ENERGY LOSSES IN WATER CONDUITS: MONITORING AND DIAGNOSIS

by

W. G. Characklis, N. Zelver,
M. Turakhia, F. L. Roe

College of Engineering
Montana State University
Bozeman, MT 59717

Presented at the 42nd International Water Conference, October 26-28, 1981, Pittsburgh, PA.

INTRODUCTION

The term fouling refers to the undesirable formation of inorganic and/or organic deposits on surfaces. These deposits can impede the flow of heat across the surface, increase the fluid frictional resistance at the surface, and increase the rate of corrosion at the surface. In each case, excess energy loss results.

Fouling Deposits

Several types of fouling and their combinations may occur in heat exchangers: (1) crystalline or precipitation fouling, (2) corrosion fouling, (3) particulate or sedimentation fouling, (4) chemical reaction fouling, and (5) biological fouling or biofouling. Biological fouling results from (a) development of an organic film (biofilm) consisting of microorganisms and their products (microbial fouling), (b) deposition and growth of macroorganisms such as barnacles (macrobial fouling), and (c) assorted detritus.

In most industrial cases, more than one type of fouling will be occurring simultaneously. For example, biofouling is not limited to microbial activity. The term includes the interaction of the microorganisms and the slime layer with both the chemistry of the solid surface and the bulk fluid. The interaction can enhance some of the more commonly known phenomena such as precipitation or crystallization (scaling), sedimentation, and corrosion. The rate and extent of fouling due to various mechanisms will partially be determined by transport processes and the physical properties of the resulting fouling deposits (e.g., thermal conductivity, rheological properties, roughness). There can be no doubt that fouling on heat exchange surfaces reduces heat transfer and lowers plant efficiency. Purkiss [1] observed a decrease of nearly 80% in the performance of a cooling system over a seven week period due to biofouling. Ritter and Suitor [2] measured fouling resistance in six power plant condensers of 240 MW design capacity and estimated the cost of extra fuel for this system due to fouling was $350,000 (1976 dollars). Other documentation related to the costs of fouling is presented elsewhere [3].

Process Description

Development of a systematic understanding of fouling from field observations has been limited because of the interaction of several contributing rate processes. Mechanistically, fouling deposit accumulation may be described as the net result of the following:

- *Transport of material from the bulk fluid to the surface and adhesion to the surface.* Transported materials can be soluble (microbial nutrients, inorganic salts, and organic salts) or particulate (viable microorganisms, their detritus, or inorganic particles). Fouling begins once these materials adhere to the surface. Biofilms form a very adsorptive surface and can enhance particulate fouling. Suspended particles of sufficient mass, on the other hand, may control deposition by "scouring" action.

- *Reactions at the wall.* Microbial growth in the biofilm, crystallization, corrosion, and polymerization at the wall contribute to deposit accumulation and promote adherence of inorganic suspended solids.

- *Fluid shear stress at the deposit surface.* Such forces can limit the overall extent of the fouling deposit by removing attached material.

- *Surface material and roughness.* Surface properties can influence micromixing near the surface and corrosion processes. Some metal surfaces may release toxic components into biofilms inhibiting growth and/or attachment. Some metals produce loosely held oxide films under the biofilms and other deposits. When the oxide film sloughs, the biofilm, scale, or other deposit is also removed.

- *Fouling control procedures.* Chlorine, the most commonly used biofouling control chemical, oxidizes biofilm polymers causing disruption and partial removal of biofilm in the fluid shear stress field. Inactivation of a portion of the microbial population also occurs. Altered biofilm "roughness" and decreased viable cell numbers influence "regrowth" rates of the biofilm. Scale inhibitors prevent scaling while chelants remove deposited precipitates. Dispersants are added to minimize deposition of suspended particulates. Mechanical cleaning physically removes a portion of the deposit and can be quite costly.

Effects of Fouling

Fouling deposits can cause the following deleterious effects in heat exchangers:

- increased fluid frictional resistance
- increased overall heat transfer resistance

Fouling deposits cause increased *fluid frictional resistance* by decreasing the effective diameter of the heat exchange tube and by increasing the tube roughness. For example, Picologlou *et al.* [4] have indicated that biofilms increase frictional resistance primarily by increasing the effective roughness of the tube.

Overall heat transfer resistance is the sum of conductive and convective heat transfer resistances. Convective heat transfer resistance will frequently decrease as fouling progresses due to the increased turbulence resulting from deposit formation. However, conductive heat transfer resistance will increase as the insulating fouling deposit accumulates. The relative changes in convective and conductive heat transfer resistance will depend on the following:

- thickness, roughness and thermal conductivity of the deposit
- fluid flow rate
- wall temperature of the clean tube

Characklis *et al.* [5] have reported the influence of fouling biofilms on conductive and convective heat transfer resistance in tubes in a laboratory system.

