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BIOFOULING CONTROL TECHNOLOGY: THE ROLE OF FOULING MONITORS

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ABSTRACT

A critical need in the effort to control biofouling in condensers is identification and development of practical and simple measurements to serve as adequate indices for adjusting chlorine dose or modifying other treatment practices (e.g., mechanical cleaning). The measurements must account for the effects of factors such as water quality and inherent vulnerability of the fouling deposit. Effective monitoring techniques (in situ and sidestream) are critical to the purpose. In addition, a suitable model is necessary to effectively use a monitoring technique in an operational mode at a power plant site. This paper discusses available monitoring techniques in the context of recently completed projects at power plant sites and suggests developments necessary for further improvements.

INTRODUCTION

Biofouling refers to the undesirable accumulation of a biotic deposit on a surface. The deposit may contain micro- and macroorganisms. Microfouling is the development of a biofilm, largely bacterial in origin, on cooling system tube surfaces. Microbial fouling biofilms consist of an organic film composed of microorganisms embedded in a polymer matrix of their own making. The composite of microbial cells and extracellular polymer is termed a biofilm. Complex fouling deposits, like those found in operating heat exchangers, often consist of biofilms in intimate association with inorganic particles (1), crystalline precipitates or scale (2), or corrosion products (3). These complex deposits often form more rapidly and are more tightly bound than biofilm alone.

Fouling biofilms impair the performance of process equipment. They can form in any fluid flow conduit and increase fluid frictional resistance (4). In addition, biofilms in heat exchangers can increase heat transfer resistance (1, 5, 6). Biofouling may also accelerate corrosion of the surface beneath the biofilm (3).

Macrofouling, the settlement and growth of larger organisms such as mussels, oysters, and hydrozoans, can severely restrict cooling water flow in conduits and on tube sheets. Additionally, attached or impinged macrofouling organisms or debris on tube sheets, can promote serious erosion/corrosion of the inlet ends of condenser tubes.

Uncontrolled fouling, of any type, can significantly impact cooling system performance and overall plant operation. Fouling in heat exchangers may cost the United States billions of dollars annually (7). Zilver et al. (1) have documented a case of biofouling at a nuclear power plant in which heat transfer rate in a fan cooler decreased by 30% due to biofouling in a 30 day period. Subsequent tests indicated continued increase in fouling over a 6 month period. The testing at this plant was partially prompted by detection of microbially-mediated corrosion problems accompanying the biofouling so two alloys (90-10 Cu-Ni and AL-6X stainless steel) were tested in parallel. Rate and extent of fouling on AL-6X was greater than on the Cu-Ni under the test conditions. In another study at a Canadian power plant (Site C), biofouling decreased heat transfer rate in a condenser by 30% over a two month period (8). The plant design had allowed for a 15% decrease due to fouling.

CONTROL TECHNOLOGIES

Fouling control strategies can include a combination of mechanical, chemical and thermal treatments. Backwashing of condensers and heat exchangers helps clear impinged macrofouling organisms and other aquatic debris from tube sheets. Traveling water screens, and in some cases debris filters, are used to prevent transport of material to the cooling water systems. Some generating stations use recirculating sponge balls to control condenser tube microfouling. Off-line mechanical cleaning techniques include passing air and water, brushes, or scrapers through condenser tubes to remove microfouling organisms from condenser surfaces. The configuration of some plants allow backwashing of heated discharge water through sections of intake piping providing thermal control of macrofouling on pre-condenser surfaces.

Restrictions on Chlorination

Chemical on-line biofouling control is the injection of a biocide, such as chlorine into the inlet cooling water. Intermittent chlorination has been the most widely used biofouling control process for condenser microfouling in power stations in the United States. A small number of utilities employ continuous low level chlorination to control macrofouling when other control options are not feasible. However, the use of chlorine has been restricted by effluent limitations imposed because of potential adverse environmental impact to aquatic organisms.

The effluent limitations on chlorine can be met either by control of the chlorination process or by the use of other methods including dechlorination. Control of the chlorination process to ensure that effluent limitations are not exceeded can be difficult and may not allow flexibility to increase the chlorine dosage as required to control biofouling at every plant site. Operating experience at a number of plants has proven that the EPA effluent limitations on TRC for once through cooling water systems cannot be met in all cases (9, 10, 11).

Optimizing Chlorine Dosage

A chlorine "optimization" (minimization) program is a good strategy for determining the best means for meeting EPA or state effluent limitations as well as determining the amount of chlorine needed for efficient condenser operation. The minimum chlorine dosage which maintains satisfactory performance will vary from one site to another and will vary with season. Factors influencing the "optimum" chlorine dosage include the water quality, water temperature, number and type of aquatic organisms present, power plant design, type and design of heat transfer equipment, age of heat transfer equipment, heat exchanger tube material(s), and water velocity through the condenser tubes.

Assessing condenser performance in situ

The problem is, in essence, to quantitatively determine the minimum chlorine dosage to control biofouling so that plant performance is not affected, while remaining within the EPA guidelines for TRC. However, there is no generally accepted method of relating condenser performance to deposit accumulation on condenser tube surfaces. Measurements of condenser vacuum, condenser performance efficiency, pressure changes from the inlet to the outlet waterbox, temperature changes across condenser surfaces, weight of removed tube fouling material, etc., have been used with various degrees of success to relate biofouling thickness or biomass to condenser performance. However, many of these approaches are quite inaccurate while others require the operating unit to be deaerated while sampling and visual inspection occur. Furthermore, using condenser performance as a measure of tube internal cleanliness (i.e., fouling) is difficult because condenser performance calculations are not solely dependent on internal tube surface cleanliness but also depend on air leakage and associated air blanketing on the steam side, location and calibration drift of sensors located within the condenser, unreliable water flow estimates, etc. For these reasons using an operating unit with associated performance calculations to conduct fouling control optimization treatment is difficult at best.

