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AN EVALUATION OF CONDENSER TUBE FOULING AT AN ESTUARINE NUCLEAR POWER PLANT

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ABSTRACT

Fouling deposits in condenser tubes impede heat transfer and can also accelerate corrosion. This test program was motivated by the retubing of an admiralty brass condenser with titanium tubes at the Indian Point 3 (IP3) power plant of the New York Power Authority (NYPA). Since titanium tubes were believed to foul faster and to a greater extent than brass, the test program gathered relevant data regarding fouling potential under various operating conditions in the two alloys. Data also indicated operating and environmental parameters important for predicting fouling potential at other sites. NYPA had no condenser fouling control program at the time of these tests. IP3 takes its cooling and service water from the Hudson River, a tidal estuary, whose salinity varies throughout the year.

INTRODUCTION

Fouling refers to the undesirable formation of deposits on equipment surfaces. In condenser tubes, the deposits impede heat transfer across the tube wall and increase fluid frictional resistance through the tube. The fouling deposits can also accelerate corrosion of the tube material. This project was motivated by the retubing of a condenser with titanium tubes at Indian Point 3 (IP3) which replaced admiralty brass tubes. Titanium is more corrosion resistant than copper alloys but is generally believed to foul faster and to a greater extent than copper alloys. The scope of the project was to determine the level of fouling in titanium condenser tubes under operating conditions prevailing in the condensers at the IP3 plant. To achieve this goal, the project had two objectives: 1) continuously monitor Fouling Factor (i.e., heat transfer resistance) over a four season (year) period using fouling monitors available at IP3 to simulate the influence of fouling on condenser performance and 2) periodically determine fouling deposit composition to estimate the influence of changes in operating parameters. Control variables were fluid velocity and tube alloy. However, environmental variables, such as water temperature, salinity, and organic carbon content of the water varied widely with the seasons.

A fouling monitor system, operating on a sidestream of the service water for 19 months, provided data on overall heat transfer resistance (OHTR), fluid frictional resistance, and deposit mass and composition. The condenser cooling water as well as the plant service water are taken from the Hudson River. Four parallel condenser tubes were tested to 1) evaluate reproducibility of the fouling processes between duplicate tubes, 2) compare fouling in different tube materials (titanium and admiralty brass), 3) evaluate effects of fluid velocity on fouling processes and 4) evaluate the seasonal effects on fouling processes.

Fouling resistance is the increase in heat transfer resistance resulting from accumulation of a fouling deposit on the water side of the tubes. The fouling resistance is generally expressed by the Fouling Factor as follows:

$$R_f = \frac{1}{U_{fouled}} - \frac{1}{U_{clean}} \qquad (1)$$

where R_f = fouling factor

U_{clean} = overall heat transfer coefficient of clean tube

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$U_{coefficient}$ = overall heat transfer of fouled tube

The inverse of U_{fouled}, i.e., U^{-1}_{fouled} or $1/U_{fouled}$, is termed overall heat transfer resistance for the water side (OHTR), and is the quantity of direct interest in this project.

Fouling resistance has been measured in three ways during this project:

heat transfer resistance
fluid frictional resistance
deposit mass

Direct measurement of overall heat transfer resistance is the most reliable parameter for estimating the effects of deposit formation on condenser performance. Fluid frictional resistance presents some difficulty because precise measurements of pressure drop across the tubes was difficult, especially when fouling deposits become pronounced. In addition, pressure ports in the fouling monitors were relatively close together reducing the sensitivity of the frictional resistance determinations. Direct measurement of deposit mass by destructive sampling is useful in relating fouling deposition to heat transfer resistance in the condenser. The deposit analysis may also aid in choosing fouling control measures specific to the type of deposit (e.g., sedimentation, biofouling, scaling) accumulating in the tubes.

Fouling factor was continuously monitored while control variables were fluid velocity and tube alloy (titanium and admiralty brass). Environmental variables, such as water temperature, salinity and organic carbon content of the water, were also monitored. Removable, unheated tube sections permitted deposit sampling.

