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TUBE MATERIAL, FLUID VELOCITY, SURFACE TEMPERATURE AND FOULING: A Field Study

by

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ABSTRACT

The purpose of this investigation was to determine the rate and extent of fouling in replacement heat exchanger tubing, AL-6X stainless steel, in the Reactor Containment Fan Cooler (RCFC) system of a 1000 megawatt nuclear pressurized water reactor. Fouling of the AL-6X stainless steel tubing was compared to fouling of the original 90:10 copper-nickel tubing using a fouling monitor system with four heat exchanger tubes. The fouling monitor is designed to continuously simulate a heat exchanger and calculate heat transfer and fluid frictional resistances. Fouling is indicated by change in heat transfer resistance and frictional resistance. Analysis of deposit mass is used as a direct measurement of the extent of fouling. The influence of tube alloy (stainless steel versus copper-nickel) and flow velocity on fouling was investigated by varying these parameters between the four fouling monitor tubes. Also, the influence of tube wall temperature was examined by comparing deposit mass on heated sections of tubing to deposit mass of unheated sections.

Results of heat transfer resistance measurements, for the conditions of this investigation, indicate the 90:10 copper-nickel had a lower rate of fouling compared to the AL-6X stainless steel. Rate of fouling in the copper-nickel was half that of the stainless steel. Furthermore, deposit mass analyses showed copper-nickel to have 28 to 54 percent less deposit than the stainless steel. A comparison of operating flow velocities between 1.7 fps and 1.0 fps showed the lower velocity tube fouled at a rate 3 times greater than the higher velocity tube. The influence of flow velocity was also indicated by an intentional and temporary (one hour) flow excursion when flow was increased to 5.5 fps. The flow excursion showed an immediate reduction in heat transfer resistance of 30 to 34 percent. Furthermore, 58 days after the flow excursion, the stainless steel tube exposed to the 5.5 fps velocity had a heat transfer resistance which was 1.5 times lower than a comparable tube without a flow excursion. Fouling deposit analyses indicate a deposit composition of 87 percent inorganic silt debris and 13 percent organic material. In general, the sections of tubing with surface temperature maintained at 95°F accumulated more deposit compared to the unheated sections of tubing.

INTRODUCTION

Fouling is the undesirable formation of inorganic and/or organic deposits on surfaces. These deposits can impede the flow of heat across the surface, increase the fluid frictional resistance at the surface, and influence chemical reactions at the surface which affect rate of corrosion or erosion. Typically, fouling deposits develop from a combination of several fouling processes occurring simultaneously. These may include: (1) crystalline or precipitation fouling, (2) corrosion and erosion fouling, (3) particulate or sedimentation fouling, or (4) biological fouling or biofouling. The purpose of this field study was to evaluate the fouling potential of replacement heat exchanger tubing, AL-6X stainless steel, in the Reactor Containment Fan Cooler (RCFC) system of a 1000 megawatt nuclear pressurized water reactor. Specifically, fouling of the stainless steel tubing was compared to fouling of the original 90:10 copper-nickel tubing. In addition to the influence of tube alloy on fouling, several other factors affecting fouling were investigated: (1) difference in operating flow velocity, (2) a sudden and temporary flow increase (flow excursion), and (3) difference in tube wall surface temperature.

The Problem

The RCFC system is designed, primarily, as a stand-by heat exchanger to control reactor containment temperature, pressure, and humidity following a Loss of Coolant Accident (LOCA). During LOCA conditions, the RCFC system is designed for a flow velocity of 5.5 fps through the new, AL-6X stainless steel, heat exchanger tubes. A secondary design function of the RCFC system is to operate at a normal flow velocity of 1.7 fps to provide day-to-day cooling of the reactor containment building. Service water for the RCFC system is brackish but varies in salinity with tidal changes, rainfall, and runoff. Water temperature varies from 35°F to 80°F seasonally. Normal service water flow velocity through the original copper-nickel tubing was 1 fps with approximately 3 fps available during a LOCA.

Corrosion and erosion of the original copper-nickel RCFC tubing resulted in deterioration and the need for replacement. AL-6X, a high molybdenum content stainless steel, was chosen as replacement because of its resistance to corrosion and erosion. However, no information existed on the susceptibility of AL-6X stainless steel to fouling. Biological deposition or biofouling was a particular concern since copper-nickel tubing presumably inhibited biological activity due to "toxicity" of the copper. Thus, this fouling monitor study was initiated.

METHODS

Fouling Monitor

A schematic of the fouling monitor used in this study is shown in Figure 1. The fouling monitor was used to simulate the RCFC heat transfer and flow rates and to monitor the effects of the fouling deposit on heat transfer and fluid frictional resistance. The fouling monitor consists of two major components:

1. One or more *tube assemblies.* Each tube assembly includes a tube with ports for pressure drop measurement and an electrically-heated 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, in this case AL-6X or 90:10 copper-nickel with outside diameter of 0.625 in. and inside diameter of 0.565 in. The tube assembly also includes a flow meter, flow control valve, and bulk water temperature probes.

4. A *microcomputer* which calculates frictional resistance and heat transfer resistance. The microcomputer also controls flow rate and tube wall temperature. Output from the microcomputer is displayed on a video monitor and recorded on diskette. For this study, four parallel tube sections were operated simultaneously from one central microcomputer.

Fluid Frictional Resistance is determined by calculating friction factor (f) from flow velocity and pressure drop as follows:

$$f = 2.0 \frac{d\Delta P}{L\rho_w V^2}$$

where d	=	tube diameter	(L)
ΔP	=	pressure drop	$L(ML^{-1}\ t^{-2})$
L	=	length between pressure ports	(L)
ρ_w	=	density of water	(ML^{-3})
V	=	flow velocity	$(L\ t^{-1})$

Fluid frictional resistance provides information on rate and extent of fouling and provides an indication of the surface roughness imparted by the fouling deposit. Frictional resistance is also used in determining convective heat transfer resistance. A detailed discussion on fouling and fluid frictional resistance is given by Picologlou *et al.* (1980).

Heat Transfer Resistance at the tube outside wall is calculated from temperature and heat flux measurements as follows:

$$\text{Heat Transfer Resistance} = \frac{T_{ow} - T_f}{q}$$

where T_{ow}	=	temperature at outside tube wall	(T)
T_f	=	temperature of fluid inside the tube	(T)
q	=	heat flux	$(M\ t^{-3})$

Heat transfer resistance is the sum of two types of heat transfer resistance:

$$\text{Heat Transfer Resistance} = \text{Convective Heat Transfer Resistance} + \text{Conductive Heat Transfer Resistance}$$

Convective heat transfer resistance can be calculated from friction factor by the Colburn Analogy (Colburn, 1933) as follows:

$$\text{Convective Heat Transfer Resistance} = \frac{8\,\mu^{0.67}}{\rho v f\, Cp^{0.33}\, k^{0.67}}$$

where μ = dynamic viscosity $(ML^{-1}\ t^{-1})$
ρ = fluid density (ML^{-3})
v = fluid velocity $(L\ t^{-1})$
f = friction factor
Cp = specific heat of fluid $(L^2\ t^{-2}\ T^{-1})$
k = thermal conductivity of fluid $(ML^{-3}\ T^{-1})$

Conductive heat transfer resistance can be calculated by the difference between heat transfer resistance and convective heat transfer resistance. A detailed discussion of fouling and heat transfer resistance is presented by Characklis *et al.* (1981).

For this study, the four tube fouling monitor was installed in a sidestream of the RCFC so that cooling water passed through each of the four tubes. Three AL-6X stainless steel tubes and one copper-nickel tube were operated from a central microcomputer.

Operating Conditions

All four tubes were operated with an inside tube wall temperature of 95°F. This temperature was considered within the operating range of the RCFC system and was specifically chosen to maximize biofouling as indicated by previous studies. All four tubes received the same water supply which varied both seasonally and daily in salinity, turbidity, and temperature. However, there was no apparent variation in water quality between tubes. Influent water temperature varied from approximately 38°F in February to 75°F in June.

