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# MANAGING THE EFFECTS OF FOULING ON HEAT TRANSFER IN POWER PLANT CONDENSERS

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*Costs & effects info*

ABSTRACT

Microbiological fouling (biofouling) of condenser tube surfaces is one of the major factors contributing to poor condenser performance at steam electric generation stations. Traditionally, water quality parameters have been used to monitor and predict fouling and to determine treatment; however, these parameters do not define surface conditions where the problem exists. Recently, a fouling monitoring system, which indicates the effects of fouling deposit on frictional resistance and heat transfer resistance, has been developed. The results of field tests using the fouling monitoring system are presented herein.

INTRODUCTION

Condenser biofouling can result in substantial loss of power plant availability and efficiency. This paper will present the factors leading to tube fouling, while focusing on a fouling monitoring technology that allows plant operators to predict fouling and take corrective action. Selected field data are presented to demonstrate the use of the monitor in power plants. Finally, research and development needs are identified.

IMPACT OF FOULING

The range of heat transfer resistances based on actual condenser service and single tube tests can be divided into five categories as given below (1):

|                       | Low (%) | High (%) |
|-----------------------|---------|----------|
| Steam Condensing Film | 10      | 32       |
| Steam Side Fouling    | 2       | 10       |
| Tube Wall             | 2       | 20       |
| Cooling Water Fouling | 6       | 50       |
| Cooling Water Film    | 12      | 40       |

The use of tube bundles can affect the proportion of individual resistance as compared to a single tube and from one location to another within the tube bundle. In addition, it can result in a reduction in effective surface area through the existence of air pockets. The bundle effect could be considered as a total resistance multiplier.

It can be concluded from the above that cooling water fouling, cooling water film, and bundle design are the most important parameters affecting heat transfer in a condenser.

Microbiological fouling of condenser tube surfaces is one of the major factors contributing to poor condenser performance at steam electric generation stations. Poor condenser performance, in turn, is a major contributor to loss of power plant availability and efficiency.

An Electric Power Research Institute (EPRI) analysis of industry data has estimated that the loss of unit availability for fossil-fueled plants 600 MW and greater, directly attributable to condenser problems, is about 3.8 percent(2). Other EPRI-sponsored studies have similar results for nuclear plants (3, 4, 5, 6).

In an attempt to establish the root cause of this availability loss, 415 fossil plants were surveyed to determine the specific reason for condenser problems (7). The results identified biofouling as the dominant cause, accounting for 3.0 percent out of the 3.8 percent total availability loss attributed to condenser problems.

Fouling can take many forms, each requiring different control measures. Information from the Edison Electric Institute's power data base, summarized in Figure 1, demonstrates that fouling is widespread, and microbiological fouling of the tubes is the major problem at 70 percent of the units (8). Biofouling reduces heat transfer and increases pressure drop and unit heat rate. Biofouling also may contribute to tube corrosion and pitting.

The costs associated with impaired condenser operations are substantial. They include increased fuel consumption, replacement power costs, condenser cleaning costs, and loss of availability.

Figure 2 illustrates the variation of unit heat rate with condenser pressure for a typical fossil-fueled power plant. An increase in backpressure from

3.75 cm to 6.25 cm HgA (1.5 inches to 2.5 inches HgA) results in a 1 percent change in heat rate, an increment of over 110 Btu/kWh. However, if the backpressure changes 2.5 cm (1 inch) again, from 6.25 cm to 8.0 cm HgA (2.5 inches to 3.5 inches HgA), the heat rate change is doubled to 220 Btu/kWh.