MONITORS IN ASSESSING CONTROL TECHNOLOGIES

Sidestream or in situ measurements

Sidestream monitors are attractive for minimization studies, where flexibility in experimental design and accuracy are required, while risk to the operating unit is no concern. In addition, using multiple side-stream test units provides a means for evaluating various control treatments simultaneously. Parallel testing of different treatments is important since the fouling characteristics of the plant source water are constantly changing. Using the operating unit to develop treatment strategies only provides information on a single treatment during one period of time. Although simulating an operating condenser in every detail with a sidestream test apparatus is virtually impossible, important parameters, i.e., water flow velocity, tube material, heat flux, can be matched to assure that a realistic effective treatment regime can be developed.

Monitor Sensitivity

One difficulty with present monitors is their lack of sensitivity. Consider that power plant condensers are generally chlorinated once a day. In one day, very little fouling deposit accumulates and no significant response is received from the

monitor. However, deposition has occurred. Several weeks may pass before a significant fouling resistance is observed as reflected by heat transfer or friction factor. In the meantime, the fouling deposit accumulation may have become refractory to the treatment. An example of a refractory deposit is the manganese accumulation which frequently results from repeated chlorination at some sites. The deposit is generally not detectable by friction factor or heat transfer resistance measurements with available instruments.

Several unique methods are under development which may provide the monitoring techniques for the near future. These techniques are highly sensitive and, in many cases, the sensors are small and inexpensive so that a number of them can be installed in the actual condenser. One sensor is a printed circuit of approximately one (1) square centimeter and measures heat transfer resistance (12). The other sensor is even smaller in area and uses optical methods to detect deposit accumulation. The latter sensor has detected a biofilm as thin as $5\mu\text{m}$ (Siebel and Characklis, unpublished data).

RESULTS OF MONITORING PROGRAMS FROM POWER PLANT SITES

The monitors used most effectively in recent times, for evaluating fouling control technologies, measure heat transfer and/or fluid frictional resistance. Several onsite research programs will be described in which such monitors were used to determine the effectiveness of chlorine and mechanical cleaning methods for power plant condensers. In addition to the monitors, an analytical program has been developed to assess the contribution of biological and chemical processes to overall fouling deposit accumulation.

We have conducted studies in a research mode in several power plant sites to measure some of the potentially important process variables and to determine the nature of their influence on the effectiveness of the fouling control method. Fouling rate studies in combination with treatment evaluations have been performed onsite at three estuarine nuclear power plant sites.

The fouling monitor programs consist of two parallel activities: 1) physical, chemical, and biological analysis of the deposits removed from the fouling monitors and operating condensers and 2) measurement of the effects of the deposits on frictional resistance and heat transfer resistance in the fouling monitor.

Description of Different Sites

Details of the process environment within the various fouling monitors are presented in Table 1. Experimentation at Site B focused on testing various chlorine concentrations to determine the effectiveness of the treatments. Experiments at Site C tested fouling reduction on admiralty brass tubes by passing "soft" sponge balls through the tubes. Results at similar run times and measurements of deposit accumulation and analyses are compared in Tables 2 - 5. The Site A project began in April 1985, Site B began in June 1986, and Site C began in April 1983. Seasonal and water quality differences undoubtedly influence the variations between sites.

Comparison of Water Velocity and Alloys

Site A fouling monitor results for deposit mass, volatile fraction, and carbon, hydrogen, and nitrogen can be seen in Table 2. The Site A fouling monitor consisted of 4 parallel tubes: 3 titanium and 1 admiralty brass tube. Deposit accumulation

is less in the admiralty brass tube. Deposit mass increased continuously in both the admiralty brass and titanium tubes with increasing run time. Volatile fraction, carbon, nitrogen, and hydrogen remained constant with increasing run time, after a brief initial period during which volatile fraction appears higher. Deposit samples were obtained from unheated tube sections. More details of this project are presented elsewhere (13).

Fouling deposit accumulated to a greater extent in the tube operated at lower velocity (Tube 3). Tubes 1 and 2 were operated at higher velocities and accumulated considerably less deposit (Table 2). The accumulation of fouling deposit was higher on the admiralty brass tube than on the titanium tubes operated at the same velocities (Table 2). The result is counter to perceptions in the industry (based primarily on plant operating parameters) that copper-based alloys are more resistant to fouling. The difference between fouling monitor results and plant observations are due to differences in design and operation compounded by seasonal variations. The heat transfer resistance measured in the different tubes indicates little difference between alloys (Figure 1).

Effectiveness of Different Chlorine Dosages

Site B fouling monitor results for deposit mass, volatile fraction, and carbon, hydrogen, and nitrogen can be seen in Table 3. The control samples (i.e. no chlorine treatment) were used for comparison with the Site A results since no chlorine was used. Also listed in Table 3 is deposit mass for each chlorine concentration at Site B. Treating the tubes with the minimum chlorine concentration, 0.05 mg l^{-1} , gave an 87% decrease in deposit mass from the control tube. The highest chlorine concentration, 1.00 mg l^{-1} , gave an 85% decrease in deposit mass. There is only a 2% difference of deposit mass between the highest and lowest chlorine concentrations so the lowest concentration is recommended for treatment.