The four tubes were operated with the following differences in tube alloy, flow velocity, and periodic flow excursion:

Tube	Alloy	Flow Velocity	Flow Excursion
1	AL-6X	1.7 fps	5.5 fps quarterly
2	AL-6X	1.0 fps	5.5 fps quarterly
3	90:10 CuNi	1.7 fps	5.5 fps quarterly
4	AL-6X	1.7 fps	none

Data Recording

Data were stored continuously by the microcomputer and then averaged every four hours. The four hour averages were recorded on diskette and later transcribed for plotting and printing.

Analysis of Deposit Composition

After the test, the fouled heat exchanger tubes were (1) removed from the fouling monitor, (2) drained on end for 30 minutes, and (3) air dried. These tubes were separated into heated and unheated sections. The heated section consisted of the length of tubing in the heat exchanger. Heat was controlled to maintain inner wall temperature at 95°F. The unheated section consisted of a 25 cm length of tubing just upstream of the heated section. The heated and unheated sections were subjected to the following analyses:

Total Dry Mass and Volatile Mass

Samples were scraped into clean, pre-ignited and weighed crucibles using a rubber policeman and distilled water. The samples were evaporated to dryness at 220°F and then further dried for two hours. The crucibles were then weighed to obtain total mass. A portion of each sample was removed for elemental analysis (C, H, N, O) and the crucibles reweighed. The samples were then ignited at 1,020°F for 90 minutes, cooled, and weighed again to obtain non-volatile or fixed solids.

RESULTS

Heat Transfer Resistance

Figure 2 is a plot of the heat transfer resistance measured in tube 1 (AL-6X, 1.7 fps) for the entire data collection period. This figure represents data averaged every 32 hours and illustrates the type of data available from the fouling monitor. The figure is divided into two periods:

1. The first period consists of data collected before treatment on day 82 consisting of a simulated LOCA flow condition (flow increased to 5.5 fps for one hour).

2. The second period consists of data collected after the treatment on day 82 up to day 140 when the test ended.

First Period

The first 82 days of heat transfer resistance in tubes 1 (AL-6X), 3 (Cu-Ni) and 4 (AL-6X), operated at a flow velocity of 1.7 fps, are shown in Figure 3. During this period influent water temperature dropped linearly from 70°F to 54°F. Figure 3 also indicates the best fit lines from linear regressions. Tubes 1 and 4 were operated as replicates during this period. Table 1 summarizes the data for this period which, at the 95 percent confidence level, indicate the following:

1. The day 0 intercepts of the replicate AL-6X tubes (tubes 1 and 4) are significantly different but differ by less than 12 percent.

2. There is no significant difference between the day 82 intercepts of the replicate AL-6X tubes (tubes 1 and 4).

3. The day 0 intercept of the copper-nickel tube (tube 3) is 32 percent lower than the average intercept of the two AL-6X replicates at day 0.

4. The day 82 intercept of the copper-nickel tube is 38 percent lower than the average intercept of the two AL-6X replicates at day 82.

5. The slopes of the best fit lines for tubes 1, 3 and 4 are significantly different. However the slopes of the two replicate AL-6X tubes differ by less than 13 percent while the slope of the best fit line for the copper-nickel tube is 38 percent below the average of the slopes of the two replicates.

Fouling Factors for each tube at day 82 can be determined by subtracting the intercept for that tube of the best fit line at day 0 from the intercept of the same line at day 82. The results are as follows:

Tube 1 (AL-6X) Fouling Factor[1] = 0.00353 Ft^2 °F hr BTU^{-1}

Tube 3 (CuNi) Fouling Factor = 0.00237 Ft^2 °F hr BTU^{-1}

Tube 4 (AL-6X) Fouling Factor = 0.00401 Ft^2 °F hr BTU^{-1}

Data in Table 1 for tube 2 (AL-6X, 1.0 fps) indicate the following:

1. The day 0 intercept for tube 2 is 10 percent greater than the day 0 intercept for the average of the AL-6X tubes at the high flow velocity (1.7 fps).

2. The day 82 intercept for tube 2 is 2 percent greater than the day 82 intercept for the average of the AL-6X tubes at the high flow velocity (1.7 fps).

3. The slope of the best fit for tube 2 is 10 percent lower than the average of the slopes of the AL-6X tubes at the high flow velocity (1.7 fps).

The Fouling Factor for tube 2 at day 82, calculated by the same method as for tubes 1, 3 and 4, is 0.00346 Ft^2 °F hr BTU^{-1}.

First Period Flow Excursion

On day 82, flow velocity excursions to 5.5 fps were conducted on tubes 1, 2 and 3 to determine the effect of LOCA test flows on the accumulated fouling deposits. Tube 4 was operated as a control and was not subjected to a flow excursion. Figure 4 shows high resolution plots (data averaged every four hours) of heat transfer resistance before and after the flow excursion. The results indicate the following:

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[1] Ft^2 °F hr BTU^{-1} = 0.1761 m^2 °C $watt^{-1}$

1. The tubes with flow excursions (1, 2, and 3) had a decrease in heat transfer resistance of 30 to 34 percent.

2. The control (tube 4) showed a 6 percent drop in heat transfer resistance over the same time period as the flow excursion test.

Second Period

The progression of heat transfer resistance during the period after the flow excursion (day 82 to day 140) for tubes 1 (AL-6X), 3 (Cu-Ni) and 4 (AL-6X), which were operated at a flow velocity of 1.7 fps, are shown in Figure 5. During this period, influent water temperature dropped from 54°F to 40°F. Figure 5 also indicates the best fit lines from the linear regressions. Tubes 1 and 4 were no longer operated as replicates after the flow excursion since tube 4 was not exposed to a flow excursion. Table 2 summarizes the data for this period which, at the 95 percent confidence level, indicate the following:

1. The intercepts of the best fit line at day 82 are significantly different for all three tubes. The highest 82 day intercept value is for the AL-6X tube which had no flow excursion (tube 4). The 82 day intercept for the AL-6X tube which had a flow excursion (tube 1) is 18 percent below the value for the control tube (tube 4). The 82 day intercept for the copper-nickel tube which had a flow excursion was 27 percent below the value for the AL-6X tube which had a flow excursion (tube 1).

2. The intercepts at day 140 for all three tubes are also significantly different. The highest 140 day intercept value is for the AL-6X tube which had no flow excursion (tube 4). The 140 day intercept for the AL-6X tube which had a flow excursion (tube 1) is 17 percent below the value for the control tube (tube 4). The 140 day intercept for the copper-nickel tube which had a flow excursion was 34 percent below the value for the AL-6X tube which had a flow excursion (tube 1).

4. The slopes of the best fit lines for all three tubes are significantly different. The slope of the AL-6X tube which was exposed to a flow excursion (tube 1) was 15 percent lower than the slope of the AL-6X tube which had no flow excursion (tube 4). The slope of the best fit line for the copper-nickel tube is 49 percent lower than the slope of the AL-6X tube which was exposed to the flow excursion (tube 1).

Fouling Factors for each tube at day 140 can be determined by subtracting the intercept for that tube of the best fit line at day 0 (Figure 3) from the intercept of the same tube at day 140 (Figure 5). The results are as follows:

Tube 1 (AL-6X) Fouling Factor = 0.00375 Ft^2 °F hr BTU^{-1}

Tube 3 (CuNi) Fouling Factor = 0.00258 Ft^2 °F hr BTU^{-1}

Tube 4 (AL-6X) Fouling Factor = 0.00591 Ft^2 °F hr BTU^{-1}

Data in Table 2 for tube 2 (AL-6X, 1.0 fps) indicate the following:

1. The intercept of the regression line of heat transfer resistance for tube 2 at day 140 is 43 percent greater than for the AL-6X tube operated identically except for a flow velocity of 1.7 fps (tube 1).

2. The slope of the best fit line for tube 2 is 64 percent greater than the slope of the AL-6X tube operated identically except for a flow velocity of 1.7 fps (tube 1).

The Fouling Factor for tube 2 at day 140, calculated by the same method as for tubes 1, 3 and 4, is 0.00953 Ft^2 °F hr BTU^{-1}. Figure 6 presents a comparison of the progression of transfer resistance in tube 2 (AL-6X, 1.0 fps) between the first and second periods. The slope of the best fit line during the second period is 68 percent greater than for the first period.

