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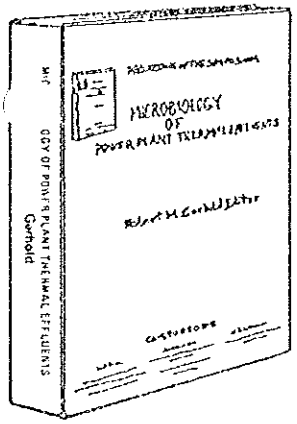

PROCEEDINGS OF THE SYMPOSIUM

MICROBIOLOGY OF POWER PLANT THERMAL EFFLUENTS

Robert M. Gerhold, Editor

1978

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Biofouling Film Development and Destruction: Experimental Systems

William G. Characklis

ABSTRACT

Microbial fouling in power plant condensers decreases heat transfer and fluid flow resulting in energy losses. Biofouling control is generally accomplished by chlorine addition creating potential toxicity problems in receiving waters. A better understanding of fouling film development and destruction (including stoichiometry and kinetics) is necessary to maintain satisfactory effluent water quality while minimizing the effects of biofouling and its control.

Methods for the direct measurement of biofilm development are presented and include electrical resistance, and volumetric and gravimetric techniques. Indirect measurement of film development, but direct measures of fouling, include frictional resistance and decrease in light transmittance. Laboratory systems have been developed to determine rate and extent of fouling as a function of wall shear stress, water quality and bulk temperature.

Results indicate that substrate concentration significantly affects biofilm growth rate *but is less of a predictor of* maximum accumulation *which is controlled primarily by hydrualic shear stress in turbulent flow. Bulk temperature affects rate and extent of film accumulation but its effect on frictional resistance is not clear. Chlorine oxidizes biopolymers responsible for the film structure causing partial removal with the aid of fluid shear forces. If removal is not complete, regrowth is more rapid than that observed on clean surfaces.*

INTRODUCTION

Fouling, the undesirable deposition of materials on surfaces, is the major cause of energy losses in fluid transport and heat exchange systems. The general term fouling can reflect any or all combinations of the following four processes:

1. *Precipitation or crystallization (scaling)* — primarily due to precipitation of calcium salts on heated surfaces.
2. *Suspended solids* — due to sedimentation and adsorption of solid particles on surfaces.
3. *Corrosion* — production of thermally insulating metal oxide scale from corrosion processes.
4. *Biological (or organic) fouling* — development of a microbial film possibly followed by a succession of higher life forms.

This paper concerns biological fouling — experimental methods for observing its development, effects and destruction.

Microbial fouling is a major cause of energy losses in power plant condenser tubes and in long pipelines supplying cooling waters to power plants. Thin, viscoelastic biofilms develop on the conduit walls causing unexpectedly large increases in fluid frictional resistance. Table 1 documents several case histories of biofouling in water supply lines, with flow reductions up to 58% cited. The case described by Pollard (1959) occurred in a power plant water supply pipeline in North Carolina. Characklis (1973a, b) and Norman (1976) have reviewed the literature concerning the growth of biofilm and its effects on frictional resistance.

Films also develop in heat exchange tubes, insulating them and causing reduced efficiency. Steam driven power plants, consumers of 80% of all industrial cooling water in the U.S., encounter significant problems. Reduced efficiency, caused by fouling on condenser surfaces, costs the power industry approximately $400 million a year for extra fuel which is equivalent to 25 million barrels of oil (Ritter and Suitor, 1976). The fouling is primarily due to microbial growths and their extracellular polymers which accelerate adsorption of fine suspended particles to the heated surfaces.

The films also accelerate corrosion processes in the metal tubes and influence deterioration in wooden cooling towers. Microbial fouling is one of the major barriers to economic utilization of ocean thermal energy conversion and membrane desalination processes.

Control of biofouling is frequently accomplished by chlorine addition. Application frequency and dose are determined arbitrarily because methods for determining the effectiveness of the chemical additive are unavailable. Economic considerations, energy conservation demands and increasingly stringent regulations on potentially toxic chlorine residuals (and their reaction products) require a systematic understanding of factors influencing microbial fouling and its control.

This paper describes several experimental systems and methods developed for observing biofouling film development and destruction in the laboratory. Preliminary results using several of these methods are presented along with a phenomenological description of the biofouling process based on our experimental observations.

EXPERIMENTAL SYSTEMS

Apparatus

Rational for Design

The objective of this research program is to study the development, effects and destruction of biofouling films. Environmental factors that can influence these processes (Table 2) must be controlled or be determined easily.

The reaction processes involved are similar to solid-catalyzed reactions and any type of reactor with known contacting pattern may be used to explore the kinetics. In one of our experimental systems, a tubular reactor was used for its geometric similarity to condenser or heat exchange tubes. A mixed reactor system (i.e., reactor contents spatially uniform) was accomplished by providing a recycle loop and operating at a high recycle ratio (Figure 1). A high recycle ratio provides a way of approximating completely mixed conditions with

TABLE 2 — *Factors affecting the biofouling process*

	Initial Attachment	Growth Rate	Ultimate Deposit
Shear Stress	•	•	•
Substrate Type		•	
Substrate Concentration		•	
Inorganic Ion Concentration	•	•	•
Solid Surface	•		
Bulk Temperature	•	•	•
Surface Temperature	•	•	•
Suspended Solids	•	•	•

TABLE 1 — *Data summary from case histories of closed conduits experiencing frictional losses due to slimes*

Reference	Minkus (1954)	Minkus (1954)	Pollard (1959)	Arnold (1963)	Wiederhold (1949)	Derby (1947)
Diameter (in)	42	36	132	36	24	14
Length (miles)	7	7	4.5	22	50	1.25
Surface	Cement	Concrete	Concrete-steel	Steel	Steel	Steel
Slime thickness (in)	1/32	1/16	1/2	1/8 1/4	1/40	
Frictional head (ft)			15 ft-900 $ft^3 s^{-1}$			
Loss in capacity (as % of design capacity)	12 (2 yr)	23		16 (3 wk)	55 (3 yr)	3.5 (1 yr)
Chemical added	[a]Chlorine		Lime	Chlorine-ammonia		Chlorine
Chemical concentration ($mg\ l^{-1}$)	50		20	0.7--0.2		9--12

[a]*Accompanied by flushing at 6 ft* s^{-1}

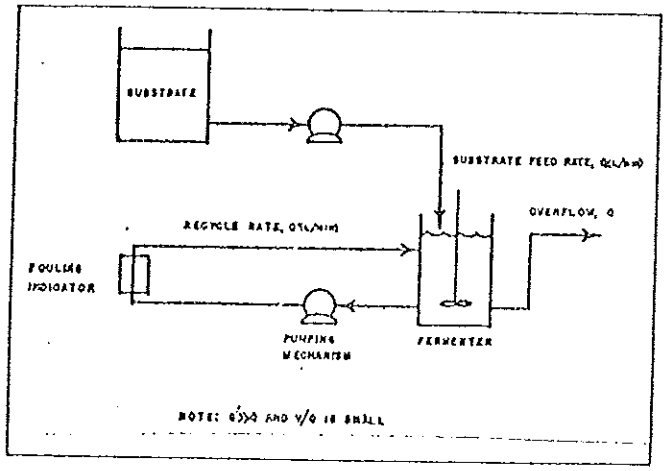


FIGURE 1 – *Schematic of Laboratory Fouling Reactor Systems.*

what is essentially a plug flow device. The fouling indicator (Figure 1) is a pressure transducer which monitors changes in frictional resistance due to biofilm development along a length of the recycle loop. Alternatively, the indicator could be a thermistor system for detecting changes in heat transfer due to film development. Advantages of the system are as follows:

1. At high recycle rates Q'>>Q, the reactor contents (including the internal recycle) are completely mixed. Mathematical description and sampling are simplified since there are no concentration gradients.
2. Biofilms in the recycle section are uniform.
3. Temperature and pH control are simplified and dissolved oxygen monitoring can be effectively accomplished by one probe in the reactor.
4. Wall shear stress is independent of hydraulic retention time.
5. Short hydraulic retention times eliminate biomass production in bulk fluid. Consequently, microbial activity is limited to the reactor surfaces.