The Problem

Fouling treatment and control depends on the extent and type of deposit (Table 1) and, in some cases, treatment for one condition may be antagonistic to control of another. Therefore, the rate of accumulation, deposit amount, and composition of a fouling deposit determines the proper treatment schedule. Traditionally, water quality parameters (chemical analysis, selective ion electrodes and bacterial enumeration in the bulk water) have been used to monitor and predict fouling and determine treatment but these parameters define conditions in the bulk water which generally are significantly different from surface con-

TABLE 1. FOULING TREATMENT FOR CONTROL OF TWO MAJOR TYPES OF FOULING

	Scaling	Biofouling
External Treatment	softening ion exchange	
Internal Treatment	pH control softening acid addition side-stream treatment flocculants dispersants surfactants chelants	pH control oxidizing biocides --chlorine —ozone --bromine —hydrogen peroxide non-oxidizing biocides —chlorinated phenolics —organo-tin compounds --quaternary ammonium salts --surfactants
Removal	mechanical cleaning acid treatment chelants	mechanical cleaning oxidizing biocides

ditions where the problem exists. More recently, fouling monitors have been developed which indicate the effects of a fouling deposit on frictional resistance and heat transfer resistance. In some cases, the instruments require extensive support equipment and maintenance. The measurements rarely yield dependable or useful information regarding the composition of the deposit. Our goal has been to develop a comprehensive, low maintenance, fouling monitor system to accomplish the following: (1) distinguish *in situ* between different deposits, (2) determine the extent of fouling, and (3) determine the influence of the deposits on energy losses in an industrial environment. The remainder of this paper will describe and discuss features of such a fouling monitor system and focus on distinguishing between biofouling and scaling deposits as an illustration of its diagnostic capability.

THE FOULING MONITOR SYSTEM

The fouling monitor system (Figure 1) consists of two major components:

(1) A *tube* which contains ports for pressure drop measurement and an electrically-heated metal block which is clamped around a section of the tube and contains temperature probes. The tube can be selected to match the alloy of interest. The system also includes a flow meter and bulk water temperature probes.

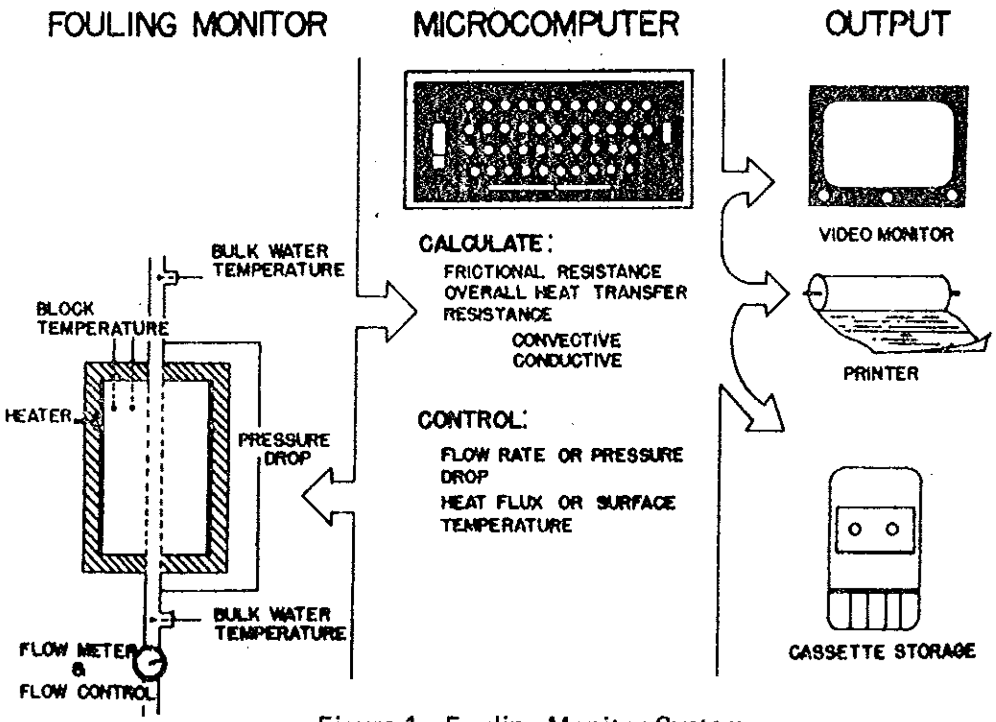

Figure 1. Fouling Monitor System.

(2) A *microcomputer* which calculates frictional resistance, convective and conductive heat transfer resistance, and overall heat transfer resistance. The microcomputer also controls flow rate *or* pressure drop in the tube and controls heat flux to the tube *or* wall temperature. Output from the microcomputer can be displayed on a television monitor and includes all pertinent measurements and calculations. A cassette recorder or disc stores the data.

Frictional Resistance

Frictional resistance is determined from pressure drop and flow measurements in the tubular section; a detailed discussion of frictional resistance due to biofilms and friction factor calculations is given by Picologlou *et al.* [4]. Figure 2 shows the increase of pressure drop and biofilm thickness with time due to biofilm accumulation in a constant flow rate laboratory experiment. The energy loss, indicated by increased pressure drop, results in an increase in power requirements for pumping. Frictional resistance due to fouling has been observed in the field. Figure 3 shows a 30% increase in friction factor during a 15 day period at a power plant location.