Frictional Resistance

Figure 7 presents a comparison of the progression of heat transfer resistance to frictional resistance in tube 3 (CuNi, 1.7 fps). This figure illustrates the good correlation between the two indicators of fouling.

Deposit Analyses

Deposit Mass. The results of deposit mass analyses are summarized in Table 3 and Figure 8. These results indicate the following:

1. Total mass on the heated portion of the heat transfer tubes was greatest for the two AL-6X tubes operated at a flow velocity of 1.7 fps (tubes 1 and 4). Tube 1 yielded 49.6 g m^{-2} (0.01 lbm ft^{-2}) and tube 4 yielded 45.5 g m^{-2} (0.009 lbm ft^{-2}).

2. Total mass on the AL-6X tube operated at a flow velocity of 1.0 fps (tube 2) was 26 percent lower than the average of tubes 1 and 4. Tube 2 yielded 35.3 g m^{-2} (0.007 lbm ft^{-2}).

3. Total mass on the copper-nickel tube (tube 3) was 52 percent lower than the average of tubes 1 and 4. Tube 3 yielded 22.7 g m^{-2} (0.005 lbm ft^{-2}).

4. Tubes 1, 3 and 4 yielded from 32 to 57 percent less total mass on the unheated portion of the heat transfer tubing compared to the heated section. In contrast, tube 2 had 21 percent less solids on the heated section compared to the unheated section of tubing.

5. Volatile solids represented an average of 12.2 percent (1.8 percent standard deviation) of the total solids for all samples. At the 95 percent confidence level, there was no significant difference in the percent volatile composition between the heated and unheated sections of tubing.

DISCUSSION

Extent of Fouling

The extent to which each tube fouled is indicated by several factors: (1) maximum heat transfer resistance compared to the heat transfer resistance of the initial clean tube condition (fouling factor) and (2) accumulated deposit mass at the experiment end. Results of these measurements suggest the following:

1. The tube alloy influences fouling rate. The extent of fouling was lowest on the copper-nickel surface (tube 2). Fouling factor for the copper-nickel tube was 0.00258 Ft^2 °F hr BTU^{-1} on day 140 compared to 0.00375 Ft^2 °F hr BTU^{-1} for the AL-6X tube operated under identical conditions (tube 1). Furthermore, the copper-nickel tube yielded the lowest deposit mass of any of the tubes (Table 3). The heated copper-nickel tube section had less than half the mass on the heated AL-6X tube operated under identical conditions. The unheated tubing sections also showed copper-nickel to have less deposit mass.

2. Flow velocity influences fouling rate. The AL-6X tube at the lowest velocity (tube 2 at 1.0 fps) fouled to the greatest extent. At day 140, the fouling factor for tube 2 (0.00953 Ft^2 °F hr BTU^{-1}) was 2.5 times greater than for tube 1 (0.00375 Ft^2 °F hr BTU^{-1}) operated at a higher flow velocity of 1.7 fps. Although the heated section of tube 2 yielded less deposit mass compared to the heated tube 1 section, the unheated samples show tube 2 had approximately twice the deposit mass as tube 1.

3. The LOCA condition flow excursion on day 82 had an immediate effect of the extent of fouling. Figure 4 indicates heat transfer resistance dropped 30 to 34 percent for tubes 1, 2 and 3 which were exposed to the LOCA flow velocity of 5.5 fps.

4. The LOCA condition flow excursion on day 82 also had a long term impact on the extent of fouling. A comparison at day 140 of tube 1 which was exposed to the 5.5 fps flow to tube 4 which was operated identically but was not exposed to the flow excursion shows the fouling factor for tube 1 (0.00375 Ft^2 °F hr BTU^{-1}) to be 1.5 times lower than for tube 4 (0.00591 Ft^2 °F hr BTU^{-1}).

5. Tube wall temperature significantly affects fouling rate. In general, deposit mass analyses indicate a much greater extent of fouling on the heated section of a tube compared to the unheated section. The heated sections of the AL-6X tubes operated at 1.7 fps (tubes 1 and 4) had approximately twice the mass of the unheated sections of the same tubes (Table 3). The copper-nickel tube also had more mass on the heated section compared to the unheated section. This implies that an unheated tube for a fouling monitor may not provide an accurate assessment of fouling deposition.

Rate of Fouling

Rate of fouling is indicated by the progression of heat transfer resistance for each tube. For tubes 3 and 4, the progression of frictional resistance is also available. These results indicate the following:

1. Rate of fouling during the first 140 days was lowest in the copper-nickel tubing. Tables 1 and 2 show the rate increase in heat transfer resistance for the copper-nickel tube to be 1.5 to 2 times lower than the rate in the AL-6X tubes operated at identical conditions.

2. Rate of fouling increased with lower flow velocity. The rate of velocity AL-6X tube (tube 2, 1.0 fps) was 3 times greater during the second period compared to the AL-6X tube operated identically except for a higher flow velocity (1.7 fps).

3. The rate of fouling in the copper-nickel tube decreased from the first to the second period while all the AL-6X tubes had increased rates in fouling.

4. The LOCA condition flow excursion at day 82 resulted in a lower rate of fouling. This is indicated in Table 2 which shows the rate of change in heat transfer resistance for the AL-6X tube exposed to the flow excursion (tube 1) was 15 percent lower than the rate of change in the AL-6X tube not exposed to a flow excursion (tube 4).

5. The rate of change in fluid frictional resistance follows a progression parallel to heat transfer resistance although the data is more scattered. This is indicated by Figure 7 which presents a comparisons of heat transfer resistance and friction factor for tube 3.

Conductive and Convective Heat Transfer Resistance

Figure 9 presents the convective, conductive, and total heat transfer resistances in the copper-nickel tube (tube 3). These heat transfer resistances are apparently affected by the following phenomena:

1. The convective heat transfer resistance *decreases* with time as the accumulation of fouling deposit results in an effectively rougher surface and the heat transfer fluid becomes more turbulent.

2. The conductive heat transfer resistance *increases* with time as the deposit insulates the tube wall.

3. The total heat transfer resistance *increases* with time because the influence of the change in conductive heat transfer resistance is greater than the influence of the change in convective heat transfer resistance.

SUMMARY

The purpose of this investigation was to determine the fouling potential of replacement heat exchanger tubing, AL-6X stainless steel, in the Reactor Containment Fan Cooler (RCFC) system of a 1,000 megawatt nuclear pressurized water reactor. Specifically, the rate and extent of biological fouling or biofouling was investigated. Fouling of the AL-6X stainless steel was compared to fouling of the original 90:10 copper-nickel tubing using a fouling monitor with four heat exchanger tube assemblies. The fouling monitor system was used to simulate the RCFC operating conditions and to monitor the effects of fouling on heat transfer resistance and fluid frictional resistance. All four tubes received the same water as the RCFC system and were operated with an inside tube wall temperature of 95°F. The four tubes were operated with the following differences in tube alloy, flow velocity, and periodic flow excursion:

Tube	Alloy	Flow Velocity	Flow Excursion
1	AL-6X	1.7 fps	5.5 fps quarterly
2	AL-6X	1.0 fps	5.5 fps quarterly
3	90:10 CuNi	1.7 fps	5.5 fps quarterly
4	AL-6X	1.7 fps	none

Quarterly flow excursions were conducted on tubes 1, 2 and 3 on day 82 of the test. These flow excursions were intended to simulate the quarterly test of the Loss of Cooling Accident (LOCA) flow velocity of 5.5 fps since the higher flow rate was expected to shear off some of the fouling deposit.

Effect of Alloy on Fouling

For the operating conditions of this test, the 90:10 copper-nickel tubing fouled less than the AL-6X tubing operated under identical conditions. The extent of fouling as indicated by the fouling factor calculated on day 140 was 0.00258 Ft^2 °F hr BTU^{-1} for copper-nickel compared to a fouling factor of 0.00375 Ft^2 °F hr BTU^{-1} for the AL-6X. Another measurement of the extent of fouling, deposit mass, indicated 54 percent less deposit mass on the copper-nickel surface compared to the AL-6X for the heated sections of tubing and 28 percent less deposit mass on the copper-nickel when comparing the unheated tubing sections.