Description of Experimental Systems

Two different geometries have been used to serve as fouling reactors. The tubular fouling reactor (TFR) simulates the most common geometry encountered in heat exchangers. In addition, turbulent flow in this system can be described by well-tested empirical relationships. The reactor system is described in Figures 2 and 3. The fluid is circulated in the recycle loop by a screw pump and flow rate is controlled by an electronic feedback system. Change in pressure drop (Δp) along a segment of the tubular reactor is a measure of fouling. Overall hydraulic retention time is maintained at approximately 10 minutes. An in-line rectangular duct section contains removable metal discs which serve as platens in a rheogoniometer. In this manner, dynamic rheological properties of *in situ* biofilms can be determined.

The annular fouling reactor (AFR) consists of two concentric cylinders with the inner cylinder rotating (Figures 4 and 5). Shear stress (speed of rotation) is independent of hydraulic retention time. The reactor is completely mixed by virtue of the pumping action of four draft tubes and an impeller situated at the bottom of the inner cylinder (after Kornegay and Andrews, 1968). Therefore, a recycle loop is not necessary. Fouling is indicated by a change in torque monitored by a torque transducer mounted on the drive shaft of the inner cyclinder.

Biofouling Measurement Techniques

Film Thickness Measurement

Film Volume – Small tubular test sections (5 cm long) are inserted as an integral part of the tubular reactor. At designated intervals, a tube is removed from the TFR and the volumetric displacement of the

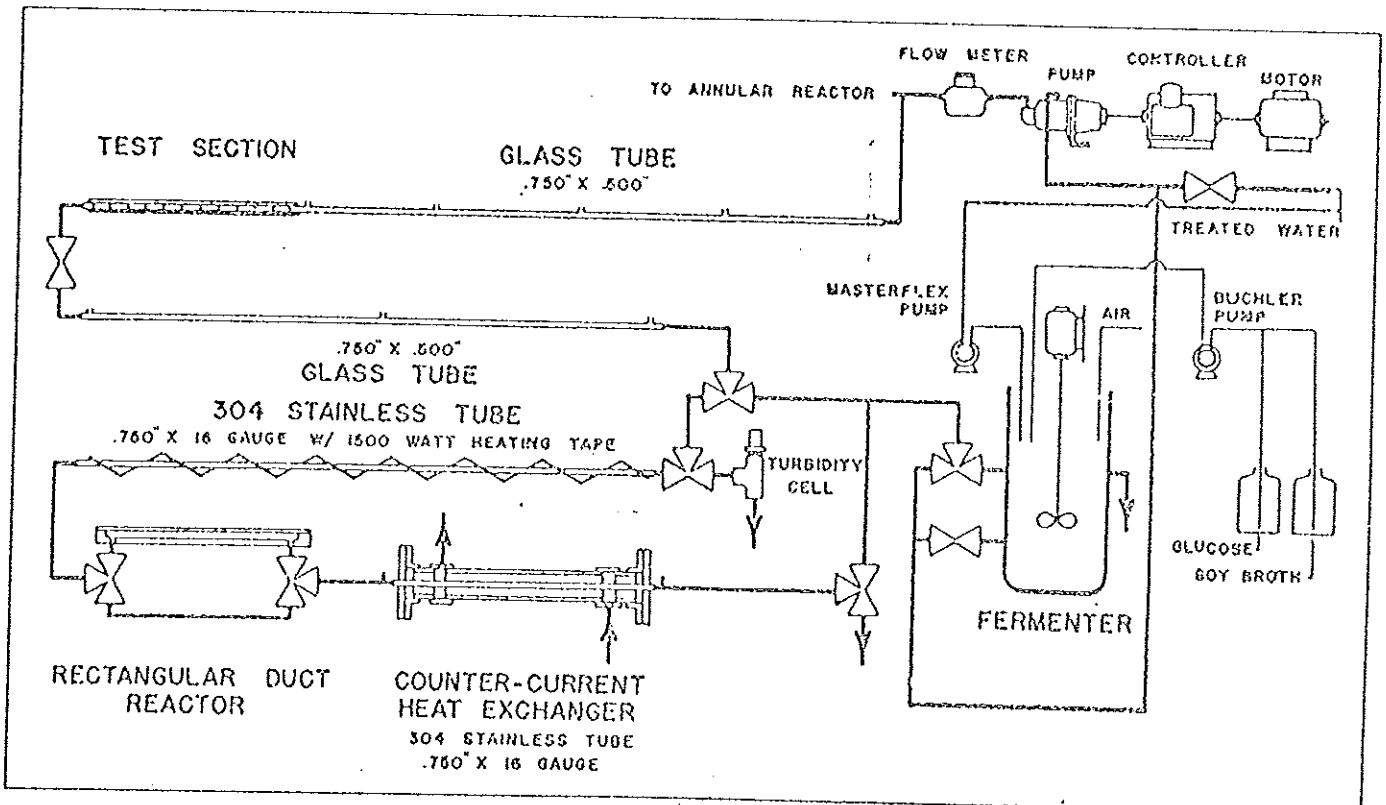


FIGURE 2 – *Experimental System for Evaluating Effect of Velocity, Water Quality, Bulk Temperature and Surface Temperature of Biofouling Rate (TFR). Also Used for Determining Kinetics of Fouling Control via Chemical Treatment (e.g., chlorine, ozone, etc.).*

biofilm is determined using the apparatus pictured in Figure 6. The displacement cell is filled with a water-surfactant solution. Initial liquid level (i.e., without the test section immersed) is measured by lowering the conductive probe, by means of a micromanipulator, until contact is made with the water surface, indicated by deflection of the ammeter. The ammeter is in series with the cell and a 1.5v power source. A 5 x 1.27 cm (ID) fouled test section is then immersed in the cell and the new liquid level (and hence, displacement) due to the fouled test section is determined. The test section is then cleaned, dried and again immersed in the cell. The difference between the displacements of the *fouled* and *clean* test section is the film volume. Wet thickness is determined by dividing film volume by the surface area of the test section.

This method was calibrated by measuring displacement of copper wire segments of known mass and therefore, known volume. Precision, based on repeated volume displacement measurements with a clean test section, is ± 9 μm. Average inside surface area of the test sections is 20.0 cm² with a range of 1.2%.

Light Transmittance — Film accumulation is measured by a light transmittance technique similar to a comparator spectrophotometer. Selenium photoelectric cells on opposite faces of a transparent rectangular duct section monitor incident and transmitted light intensities normal to the direction of flow (Figure 7). Percent reduction in light transmitted (% RLT) is proportional to film accumulation. The measurements are consistent and are presently being related to thickness and densities.