MEASUREMENTS

Fouling Monitor System

The fouling monitor system has been described in detail previously[1]. Four heated tubes were supplied with a sidestream of the service water and were instrumented to provide heat transfer resistance, fluid frictional resistance, and deposit samples for mass and composition determinations. The removable tube sections were not heated. The fouling monitor was in operation from 27 April 1985 to 30 November 1986 except from 23 July 1985 to 25 September 1985 when the water supply to the fouling monitors was discontinued and again from 28 April 1986 to 19 May 1986, days 365 to 385, when the heaters shut down.

Deposit Analysis

Deposit analyses were conducted on deposits removed from test sections which were an integral part of the fouling monitor tubes (Table 2). In addition, deposit analyses were conducted on samples obtained from the actual admiralty brass condenser tube bundles which were replaced by titanium tubes at IP3 in 1985.

RESULTS FROM THE FOULING MONITOR PROGRAM

A summary of experimental conditions is presented in Table 1. The initial and maximum measured values of the principal variables are also listed in Table 1. Tubes 1, 2, and 3 were titanium (Ti) and the fourth was admiralty brass; Tubes 1, 2, and 4 were operated at fluid velocities consistent with scheduled cooling water flows in the plant, while Tube 3 was operated at a constant velocity of 4.1 fps throughout the testing period.

Overall Heat Transfer Resistance

The progression of overall heat transfer resistance (OHTR) in the four tubes is presented in Figures 1-4. Fouling resistance accumulated to extreme values during the period from 150-300 days, culminating in fouling factors between 0.006 and 0.008 ft^2 hr F/BTU. Thus, a high rate of fouling ultimately resulted in approximately 80% loss in heat transfer capacity. The fouling factor, R_f, was as high as 0.007 ft^2 hr F BTU^{-1}.

While a plateau would be expected to result from the competing processes of accumulation and detachment, no such plateau was observed. However, a massive slough of deposit material occurred in all tubes between 300 and 380 days. No such sloughing events have been observed in studies when control treatments (e.g., chlorination) have been used regularly.

The rate of accumulation of resistance to heat transfer in the fouling monitor tubes was affected by a number of factors including interruptions in operation, flow velocity, and tube material. Seasonal effects, originally thought to be important, appear to be of minimal impact. The OHTR appeared to increase more rapidly in Fall and Winter 1985 than in the late spring and early summer. In Fall and Winter 1986, however, the OHTR appeared to increase less rapidly as the seasons progressed toward colder temperatures. Thus, tube wall temperature (95 F) may influence fouling processes more than bulk water temperature when the wall temperature of the tube is maintained at 95 F. If fouling continues unabated with warm and cold water temperatures, a fouling control program may have to be operated throughout the year.

Reproducibility of results (Tubes 1 and 2). The replication of results between tubes in the fouling monitor was good as indicated by comparing heat transfer resistance measurements in Tube 1 and Tube 2 which were operated as replicates (Figures 1 and 2). Reproducibility decreased temporarily following the sloughing event but returned to within acceptable limits after approximately 380 days (Figure 5). Except for the period between 320 and 365 days, the standard deviation of the mean OHTR between Tubes 1 and 2 was quite low, rarely exceeding 6.0×10^{-4} ft^2 hr F/BTU. The mean coefficient of variation over the entire test period is 13.6% including the 320-365 day period, and only 10.5% if the that period is neglected. Standard deviations generally increased with the measured average resistances. Thus, it appears that trends observed in the fouling monitors are accurate to within about 10%. Differences due to changes in operational variables (i.e, velocity and tube material) are higher than 10%. Therefore, significant differences in fouling process rate and extent due to the operational variables were observed.

Effect of Flow Velocity. Periodic changes in fluid velocity can reduce the overall rate of deposit accumulation. However, the effect is not dramatic. Fluid velocity was purposefully varied in Tubes 1, 2, and 4 during the test period to simulate operation of the condenser through the seasons (Figures 1-4). Tube

3 was maintained at 4.1 fps throughout to serve as a control and exhibited a continuous increase in OHTR over the test period. The largest fouling resistance after 264 days was observed in Tube 3 which was maintained at the lowest fluid velocity throughout the test.

Fluctuating OHTR in the early stages of the monitoring (0-90 days) in Tubes 1, 2, and 4 was due to purposeful changes in fluid velocity resulting in changing convective heat transfer resistance. Fluid velocity influences overall heat transfer resistance in several ways. First, an increase in fluid velocity results in a lower convective heat transfer resistance which will result, at least temporarily, in a lower overall heat transfer resistance. This was directly observed in Tubes 1, 2, and 4 during the first 90 days operation when fluid velocity was increased from 4.1 to 6.8 fps resulting in a decrease in OHTR (Figures 1 - 4). The decrease in OHTR as velocity is increased is due to increases convective heat transfer.