Rate of fouling, as indicated by the progression of heat transfer resistance, was also lower for the copper-nickel tube during the first 140 days compared to the AL-6X tubing operated under identical conditions. The rate of fouling for the copper-nickel tube was 1.5 to 2 times lower than the AL-6X tube. The copper-nickel tube showed a reduced rate of fouling during the period after the LOCA flow excursion test (day 82) compared to the rate prior to the flow excursion. In contrast, all three AL-6X tubes had increased fouling rates for the period after the LOCA flow excursion test compared to the period before the flow excursion.

Effect of Operating Flow Velocity on Fouling

A comparison of the AL-6X tubes operated at identical conditions except for flow velocity showed more fouling at the lower flow velocity. The AL-6X tube operated at 1.0 fps had a fouling factor at day 140 of 0.00953 Ft^2 °F hr BTU^{-1} compared to only 0.00375 Ft^2 °F hr BTU^{-1} for the AL-6X tube operated at 1.7 fps. Although the heated section of the 1.0 fps AL-6X tube yielded less deposit mass compared to the heated section of the 1.7 fps AL-6X tube, the unheated samples showed twice as much deposit mass on the low velocity tube. Rate of fouling during the first 82 days was approximately the same for the AL-6X tubes operated at different velocities. However, after the flow excursion, the rate of fouling in the tube operated at 1.0 fps was 3 times greater than the AL-6X tube operated identically except for a flow velocity of 1.7 fps.

The effect of flow velocity on fouling has been attributed to differences in fluid shear stress at the surface. Higher flow velocities are associated with greater fluid shear stress which can keep particles in suspension thereby reducing sedimentation fouling and detaching fouling deposits from the surface.

The Effect of the LOCA Test Flow Excursion on Fouling

All three tubes subjected to the simulated LOCA test flow excursion showed an immediate reduction in fouling of 30 to 34 percent as indicated by a reduction in heat transfer resistance. This effect is attributed to increased fluid shear stress at the higher velocity. The flow excursion also had a long term impact on the extent of fouling as indicated by a comparison of fouling factors between the AL-6X tube operated at 1.7 fps with a flow excursion and the AL-6X tube operated at 1.7 fps without a flow excursion. On day 140 the fouling factor for the tube which had been exposed to the flow excursion on day 82 had a fouling factor of 0.00375 Ft^2 °F hr BTU^{-1} which was 1.5 times lower than for the tube without the flow excursion.

The Effect of Surface Temperature on Fouling

For all tubes except the low velocity AL-6X tube, more fouling deposit accumulated on the heated (95°F) section of tubing compared to the unheated entrance section. The heated sections of the AL-6X tubes operated at 1.7 fps had approximately twice the deposit mass as the unheated sections of the same tubes. The greater deposit mass on the heated section may be attributed to increased microbial metabolism at the 95°F temperature. This result implies that monitoring of fouling with unheated tube sections may lead to inaccurate results.

Deposit Composition

The deposit was composed primarily of inorganic silt debris within a matrix of organic material. The organic material consisted of approximately 13 percent of total deposit mass as indicated by volatile mass analyses. Visual observations of all four tubes indicated more deposit mass on the bottom of the tube. This observation was most noticeable on the low velocity tube (1.0 fps) and was attributed to settling of silt debris and other particulate matter in the cooling water.

CONCLUSIONS

The following conclusions can be stated with the range of operating conditions tested in this investigation:

1. The 90:10 copper-nickel tubing fouled to a lesser degree compared to the AL-6X stainless steel tubing operated under identical conditions (flow velocity = 1.7 fps and

surface temperature = 95°F) as indicated by: (1) a lower rate of increase in heat transfer resistance, (b) a lower fouling factor on day 140, and (c) less deposit mass at the experiment end. Furthermore, the rate of fouling as indicated by progression of heat transfer resistance decreased in the copper-nickel tube with time while the three AL-6X tubes showed increase in rate of fouling. Although analyses of corrosion of the AL-6X stainless steel and 90:10 copper-nickel were not a part of this investigation, it should be noted that premature corrosion of the original copper-nickel tubing was the justification for changing to the new stainless steel tubing. Therefore, increased fouling in the stainless steel compared to the copper-nickel may be acceptable if fouling is maintained below the maximum design fouling factor and corrosion is less severe compared to the copper-nickel.

2. A higher operating flow velocity reduces fouling. A comparison of the AL-6X tubes operated at different flow velocities shows more fouling in the tube operated at the lower flow velocity of 1.0 fps compared to the tube operated at 1.7 fps.

3. The flow excursion is effective in reducing fouling. All three tubes which were subjected to the simulated LOCA test flow excursion showed immediate reduction of fouling of 30 to 34 percent as indicated by a reduction in heat transfer resistance. A comparison of the two AL-6X tubes which were operated identically (surface temperature = 95°F and velocity = 1.7 fps) except for the flow excursion showed that the extent of fouling in the tube which had a flow excursion remained lower for at least 60 days after the flow excursion.

4. The heated section of heat transfer tubing (surface temperature = 95°F) fouls more than the unheated section. For all tubes except the low velocity AL-6X tube 33 to 57 percent more fouling deposit had accumulated on the heated section compared to the unheated section.

5. The deposit was composed of only 13 percent organic material surrounded by inorganic silt debris.

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Table 1. Summary of Heat Transfer Resistance Data for First Period

Tube	Influent Water Temperature Day 0	Influent Water Temperature Day 82 (°F)	Slope Ft² °F hr BTU⁻¹ Days⁻¹ X 10⁵	Intercept Day 0 Ft² °F hr BTU⁻¹ X 10⁵	Intercept Day 82 Ft² °F hr BTU⁻¹ X 10⁵
1	70	54	4.30	4.30	7.8
2	70	54	4.22	4.49	8.0
3	70	54	2.90	2.75	5.1
4	70	54	4.88	3.80	7.8

Table 2. Summary of Heat Transfer Resistance Data for Second Period

Tube	Influent Water Temperature Day 0	Influent Water Temperature Day 82 (°F)	Slope Ft² °F hr BTU⁻¹ Day⁻¹ X 10⁵	Intercept Day 82 Ft² °F hr BTU⁻¹ X 10³	Intercept Day 140 Ft² °F hr BTU⁻¹ X 10³
1	54	40	4.79	5.2	8.0
2	54	40	13.20	6.4	14.0
3	54	40	2.46	3.8	5.3
4	54	40	5.61	6.5	9.7

Table 3. Analysis of Fouling Deposits

Tube	Heated	Total Solids (g m⁻²)	Volatile Solids	Organic Carbon	Nitrogen	Hydrogen
			Percent of total solids			
1	Y	49.6	14.1	5.0	0.36	1.17
2	Y	35.3	11.5	2.7	0.18	0.66
3	Y	22.8	12.7	5.0	0.29	1.05
4	Y	45.5	13.6	3.8	0.34	0.97
1	N	21.1	13.1	4.2	0.38	1.02
2	N	42.8	10.4	2.3	0.18	0.59
3	N	15.3	14.2	6.2	0.20	1.03
4	N	26.5	11.3	4.1	0.35	1.05