Conductance — This technique was adapted from Hoehn and Ray (1973) and utilizes an apparatus consisting of a steel needle mounted on a micromanipulator (Figure 8). Film thickness is measured in a

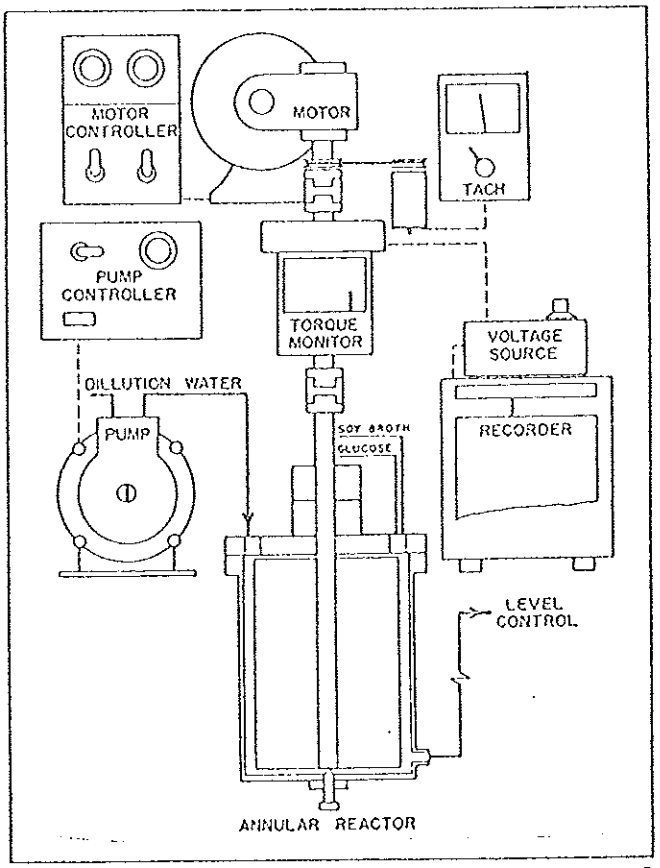


FIGURE 4 — *Experimental System for Evaluating Effect of Velocity, Water Quality and Bulk Temperature on Biofouling Rate (AFR). Also Used for Determining Kinetics of Fouling Control via*

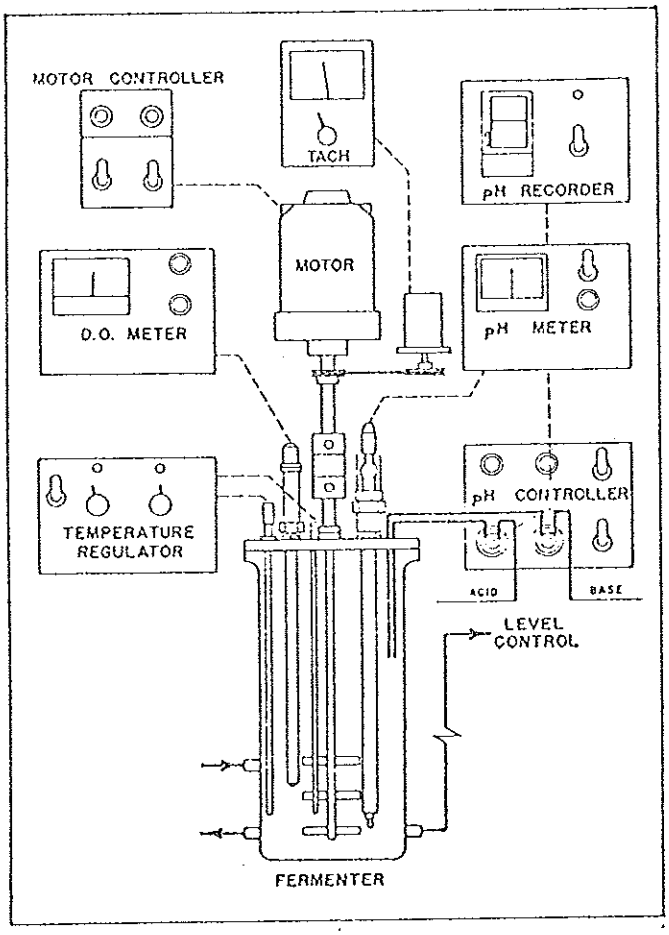


FIGURE 3 — *Controls and Monitors for TFR Experimental System.*

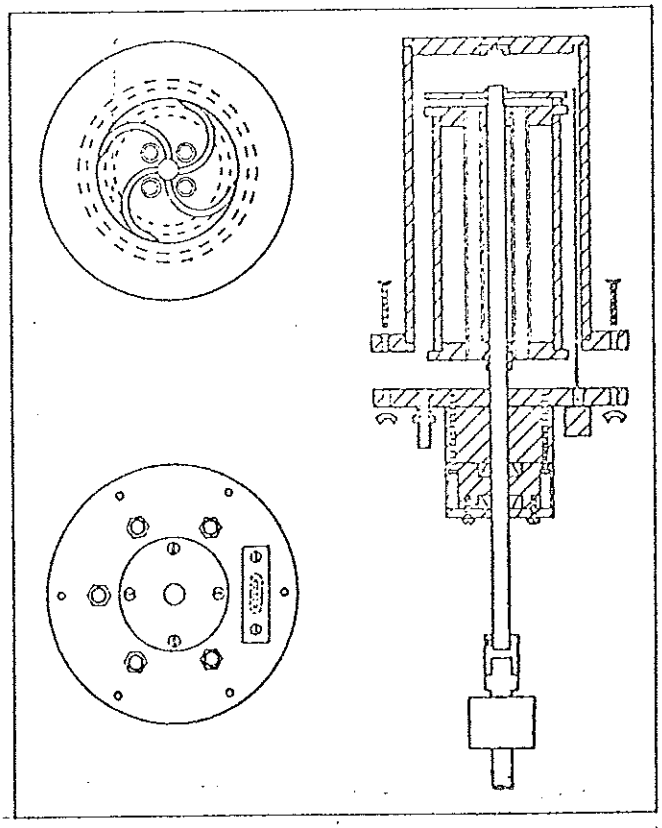


FIGURE 5 — *Annular Fouling Reactor (AFR) Apparatus.*

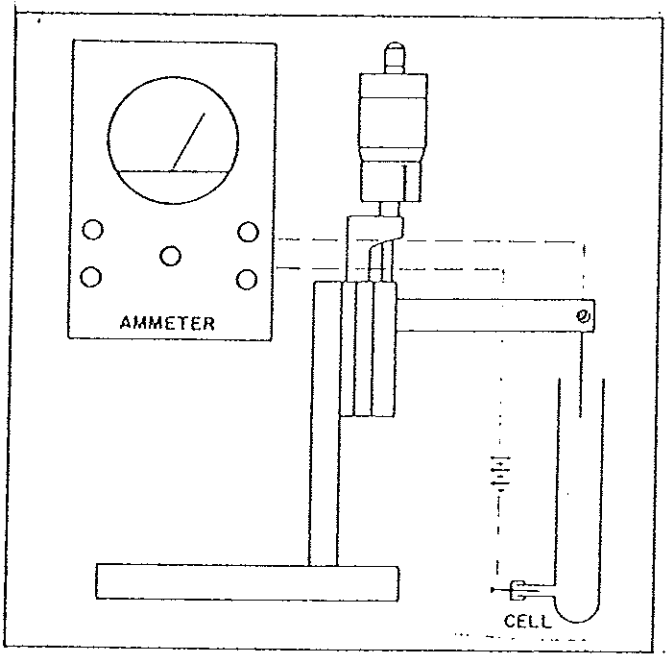


FIGURE 6 — *Volumetric Displacement Method for Biofilm Thickness Measurement.*

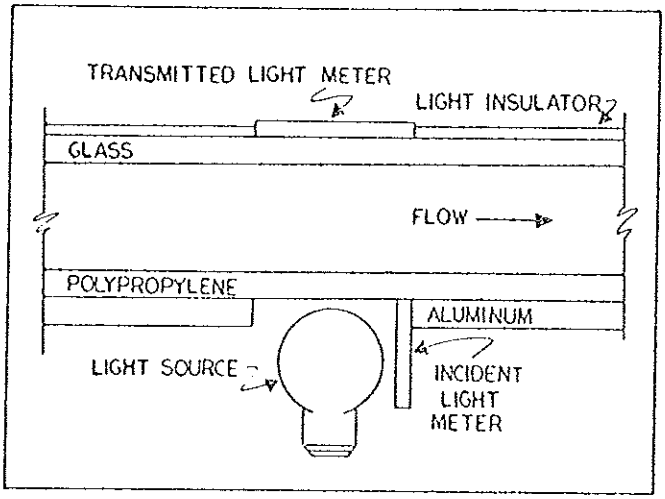


FIGURE 7 — *Light Transmittance Technique for Measurement of Biofilm Accumulation.*