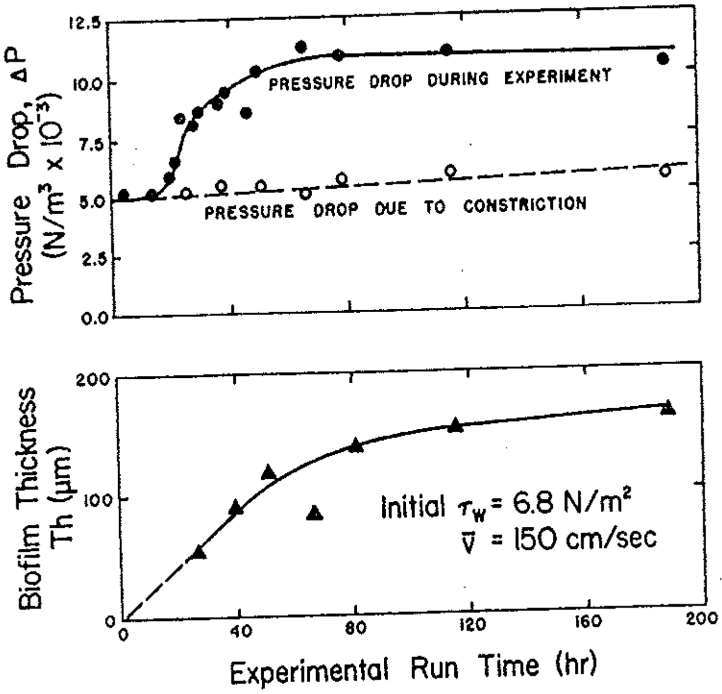

Figure 2. Progression of Pressure Drop and Biofilm Thickness with Time in a Constant Flowrate Experiment.

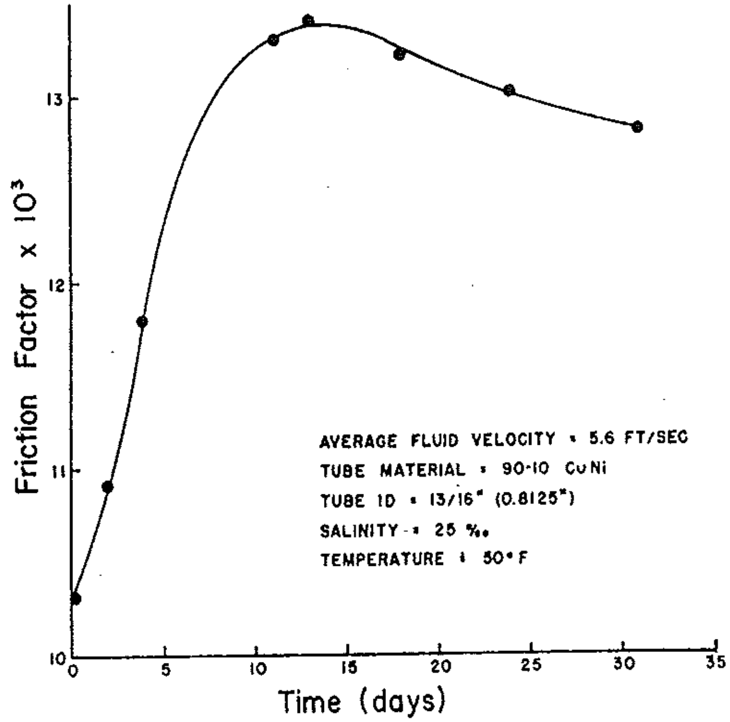

Figure 3. Progression of Friction Factor with Time Due to Fouling in the Field [11].

Picologlou *et al.* [4] have shown *constriction* of a tube to be an insignificant cause of frictional resistance resulting from biofilm formation. Figure 2 indicates (1) the increase in pressure drop and biofilm thickness with time during a laboratory experiment and (2) the increase in pressure drop as calculated from the Blasius equation for a smooth tube for a decrease in radius equal to the measured biofilm thickness. Tube constriction accounts for approximately 10% of the measured pressure drop. In contrast, constriction of tubing by scale deposits has been shown to be substantial [6].

Figure 4 illustrates the pronounced *relative roughness* of a biofilm as indicated by calculated equivalent sand roughness. Equivalent sand roughness can be significantly greater than biofilm thickness (Figure 5). Scale, a relatively rigid rough surface, affects frictional resistance differently than biofilms and is characterized by a low relative roughness (Table 2).

Frictional resistance measurement has several advantages as an indicator of fouling:

1. very simple and inexpensive
2. in water distribution systems, it monitors the quantity of most concern . . . . head loss or loss in carrying capacity.

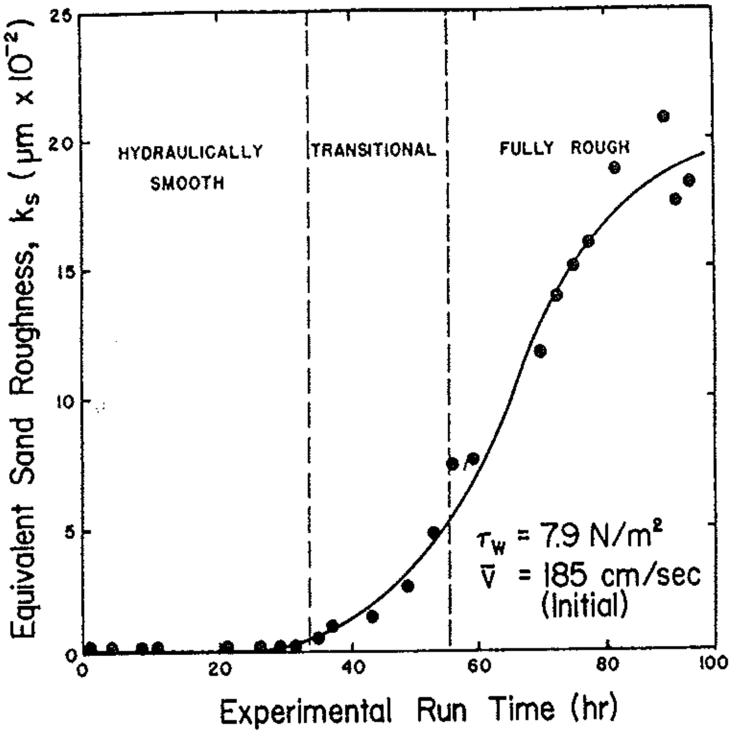

Figure 4. Progression of Calculated Equivalent Sand Roughness with Time in a Laboratory Experiment.