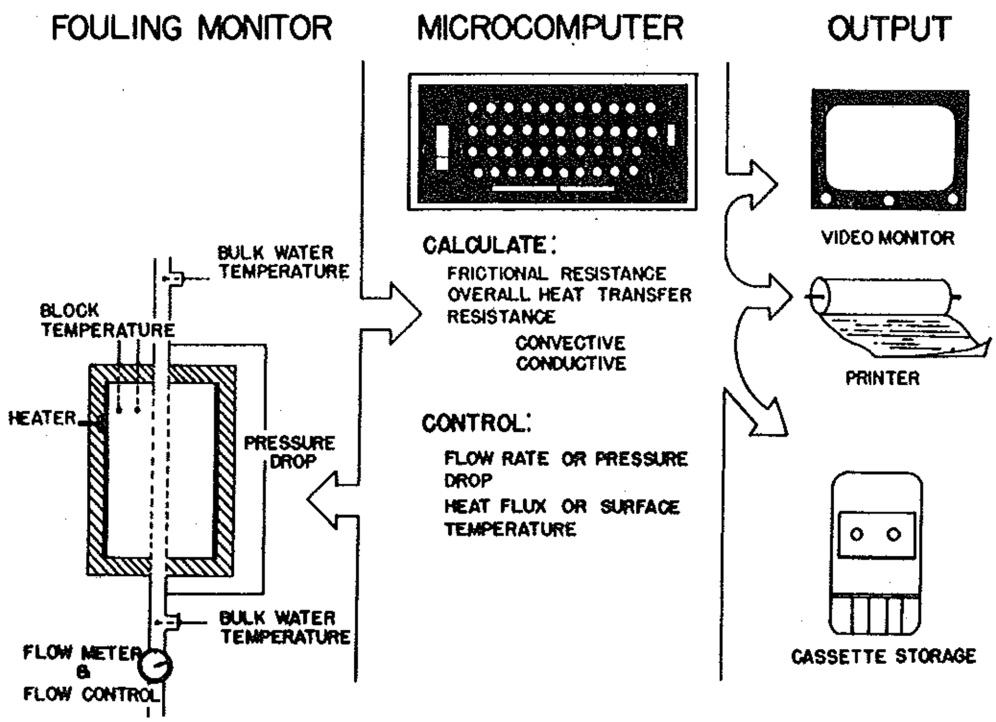

Figure 1. Schematic of Fouling Monitor System.

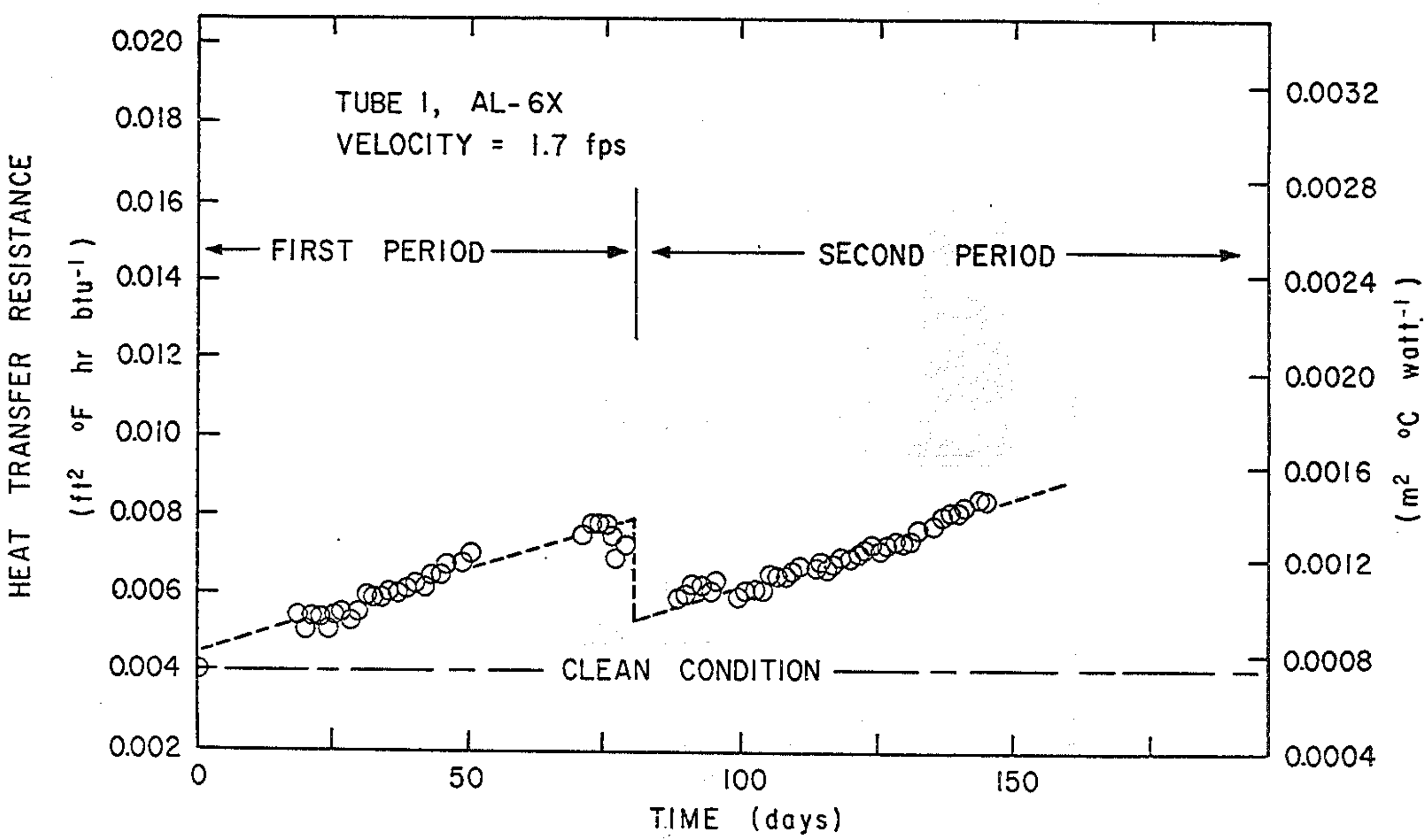

Figure 2. Progression of Heat Transfer Resistance in Tube 1 (AL-6X, 1.7 fps).

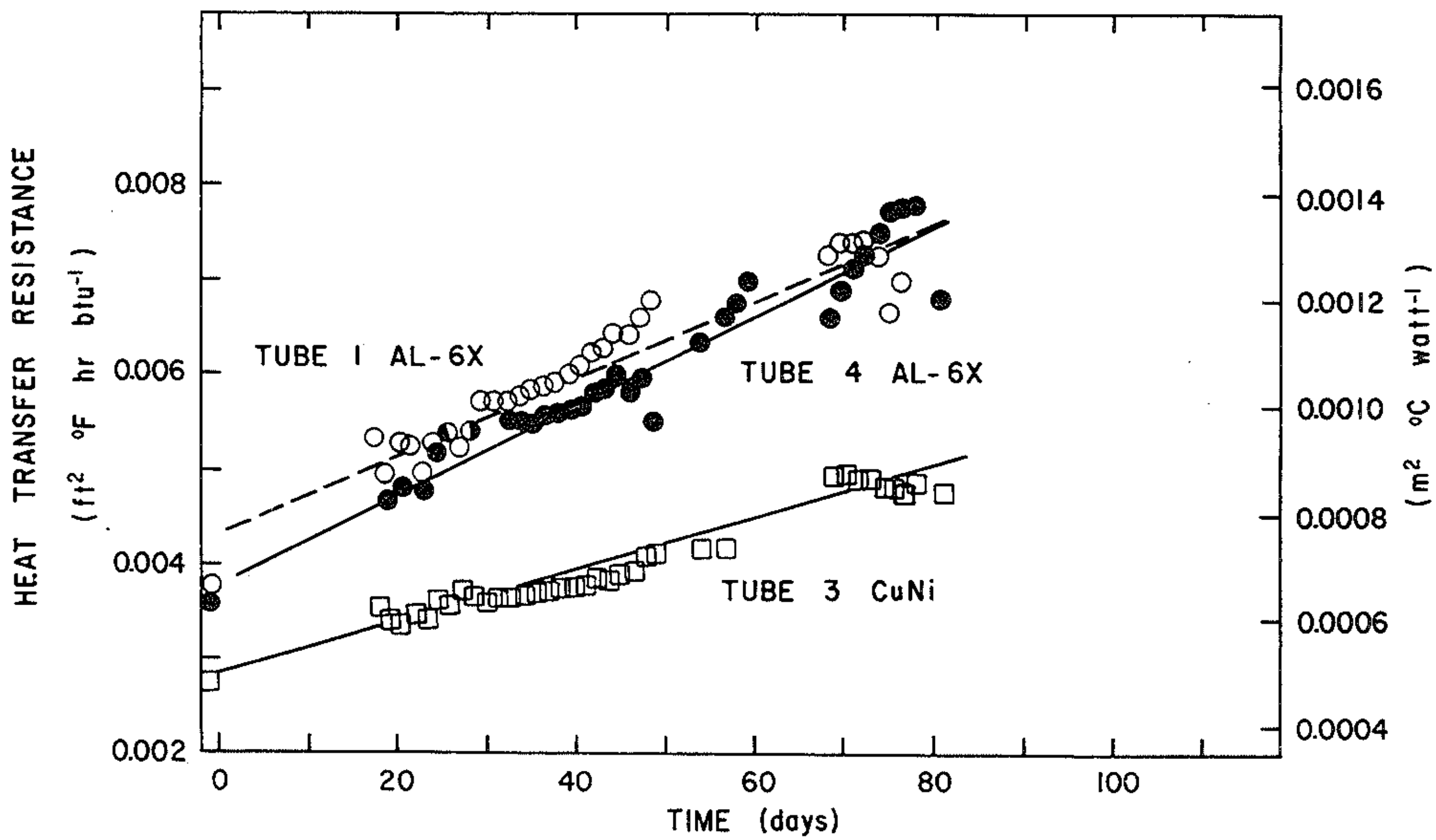

Figure 3. Heat Transfer Resistance in Tubes 1, 3, and 4 During the First Period. Fluid Velocity was 1.7 fps.