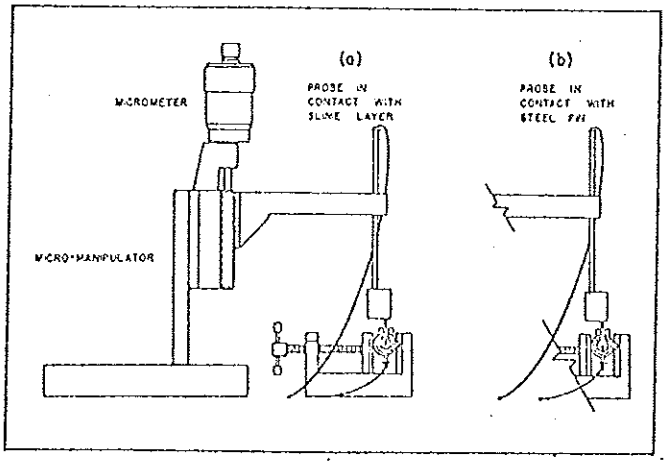


FIGURE 8 — *Slime Layer Thickness Measurement.*

removable circular test section (Figure 9) fabricated from acrylic plastic tubing. The test section contains six measurement points, each consisting of a stainless steel rod (3 mm ID) mounted flush with the inside tube wall. Opposite each rod is a threaded hole in the tube wall which can be sealed with a screw and O-ring. The thickness of the biofilm on the stainless steel surface is measured. The test section has two rods in the bottom, two at the top and one on each side (total of six measurement points).

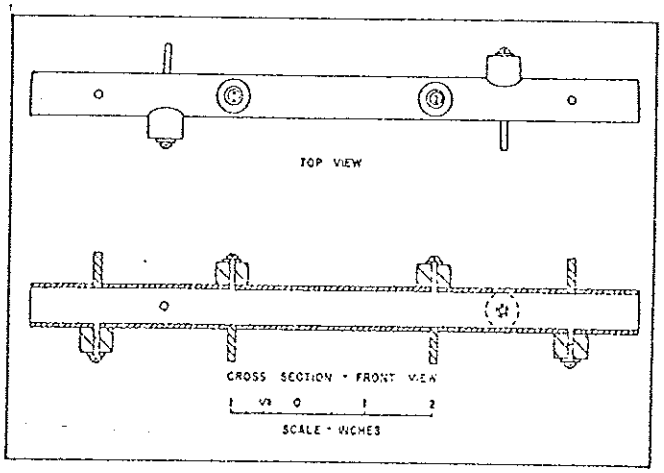


FIGURE 9 — *Detail of Thickness Test Section.*

To obtain a measurement, the test section is removed from the reactor, the screws are withdrawn and the test section drained for two minutes. The steel needle and stainless steel rod at the first measuring location are connected to an electrical circuit completed by an electrometer and the steel needle is lowered into the section through the threaded hole. When the needle contacts the biofilm, a current (approximately 10^{-4} amp.) is registered and the depth noted on the micromanipulator. The needle is lowered further until it contacts the steel surface when further deflection (approximately 3×10^{-4} amp.) occurs and again depth is noted. The difference in depths is the film thickness. The procedure is repeated for the five remaining locations. Precision is about ± 6% and accuracy, compared to Vernier micrometer measurements, is within 5%.

Optical Microscope — This technique was adapted from that of Sanders (1964) and requires film growth on a transparent surface. In this case, microbial film develops on a thin acrylic plastic slide which forms an integral part of the AFR reactor wall. The slide is withdrawn from the reactor and placed on a microscope stage. The 100X objective is lowered until the film surface is in focus and the fine adjustment dial setting is recorded. The objective is then lowered further until the inert plastic growth surface is in focus (Figure 10).

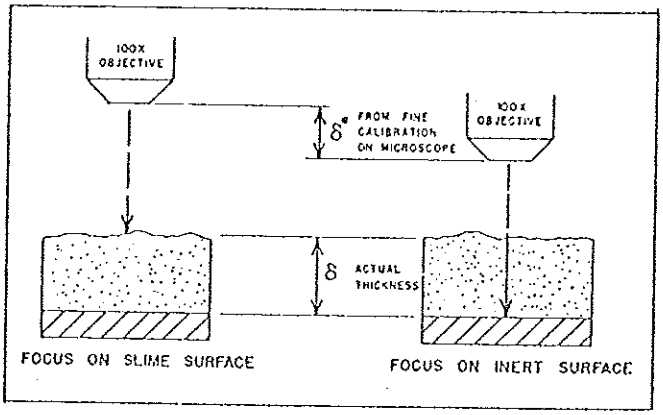


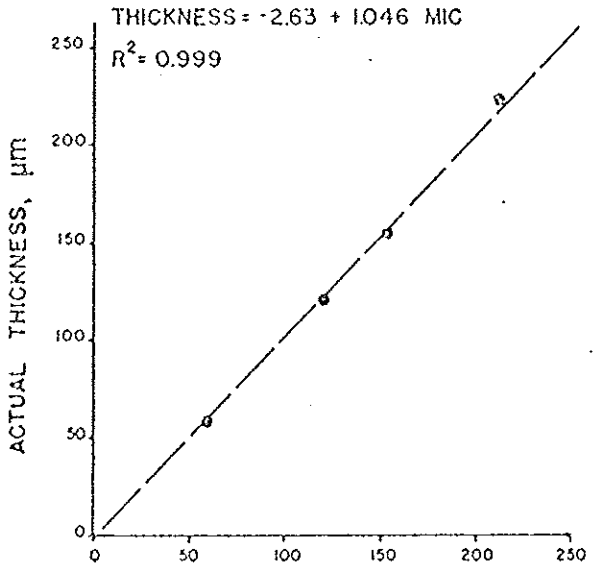
FIGURE 10 — *Representation of Film Thickness Measurement Using the Optical Microscope Technique.*

The difference in fine adjustment settings is compared with a calibration curve (Figure 11) and the thickness obtained.

Areal Mass Density Measurement

Small test sections (5.0 cm long) are an integral part of the tubular reactor wall. At regular intervals, a test section is removed, dried and weighed. The tube is then cleaned, dried and weighed again. The difference is the dry film weight. The length and diameter of the tubes are known so an areal mass density can be calculated. If thickness or volume has also been measured, a wet mass density is obtained.

FIGURE 11 – *Calibration Curve for Film Thickness Measurement Using the Optical Microscope Technique. Each Point is a Measurement of a Solid Material (e.g., metal shims) with* Actual *Thickness Being the Average of Repeated Measurements with a Vernier Micrometer.*



Frictional Resistance

The development of biofilms on surfaces increases fluid frictional resistance and therefore, energy consumption. Consequently, friction factor (ff) increase is a good indicator of microbial fouling and biofilm development. In the TFR, friction factor is calculated by the following equation:

$$ff = 0.5 \frac{D}{L} \left[\frac{\Delta P}{\rho v_m^2}\right]$$

where D: tube diameter (L)
L: tube length (L)
ρ: fluid density (M/L^3)
v_m: mean fluid velocity (L/t)
ΔP: pressure drop across length L ($M/L\text{-}t^2$)

ΔP is measured by a pressure transducer valved between six ports of the TFR system. The transducer operates on a 0–5 psig range with a 0–1 psig option. A mercury manometer is used for calibration and back-up.

In the AFR, friction factor is defined as follows:

$$ff = \frac{\tau_q}{\rho \pi R_i^3 (R_i + R_o) \Omega^2 H}$$

where R_i: radius of the inner cyclinder (L)
R_o: radius of the outer cylinder (L)
Ω: rotational velocity (t^{-1})
H: height of the cylinders (L)
τ_q: torque (ML^2/t^2)

Torque is measured by a torque transducer mounted to the shaft which drives the inner cylinder. The torque is monitored in the range of 0–0.035 N-m.

Frictional resistance correlates in a non-linear form to thickness in both the TFR and AFR (Figures 12 and 13).