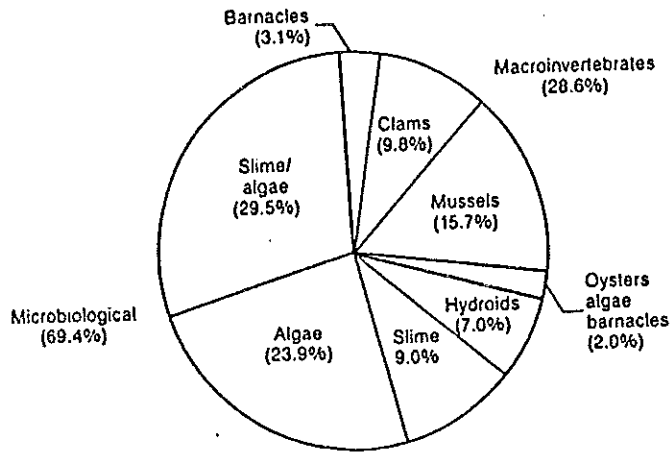


Fig. 1. Biofouling Organisms in Cooling Systems

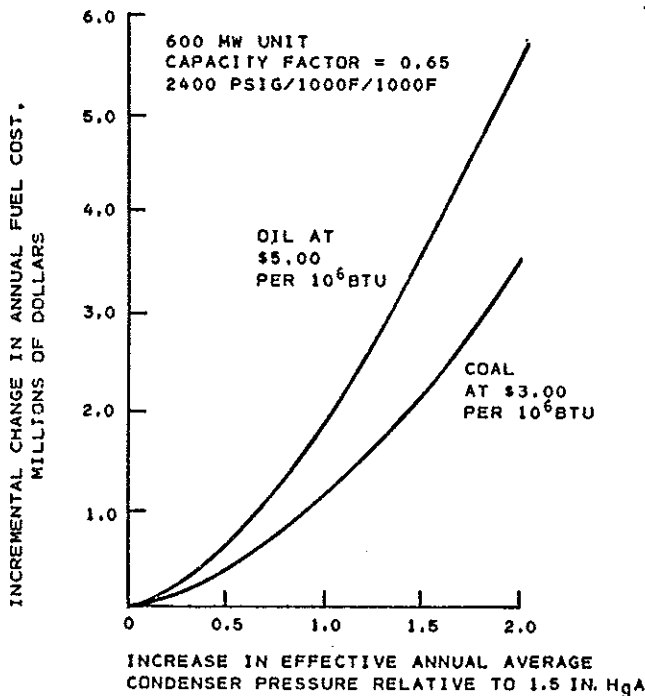


Fig. 2. Incremental Annual Fuel Cost Associated with an Increase in Condenser Pressure, Typical Fossil-Fueled Power Plant

For a plant that is not base-loaded a significant portion of the year, the annual cost of performance losses from tube fouling can be approximated from the change in heat rate as measured at the effective annual average backpressure with and without fouling. Figure 3 shows an increase in annual fuel cost for a typical plant with an effective annual average backpressure of 3.8 cm HgA (1.5 inches HgA) without fouling.

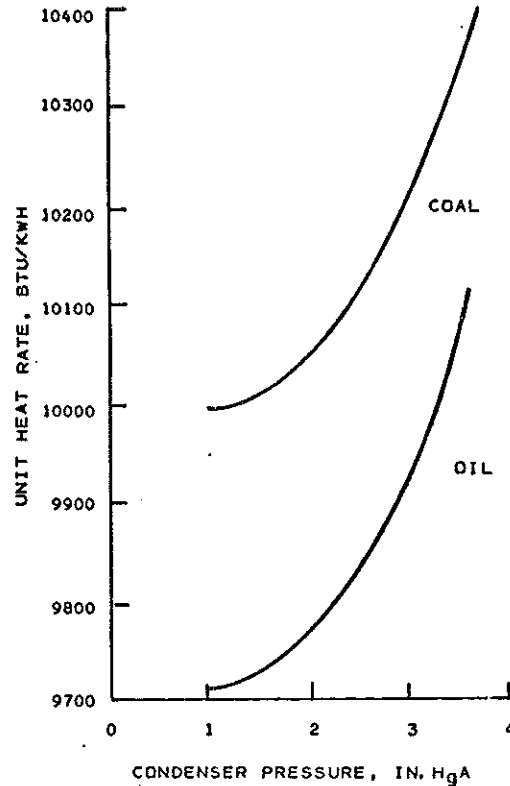


Fig. 3. Variation of Unit Heat Rate with Condenser Pressure, Typical Fossil-Fueled Power Plant

Typically, nuclear plants and many large efficient fossil-fueled units are base-loaded for most of the year. Under this condition, an increase in condenser backpressure due to tube fouling reduces the gross power generation, while the unit fuel consumption rate remains at the maximum level. To maintain the ability to meet customer demand, the electric utility company must make up lost generation at other less efficient power plants. Figure 4 illustrates the effect of backpressure increase on the annual cost of energy replacement. Typically, an increase in backpressure of 0.76 cm (0.3 inch) at a 600 MW coal-fired plant can cost \$500,000 annually; at a 1150 MW nuclear plant, about \$1.5 million.

