difference between the SW/slime echo and the slime/aluminum echo is predicted by (1). Fortunately the SW/Slime echo arrives ahead of the slime/aluminum echo, making its detection possible with high enough signal gain, if the initial signal can be distinguished from noise.

In order to perform normally incident pulse-echo measurements within a pipe with the available 30MHz transducer, we utilized a mirror inside the pipe to bend the sonic beam 90 degrees. An echo of a thick lacquer ridge inside the pipe is shown in Figure 5. The mirror and transducer lens are adjusted for focus on the inside surface of the pipe (see Figure 7, A. 2, and Figure 8). Future operational systems could utilize tiny transducers at the end of extremely narrow rods, aimed/focussed directly at the inner pipe wall, without requiring the use of mirrors.

2. Oblique Incidence Effects

a) Critical angles

Both longitudinal and transverse waves are possible in a solid when the material is subjected to longitudinal waves at a liquid/solid interface. At oblique angles of incidence this results in more than one critical angle, because the longitudinal wave and the transverse waves have different velocities in the same material. For aluminum, two sharp angles of total reflection (critical angles) occur, one for each of these waves. A layer of different material (i.e., bacterial slime) between the liquid (water) and the solid (aluminum) could produce a measurable shift in these angles if refraction of the sound beam occurs in the slime layer. The intermediate material has to have sufficient acoustic velocity contrast and thickness to be "felt" at the acoustic frequency used.

If such a critical angle shift can be produced by a slime layer when it reaches a significant thickness; transmit and receive transducers at opposite ends of a heat exchanger tube can, for example, be set up to detect a "wave guide" effect when all the energy goes into the water inside the tube, as the second critical angle is reached.

b) Other effects

Other materials (e.g., some stainless steels) exhibit sharp reflection minimums at particular incidence angles as a function of grain size and acoustic frequency. These angles should also exhibit an incidence angle shift (to produce a minimum in this case) with the presence of a suitable intermediate layer providing additional refraction ahead of the metal.

3. Acoustic Interferometer

At particular oblique angles, wave reinforcement can occur between the reflections from the front and back of the slime layer, producing signal intensity maxima. The oblique angles at which these maxima occur are a function of slime layer thickness and occur when the difference in pathlength between echoes is a multiple of a full wavelength of the sound in the slime.

4. Miscellaneous methods

a) Velocity Measurements

A Sonics Model USSM sing-around acoustic velocimeter is available at NYITRC for making velocity measurements on materials. In order to make this measurement, it is necessary to know (or measure) the thickness of the material, since transmission time through the material is the measured parameter.

b) Acoustical Diffraction

The surface roughness of a fouling layer and of the metal substrate might be measured using acoustical diffraction. The distribution of sound around the focal point of the beam reflected from a surface is the fourier transform of the spatial frequency distribution of the surface roughness.

c) Doppler Flow Velocity Profile Measurements

Doppler ultrasound has been used for years to measure blood flow velocityand the presence of turbulent flow in the circulatory system of patients. This method can probably be used to plot the velocity profile of the fluid near the surface. It can probably also be used to detect the presence of turbulent flow. If the profile can be plotted with high enough resolution, the fouling layer will show up as a region of zero velocity. Its effect on the turbulence of the boundary layer can also be detected.

D. Results

The sections below describe the results obtained with the different methods tested. Very little hard data (numbers) is presented, because most of the methods (with the exception of the pulse-echo technique) produced no detectable effect due to the slime layers on the samples available to us. Most of our effort was directed at an attempt to devise and to try techniques sensitive enough to detect a layer that is theoretically very close to invisible to sound. Where the layer is detected (pulse-echo method) the data obtained is presented in numerical form. Where the layer is not detected, the measurements show no significant difference from a clean metal substrate whose acoustic properties are well known, and are not pertinent to this research.

This presentation is consistent with this type of feasability project; where a number of techniques and variations thereof, were tried in the laboratory, with available equipment, in the hope that one or more of these would prove positive.