FIGURE 12 – *Relationship of Friction Factor to Thickness During an Experiment in the TFR.*

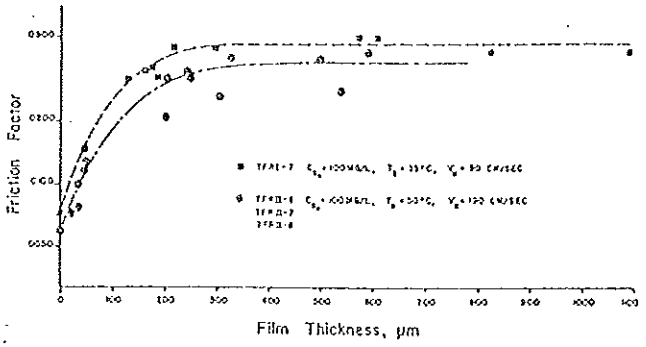
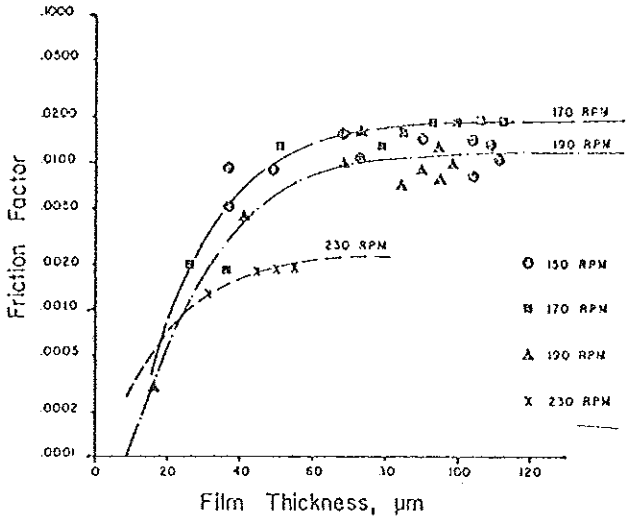


FIGURE 13 – *Relationship Between Friction Factor and Film Thickness During an AFR Experiment.*

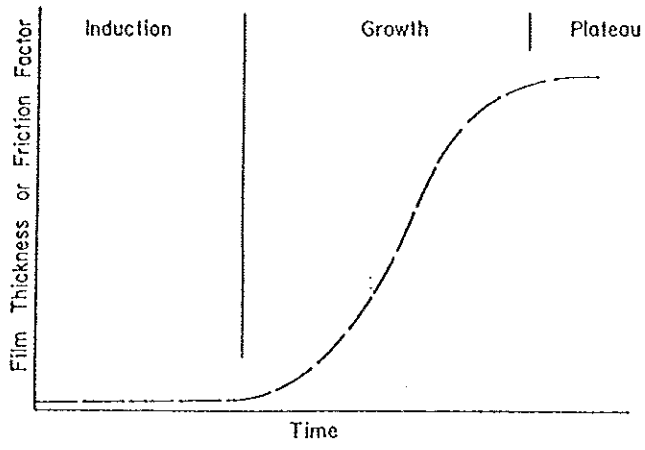


RESULTS

Development of Biofouling Films

Laboratory experiments have been conducted in the tubular and annular reactors to determine the effect of shear stress (SSt), substrate concentration (Cs) and bulk temperature (Tb) on biofouling. The change in fluid frictional resistance, as measured by pressure drop and represented by friction factor (ff), has been used as an indicator of fouling. The change in friction factor with time during a typical experiment is presented in Figure 14. The *induction* period is dependent on the composition of the attachment surface (e.g., copper alloys, carbon steel, glass, etc.) and often requires several days. This research is not considering the effects of tube materials since the necessary experiments already number greater than 20 for each apparatus. Consequently, procedures are being used to minimize the induction period in the TFR and AFR.

FIGURE 14 -- *Progression of a Typical Biofouling Experiment.*



The effects of fouling are negligible during the induction period, so the change in $\log_{10}$ friction factor with time during the *growth* period is defined as the fouling rate (Rf). The *plateau* attained is analogous to a stoichiometric parameter, indicating the *maximum extent* of biofouling.

Our present concept of the biofouling process suggests that the biofilm thickness initially increases at a rate controlled by substrate availability. As the film gets thicker, however, fluid shear stress strips away a greater fraction of the newly formed cells and begins to exert a controlling influence on growth rate. At plateau, all new cells are removed as they are formed and a steady state exists.

Growth of the biofilm causes an increase in hydraulic roughness, and therefore, an increase in pressure drop. The "roughness" effect is partially due to the rippled nature of the film (Figure 15). The microbial growth begins as isolated colonies which grow by the combined processes of replication and adsorption. The colonies are similar to those observed on agar plates except for the distortion in shape caused by the shear stress. In addition to forming a rippled surface, the biofilm is viscoelastic. This has been determined by *in situ* measurements conducted with a rheogoniometer and results indicate a lightly cross-linked gel with a significant elastic modulus and a very high viscous modulus. The large viscous modulus is the other contributing factor, in addition to the rippled surface, to the excessive energy losses observed in fouled conduits.

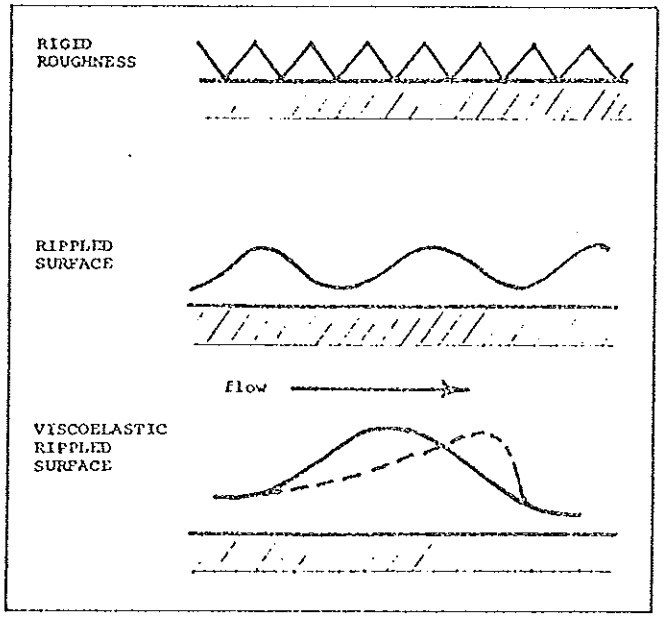


FIGURE 15 -- *Surface Morphology of Microbial Films.*

A further comment regarding hydraulic roughness is of interest. For turbulent flow through a conduit, a thin laminar (or viscous) boundary layer exists adjacent to the wall. If the roughness elements of the wall lie within this layer, there is no affect on flow properties and the pipe appears hydraulically "smooth." However, if the roughness elements protrude well into the faster turbulent region, they cause drag which reduces local velocities causing losses in energy characteristic of "rough" surfaces. The thickness of the boundary layer varies with Reynolds number as indicated in Figure 16 for the case of a 0.5" ID tube used in the TFR. Accordingly, the data suggest that the biofilm development has no significant effect on frictional resistance until biofilm thickness (TH) reaches some critical value (THcrit), at which time significant changes in Rf occur (Figure 17). THcrit depends of course on the thickness of the laminary sublayer and on the morphology of the film surface which can in turn be influenced by SSt and Cs.