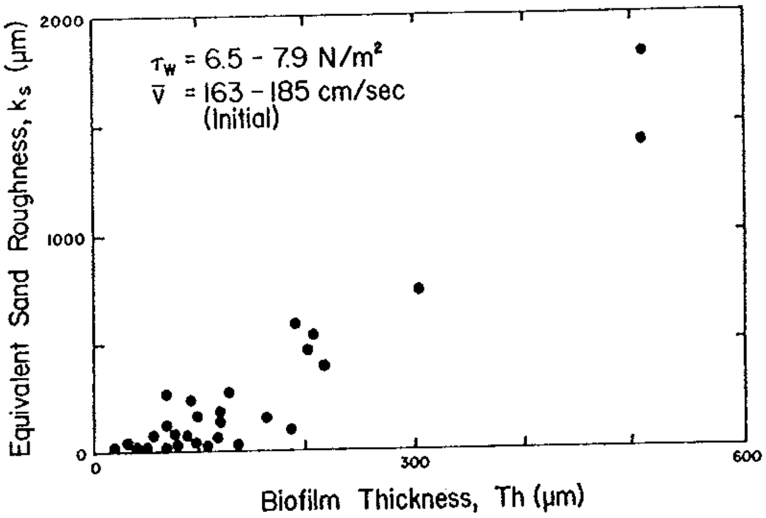

Figure 5. Calculated Equivalent Sand Roughness Versus Biofilm Thickness for a Series of Laboratory Experiments.

TABLE 2. ROUGHNESS CHARACTERISTICS OF BIOFILMS AND SCALE DEPOSITS

Type Deposit	Deposit Thickness (cm)	Relative Roughness (dimensionless)**
Biofilms (4)	0.0040	0.003
	0.0165	0.014
	0.0300	0.062
	0.0500	0.157
$CaCO_3$ Scale (7)	0.0165*	0.0001
	0.0224*	0.0002
	0.0262*	0.0006

*Calculated from overall heat transfer resistance assuming a thermal conductivity for $CaCO_3$ of 0.026 watts cm^{-1} °C^{-1} [7].

**Inside tube diameter is 1.27 cm.

However, in some situations, frictional resistance measurements alone are of limited value and sometimes misleading:

1. Frictional resistance measurements are relatively insensitive until the fouling deposit thickness exceeds a certain value (Figure 6), approximately the thickness of the viscous sublayer [4]. The thickness of the viscous sublayer is inversely proportional to flow velocity.
2. Some deposits such as $CaCO_3$ scale, exhibit a relatively low relative roughness (Table 2) but have a low thermal conductivity. Therefore, frictional resistance will be relatively low but heat transfer resistance will be high.
3. In heat exchangers or condensers, the major concern is heat transfer resistance.

Frictional resistance measurements, in conjunction with heat transfer measurements, do yield valuable information.

Heat Transfer Resistance

Overall heat transfer resistance in the fouling monitor is calculated from measurements of bulk water temperature and temperature in the aluminum block. *Convective heat transfer resistance* is dependent on turbulence and is calculated from the friction factor and the properties of the water using the Colburn equation [8]. *Conductive heat transfer resistance* is simply determined as the difference between overall and convective heat transfer resistance:

$$\begin{matrix}\text{Overall Heat} \\ \text{Transfer Resistance}\end{matrix} = \begin{matrix}\text{Conductive Heat} \\ \text{Transfer Resistance}\end{matrix} + \begin{matrix}\text{Convective Heat} \\ \text{Transfer Resistance}\end{matrix}$$