Secondly, as fluid velocity increases, the shear stress at the tube wall increases which leads to increased detachment of material from the deposit, which reduces deposit thickness. Tube 3, which operated continuously at 4.1 fps accumulated more deposit than any of the tubes which operated periodically at higher velocities (Figure 3). The thinner deposit results in a lower conductive heat transfer resistance. Changes in velocity may also result in a change in deposit properties (e.g., deposit density) which may affect (increase or decrease) the heat conductivity of the deposit. No significant variations in deposit composition were observed in these tests.

Effect of tube material. The heat transfer resistance attributed to the fouling deposit in the admiralty brass tube was approximately the same as in the titanium tubes. Thus, combined with the relatively high conductivity of the admiralty brass tube (Table 1), fouling resistance in the defunct admiralty brass condenser at IP3 was probably significantly lower than in the new titanium condenser. Tubes 1, 2, and 4 were operated under identical conditions for nearly the entire period of the study, but it is clear that the progression of heat transfer resistance was not the same in Tube 4 as in Tubes 1 and 2. The consistently lower heat transfer resistance in Tube 4 was not unexpected, as biofilms have been shown to accumulate more slowly on copper alloys than on "inert" metal surfaces, such as titanium. Although reduced fouling on copper alloys is thought to be due to copper toxicity to the bacteria, another cause is possible. Copper alloys corrode much faster than titanium and tend to spall or slough their corrosion products. The spalled corrosion products carry much of the biofouling deposit into the bulk fluid also, thus reducing biofouling[2].

The deposit formed on copper alloys also has a characteristically lower fraction of volatile solids. Characklis et al[2] observed fouling on a copper-nickel 70-30 in seawater. The deposit generally contained a volatile solids content between 15-25%. The volatile content from titanium tubes was significantly greater. Volatile content of deposits from the defunct admiralty brass condenser were approximately 15 to 20%. At an estuarine power plant site in Canada, carbon content (an indicator of volatile solids content) of deposits on admiralty brass tubes was generally between 10 to 15%.[3] Carbon content of deposits from the defunct admiralty brass condenser at IP3 was approximately 6%.

Following the major slough of material, the admiralty brass fouling monitor consistently showed a 0.0005-0.002 ft^2 hr F/BTU higher resistance than Tube 2 (Ti). The magnitude of the drop in OHTR from the slough was much less in Tube 4, 0.001 ft^2 hr F/BTU, compared to 0.004 ft^2 hr F/BTU in Tube 2. While the rate of increase of OHTR was about 20% lower in Tube 4 than in Tube 2, the higher starting point subsequent to the sloughing occurrence resulted in a higher overall OHTR. Corrosion processes occurring on the inside of the admiralty brass tube may have contributed to a more tightly bound deposit, less of which was lost during the sloughing occurrence.

Influence of chlorine. In November, 1986, chlorination of Tube 2 was initiated to determine the susceptibility of the deposit to strong oxidizers. Sodium hypochlorite was applied once a day for two hours at 1.0 mg/l over a period of two weeks. Chlorination was effective in reducing the heat transfer resistance in a titanium tube which had been accumulating fouling deposit for approximately 1.5 years (Figure 6). Although the relative reduction is not great, it must be remembered that the fouling deposit had been accumulating for a very long period. In fact, the observation of any reduction in heat transfer resistance on such an "old" deposit suggests that chlorine (or possibly another oxidant) may be effective in controlling fouling within acceptable limits if applied regularly.

Fouling Deposits in the Operating Titanium Condenser

In early Spring, 1986, the new titanium condenser at IP3 was inspected because heat transfer had decreased by more than 40% in approximately 6 months operation. Deposits from seven condenser tubes (the last inch of the condenser tube at the outlet end) were analyzed (Table 3). The deposit in the titanium condenser at IP3 was the same composition as the deposit in the fouling monitor. In both systems, fouling resistance was exceedingly high. The deposit in the condenser averaged 78.5 g m^{-2}, by far the largest deposit mass measured in any condenser tube by CCE. For example, in May 1982, CCE analyzed a deposit from a titanium condenser tube at a nuclear power plant operating on another East Coast estuary. The deposit was 14.6 g m^{-2} with a volatile solids content of 3.3% (10% carbon and 1% nitrogen) with a total bacterial count of 1.5×10^{12} m^{-2}. However, this particular power plant chlorinates regularly. The largest deposit mass measured in the fouling monitors at IP3 was approximately 100 g m^{-2} (Table 1).