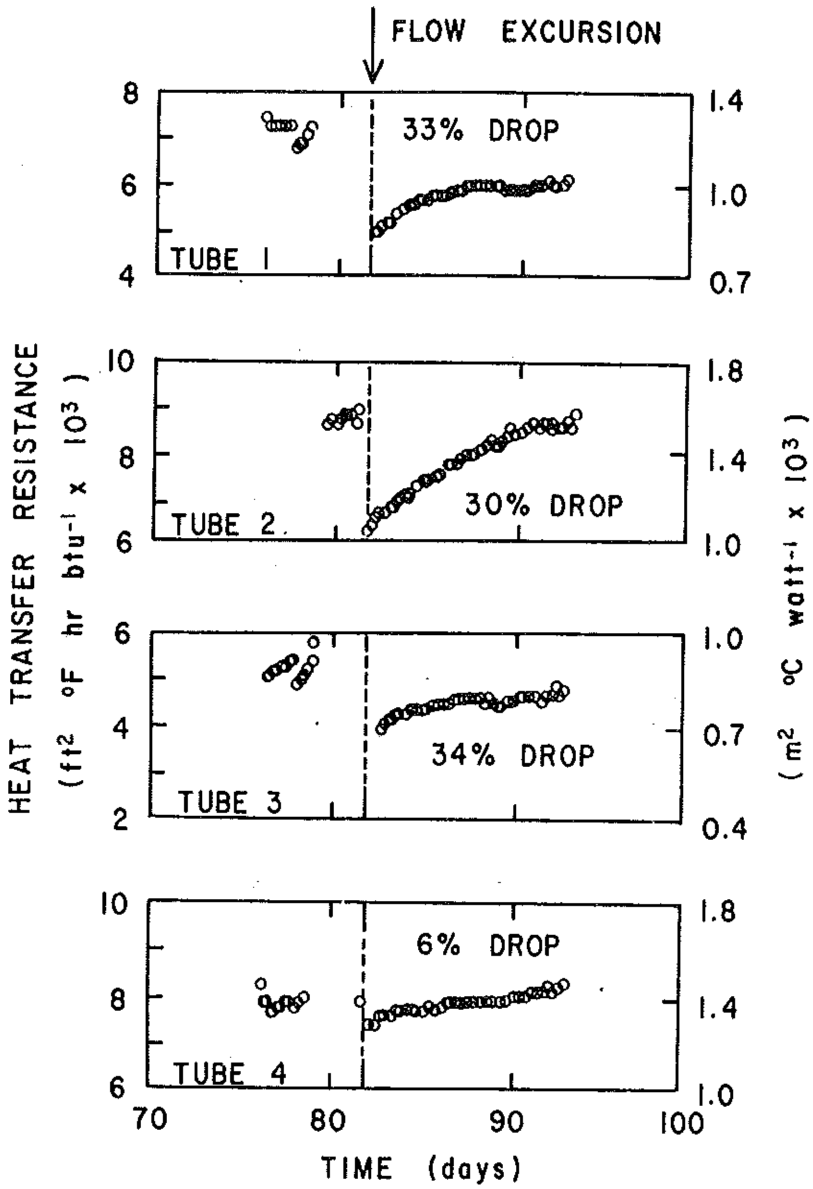

Figure 4. Progression of Heat Transfer Resistance Before and After the First Period Flow Excursion Performed on Day 82.

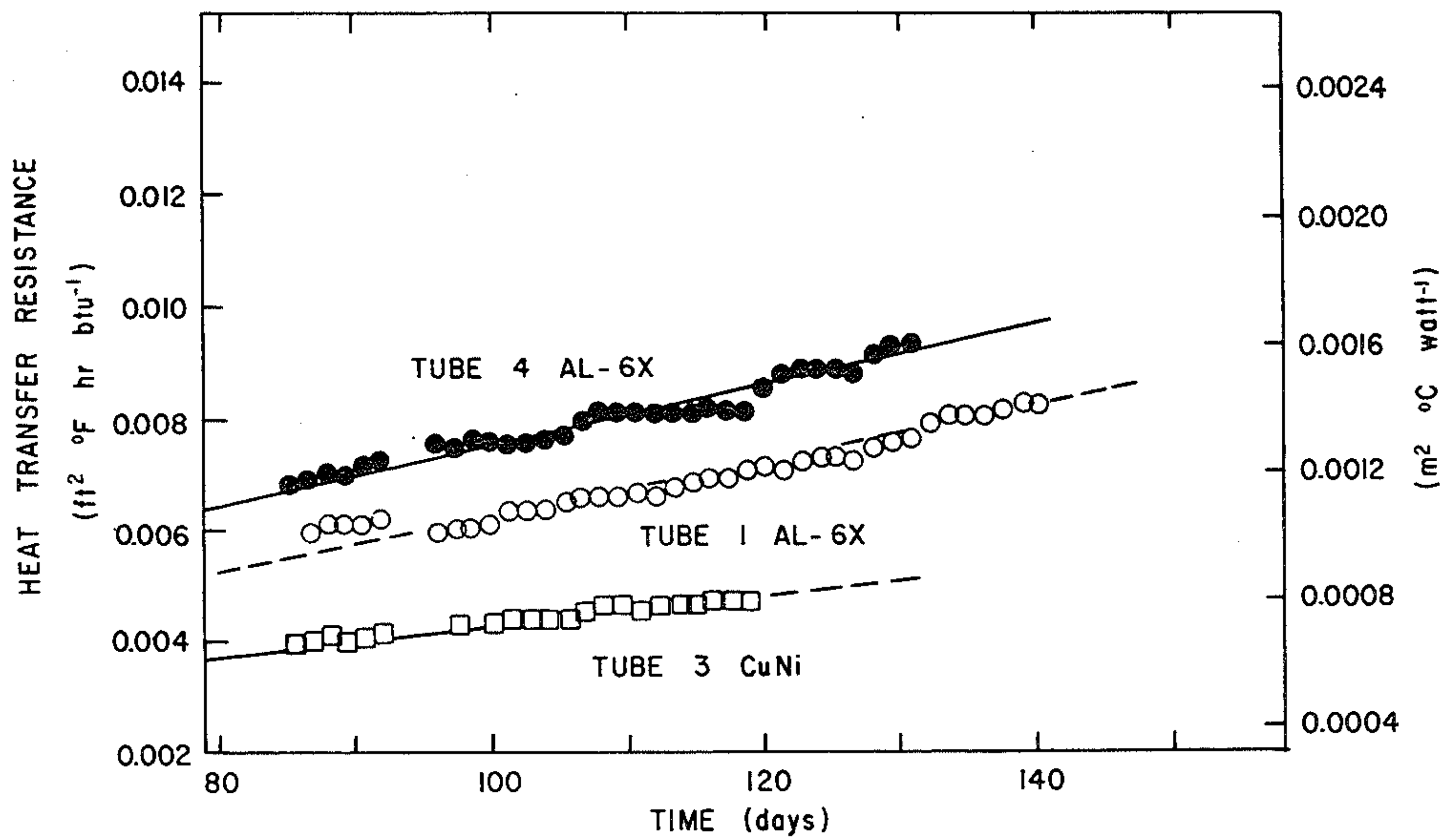

Figure 5. Heat Transfer Resistance for Tubes 1, 3, and 4 for the Second Period. Fluid Velocity was 1.7 fps.