1. Pulse-Echo Effects

Of the techniques tested, the pulse-echo or reflection technique was the only successful one. Fouling layers of 40 μm and thicker could be measured acoustically*, using a focused "30MHz" ceramic transducer. The observed time differences between the slime and aluminum reflections ranged from .05μs to 0.4μs on different parts of the sample. Thus, the thinnest fouling layer detected at this frequency was roughly 2/3 wavelength with the thickness of the fouling layers varying considerably along a given sample (from 40μm to 320μm). These successful tests were performed in the summer months when fairly thick slime layers could be produced rapidly in local waters. No photographs of the oscillograph plots of the echograms were made at the time of these initial tests.

Tests were then made on the inside of fouled one-inch aluminum pipe using the apparatus shown in Figure 8. These produced slime thickness measurements that varied from 75μm to 125μm. The thinnest layer observed above was about 1-1/4 wavelength. Variations in slime on both the plates and tubes were visible to the eye. Again, no photographs of slime echograms were made at the time of these tests.

Due to unforeseen circumstances, the tests were not repeated for the camera until the winter months. At this time, the original successful results could not be reproduced. It is not known whether the slime layers on the winter samples were too thin (no optical measurements were provided) or whether some undetected difference in the test system is responsible; although the former is strongly suspected.

The lacquer (acrylic) experiments were repeated and a series of photos of echograms were produced showing a progression of thicknesses of lacquer on aluminum plate (Figs. 2-4), compared to a clean aluminum plate (Fig. 1). Figure 5 is a photo of a ridge of lacquer taken inside a one-inch aluminum pipe, using the mirror apparatus shown in Figure 8. The thinnest lacquer

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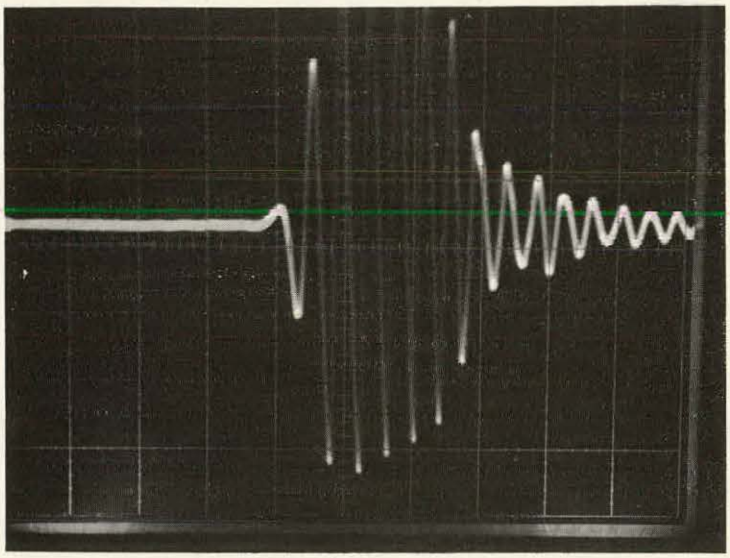
*The velocity of sound in slime used in our calculations is 1.011 times seawater velocity, as measured by Loeb and Jarzynski (1).

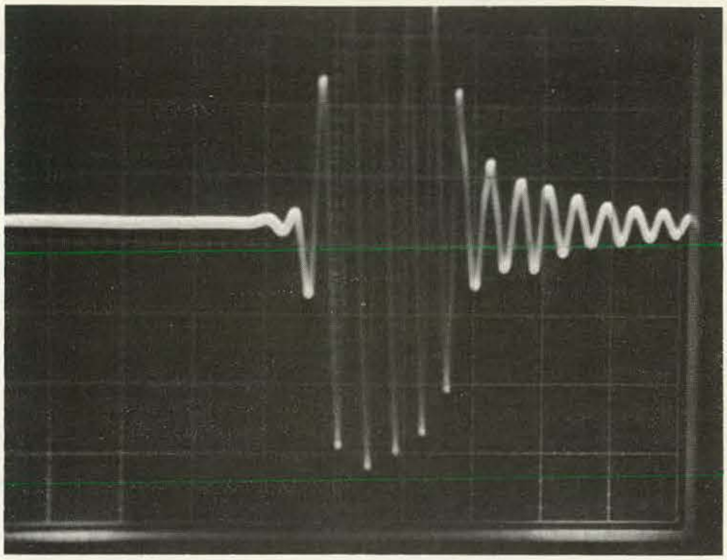


Oscilloscope Settings:

a) Vert.: 0.5 volts/div.

b) Horiz.: 0.1μsec/div.

Figure 1. Echogram from clean aluminum plate (unpolished and no lacquer layer). 25MHz predominant pulse.

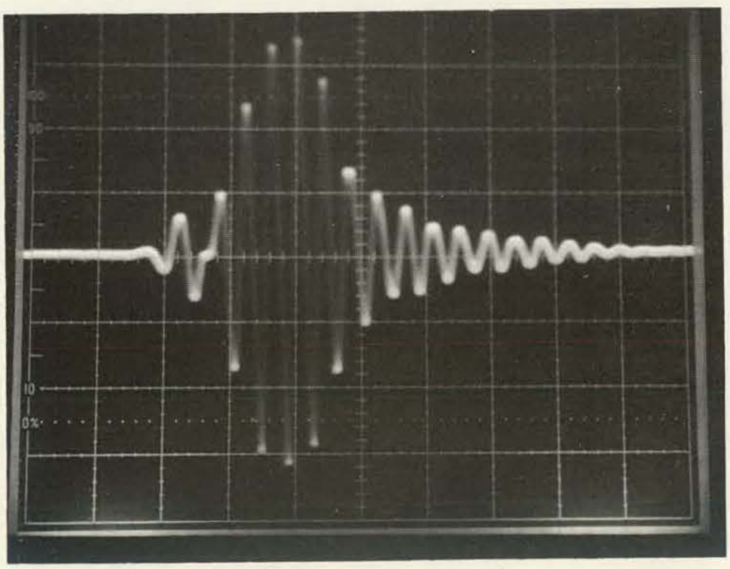


Oscilloscope Settings:

a) Vert.: 0.5 volts/div.

b) Horiz.: 0.1μsec/div.

Figure 2. Echogram from lacquer layer 46μm thick on unpolished aluminum plate. Lacquer layer is one-half wavelength thick (pulse frequency 25MHz , lacquer acoustic velocity 2.3 x 10^3 m/sec).

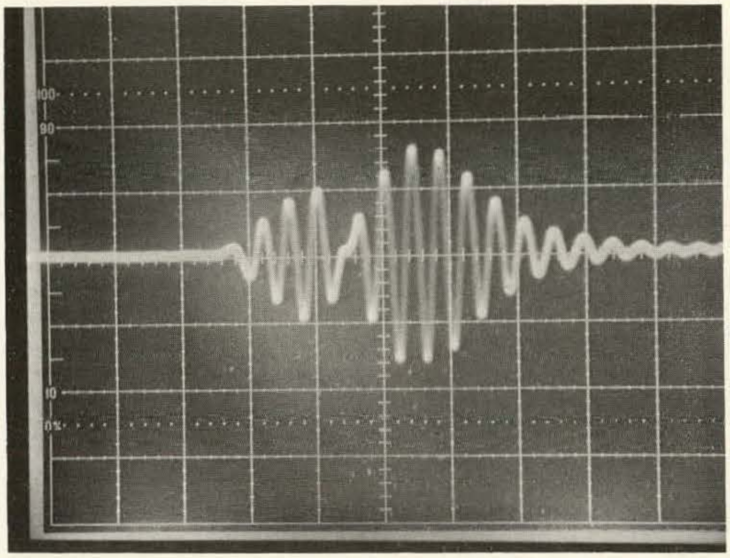


Oscilloscope Settings:

a) Vert.: 0.5 volts/div.

b) Horiz.: 0.1μsec/div.