Cleaning costs can also be significant. Some condensers on the Gulf of Mexico must be manually cleaned every 2 weeks during the fouling season. The cost of cleaning those condensers can approach \$500,000 per year, including material, labor, and lost revenues from reduced power generation. Recent chlorine discharge limitations at the federal level and even more restrictive limitations at the state level also make it more difficult to maintain condenser performance within allowable discharge limits.



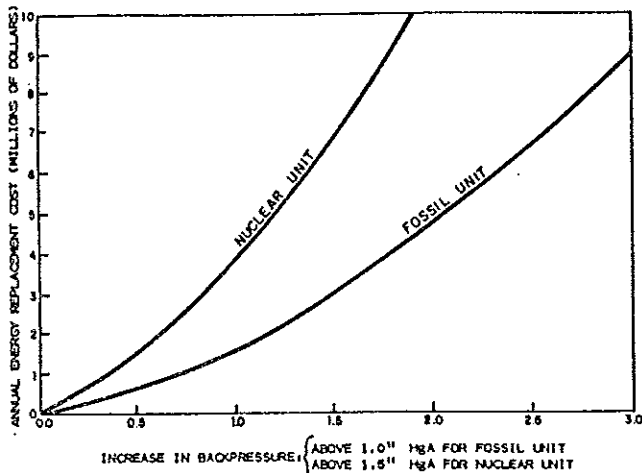


Fig. 4 Incremental Annual Energy Replacement Cost with an Increase in Backpressure, Typical Fossil-Fueled Power Plant

#### THE FOULING PROCESS

The term fouling refers to the undesirable formation of inorganic and/or organic deposits on condenser tube surfaces. These deposits can impede the flow of heat through the surface, and increase the fluid frictional resistance and the rate of corrosion at the surface. Each case results in an energy loss.

Several types of fouling that could occur in heat exchangers are:

- Crystalline or precipitation fouling
- Corrosion fouling
- Particulate or sedimentation fouling
- Chemical reaction fouling
- Biological fouling or biofouling resulting from--
  - development of an organic film (biofilm) consisting of microorganisms and their products (microbial fouling)
  - deposition and growth of macroorganisms such as barnacles (macrobial fouling)
  - assorted detritus

Development of a systematic understanding of fouling from field observations has been limited because of the interaction of several contributing processes. 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, detritus, or inorganic particles). Fouling begins once these materials adhere to the surface. Biofilms form an 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 systems physically remove a portion of the deposit but can represent a significant capital cost.

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

- Increased fluid frictional resistance
- Increased overall heat transfer resistance
- Increased potential for tube corrosion

Fouling deposits cause increased fluid frictional resistance by decreasing the effective diameter of the heat exchange tube and/or by increasing the tube roughness. For example, Picologlou et al (9) 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 thickness, roughness, and thermal conductivity of the deposit; the fluid flow rate; and the wall temperature of the clean tube.

Characklis et al (10) have reported the influence of fouling biofilms on conductive and convective heat transfer resistance in tubes in a laboratory system.

Fouling treatment and control depends on the extent and type of deposit, and, in some cases, treatment for one condition may be antagonistic to control of another. Therefore, the rate of accumulation, the

deposit amount, and the composition of a fouling deposit determine 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 to determine treatment, but these parameters define conditions in the bulk water which generally are significantly different from surface conditions 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. One goal has been to develop a comprehensive, low maintenance fouling monitor system to--

- Distinguish between different deposits, in situ
- Determine the extent of fouling
- Determine the influence of the deposits on energy losses in an industrial environment to allow plant operators to take corrective action.