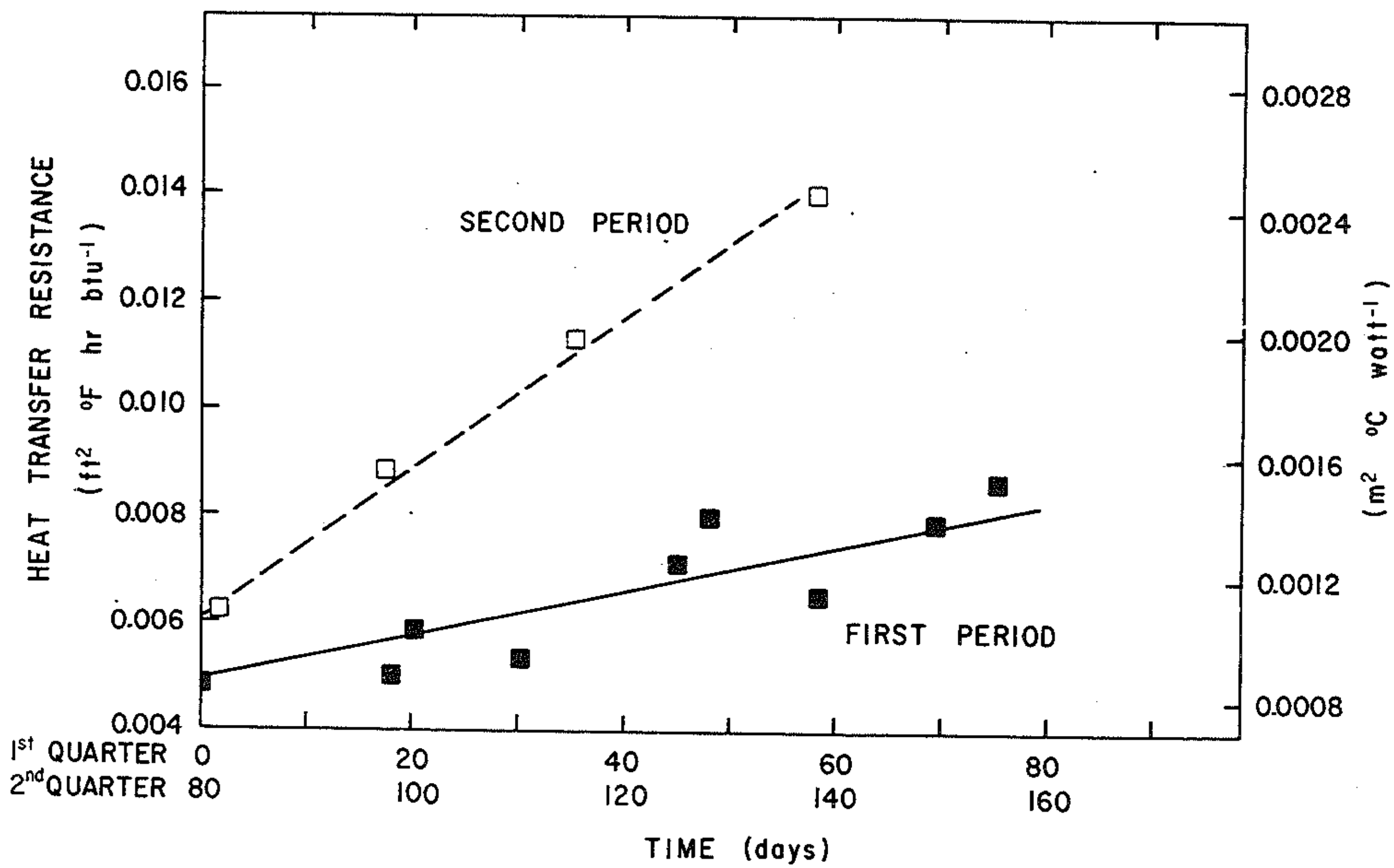

Figure 6. Comparison of Heat Transfer Resistance in Tube 2 (AL-6X, 1.0 fps) Between the First and Second Periods.

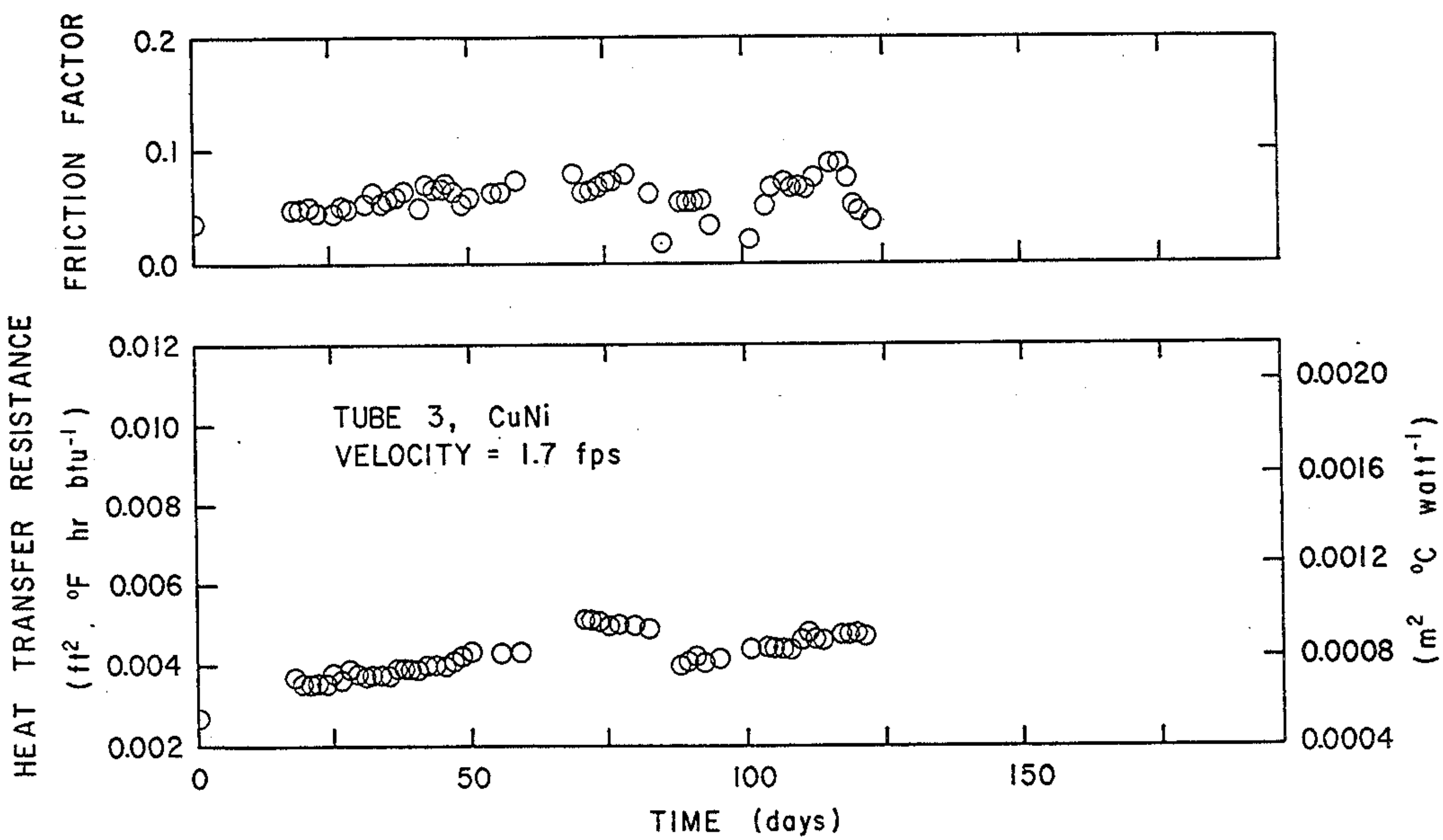

Figure 7. Comparison of Heat Transfer Resistance and Frictional Resistance for Tube 3 (CuNi, 1.7 fps).