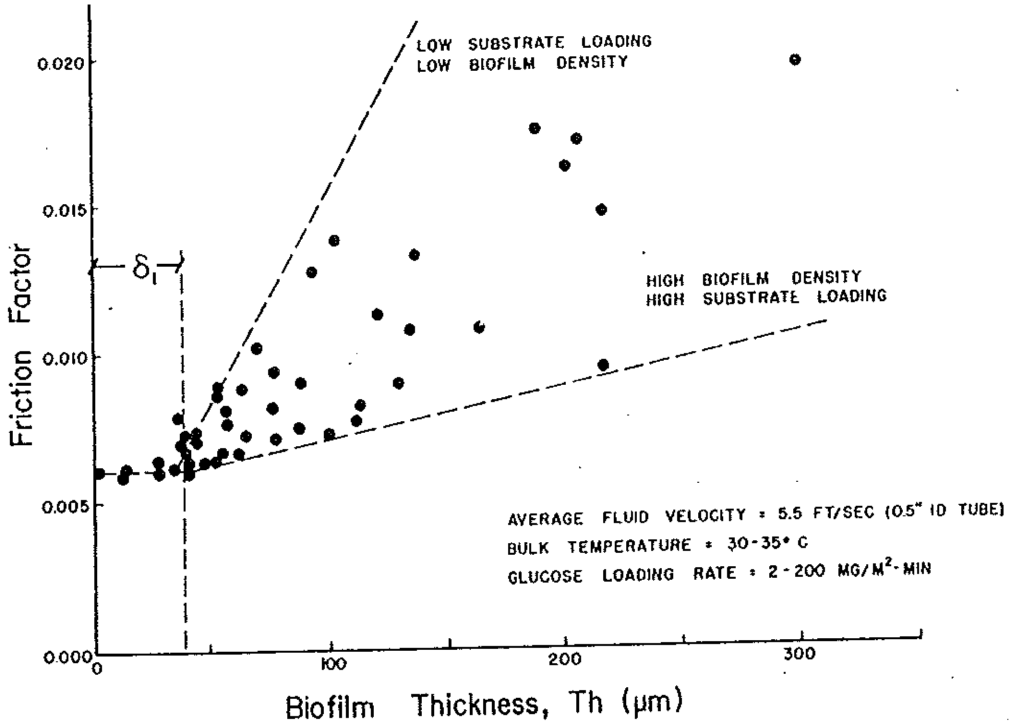

Figure 6. Change in Friction Factor with Biofilm Thickness for a Series of Laboratory Experiments Indicating the Influence of the Viscous Sublayer Thickness (δ_1). Friction factor remains constant until deposit thickness becomes equal to δ_1.

A detailed description of the heat transfer resistance measurement and results for biofilm deposits are presented by Nimmons [9] and Characklis *et al.* [5].

Figure 7 compares the *measured* increase in overall heat transfer resistance in a laboratory experiment with the increase *calculated* from measured fluid frictional resistance and biofilm thickness. *Measured* heat transfer resistance refers to that determined from bulk water and heated block temperatures. Changes in friction factor and biofilm thickness are used to determine *calculated* heat transfer resistance. The Colburn equation uses the friction factor to calculate convective heat transfer resistance. Conductive resistance is calculated from biofilm thickness assuming biofilm thermal conductivity is the same as water (biofilms are generally 95-99% water). The assumption regarding biofilm thermal conductivity appears reasonable as evidenced by the agreement between calculated and measured heat transfer resistance [5].

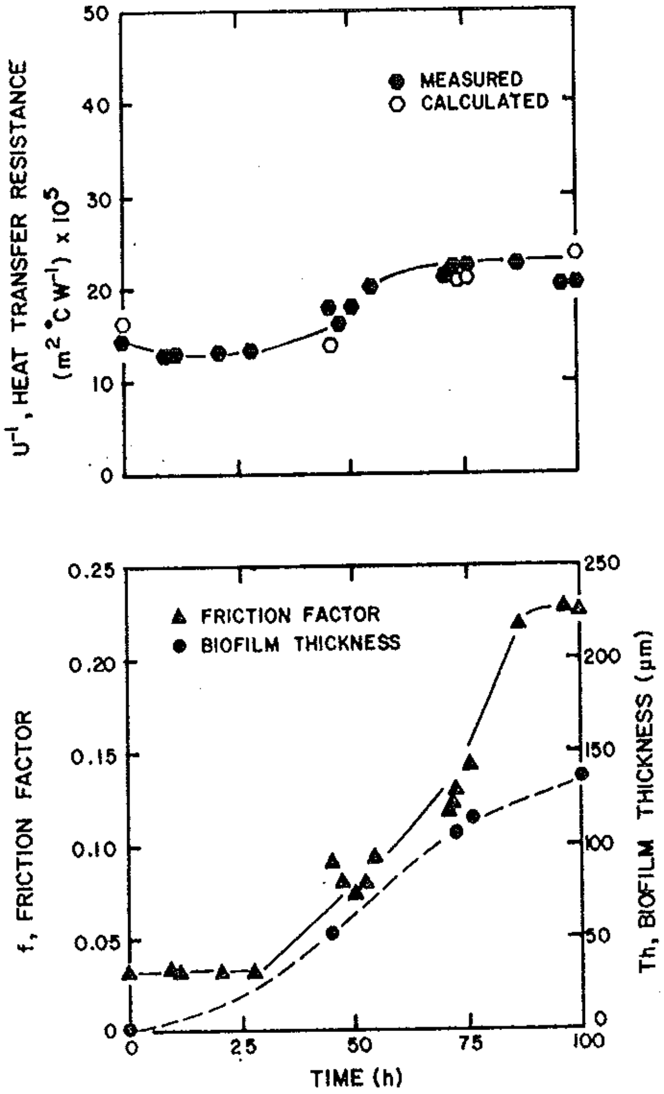

Figure 7. Progression of Heat Transfer Resistance Due to Biofilm Accumulation in a Laboratory Experiment [5].

A comparison of thermal conductivities for biofilm and scale is shown in Table 3. The difference in thermal conductivity between the more common inorganic scale deposits and biofouling deposits provide another distinguishing feature. Figure 8 illustrates how this difference in thermal conductivity affects conductive heat transfer resistance due to the different deposits.

TABLE 3. THERMAL CONDUCTIVITIES OF SCALES AND BIOFILM

	Thermal Conductivity (watt $m^{-1}\,{}^{\circ}C^{-1}$)
Scale (6)	
Calcium Carbonate	2.26-2.93
Calcium Sulfate	2.31
Calcium Phosphate	2.60
Magnesium Phosphate	2.16
Magnetic Iron Oxide	2.88
Analcite	1.27
Biofilm (5)	
(Water)	0.63

The relative contribution of convective resistance and conductive resistance to overall heat transfer resistance due to a biofilm deposit in a laboratory experiment [5,9] is shown in Figure 9. The low convective resistance is due to the pronounced relative roughness of the biofilm which causes increased turbulence. Recent experiments in our laboratory indicate that the effective roughness of $CaCO_3$ scale deposits is small compared to that of biofilms (Table 2) resulting in negligible changes in convective heat transfer resistance.