#### THE FOULING MONITORING SYSTEM

The fouling monitoring system (see Figure 5) consists of two major components -- a tube and a microcomputer.

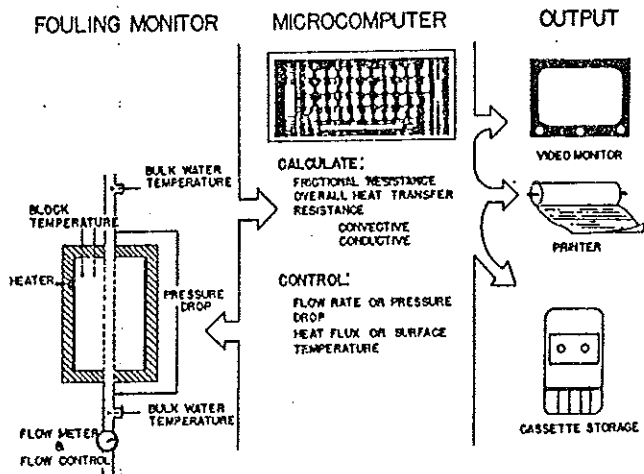


Fig. 5 Fouling Monitoring System

The tube 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.

The microcomputer calculates frictional resistance, convective and conductive heat transfer resistance, and overall heat transfer resistance. The microcomputer can also control flow rate or pressure drop in the tube and heat flux to the tube or tube wall temperature. Output from the microcomputer can be displayed on a television monitor and includes all pertinent measurements and calculated quantities.

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 (9). Figure 6 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 7 shows a 30 percent increase in friction factor during a 15-day period at a power plant location.

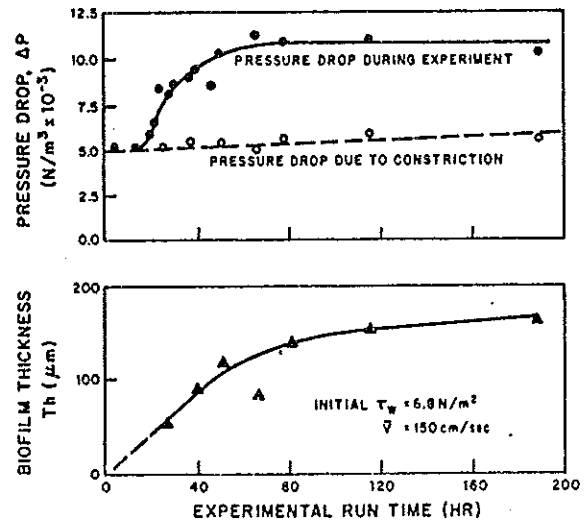


Fig. 6 Progression of Pressure Drop and Biofilm Thickness with Time in a Constant Flow-rate Experiment

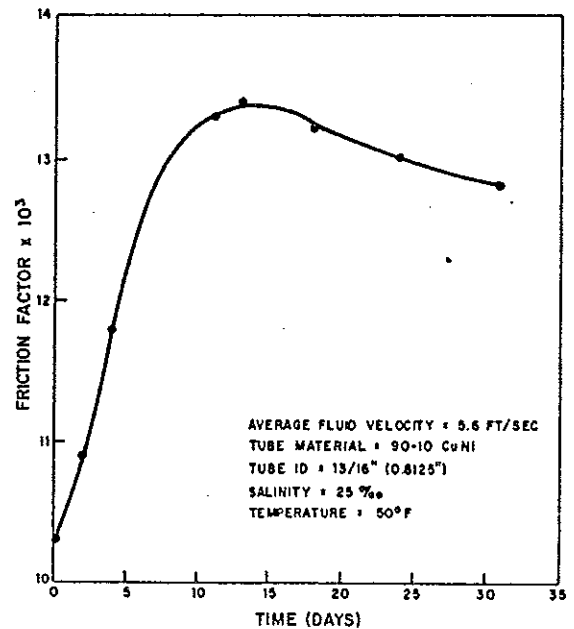


Fig. 7 Progression of Friction Factor with Time Due to Fouling in the Field, Marine Research, Inc., Sandwich, MA