The deposit composition in the titanium condenser at IP3 was essentially the same as that observed in titanium tubes in the fouling monitor at IP3 in terms of volatile solids, carbon, and nitrogen. The water and wall temperature at the outlet end of the condenser may be somewhat higher than in the fouling monitor and may cause some of the disparity in the deposit mass between the fouling monitor and the condenser at IP3.

Conductive and Convective Components

Heat transfer resistance in the fouling monitor, 1/U, is the sum of contact resistance in the test unit, conductive resistance through the tube wall, conductive resistance (CoHTR) through the fouling deposit, and convective heat transfer resistance (CvHTR) due to fluid flow past the wall (Table 1):

$$1/U = HTR_{contact} + HTR_{wall} + CoHTR + CvHTR \quad (2)$$

HTR(contact) and HTR(wall) are constant. Thus, overall heat transfer resistance (OHTR), as discussed in this paper, only refers to the sum of CoHTR and CvHTR eliminating consideration of factors not influenced by the fouling deposit:

$$OHTR = CoHTR + CvHTR \quad (3)$$

The conductive resistance in the deposit can be expressed as:

$$CoHTR = X/\rho_d k_d, \quad (4)$$

where X = deposit mass ($M\ L^{-2}$), ρ_d = deposit density ($M\ L^{-3}$), and k_d = deposit thermal conductivity. Changes in the conductive resistance can be a result of the following:

1) increase in the deposit thickness
2) change in deposit composition or properties

Increases in overall heat transfer resistance (OHTR) were primarily a result of increases in conductive heat transfer resistance (CoHTR). CoHTR was primarily a result of increasing deposit accumulation as indicated by Figure 7. Thus, an increasingly greater proportion of OHTR was attributed to conductive resistance through the fouling deposit. Prior to the slough of deposit material in the heated sections, CoHTR increased approximately linearly with deposit mass suggesting that

$$\rho_d k_d = \text{a constant} \quad (5)$$

i.e., the product of the deposit density and deposit thermal conductivity remained constant. No significant changes in deposit properties were detectable.

Deposit Analysis: Fouling Monitor

Samples of deposit from the fouling monitor tubes were analyzed for fixed and volatile solids, deposit mass (per unit area), carbon, hydrogen, and nitrogen (Table 2).

Progression of deposits. Deposit mass increased for the first 90 days of the testing in each tube (Figure 8). However, after the first outage, some loss of deposit occurred especially in Tubes 1 and 2. Immediately upon resuming testing, deposit mass began increasing at a rate slightly higher than in the previous series of tests except for Tube 4. The drop in OHTR subsequent to the slough was significantly lower in Tube 4 (admiralty brass) than in the other three tubes. The subsequent rate of OHTR increase in Tube 4 after the slough was higher than the rate observed prior to the sloughing of the deposit.

Deposit composition. Samples of the deposit from the fouling monitor tubes were analyzed for fixed and volatile solids, and carbon/hydrogen /nitrogen (CHN). (Table 2).

Carbon and nitrogen are indicators of organic content or, more specific to IP3, microbiological content. Generally, C/N = 5 is typical for microbial cells on a mass basis. In the IP3 deposits, C/N was approximately 8 or 9. The high C/N ratio may be attributed to at least three different causes:

1. Carbon may not have limited growth of the microorganisms in the deposit over the entire test period. Water quality analyses indicate that phosphorus could have been the limiting nutrient in the IP3 condenser tubes during portions of the test period.

2. Organic compounds with low nitrogen content adsorb or become entrapped in the fouling deposit. Particulate organic carbon in the water was relatively high during certain periods (5-10 mg/l).

3. Some of the deposit carbon is inorganic and becomes immobilized in the deposit by precipitation (e.g., $CaCO_3$, $CaSO_4$).