Figure 3. Echogram from lacquer layer 92μm thick on unpolished aluminum plate. Lacquer layer is one wavelength thick (pulse frequency 25MHz , lacquer acoustic velocity 2.3 x 10^3 m/sec).

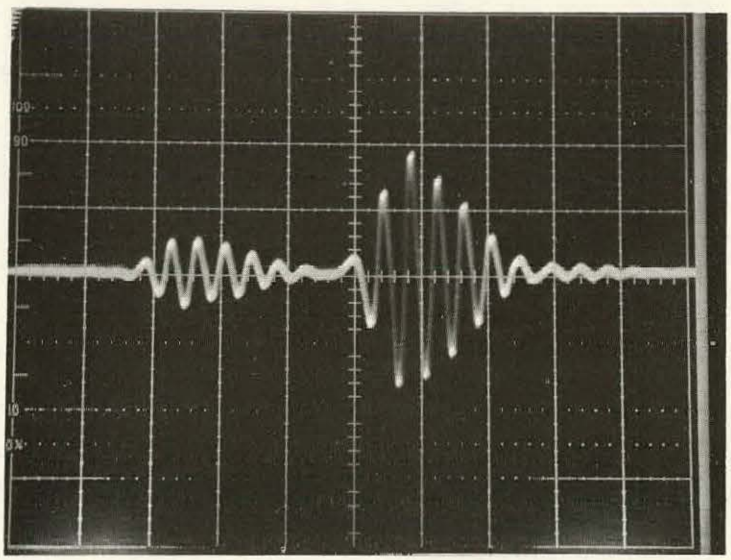


Oscilloscope Settings:

a) Vert.: 1.0 volt/div.

b) Horiz.: 0.1 μsec/div.

Figure 4. Echogram from lacquer layer 184 μm thick on unpolished aluminum plate. Lacquer layer is two wavelengths thick (pulse frequency 25MHz, lacquer acoustic velocity 2.3 x 10^3 m/sec).



Oscilloscope Settings:

a) Vert.: 0.5 volts/div.

b) Horiz.: 0.1 μsec/div.

Figure 5. Echogram from ridge of lacquer inside unpolished one-inch aluminum pipe. Lacquer is 368 μm thick, equivalent to three wavelengths (at frequency of 25MHz , lacquer acoustic velocity 2.3 x 10^3 m/sec).

layer we were able to detect was 1/2 wavelength (Fig. 2).

Several things can be noted in the photos.

a. The "30MHz" transducer (manufacturer's designation) operates at 25MHz in our system. We therefore use 25MHz as the operating frequency in all our calculations.

b. The signal level from the water/lacquer interface increases significantly as the thickness of lacquer increases (Figs. 2-4), and becomes much more distinct when echoes from the front and back surfaces do not overlap (Fig. 5). Prototype systems should thus have short wavelengths and short pulselengths compared to the layers to be measured to enhance the signal.

2. Critical Angle Effects

Although a large number of critical angle measurements were made with both flat plates and tubes, no effects due definitely to the slime layer were detected. The effects predicted in the literature for a clean liquid/metal interface were detected, indicating the equipment was functioning properly. However, because the difference in acoustic velocity between water and slime is small, the shift angle would be small, and the goniometer did not have sufficient angular accuracy to detect the predicted shift due to the slime layer. The equipment was incapable of detecting the shift due to lacquer layers up to two wavelengths thick, as well. It is possible that more accurate angle measuring equipment (better than ± ½ degree) could detect a shift. However, slime layer thicknesses would have to be much higher for detection than desired.

3. Velocity Measurements

Velocity measurements using fouled plates were proposed using the sing-around velocimeter. This method was not possible because the prerequisite of an accurate slime layer thickness measurement was not possible, as the slime layers could not be measured optically, and were highly irregular.