Picologlou et al (9) have shown constriction of a tube to be an insignificant cause of frictional resistance from biofilm formation. Figure 6 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 percent of the measured pressure drop. In contrast, constriction of tubing by scale deposits has been shown to be a substantial contributor to increased differential pressure (11)

Frictional resistance measurements have several advantages as indicators of fouling. They are simple and inexpensive, and, in water distribution systems, they monitor the quantity of most concern--head loss or loss in conveyance capacity. However, frictional resistance measurements alone are of limited value and misleading in some situations. Frictional resistance measurements are relatively insensitive until the fouling deposit thickness exceeds a certain value, approximately the thickness of the viscous sublayer (9). The thickness of the viscous sublayer is inversely proportional to flow velocity. Some deposits such as  $\text{CaCO}_3$  scale exhibit a relatively low roughness but have a low thermal conductivity. Therefore, frictional resistance will be relatively low, but heat transfer resistance will be high. In heat exchangers or condensers, the major concern is heat transfer resistance. The use of frictional resistance measurements, in conjunction with heat transfer measurements, do yield valuable information.

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 depends on turbulence and is calculated from the friction factor and the properties of the water using the Colburn equation (12). Conductive heat transfer resistance is simply determined as the difference between overall and convective heat transfer resistance:

A detailed description of the heat transfer resistance measurements and results for biofilm deposits are presented by Nimmons (13) and Characklis et al (10).

#### FIELD TESTS

The fouling monitoring system has been operated in sidestreams of a chemical process plant recirculating cooling water system, a power plant fan cooler, and a power plant once-through condenser. Several test conditions are listed in Table 1.

A summary of the results from the chemical process plant location is presented in Figure 8. The following observations are noteworthy:

- Total viable bacterial counts (obtained 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).
- Heat transfer resistance determined by the fouling monitor correlated extremely well with heat transfer rate determined by process plant personnel.

- Friction factor correlated well with heat transfer resistance for 20 to 30 days. However, friction factor began to increase while heat transfer resistance stayed constant 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.
- 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.
- 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.

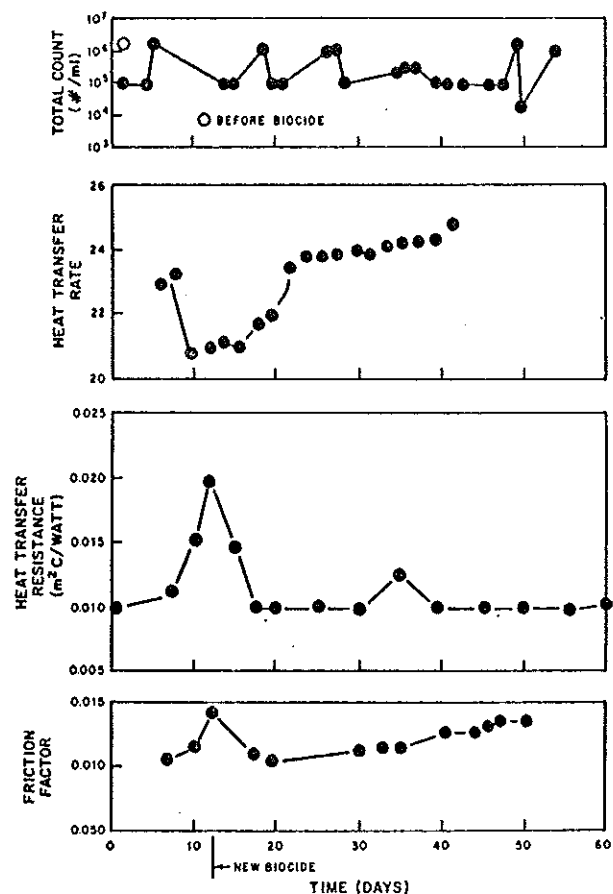


Fig. 8 Results from Monitoring at a Chemical Process Plant. (Heat Transfer rate was determined by plant personnel; total counts were determined by water treatment chemical vendor)