Deposit Thickness

Various methods of determining deposit thickness have been developed and are reviewed elsewhere [10]. Most methods are tedious and more properly suited for the research or testing laboratory. Our laboratory is presently testing a method for *automatically* determining deposit thickness in the field using the fouling monitor system described here.

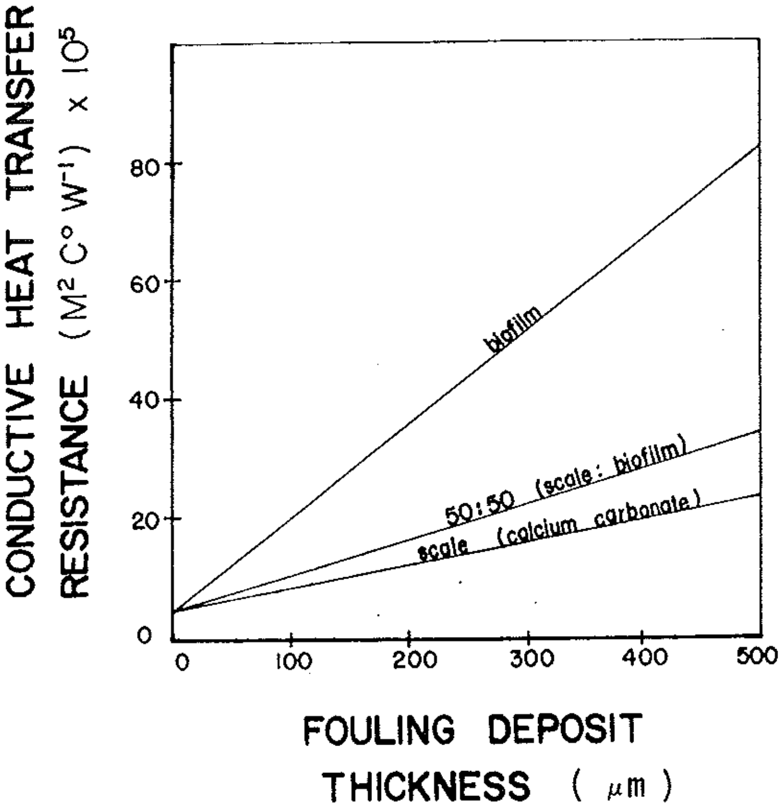

Figure 8. Difference in Calculated *Conductive* Heat Transfer Resistance between Biofilm and Scale. Changes in *Convective* Heat Transfer Resistance is not considered.

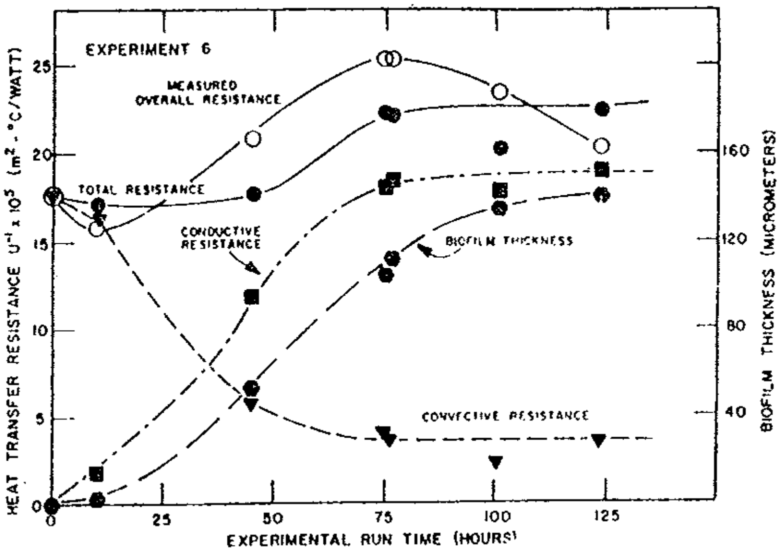

Figure 9. Relative Contribution of Convective Resistance and Conductive Resistance to Overall Heat Transfer Resistance Due to a Biofilm Deposit in a Laboratory Experiment.

FIELD TESTS*

The fouling monitor system has been operated in sidestreams of a chemical process plant recirculating cooling water system and a power plant once-through condenser. Test conditions at the two sites are listed in Table 4.

TABLE 4. OPERATING CONDITIONS FOR THE FOULING MONITOR DURING FIELD TESTS

	Chemical Process Plant	Power Plant
Tubing alloy	carbon steel (schedule 40)	AL-6X stainless steel
Inside diameter of tubing, cm (in)	1.27 (0.50)	1.44 (0.57)
Outside diameter of tubing, cm (in)	2.10 (0.83)	1.59 (0.62)
Length between pressure ports, cm (in)	107.9 (42.5)	25.7 (10.5)
Flow rate, $m^3 s^{-1}$ (gpm)	1.13×10^{-5} (1.8)	5.4×10^{-5} (0.86)
Flow velocity, ms^{-1} (fps)	0.9 (3.0)	0.33 (1.0)
Initial pressure drop, Nm^{-2} (psi)	6757 (0.98)	34.5 (0.005)
Initial friction factor, dimensionless	0.085	0.040
Heat flux at inside wall, watts m^{-2} (BTU hr^{-1} ft^{-2})	2555 (810)	18,915 (6000)
Bulk water temperature, °C (°F)	40 (104)	17-27 (63-81)
Initial inside wall temperature, °C (°F)	46 (116)	35 (95)
Initial heat transfer coefficient, watts m^{-2} $°C^{-1}$ (BTU hr^{-1} ft^{-2} $°F^{-1}$)	118 (21)	965 (170)

A summary of the results from the chemical process plant location is presented in Figure 10. Certain observations are worthy of note:

1. Total viable bacterial counts (accomplished by the water treatment chemical vendor) show no correlation to fouling deposition as determined by friction factor and heat transfer resistance measured by the fouling monitor or heat transfer rate measured independently by process plant personnel.
2. Heat transfer resistance determined by the fouling monitor correlated extremely well with heat transfer rate determined by process plant personnel.
3. Friction factor correlates well with heat transfer resistance for 20-30 days. However, friction factor begins to increase while heat transfer resistance stays constant

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*Field tests were conducted by W. G. Characklis and Associates, Consulting Engineers, 516 W. Cleveland, Bozeman, MT 59715.