Similar carbon and nitrogen contents have been observed in another power plant having titanium condenser tubes operating on an estuary. Carbon and nitrogen ratios in the deposit were not subject to great variation during the fouling monitor program once the initial deposit formed. With a nitrogen content of around 1%, and using the formula $C_5H_7NO_2$ for a bacterial cell, it appears that as little as 6% of the total deposit mass was microbial mass.

Volatile solids were generally between 15 - 20% (Table 2) of total deposit mass. Thus, up to 75% of the volatile material in the deposit may have consisted of non-biological material. From microscopic observations of the fouling deposit, a significant fraction of the deposit mass consisted of silt and clay particles, which are known to be sites for adsorption of bacteria in natural waters. Thus, a significant contribution to the accumulation of the deposit may be entrapment of small particles which contain bacteria.

DEPOSIT ANALYSIS - ADMIRALTY BRASS CONDENSER TUBES

The admiralty brass tube bundles in the condensers at IP3 were in service for approximately eight (8) years. On dismantling the condenser, several condenser tubes were sampled for analysis of water side deposits. These tubes were flattened prior to being cut into small sections for shipment. The average deposit mass in the admiralty brass tubes was approximately 8 $g\ m^{-2}$, the same deposit mass measured in an admiralty brass tube at an estuarine Canadian power plant site.[3] Differences between tubes are the dominant source of variation in the samples. Within the limits of the sampling, no pattern was evident in the amount of deposit mass along the length of the tubes.

COMPARISON OF IP3 RESULTS WITH OTHER POWER PLANT SITES

Deposit analysis from condensers and fouling monitor tubes at other sites have been analyzed for volatile solids, deposit mass per unit area, carbon, hydrogen, and nitrogen (CHN). The results indicate that the fouling potential at NYPA IP3 is less than other sites (Table 4).

CONCLUSIONS

1. A high rate of fouling measured in the fouling monitor ultimately resulted in approximately 80% loss in heat transfer capacity on the water side of the titanium tubes. The fouling factor, R_f, was as high as 0.007 $ft^2\ hr\ F\ BTU^{-1}$.

2. The effect of water temperature on the rate of fouling appears to be minimal when the wall temperature of the tube is maintained at 95 F.

3. Reproducibility between tubes in the fouling monitor was good for most of the study.
4. Periodic changes in fluid velocity can reduce the overall rate of deposit accumulation. However, the effect is not dramatic.

5. The heat transfer resistance attributed to the fouling deposit in the admiralty brass tube was approximately the same as in the titanium tubes. However, combined with the relatively high conductivity of the admiralty brass tube (Table 1), fouling resistance experienced in the defunct admiralty brass condenser at IP3 was probably significantly lower than HTR expected in the new IP3 titanium condenser.

6. The deposit in the titanium condenser at IP3 was the same composition as the deposit in the fouling monitor. In both systems, fouling resistance was exceedingly high. The deposit accumulation in the titanium condenser was very high compared to results from other sites.

7. About 25% of the deposit mass consisted of organic compounds. It appears that the fouling deposit contained mainly inorganics (clay and silt) imbedded in a matrix of organics. Because of specific gravity differences, the organic material in the deposit could have been as much as 40-50% by volume.

8. Chlorine treatment was effective in reducing the heat transfer resistance in a titanium tube which had been accumulating fouling deposit for approximately .5 years.

9. Comparing operational data of the condensers at IP3 with the fouling monitor system indicates consistency of results (e.g., heat transfer resistance due to fouling in both systems increased at the similar rates over identical periods of operation).

10. The fouling monitor has proven to be a valuable tool for readily measuring the fouling characteristics (e.g., heat transfer resistance) at Indian Point 3.

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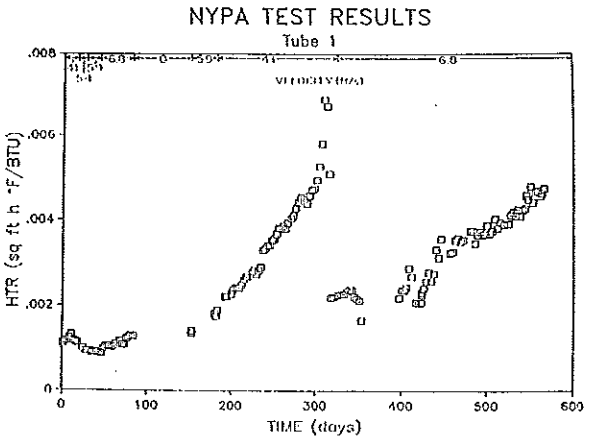


Figure 1. Progression of Heat Transfer Resistance (OHTR) in Tube 1 (titanium), operated at velocities consistent with plant operation.