TABLE 1  
OPERATING CONDITIONS FOR THE FOULING  
MONITOR DURING FIELD TESTS

|                                                                                                                                        | Chemical Process Plant        | Power Plant(1)                | Power Plant(2)  |
|----------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|-------------------------------|-----------------|
| Tubing alloy                                                                                                                           | Carbon steel (schedule 40)    | AL-6X stainless steel         | Admiralty brass |
| Inside diameter of tubing, cm (in)                                                                                                     | 1.27 (0.50)                   | 1.44 (0.57)                   | 2.22 (0.875)    |
| Outside diameter of tubing, cm (in)                                                                                                    | 2.10 (0.83)                   | 1.59 (0.62)                   | 2.54 (1.00)     |
| Length between pressure ports, cm (in)                                                                                                 | 107.9 (42.5)                  | 25.7 (10.5)                   | 25.7 (10.5)     |
| Flow rate, m <sup>3</sup> /s (gpm)                                                                                                     | 1.13 x 10 <sup>-5</sup> (1.8) | 5.4 x 10 <sup>-5</sup> (0.86) | 0.17 (45)       |
| Flow velocity, m/s (fps)                                                                                                               | 0.9 (3.0)                     | 0.33 (1.0)                    | 2 (6)           |
| Initial friction factor, dimensionless                                                                                                 | 0.085                         | 0.040                         | 0.0026          |
| Heat flux at inside wall, watts/m <sup>2</sup><br>(BTU hr <sup>-1</sup> ft <sup>-2</sup> )                                             | 2555 (810)                    | 18,915 (6000)                 |                 |
| Bulk water temperature, °C (°F)                                                                                                        | 40 (104)                      | 17-27 (63-81)                 | 5-17 (41-63)    |
| Initial inside wall temperature, °C (°F)                                                                                               | 46 (116)                      | 35 (95)                       | 13-24 (55-75)   |
| Initial heat transfer coefficient,<br>watts m <sup>-2</sup> °C <sup>-1</sup> (BTU hr <sup>-1</sup> ft <sup>-2</sup> °F <sup>-1</sup> ) | 118 (21)                      | 965 (170)                     |                 |

The results of the power plant fan cooler tests are presented in Figure 9. These tests were conducted to determine the rate and extent of fouling on a new alloy to be used in a fan cooler design. The following observations were made during these tests:

- The heat transfer capacity of the new tube alloy was decreased by 30 percent within 30 days.
- On day 33, a momentary flow excursion occurred from 0.3 m/s (1 fps.) to 0.6 m/s (2 fps.) The heat transfer coefficient increased significantly as a result of the flushing action. Subsequent fouling, however, was faster than before.
- The fouling deposit was probably sensitive to flow excursions because of its composition, which was primarily inorganic particles (clay, silt, etc.) embedded in a biofilm matrix.
- The fouling deposit accumulation was twice as great on the heated surface in the fouling monitor (35°C; 95°F) as it was on the unheated surface (24 to 28°C; 74 to 82°F) indicating that heat flux significantly influences fouling deposition. Fouling monitors without continuous heat flux are less effective in simulating heat exchanger tubes.
- Control of thermohydrodynamic conditions in the fouling monitor can be interfaced to actual fluctuating conditions in plant equipment.
- Computer output can be interfaced with the plant process control computer facility.

- 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
- Tabular and graphical historical records of heat exchanger performance may be obtained.
- 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.

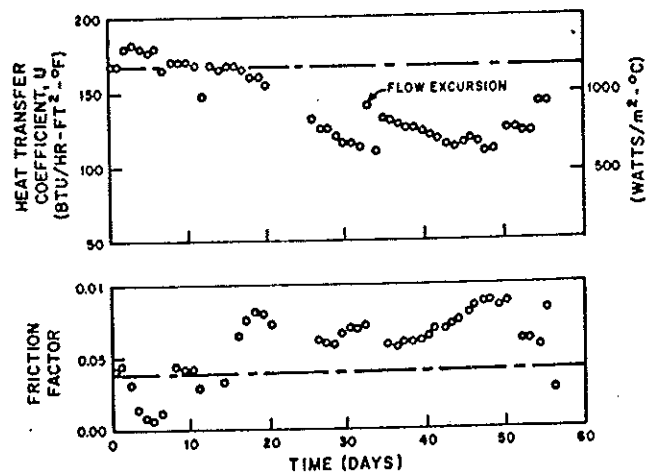


Fig. 9 Results from Monitoring at a Power Plant



Field test results at a second power plant location are summarized in Figure 10. The tests were conducted to determine the fouling potential in Admiralty brass condenser tubes (see Table 1). Certain noteworthy observations follow:

- After 30 days, fouling reduced heat transfer rate by approximately 30 percent. The design cleanliness factor was 85 percent.
- Treatment with sponge rubber balls at day 59 increased the heat transfer rate substantially, but did not reach "clean" conditions. Subsequent treatments over 30 days at varying frequencies and duration had decreasing effects.

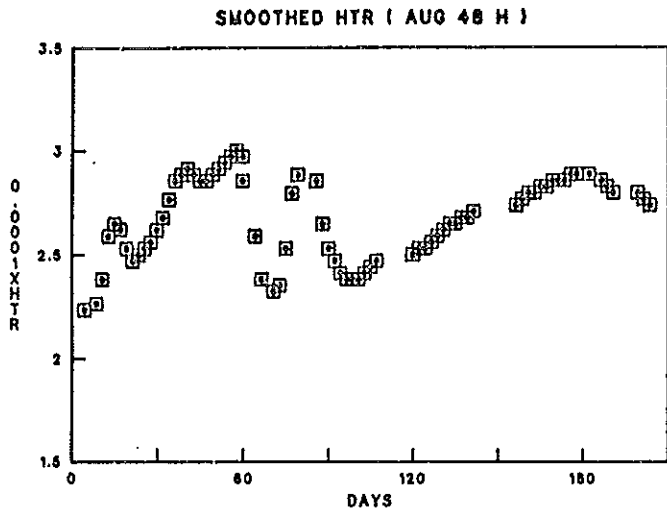


Fig. 10 Results from Monitoring at a Power Plant

#### MODEL CONDENSERS

EPRI sponsored the evaluation of model condensers at two power plants in New Jersey. The model condensers have nine tubes arranged in three passes. The tubes have 19-gauge (0.75-inch OD, 0.652-inch ID), 316 stainless steel tubes (14). The tube length in each pass is 2.4 m (8 feet). Each condenser has its own electrically heated boiler. Vacuum is maintained in the condenser by a vacuum pump.

The fouling characteristics of the model condenser were compared to those of an actual plant condenser (see Figure 11). The plant and model condensers have similar fouling development characteristics. Both overall heat transfer coefficient and pressure drop, using the same chlorinated water, displayed parallel trends. Collected biomass samples showed that the plant and chlorinated model condenser developed similar amounts of fouling material, both being much less than that developed in the untreated model condenser.

#### RESEARCH AND DEVELOPMENT NEEDS

In order to understand the factors that influence fouling and to develop methods to control fouling, the following research and development needs are presented:

- Identify the environmental variables that exert significant influences on the fouling process. As an example, wall and water

temperatures and organic carbon appear quite important in the biological fouling phenomena. This information would be most valuable in predicting fouling at a given location and also would be useful in estimating seasonal effects.

- Determine the rate and extent to which fouling control methods remove fouling deposits. For example, there are no data on the known relationship between chlorine application rate, frequency, and duration and extent of biological fouling.
- Identify the extent of "regrowth phenomena" under varying operating conditions using different control methods. Identify "refractory" deposits that form after repeated treatment. Determine methods for their removal in situ.
- Develop an integrated system, combining a fouling monitor with a fouling control method (e.g., chlorination), to maintain a satisfactory cleanliness factor while minimizing cost and environmental damage.
- Standardize methods for sampling and analyzing fouling deposits, and initiate a "library" of deposit analyses. The deposit analyses should be catalogued according to the fouling environment and the effect of the deposit on heat transfer.