Heat transfer resistance in the fouling monitors at Site B for three separate tubes are presented in Figure 2. The OHTR in the control tube (no chlorine added) rapidly increased to $0.003 \text{ ft}^2\text{hr}^\circ\text{F}/\text{BTU}$ after 50 days. In the tube treated with 0.05 mg/L chlorine, OHTR gradually increased and at day 50 was only $0.0011 \text{ ft}^2\text{hr}^\circ\text{F}/\text{BTU}$. Data for all tubes treated with chlorine concentrations greater than or equal to 0.1 mg/L were combined in the third data set. OHTR at day 50 was $0.0008 \text{ ft}^2\text{hr}^\circ\text{F}/\text{BTU}$. For the period tested, chlorine concentration of 0.1 mg/l was sufficient to control fouling.

Effectiveness of Mechanical Cleaning

In this investigation, "spft" sponge balls were initially effective in reducing the effects of fouling. However, subsequent treatments with the soft balls resulted in the formation of a refractory deposit, perhaps partly due to the continuous application of ferrous ion for corrosion inhibition. Treatment with abrasive balls (carborundum) was then initiated but was not effective in significantly improving conditions. More frequent treatment with abrasive balls may have been effective but there was concern that erosion of the heat exchanger tubing (admiralty brass) could become significant.

The OHTR data at Site C in the fouling monitor was collected over approximately 200 days. Details of this experimental program are presented elsewhere (8). The fouling factor based on the maximum extent of fouling (at approximately day 60) was $0.0004 \text{ ft}^2\text{hr}^\circ\text{F}/\text{BTU}$. The cleanliness factor was less than 70% as compared to a design

value of 85%. Site C results for deposit mass, carbon, hydrogen and nitrogen are presented in Table 4. Total deposit mass was around 7.77 g/m². The total carbon present in the fouling deposit varied between 10 and 18%. The heat transfer resistance resulting from the deposit accumulation is presented in Figure 3.

Comparison Between Sites

Comparative values for deposit mass, volatile fraction, carbon, nitrogen, and hydrogen for Site A, Site B and Site C are presented in Table 5. Site B control tubes, no chlorine treatment, had a higher deposit mass accumulation and volatile fraction than the Site A titanium tubes. Site C's admiralty brass tubes had a higher deposit mass accumulation than Site A's admiralty brass tubes. Thus, fouling rate and extent at Site B and Site C appears greater than at Site A. However, the problem is kept to a minimum with extremely low chlorine dosages at Site B and with "soft" sponge balls at Site C.

Comparison Between Results in the Monitors and Performance of the Condensers

Description of the condenser environment within the two nuclear power plant condensers (Sites A and B) is presented in Table 6. A major difference between the two condensers is that Site B chlorinates to control fouling while Site A had no treatment at the time of the tests. A summary of deposit analysis results from the two condensers is presented in Table 7.

The Site A condenser has nearly 10 times the deposit accumulation observed at Site B. The accumulation at Site A occurred over a much shorter exposure period (approximately 6 months) further accentuating differences in the two condensers. Clearly, chlorine treatment is effective in reducing deposit accumulation at Site B. The accumulation of fouling deposit in the fouling monitors at Site A was considerably less than in the control tubes (no chlorine added) in the fouling monitors at Site B (compare Tables 2 and 3). However, chlorination reduced fouling deposit accumulation at Site B below that at Site A. The condenser deposit accumulations reflect the same trend (Table 6) as observed in the fouling monitors. Thus, although Site B has a higher fouling potential, chlorination maintains fouling deposit accumulation at a level below that at Site A.

Site B also has a higher percentage of volatile fraction, carbon, hydrogen, and nitrogen, and, therefore, a lower inorganic fraction. The results of the Site A study suggests a slightly higher organic content in the early phases of accumulation. Perhaps, organic material also deposits initially on chlorinated tubes, thus explaining the higher volatile (and carbon) content in the Site B tubes. The composition of the Site A condenser deposit is very close to deposit composition observed in the fouling monitor at Site A (Table 2). Similarly, the composition of the Site B condenser deposit is very close to the deposit composition observed in the fouling monitor at Site B (Table 3).

Summary

In order to move from research mode to operating mode, other indices must be evaluated which can be practically and simply measured on a routine basis. These indices will substitute for some of the variables which heretofore have been measured only during elaborate research studies and which have previously not been measured during actual operations. One index which may substitute for several more sophisticated indices is the output from a fouling monitor.

RESEARCH TO PRACTICE

How Do Results from Fouling Monitor Tests Relate to Operation of Condenser?

Fouling monitors are presently qualitatively simulating fouling processes as they occur in operating condensers. For example, an experimental program using monitors in an onsite sidestream at a nuclear power plant have resolved an important qualitative issue: Is the effective chlorine dose a simple product of concentration times duration? The answer is "No". We have found that, under realistic (but not necessarily representative) conditions of temperature and flow, over a realistic range of chlorine concentrations and daily exposure, accumulation of a biofouling deposit on titanium tubes is much more dependent on chlorine concentration than on duration of the treatment. Accordingly, by implementing higher concentrations and shorter durations, it is possible to achieve a greater degree of fouling control for the same total chlorine dosage (i.e., concentration*duration), within regulatory limits. The experimental program will, at completion, allow us to identify an optimal daily dose schedule under the conditions of the test.