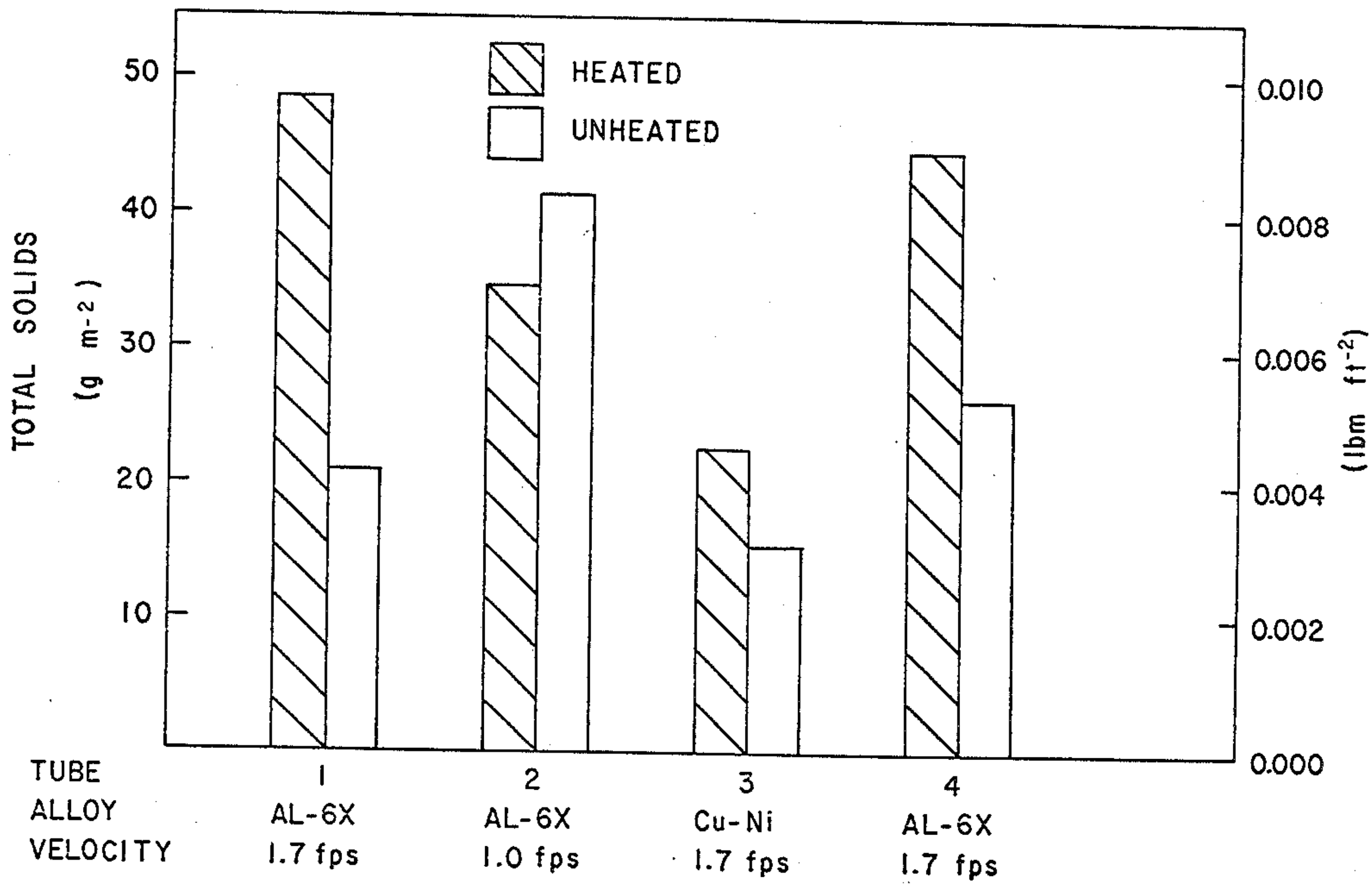

Figure 8. Deposit Mass on Heated (95°F) and Unheated Sections of Tubing.

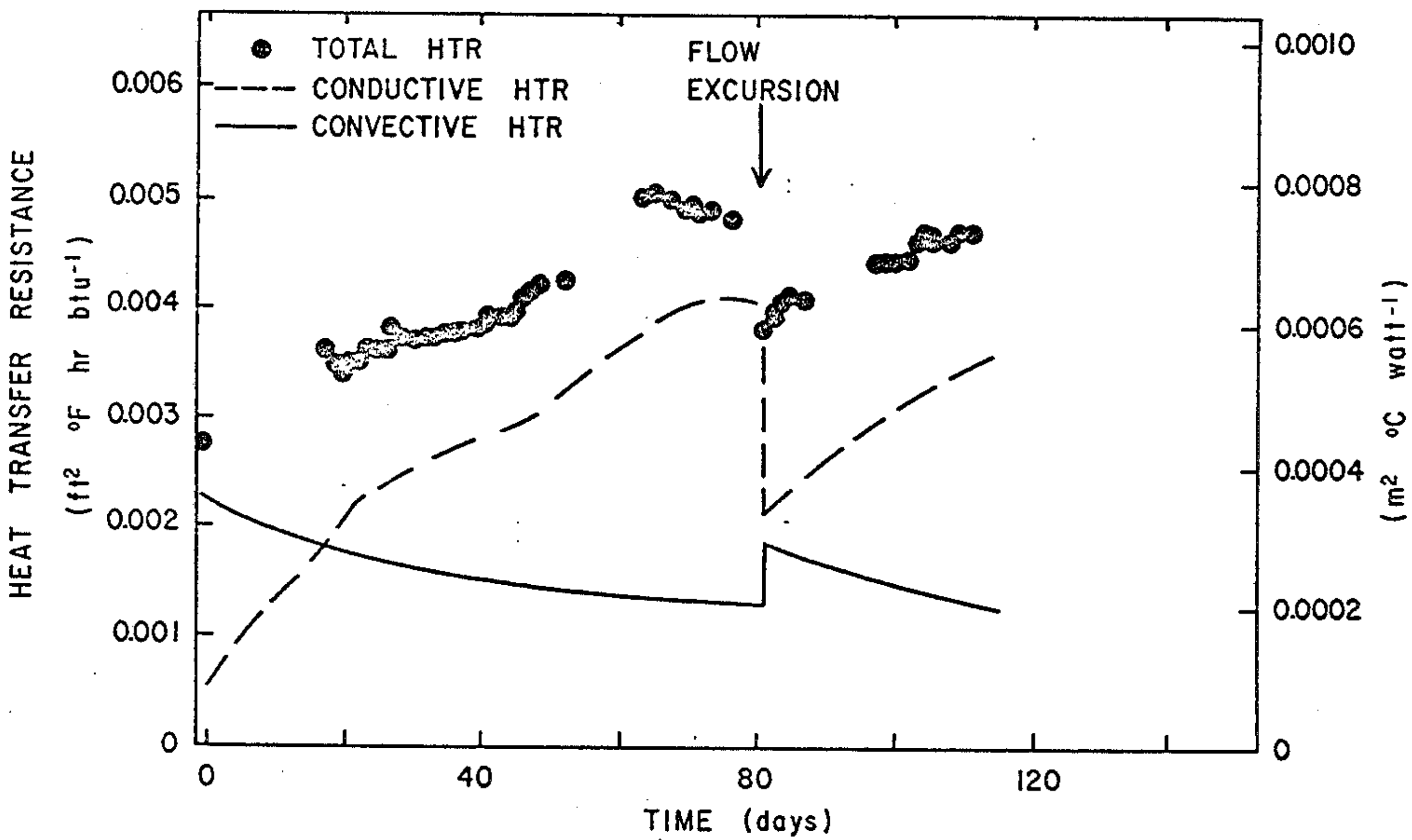

Figure 9. Progression of Convective and Conductive Components of Heat Transfer Resistance for Tube 3 (CuNi, 1.7 fps).