4. Acoustic Interferometer

Acoustic interferometer measurements were also attempted; however, the tremendous difference in reflection intensity (greater than 45db) between the liquid/slime interface and the slime/metal interface prevented realistic reinforcement to produce the maxima required to make the measurement.

5. Surface (shear) Wave Effects

Attempts were made to detect surface waves in the slime layer. These were unsuccessful. Several surface wave techniques exist in the NDT literature to measure thickness of thin layers (e.g., Love waves can be used to produce dispersion patterns that can be used to measure layers about one wavelength thick). However, no surface waves in the slime itself were identified. The slime is so close to being a liquid physically that it probably cannot sustain any degree of shear, and transmits only longitudinal waves.

We were not set up to measure changes in surface waves in the metal, as affected by the slime layer, as suggested by (1).

6. Diffraction and Doppler

The Acoustical Diffraction Method and the Doppler Flow Velocity Profile Measurements (discussed previously but not required by contract) were not attempted because of the similarity of the diffraction method and the unsuccessful interference method and the difficulty in getting short enough range gates for high resolution doppler.

III. Test Instrument System Description

A. The basic electronic test system is illustrated in Figure 6, Block Diagram. All the major equipment components are commercially available and are used conventionally. Manufacturers and Model Numbers are listed.

1. A number of transducers were tried. Two that gave the best results were used extensively.

   a) Panametrics V353, 30MHz, ceramic.

   b) Panametrics V315, 10MHz, ceramic.

2. A number of homemade (for other uses) spherical apodized lenses were tried. One type with a 7cm focal length was found to be most useful for our purposes.

   a) Some additional machining was performed on the lens used for the in-pipe flowing water tests.

   b) A special cylindrical lens was designed and fabricated for some of the oblique angle pipe tests.

B. The auxiliary equipment used in the tests is described below. Figure 7 illustrates the basic test configurations.

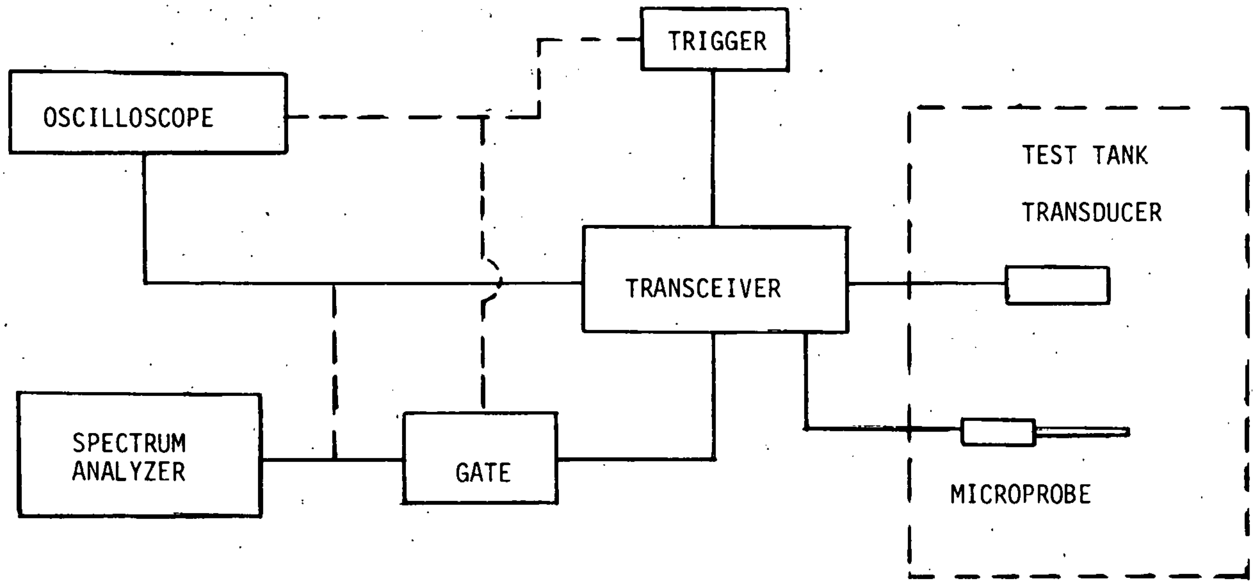
1. A goniometer type apparatus with two independent arms:

   a) permits adjustment of distances and attitudes of transducers, mirrors and test samples, and

   b) permits measurement of angular relationships between the arms, and the arms and the samples.