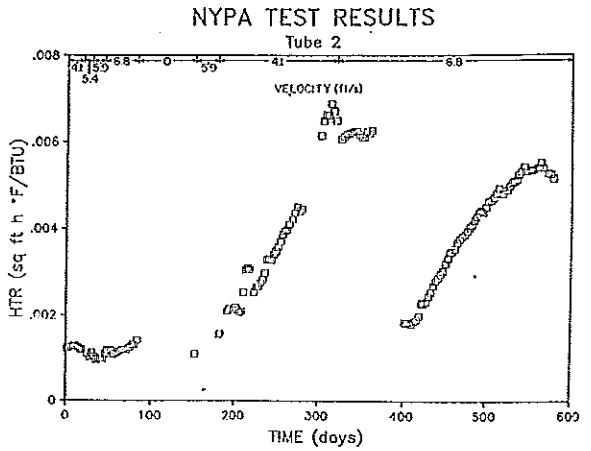


Figure 2. Progression of Heat Transfer Resistance (OHTR) in Tube 2 (titanium), operated at velocities consistent with plant operation.

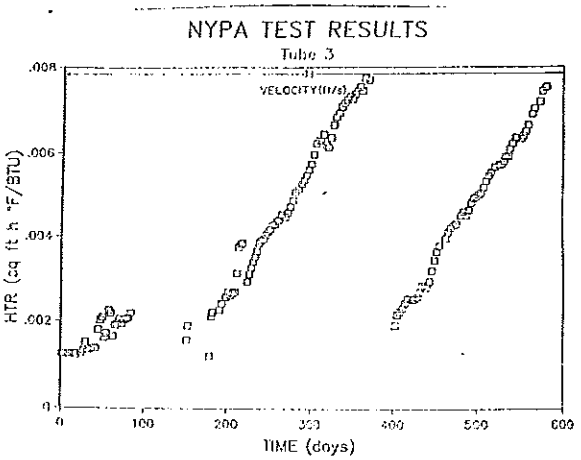


Figure 3. Progression of Heat Transfer resistance (OHTR) in Tube 3 (titanium) operated at constant velocity = 4.1 ft/sec.

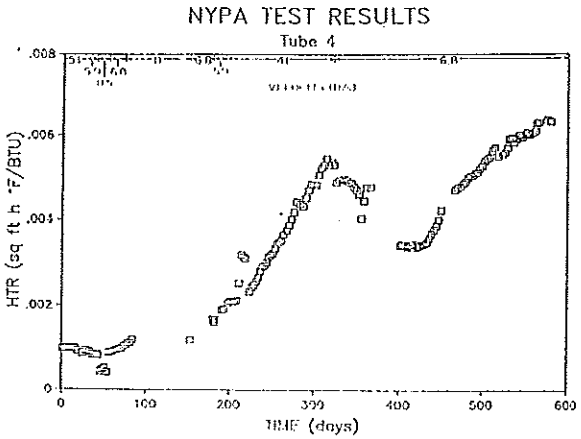


Figure 4. Progression of Heat Transfer Resistance (OHTR) in Tube 4 (admiralty brass), operated at velocities consistent with plant operation.

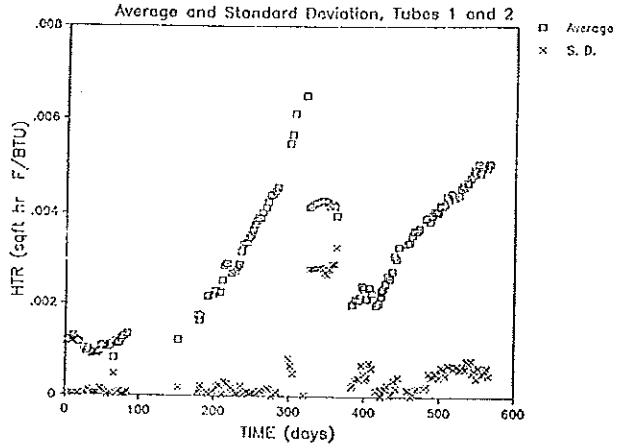


Figure 5. Average and standard deviation for heat transfer resistance (OHTR) measurements from Tubes 1 and 2 which were operated as replicates.