FIGURE 16 -- *Laminar Boundary Layer Thickness as a Function of Reynolds Number in a 0.5" I.D. Tube.*

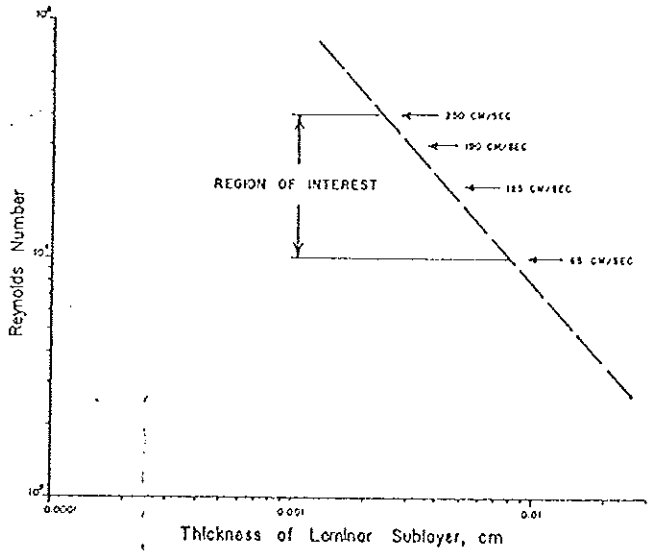
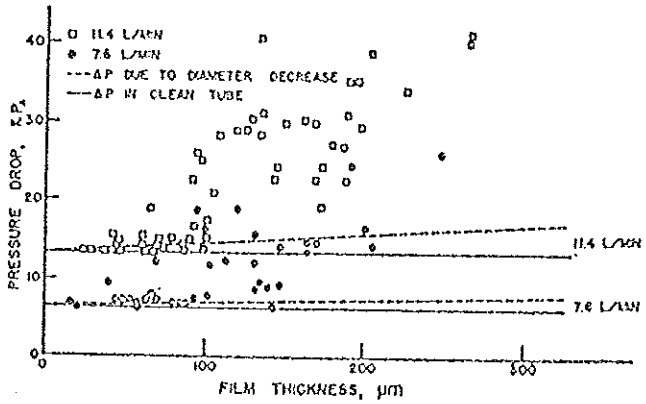


FIGURE 17 -- *Effect of Film Thickness on Pressure Drop in a 1.27 cm Circular Tube (552 cm in length).*



Fouling Rate

Results from the TFR are described very well by a saturation kinetic expression as follows:

$$Rf = \frac{Rf^* \cdot (Cs - 0.65)}{Rs + Cs - 0.65}$$ See Figure 18.

Rf^* is the maximum fouling rate and is strongly dependent on SSt (Figure 19). Rs, the saturation constant, probably depends on SSt but, because of its magnitude, a meaningful expression has not been developed. The low Rs values (< 1) indicate that fouling rate becomes independent of Cs at a very low value. In fact, fouling rate is zero order with respect to Cs for $Cs \geq 4$ mg/l. Note also that no fouling should be expected for $Cs < 0.65$ mg/l.

Fouling rates determined from film thickness measurements correlate extremely well with rates calculated from ff as indicated in Figure 20.

Extent of Fouling

The extent of fouling, or plateau, is primarily a function of SSt as indicated in Figures 21 and 22. The effect of Cs, although pronounced at high levels (100 mg/l compared to 20 mg/l) appears negligible for $Cs \leq 20$ mg/l. Figure 22 suggests that a SSt exists, beyond which, fouling will not occur. For $Cs \doteq 20$ mg/l, the "threshold" SSt is estimated at 21.5—25.0 newton/m² which corresponds to an average velocity of 7—8 feet per second in a 0.5" ID tube.

Control of Biofouling with Chlorine

Chlorination of power plant intake waters is the predominant means of controlling or preventing biofouling. Recently, concern over toxicity of chlorine residuals in natural waters has led to further inquiries into the mechanism of control. Characklis and Dydek (1976) have shown that chlorine functions primarily as a chemical oxidizer which disrupts microbial film through hydrolysis of exocellular polymers, especially polysaccharides, which lend structural strength to the deposit. Combined with fluid shear stress, the chemical action causes detachment and partial solubilization of the film. Mercuric chloride (500 mg/l) had no physical effect on the film although substrate removal was completely inhibited. Chlorine reaction rates are expected to vary with biofilm composition which is controlled to a larger degree by substrate composition (Pavoni *et al.*, 1972).

Norman *et al.* (1977) describe the effect of chlorination on

FIGURE 19 — *Maximum Fouling Rate (Rf^*) as a Function of Shear Stress.*

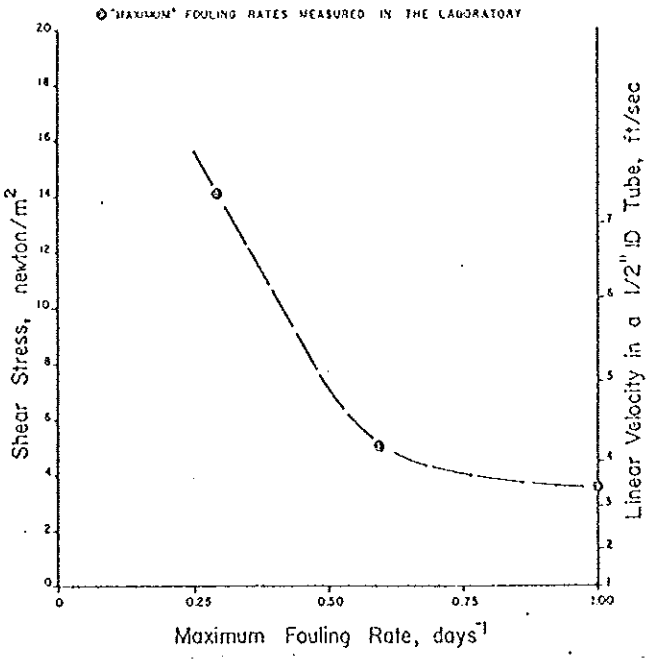
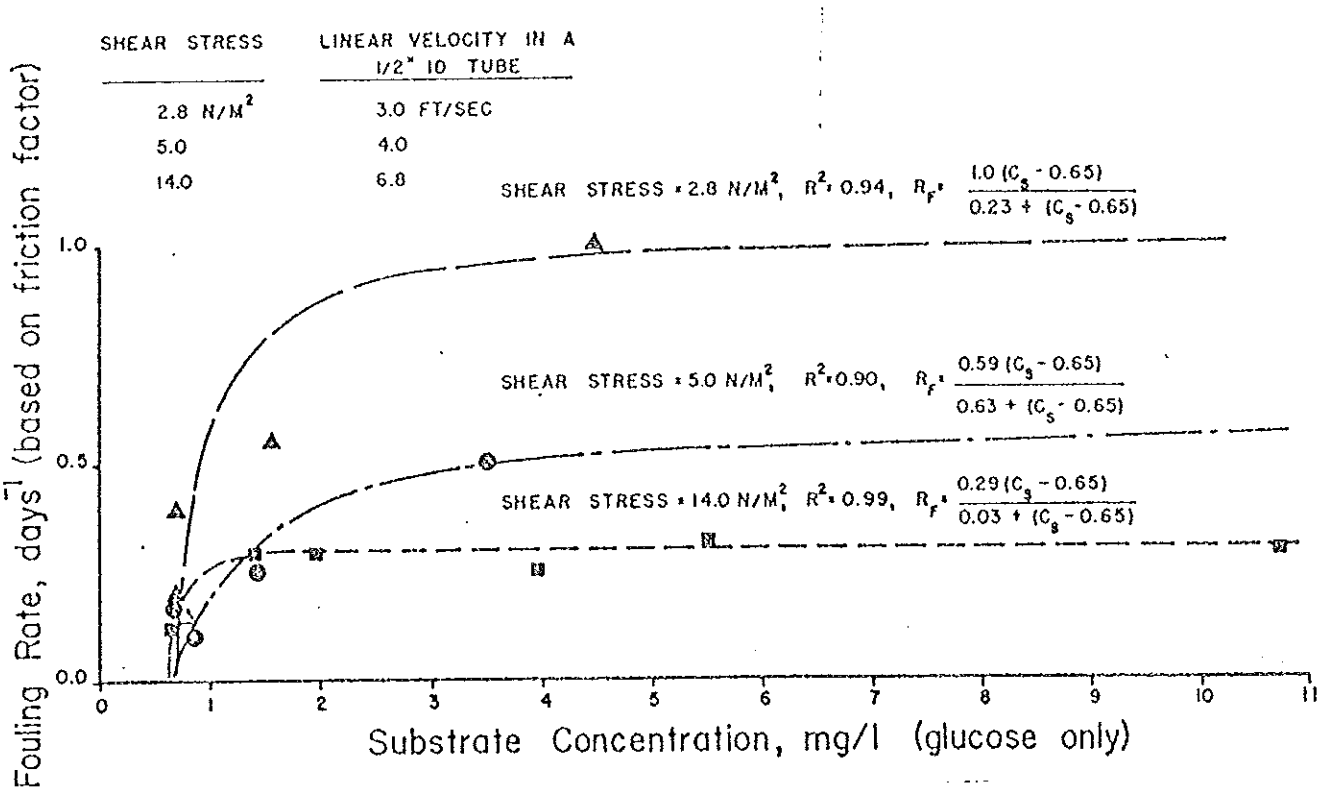