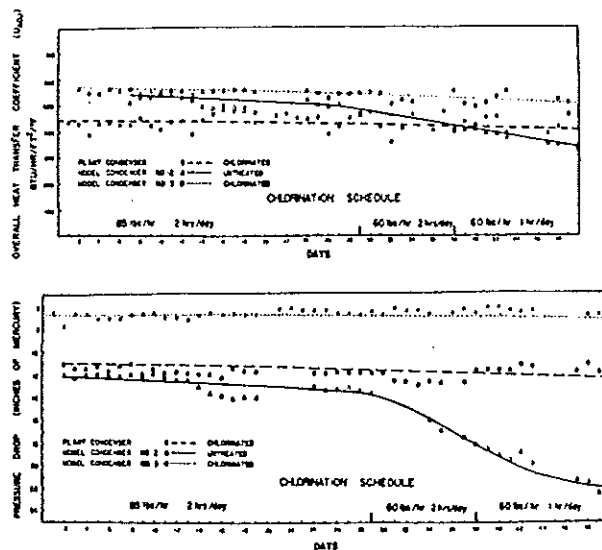


Fig. 11 Comparison of Pilot-Scale Condensers with Bergen Station Condensers

#### SUMMARY

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

- Tubes may be made of any alloy and are easily changed.



- Flow rate or pressure drop and surface temperature or heat flux may be controlled at conditions simulating actual plant conditions.

Fouling deposits are rarely homogeneous. Generally, the fouling deposit is a combination of biofilm, scale, and corrosion products. The extent to which each kind of deposit contributes to fouling depends on such factors as water quality changes, plant upsets, operation schedules, and water treatment programs. Differences in the effects of these 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.

Research needs were also identified. These allow plant operators to predict fouling prior to occurrence and take corrective action that will minimize costs.

#### ACKNOWLEDGEMENTS

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#### REFERENCES

1. Mussalli, Y. G., et al. "High Reliability Condenser Design Study," EPRI report CS-3200, July 1983, P. 4-2.
2. Anson, D., "Availability of Fossil-Fired Steam Power Plants," EPRI FP-422-SR, June 1977.
3. Frederick, L.G., et al, "Limiting Factor Analysis of High Availability Nuclear Plants (Boiler Water Reactor)," EPRI NP-1136, August 1979.
4. Hewitt, E.W., "Limiting Factor Analysis of C-E Nuclear Plants," EPRI NP-1137, August 1979.
5. Clark, R.H. and Barrow, W.E., "Limiting Factor Analysis of High Availability Nuclear Plants," EPRI NP-1138, September 1979.
6. Paggon, V.A., et al, "Limiting Factor Analysis of High Reliability Nuclear Plants," EPRI NP-1139, August 1979.
7. Bell, R.J., Mussalli, Y. G., et al, "Failure Cause Analysis - Condensers and Associated Systems," EPRI CS-2378, Prepared by Stone & Webster Engineering Corporation, June 1982.
8. Graham, J., "Biofouling Control Assessment - A Preliminary Data Analysis," Final Report CS-2469, Electric Power Research Institute, Palo Alto, California, July 1982.
9. Picologlou, B.F., Zelver, N., and Characklis, W.G., "Biofilm Growth and Hydraulic Performance," J. Hyd. Div., ASCE, 106, 1980, pp. 733-746.
10. Characklis, W.G., Nimmons, M.J., and Picologlou, B.F., "Influence of Fouling Biofilms on Heat Transfer," Heat Transfer Engineering, accepted for publication (1981).
11. Cowan, J.C. and Weintritt, D.J., "Water-Formed Scale Deposits," Gulf Publishing Company, Houston, Texas, 1979.
12. Colburn, A.P., "A Method of Correlating Forced Convection Heat Transfer Data and a Comparison with Fluid Friction," Trans. AIChE, 29, 174, 1933.
13. Nimmons, M.J., "Heat Transfer Effects in Turbulent Flow Due to Biofilm Development," M.S. Thesis, Rice University, Houston, Texas, 1979.
14. Sugam, R., et al, "Biofouling Control with Ozone at the Bergen Generating Station," EPRI Report CS-1629, November 1980.