The essential qualitative result, that there is an optimal combination of concentration and duration (which is almost certainly different from the simple regulatory constraint of 2 hours per day at a dose that just meets the discharge limit), must hold true for operating condensers as well as for the test systems. The test systems are similar enough to operating condensers, in all important respects, that there is no reason this should not be true.

Quantitatively, however, the specific values defining the optimal combination (i.e., the most efficient combination of concentration and duration) in an operating condenser is bound to be somewhat different from that identified in a test system at that site, and will doubtless be even more different during other seasons and at other sites. Some of the problem related to seasonal variations in fouling are dependent on design of the condenser and the change in "heat rate" throughout the year. The least tractable causes of difference from season to season and from site to site are differences in tube material, water chemistry, nutrient supply, and source microbial species composition. The variability owing to season and to site conditions can, of course, be taken into account by conducting measurements with a test system at that site and that time. What is not so simply accomplished is the lesser correction between the test system and the operating condenser.

The key to the differences between the test system and the operating condenser is scale. The operating condenser bundle is fed by a water box, with the result that different tubes experience different temperatures and flow regimes. Each condenser tube itself is an order of magnitude longer than the test section of the monitors. Because of the gradient in the heat exchange process in the condenser, and because of the nature of the long tube as a plug flow reactor, there will be systematic differences along the length of the condenser tube with respect to wall temperature, water temperature, residual chlorine, nutrient availability, and possible other chemical changes wrought by the upstream deposit. For example, operations personnel frequently observe more fouling at the exit of the condenser as compared to the entrance tube region. Thus, we could readily set up a monitored test section to mimic any particular short section of the tube, but the same test section cannot mimic the entire span simultaneously.

Our experience with a dismantled condenser from a nuclear power plant (admiralty brass) was that the differences between tubes overwhelmed whatever pattern may have existed in the fouling gradient along the tubes (13).

What limits our ability to transfer conclusions from the test monitors to the condenser?

The extrapolation from the monitors to the operating condenser is constrained both by the amount of effort and attention that can be devoted to monitoring in an operational mode and by the available scientific information for adjusting fouling predictions on the basis of changes in various conditions.

Our studies with the fouling monitors have been conducted in an experimental mode, where considerable manpower and resources are dedicated to maintaining controlled conditions, and to exploring a substantial number of combinations of chlorination treatments in a search for the optimum. When a monitoring program is implemented in an operational mode at a plant, we must require that it place far less demands on personnel and budgets as compared to a research program. Therefore, we expect that the operational mode monitoring cannot be as precise as it is in a research mode. Nor can the operational monitoring be as extensive as in a research mode. While research monitoring can identify an optimal chlorination schedule empirically, a feasible operational monitoring program will only deliver indices to the fouling rates and responses to treatment. Then, in operational mode, it is really a modelling problem to translate the index information into a recommended treatment that can be expected to be satisfactorily efficient.

The modeling objective is to determine the coefficient that describes the effects of operating variables such as temperature, flow rate, and differences in nutrient supply on the dynamics of fouling growth, chlorine demand, and susceptibility of the deposit to chlorine, with respect to concentration and duration of treatment. The operational monitoring will serve essentially to calibrate the model for the given application (season and site). This modeling objective is realistic but it is not yet in our grasp, since we do not yet have adequate representations of some of the component processes and relationships. The elucidation of these will necessarily be subjects for further use of the biofouling monitors in the experimental mode.

Frequently, experiments are only conducted for several months of fouling starting from a clean tube. There may be slow processes that only manifest themselves in the fouling dynamics after longer periods of time. However if monitors are installed in operating mode, they will supply long term data which can serve adequately for calibrating, provided the models are validated from some long term experimental observations.

CONCLUSIONS

Sidestream fouling monitors presently are capable of qualitatively simulating fouling processes in a condenser. In addition, sidestream monitors will continue to be useful in testing the effects of various design, operating, and environmental variables on fouling processes. However, in situ fouling monitors are needed for regulating fouling control programs in the condenser. More sensitive fouling monitors (sidestream and in situ) are needed to detect very thin biofilms (and/ or their effects) and, thus, permit rapid feedback for fouling control treatments.

A mathematical model for biofilm accumulation in a condenser is necessary for relating fouling monitor data to the operating condenser. The "plug flow" nature of the condenser tube, the seasonal variation of fouling, and variations of fouling between different tubes in the same condenser are concerns that could be resolved by a validated mathematical model.