2. Miscellaneous parts for holding sample plates and tubes at specific heights and angles. Various devices for holding transducers and mirrors. A vernier device for holding acoustic probes and moving them with precision in two dimensions.

C. In order to perform tests inside a simulated heat exchange pipe with running water, the device illustrated in Figure 8 was fabricated. This device holds the transducer assembly so that the sonic beam is focussed on the pipe's inner surface. It also permits the pipe to be moved in and out and rotated with respect to the sonic beam so that large areas of pipe can be examined.



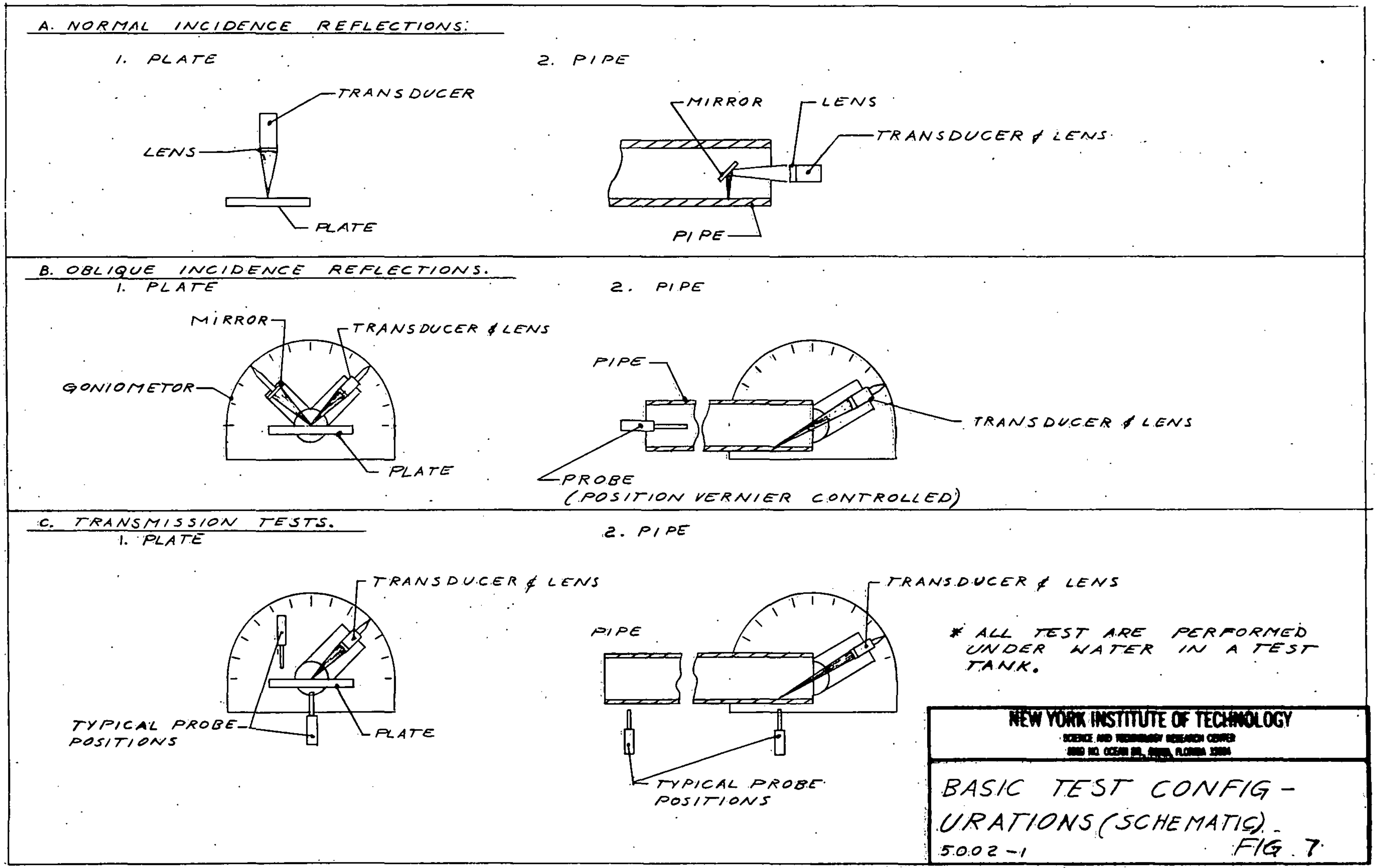
MAJOR TEST EQUIPMENT

Oscilloscope: TEKTRONIX, Model 465
Spectrum Analyzer: HEWLETT PACKARD, Model 0557A
Transceiver (Internal Trigger):
PANAMETRICS PULSER/RECEIVER, Model 5050PR
Gate: PANAMETRICS STEPLESS GATE, Model 5052G
Transducers: PANAMETRICS V353, 30MHz
PANAMETRICS V315, 10MHz
Probes: DAPCO
MEDISCAN