FIGURE 18 — *Biofouling Rate as a Function of Reactor Substrate Concentration and Shear Stress in a Tubular Reactor System.*



established biofilms. Figure 23 indicates the effect of chlorine addition on effluent suspended solids, film thickness and pressure drop in the TFR during a typical experiment. Chlorine input was constant for a 30 minute period. The film was partially removed by the chlorine treatment causing an increase in effluent suspended solids. Film thickness decreased from 150 to 50 μm and pressure drop was reduced to essentially "clean" conditions.

FIGURE 20 – *Relationship Between Fouling Rates Determined from Film Thickness and Friction Factor Measurements.*

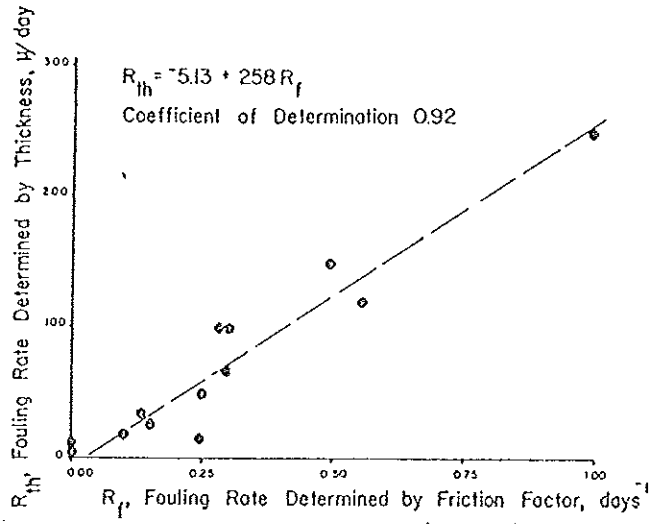


FIGURE 21 – *Extent of Fouling (as measured by friction factor) as a Function of Shear Stress in a Tubular Reactor 0.5" I.D. for Substrate Feed Concentration Ranging from 5–20 mg/l.*

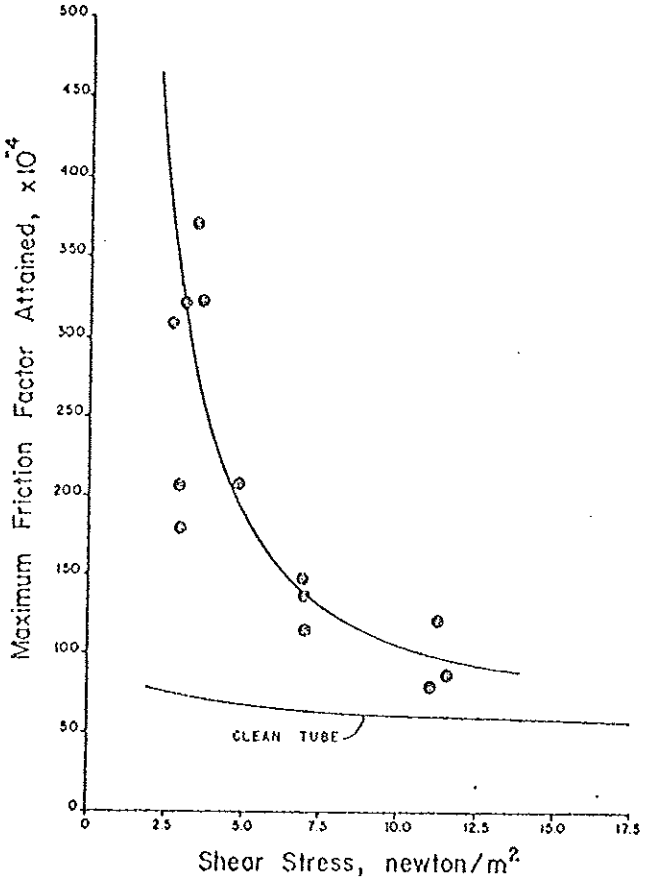


FIGURE 22 – *Extent of Fouling (as measured by film thickness) as a Function of Shear Stress in a Tubular Reactor.*

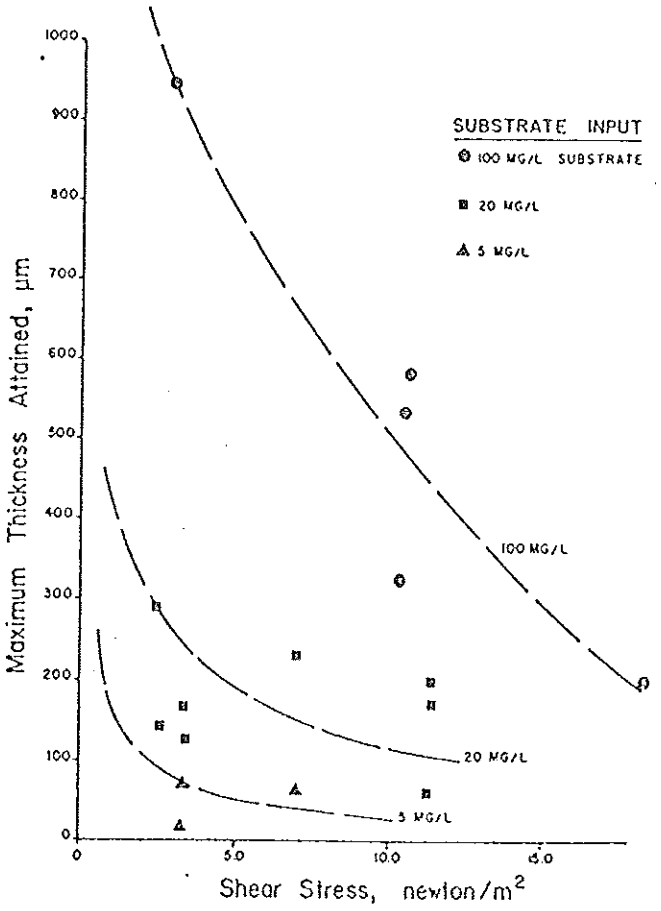
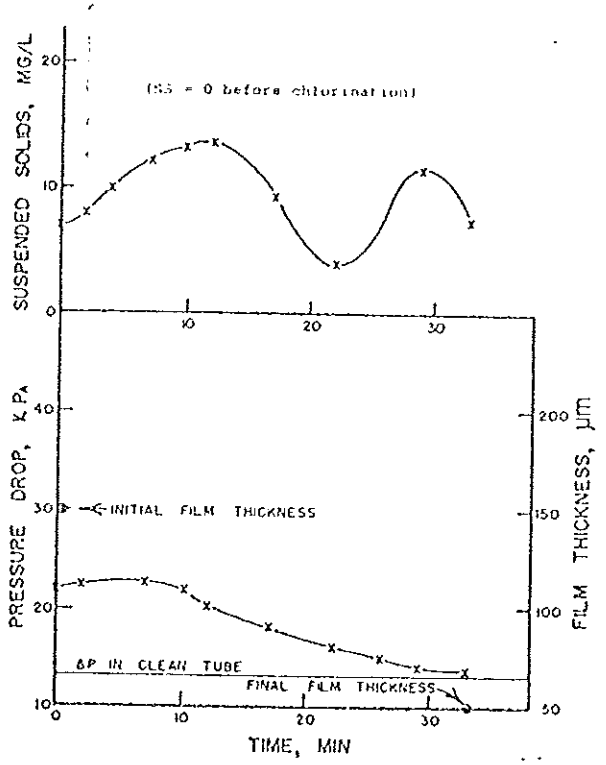