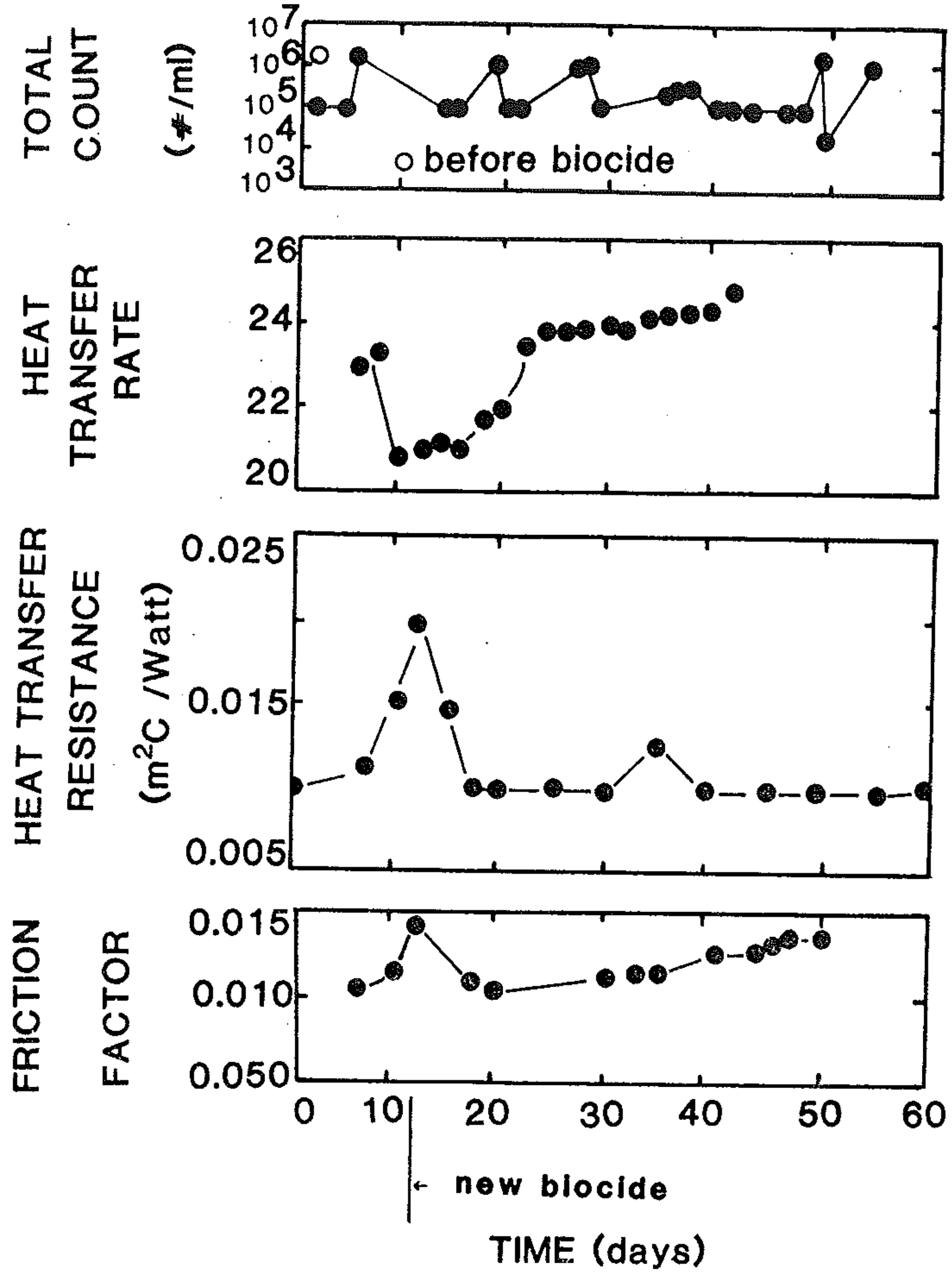

Figure 10. Results from Monitoring at a Chemical Process Plant. Heat transfer rate was determined by plant personnel. Total counts were determined by the water treatment chemical vendor.

at essentially "clean" conditions. Deposit analyses and observations indicated low bacterial numbers and high levels of iron oxide accumulating in a *very* rough deposit. Iron oxide has a relatively high thermal conductivity and, in conjunction with the enhanced turbulence caused by the deposit roughness, was probably responsible for the low heat transfer resistance.

4. On approximately day 30, dispersant was not added according to schedule and a significant amount of migratory iron in the water deposited on the surface. The heat transfer resistance measurement immediately sensed the change.
5. The fouling monitor was useful for evaluating the effectiveness of the chemical treatment program in maintaining heat transfer. Chlorine was used from day 0 to day 12 at which point a new treatment program was initiated.