ACKNOWLEDGMENTS

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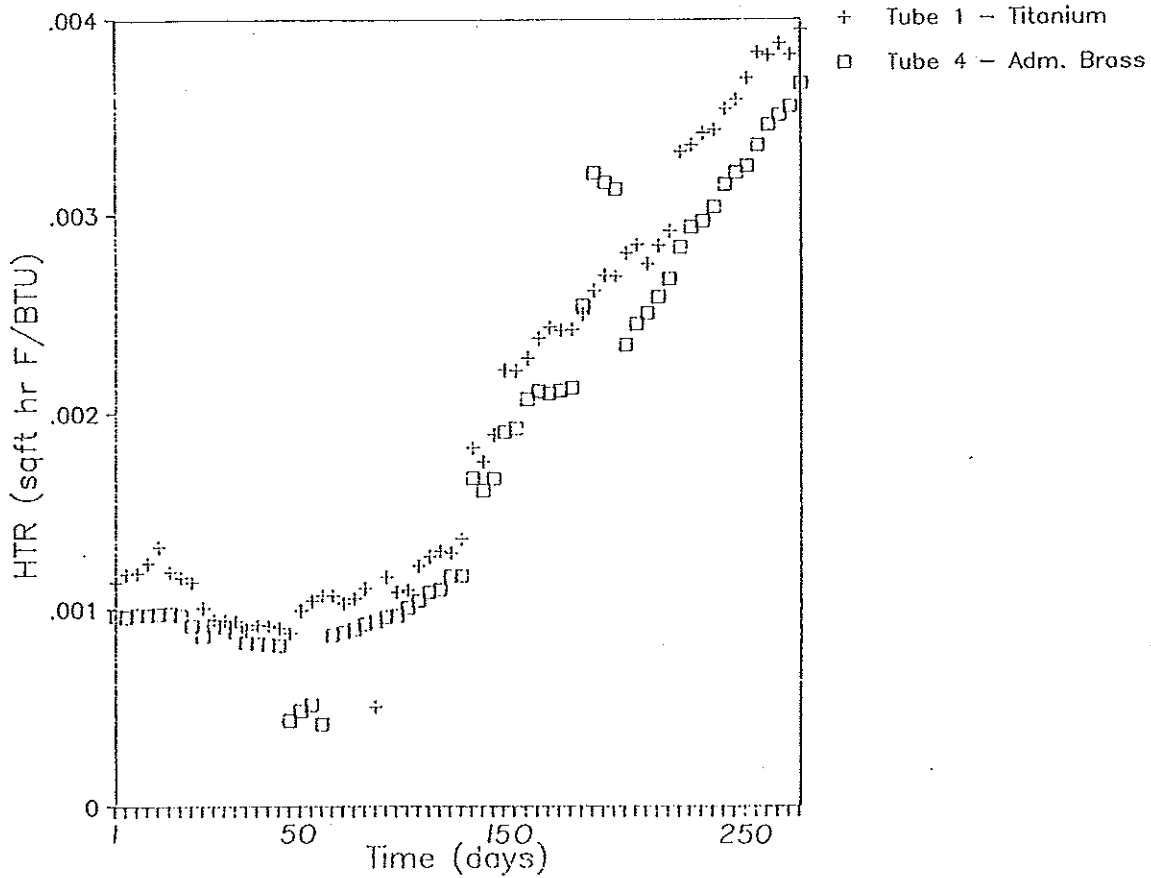


Figure 1. Heat transfer resistance in a titanium and an Admiralty fouling monitor tube at Site A. Water velocity varied from 4.1 to 6.8 fps. The tubes received no treatment.