FIGURE 23 – *Pressure Drop, Thickness, and Suspended Solids Concentration During Shock Chlorination at 4.1 mg/l, Flow Rate = 11.4 l/min.*



The effect of dosing level and dosing concentration is indicated by Figure 24. In these experiments, either 2 or 4 grams of chlorine was added for a thirty minute period either every day or every other day. The top graph indicates that a dose of 2 or 4 grams applied every other day is insufficient for control of biofouling. In fact, regrowth subsequent to chlorine addition was extremely rapid. The bottom graph indicates that a dose of 2 grams every day was not satisfactory for control. The addition of 4 grams per day, however, was sufficient for maintaining "clean" conditions. Thus, the results suggest that a stoichiometry exists for the chlorination of biofilms, and, if the reaction is not carried to "completion," the remaining biofilm will catalyze the redevelopment of the film.

FIGURE 24 — *Shock Chlorination Effect on Frictional Resistance.*

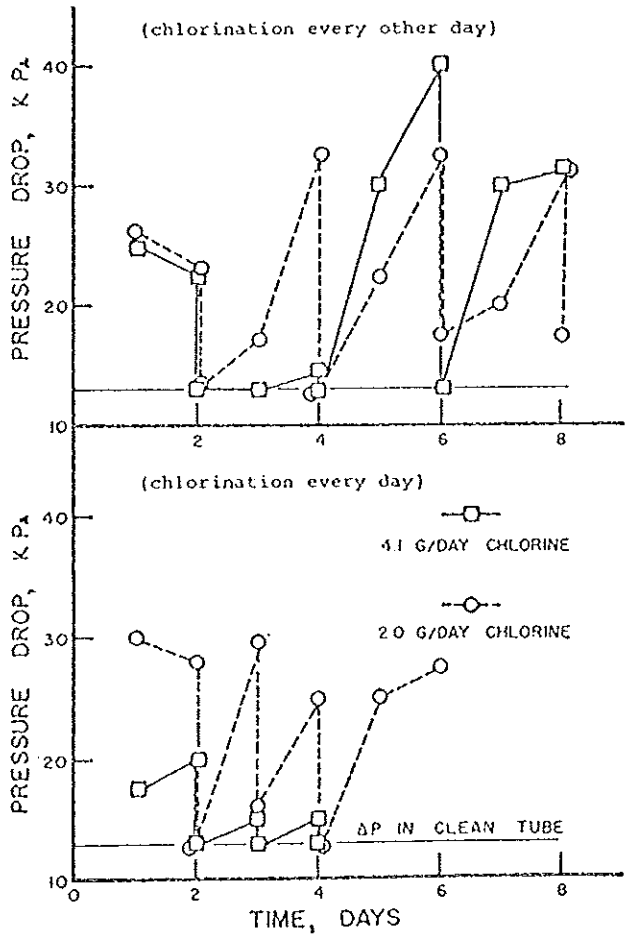


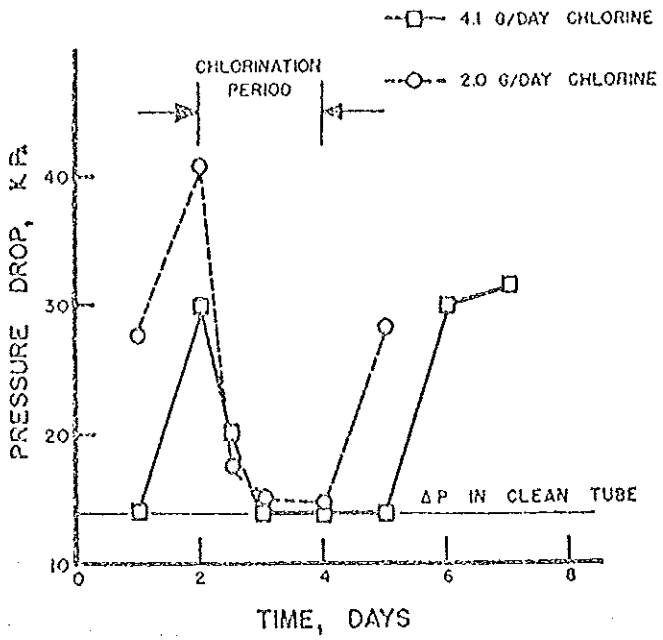
Figure 25 indicates the effect of dosing concentration when chlorine is added continuously over a period of two days at a rate of 2 and 4 grams per day. Note the difference in time for regrowth of the biofilm when chlorine addition ceases.

CONCLUSIONS

Analytical techniques and experimental systems have been developed and tested for quantitatively determining biofouling film development and its effects, as well as, the effectiveness of control by chemical and physical techniques. Experimentation is continuing but the following conclusions are useful at this time:

1. Substrate concentration affects the *rate* but not necessarily the extent of biofouling.
2. Extent of biofouling is primarily controlled by wall shear stress in turbulent flow. Microbial fouling cannot occur to any significant extent when shear stress exceeds 200 g/cm-sec^2.
3. Chlorine can affect partial film removal by depolymerizing extracellular macromolecules that form the film supportive structure.
4. Any remaining biofilm subsequent to chlorination catalyzes the regrowth of film.

FIGURE 25 — *Effect of Continuous Chlorination on Frictional Resistance at Flow Rate = 11.4 l/min.*



Data collection continues in order to further corroborate the above conclusions and determine the effect of surface temperature on biofouling. More research is necessary to determine the effects of inorganic cations, pH, ionic strength and suspended solids. Further definition of the kinetics of the chlorine reaction with biofilm is also desirable.

ACKNOWLEDGMENTS

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OPEN DISCUSSION OF PAPER

George Zivtins, Nalco Chemical Co. — What was the substrate material you used in measuring the buildup of the slime layer?

Characklis — In the runs, I've discussed today, we use a mixture of (50/50) glucose-soy broth. By the way, the concentrations that I showed you on that kinetic plot were input substrate concentrations. That's not really a good way to do a kinetic analysis. I have the other data based on reactor concentration which indicates the limiting substrate concentration where the fouling rate levels out is less than 4 milligrams/liter. After 4 milligrams/liter in the reactor the substrate really doesn't affect biofouling rate.

H.W. Rossmoore, Wayne State University — What was the concentration of chlorine in milligrams/liter during the continuous experiment?

Characklis — The flow rate was 11.4 liters per minute. We were feeding either 4 ro 2 grams per day, depending on the particular experiment. Input concentration can be determined from those numbers.

Tom Waite, Northwestern — Is the growth rate dependent on velocity?

Characklis — It is dependent on velocity. I may have interchanged two terms — velocity and shear stress, and that's where the confusion may have arisen. Shear stress and velocity in our system are interchangeable because all experiments were conducted in a ½ inch tube.

Fred Roensch, Nalco Chemical Co. — Why doesn't the laminar boundary layer become reestablished after the slime layer developes?

Characklis — The film is rippled. The rippled nature of the film and the fact that it moves with the flow actually introduces a resonance or vibration movement in the film. It's a viscoelastic material, so when you push it it wants to come back. In water tunnel tests, we have actually seen the vibration of these films. Presumably, it is enough to destroy the laminar boundary layer and it is really what causes tremendous friction losses. Prandtl viewed turbulent flow as little bundles of energy that are flowing down the pipe and if they hit a roughness element they get deflected back into the bulk flow and hold up the flow somewhat. When the film is resonating the bundles of energy not only get deflected, but can even be directed back into the flow. A lot more energy loss results from that kind of process. We have actually observed (measured) this on a rheogoniometer *in situ*.