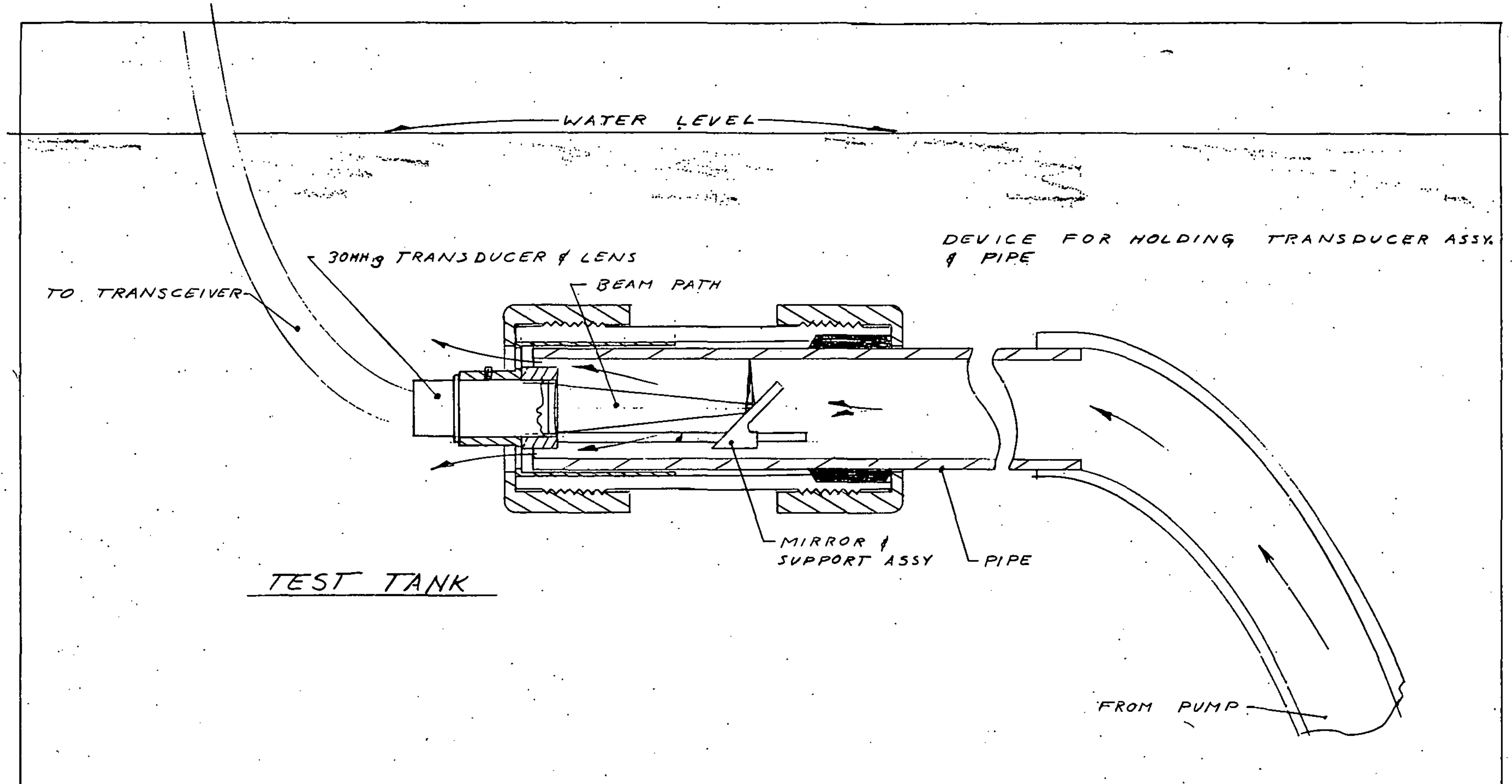
BLOCK DIAGRAM

BASIC TEST SYSTEM

FIGURE 6



BASIC TEST CONFIGURATIONS (SCHEMATIC) FIG. 7



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TEST APPARATUS WITH FLOWING WATER IN PIPE

5002-2

FIG. 8

IV. Conclusions and Recommendations

A. Conclusions

1. The pulse-echo technique has produced direct slime thickness measurements in this phase of work (during the summer months). Of the ultrasonic techniques tested, this technique shows the best potential for development into a useful instrument system for field thickness measurements of bacterial slime layers on heat exchanger tubes.

2. We could not produce consistent (season to season) reflections from the water/slime interface due, we believe, to the difficulty of obtaining thick enough slime layers (thicker than 60μm, one wavelength at 25MHz) in the milder months (winter).

3. The independent optical measurements of slime thickness that were to be provided would have been useful to confirm whether an unsuccessful run was due to slime layers too thin for the acoustic frequencies available; and to confirm any acoustic thickness measurements that were made.

B. Recommendations

1. We recommend that the construction of a prototype slime thickness measurement instrument be postponed until further applied research and exploratory development work is performed at higher acoustic frequencies (with the thinner fouling layers available) to produce consistent water/slime interface echoes in the pulse-echo mode of operation.