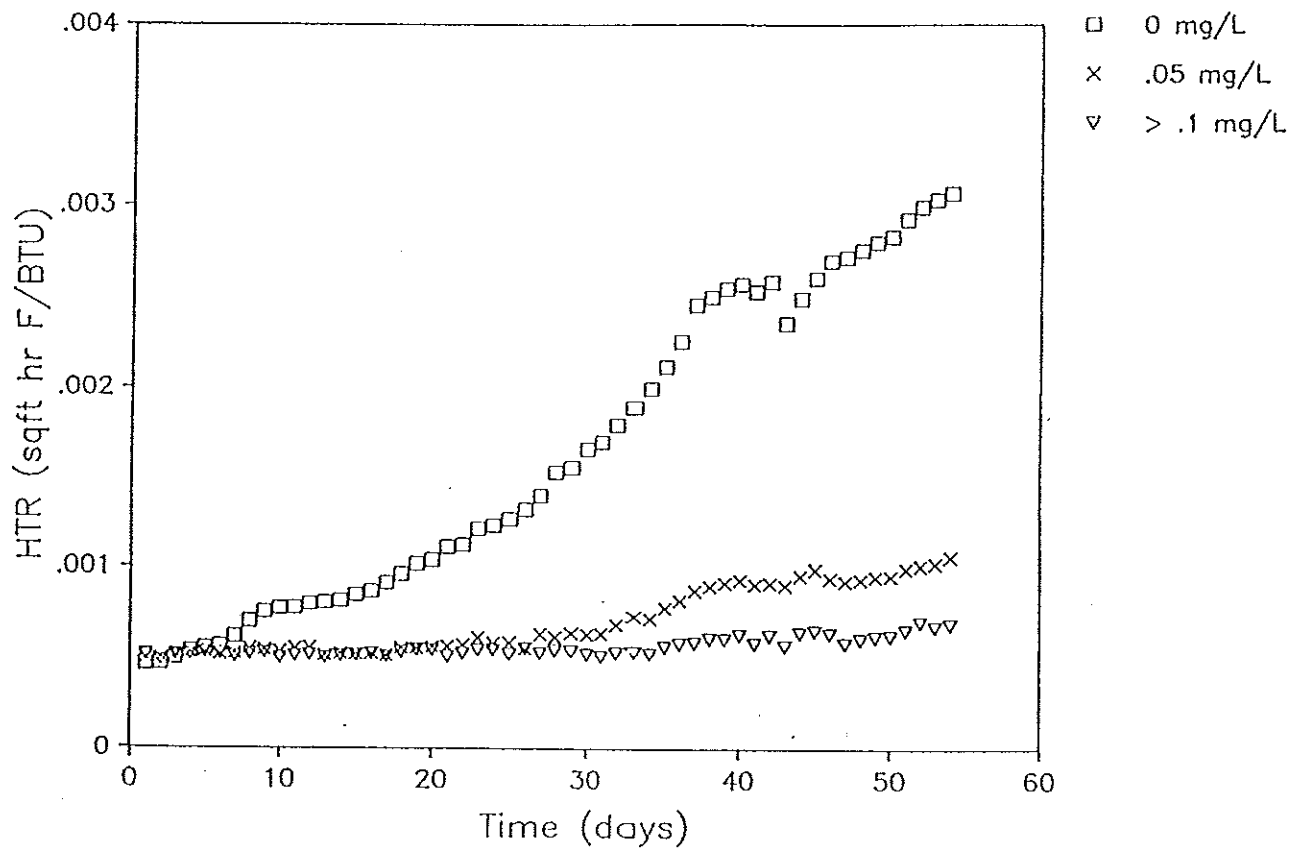


Figure 2. Heat transfer resistance in the titanium fouling monitor tubes for the condenser chlorination study at Site B. Water velocity was 6.6 fps. All chlorinated tubes received the specified total residual chlorine concentration (measured at the discharge of the treated tube) once a day for a 2-hour period.

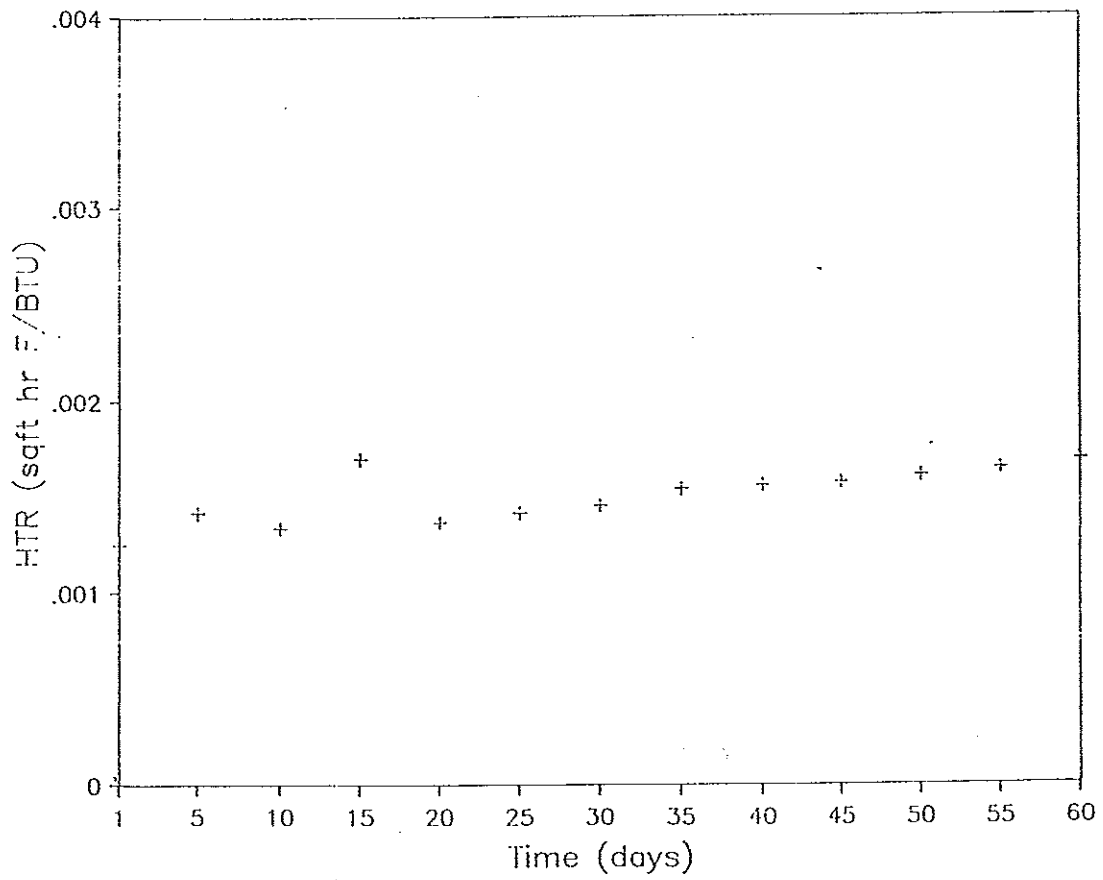


Figure 3. Heat transfer resistance in the Admiralty brass fouling monitor tube at Site C. Water velocity was 6.0 fps. The tube received no treatment during this period.