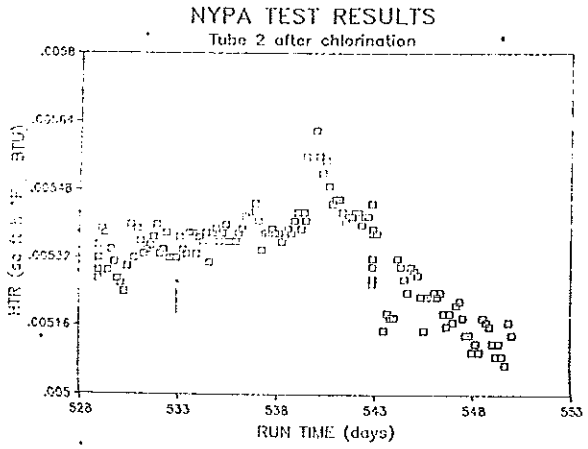
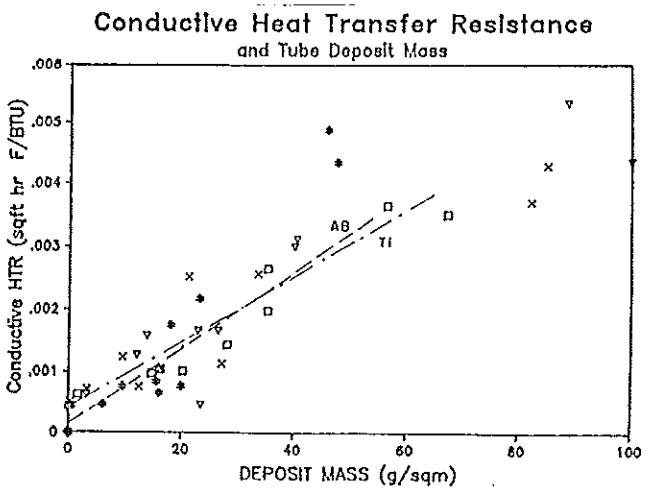


Figure 6. The influence of daily chlorine treatment on heat transfer resistance in Tube 2 (titanium). The arrow indicates the beginning of chlorine treatment. Tube 2 was operated at a constant velocity of 6.8 fps during the chlorine treatment period.



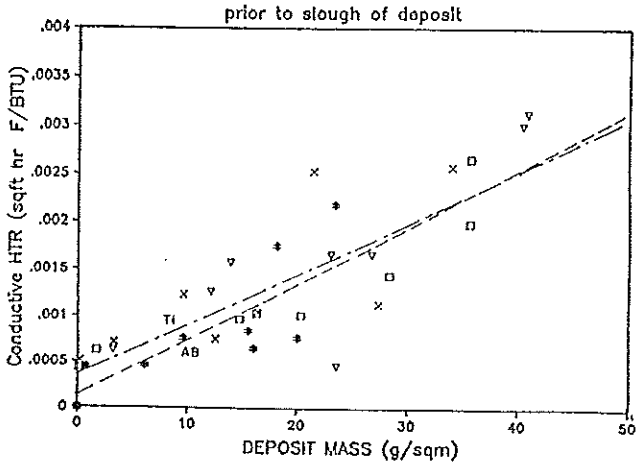


Figure 7. Conductive Heat Transfer Resistance and Tube Deposit Mass on NYPA fouling monitor tubes. Lines show results of linear regression for each tube material: (---) admiralty brass, from Tube 4 (#), and (- -) titanium, from Tube 1 (□), Tube 2 (X), and Tube 3 (▽). a) entire data set, b) data collected prior to slough (note change in scale).