An illustration of results from the power plant location is presented in Figure 11. These tests were conducted to determine the rate and extent of fouling on a new alloy to be used in a fan cooler design. Certain observations were made during this test:

1. The heat transfer capacity of the tube was decreased by 30% within thirty (30) days.
2. On day 33, a momentary flow excursion occurred from 0.3 ms^{-1} (1 fps) to 0.6 ms^{-1} (2 fps). The heat transfer coefficient increased significantly as a result of the flushing action. Subsequent fouling, however, was faster than before.
3. The fouling deposit was probably sensitive to flow excursions because of its composition which was primarily inorganic particles (clay, silt) embedded in a biofilm matrix.
4. The fouling deposit accumulation was twice as great on the heated surface in the fouling monitor (35°C) as it was on the unheated surface (24-28°C) indicating that heat flux significantly influences fouling deposition. Fouling monitors without continuous heat flux are less effective in simulating heat exchanger tubes.

SUMMARY

A compact fouling monitor system has been described which continuously measures fluid frictional resistance and heat transfer resistance in industrial environments. The monitor has several unique characteristics including the following:

1. Tubes may be made of any alloy and are easily changed.
2. Flow rate *or* pressure drop and surface temperature *or* heat flux may be controlled at conditions simulating actual plant conditions.

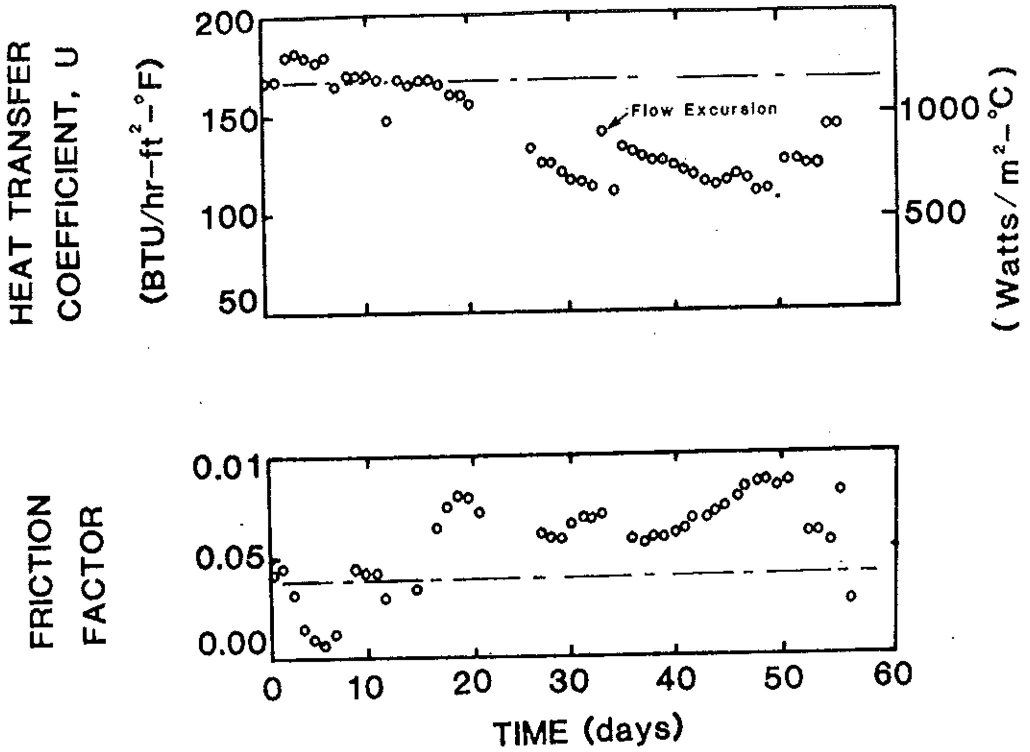

Figure 11. Results from Monitoring at a Power Plant.

3. Control of thermohydrodynamic conditions in the fouling monitor can be interfaced to actual fluctuating conditions in plant equipment.
4. Computer output can be interfaced with the plant process control computer facility.
5. Changes in tube surface conditions are indicated instantaneously via change in heat transfer and fluid frictional resistance:
   - Indicates the effectiveness of treatment
   - Useful in comparing treatments and operating conditions
   - Early warning system
6. Tabular and graphical historical records of heat exchanger performance may be obtained.
7. If a thickness measurement is incorporated, the output can include the thermal conductivity and relative roughness of the deposit. These properties can be useful in determining the deposit composition *in situ*.

Fouling deposits are rarely homogeneous. Generally, the fouling deposit is a combination of biofilm, scale and corrosion products. The degree to which each type of deposit contributes to fouling is dependent on such factors as water quality changes, plant upsets, operation schedules, and water treatment program. Differences in the effects of these different deposits on thermohydrodynamic measurements, in conjunction with water quality measurements, can provide useful insight to distinguishing between them *in situ*, particularly once a history of heat exchanger performance has been established.

ACKNOWLEDGMENTS: The authors gratefully acknowledge the following for partial financial support: Office of Naval Research (N00014-80-0475), National Science Foundation (CPE-8017439), Calgon Corporation and Montana State University Engineering Experiment Station. James Flandreau (Power Authority of the State of New York) and E. V. Somers (Westinghouse Electric Corporation) provided valuable assistance in the power plant monitoring program. Carl Johnson and Rod Sergent (Great Lakes Chemical Corporation) and Dr. J. V. Matson provided technical assistance and support for the chemical process plant monitoring program. Jean Julian prepared the manuscript.

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