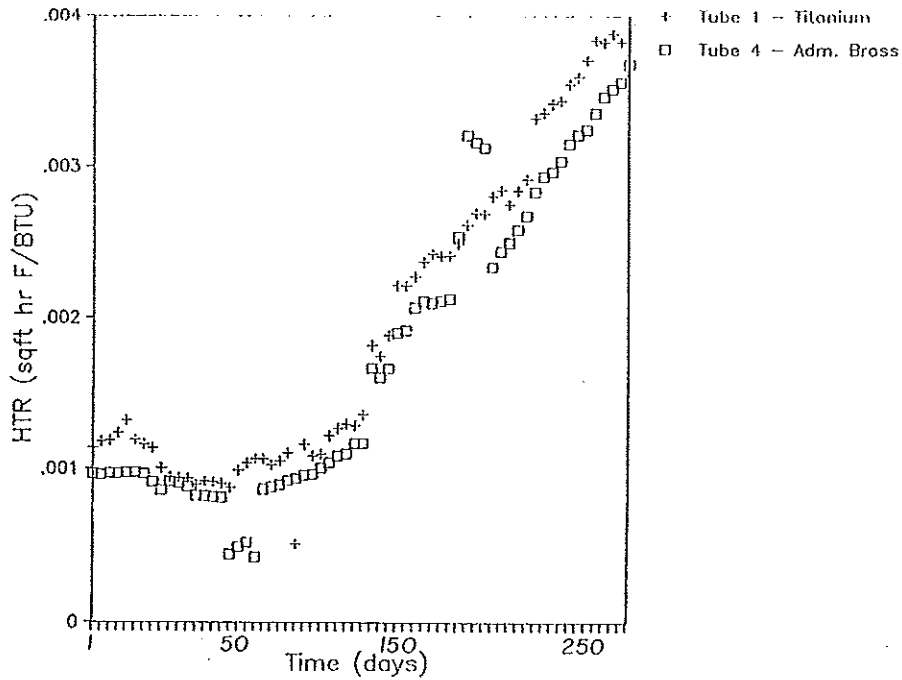


Figure 1. Heat transfer resistance in a titanium and an Admiralty fouling monitor tube at Site A. Water velocity varied from 4.1 to 6.8 fps. The tubes received no treatment.

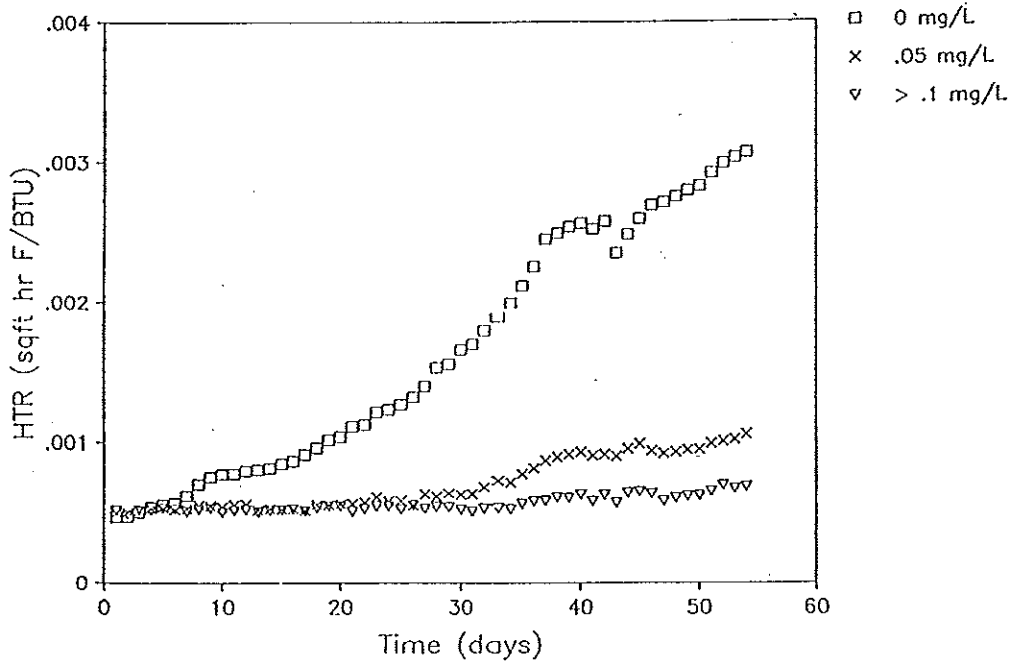


Figure 2. Heat transfer resistance in the titanium fouling monitor tubes for the condenser chlorination study at Site B. Water velocity was 6.6 fps. All chlorinated tubes received the specified total residual chlorine concentration (measured at the discharge of the treated tube) once a day for a 2-hour period.

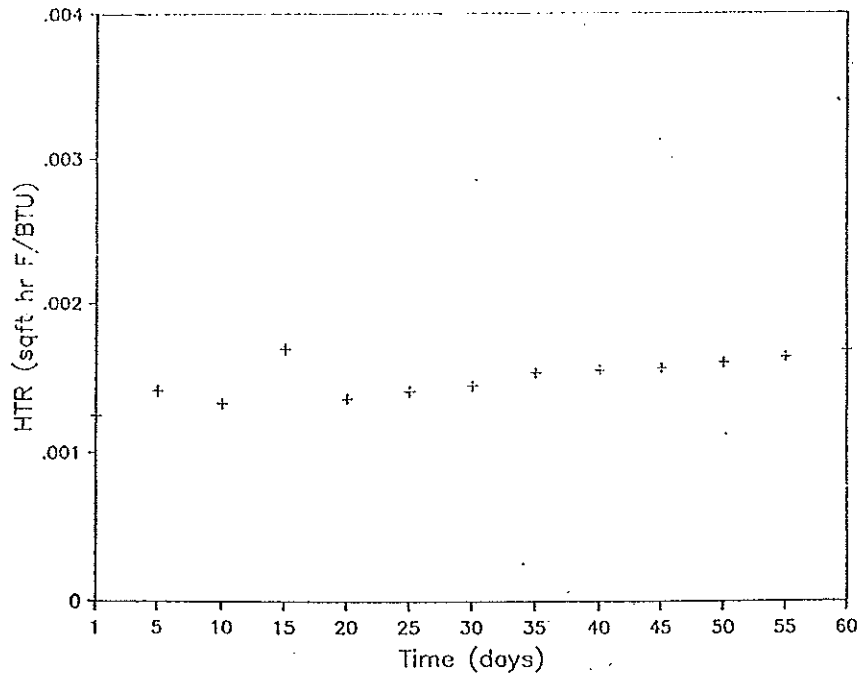


Figure 3. Heat transfer resistance in the Admiralty brass fouling monitor tube at Site C. Water velocity was 6.0 fps. The tube received no treatment during this period.