2. Recent experimental work at this laboratory has been with electret (condenser type), plastic film and other plastic types of transducers. Our work indicates that these types of transducers would be more suitable for these purposes because they can be operated at very high frequencies and have extremely wide bandwidth making much shorter pulses

possible. We can produce much better resolution for quantitative measurements with these than with conventional transducers. At the time of this work, these transducers were not developed to the point where they could be applied to this project.

Other workers have produced zinc oxide transducers exhibiting properties suitable for measurement of thin biological layers. This technology is well known.

Application of these experimental transducers (electret), or zinc oxide, or other high frequency broadband transducers to the microbial slime measurement problem in heat exchanger tubes would be a fertile area for applied research, and is recommended at this time.

3. Somewhere between the extremely high frequencies used for acoustic microscopes (3GHz) and the high frequencies used in our tests (10-30MHz), lies an ideal frequency/bandwidth for measuring thin bacterial slime layers. Transducers would have to be specially prepared to generate these frequencies, since they are not available commercially.

Transducers for this follow-up work should exhibit the following general characteristics for minimum layers (one wavelength) in the 7-10μm range.

a. Center frequency: 150-200MHz

b. Band width: 75-100MHz

c. Size: potential for production of tiny transducers for use inside heat exchanger tubes

d. Resistance to water (at HX temperatures)

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