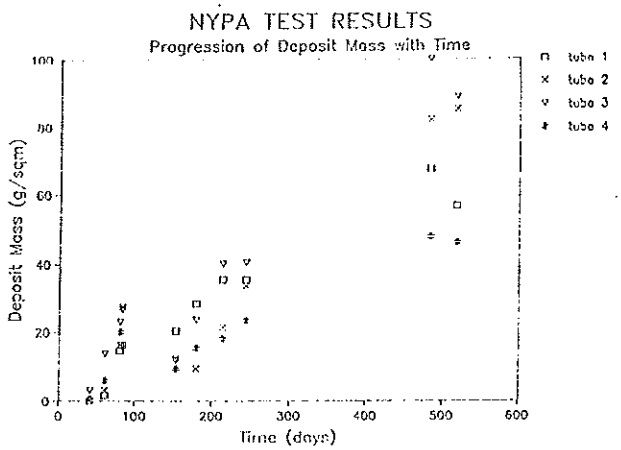


Figure 8. Progression of Deposite Mass in NYPA Fouling monitors.

Table 1. Summary of initial experimental conditions and maximum values observed for major experimental variables. Testing began on 27 April 1985. All data for all tubes were obtained at a fluid flow velocity of 4.1 fps. Heat transfer resistance data is reported as ft^2 h F BTU^{-1}.

Tube No.	1	2	3	4
Alloy	Ti	Ti	Ti	Admiralty
Tube Radius (in)	0.475	0.475	0.475	0.425
Conductive Heat Transfer Resistance - alloy	2.12E-4	2.12E-4	2.12E-4	0.96E-4
Heat Transfer Resistance of Contact	6.49E-4	6.83E-4	6.27E-4	5.19E-4
Overall Heat Transfer Resistance at 0 Days	11.4E-4	12.3E-4	12.3E-4	9.8E-4
Friction Factor at 0 Days	2.46E-2	2.46E-2	2.18E-2	1.46E-2
Maximum Overall OHTR at 310 Days	59.0E-4	64.0E-4	79.0E-4	68.0E-4
Maximum Fouling Factor, R_f	48.0E-4	52.0E-4	67.0E-4	59.0E-4
Maximum Decrease in Heat Transfer Capacity (%)	81	81	85	87
Friction Factor at 310 days	0.063	0.049	0.047	0.050
Maximum Deposit Mass at 480 days (g m^{-2})	67.5	82.3	100.0	48.0
Volatile solids (ave) (% deposit mass)	18.7	17.4	16.5	15.1
Total Carbon (ave) (% deposit mass)	6.32	6.23	5.77	5.42
Total Nitrogen (ave) (% deposit mass)	0.73	0.78	0.75	0.62

Table 2. Average and Standard Deviation of Deposit Composition Analyses, Fouling Monitors at IP3.

		Average (standard deviation)			
Tube #	Material	% volatile solid	%C	%N	C:N
1	Ti	18.7 (1.6)	6.32 (.75)	.73 (.14)	8.7
2	Ti	17.4 (2.6)	6.23 (.66)	.78 (.23)	8.0
3	Ti	16.5 (2.2)	5.77 (.84)	.75 (.17)	7.7
4	Adm.Brass	15.1 (2.5)	5.42 (.49)	.62 (.24)	8.7

Table 3. Summary of analyses on deposits removed from IP3 titanium condenser tubes after six months of operation.

Sample no.	Deposit Mass (g/m^2)	% volatile solids	%C	%N
1	97.7	15.1%	4.83%	.45%
2	40.1	17.1%	5.70%	.75%
3	112.6	9.9%	4.93%	.59%
4	80.2	15.0%	4.89%	.60%
5	74.1	13.3%	2.55%	.29%
6	63.5	14.1%	4.60%	.56%
7	81.2	12.5%	4.60%	.54%

Table 4. Comparison of deposit analyses conducted on fouling monitors untreated tubes at NYPA IP3 and two other power plant sites (A & B).

Time (Days)	Tube Material	Deposit Mass (g/m^2)	Volatile Fraction	%C	%N	%H
			NYPA PROJECT			
40	Titanium	1.15	6.28	4.07	0.41	1.27
61	Titanium	6.30	13.45	5.55	0.75	1.35
			PROJECT A			
35	Titanium	14.89	26.65	9.50	0.03	1.43
62	Titanium	37.79	26.70	10.03	1.02	1.85
			PROJECT B			
	Admiralty Brass	7.77		14.07	0.55	2.59
			NYPA PROJECT			
	Admiralty Brass	6.10		4.92	0.61	1.19