Table 1. Description of the process environment in the fouling monitors used at the three nuclear power plants each located on an East Coast estuary.

	<u>SITE A</u>		<u>SITE B</u>		<u>SITE C</u>	
TUBE MATERIAL	Admiralty Brass	Titanium	Titanium	Admiralty Brass		
DIAMETER (INCHES)						
I.D.	0.90	0.819	0.819	0.90		
O.D.	1.00	0.875	0.875	1.00		
DESIGN FLOW VELOCITY (fps)	6.80	6.80	6.60	6.60		

Table 2. Results of analysis conducted on fouling deposits from fouling monitors at Site A. No treatments were used to control fouling. Deposit samples were obtained from unheated tube sections. Tubes 1, 2, and 4 were operated at water velocities consistent with plant operation. The velocity range was 4.1 - 6.8 fps. Tube 3 was operated at a constant water velocity of 4.1 fps.

SAMPLE NUMBER	TIME (days)	TUBE MATERIAL	DEPOSIT MASS (g/m ²)	VOLATILE FRACTION	% C	% N	% H
1	40	TITANIUM	0.09	NR	NR	NR	NR
2	40	TITANIUM	0.18	NR	6.14	0.52	1.09
3	40	TITANIUM	3.18	18.83	6.07	0.70	1.45
4	40	ADMIRALTY BRASS	0.69	33.00	1.35	0.73	0.21
1	61	TITANIUM	1.69	16.00	6.19	0.80	1.45
2	61	TITANIUM	3.27	12.07	5.67	0.76	1.38
3	61	TITANIUM	13.93	12.28	4.80	0.69	1.22
4	61	ADMIRALTY BRASS	6.10	12.61	4.92	0.61	1.19

Table 3. Results of analysis conducted on fouling deposits from fouling monitors at Site B. All tubes were titanium and water velocity was 6.6 fps. Deposit samples were obtained from heated tube sections.

SAMPLE NUMBER	TIME (days)	CHLORINE (mg l ⁻¹)	DEPOSIT MASS (g/m ²)	VOLATILE FRACTION	% C	% N	% H
1	35	control	12.22	26.97	9.12	0.00	1.07
2	35	0.05	1.61				
3	35	0.10	0.33				
4	35	0.20	0.40				
5	35	0.40	1.49				
6	35	1.00	1.89				
7	35	control	17.56	26.33	9.87	0.05	1.79
1	62	control	32.37	27.05	10.21	1.05	1.88
2	62	0.05	15.46				
3	62	0.10	5.45				
4	62	0.20	4.41				
5	62	0.40	3.86				
6	62	1.00	4.93				
7	62	control	43.21	26.34	9.84	0.98	1.82

Table 4. Results of analysis conducted on fouling deposits from fouling monitors at Site C. All tubes were admiralty brass with a water velocity of 6.0 fps. Deposit samples were obtained from unheated tube sections after 60 days exposure.

SAMPLE NUMBER	DEPOSIT MASS (g/m ²)	% C	% N	% H
1	8.61	11.80	0.71	2.19
2	7.75	9.77	0.77	1.94
3	7.75	18.56	0.43	3.29
4	6.98	16.15	0.35	2.95

Table 5. Comparison of analyses conducted on fouling monitors at Sites A, B, and C control tubes. Site A tube velocity ranged from 4.1 - 6.8 fps based on the plant operating schedule (Tube 3 was not included in this summary). Site B tube velocity was 6.6 fps. Site C tube velocity was 6.0 fps.

Time (Days)	Tube Material	Deposit Mass (g/m ²)	Volatile Fraction	% C	% N	% H
<u>SITE A Fouling Monitor (no chlorine)</u>						
40	Titanium	0.14	6.28	4.07	0.41	1.27
61	Titanium	2.48	13.45	5.55	0.75	1.35
40	Admiralty	0.6	33.00	1.35	0.73	0.21
61	Admiralty	6.1	12.61	4.92	0.61	1.19
<u>SITE B Fouling Monitor (no chlorine)</u>						
35	Titanium	14.89	26.65	9.50	0.03	1.43
62	Titanium	37.79	26.70	10.03	1.02	1.85
<u>SITE C Fouling Monitor (prior to mechanical treatment)</u>						
60	Admiralty	7.77		14.07	0.55	2.59
<u>SITE A Admiralty Brass Condenser</u>						
	Admiralty Brass	6.10		4.92	0.61	1.19

Table 6. Details of the process environment in the Site A and Site B condensers and analysis of deposits from the condensers. Site B condenser is chlorinated regularly. Exposure time for the titanium tubes was approximately six (6) months at Site A and approximately twelve (12) months at Site B. The Admiralty tubes at Site A were in place for approximately 6 years before being replaced.

TUBE MATERIAL	<u>SITE A</u>		<u>SITE B</u>
	Admiralty Brass (18 gauge)	Titanium	Titanium (22 gauge)
LENGTH (FEET)	49.75	49.75	42.00
DIAMETER (INCHES)			
I.D.	0.90	0.819	0.819
O.D.	1.00	0.875	0.875
DESIGN FLOW			
VELOCITY (fps)	6.8	6.8	6.27
TREATMENT	none	none	chlorine
DEPOSIT MASS (g m^{-2})	8.0	37.3	4.13
VOLATILE FRACTION (%)		13.9	31.8
%C	4.8	4.6	9.1
%N	0.46	0.54	0.61