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Title: SURFACE TEMPERATURE EFFECTS ON THE FOULING CHARACTERISTICS OF COOLING WATER

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A cooling tower system was built and fouling resistances were studied for cooling water flowing over a heated tubular surface. The cooling water studied was formulated in an effort to match industrial cooling water quality. The water used in this study had an average Ryznar Stability Index of 6.23 and was formulated by adding calcium chloride and magnesium carbonate to tap water. Fouling resistance versus time was plotted for each experimental run, and the resulting curves indicate a close approximation to industrial conditions can be made in a laboratory environment. Fouling resistances were obtained at surface temperatures from 136°F to 199°F. The flow velocity and water quality were held constant during these runs. A correlation modeled after the Arrhenius temperature function was developed for surface temperature and asymptotic fouling resistance values. The model obtained has a correlation coefficient of .95 and a standard deviation of 4.08% for data obtained in this study. The Ryznar Stability Index proved to be a poor indicator of water fouling tendency with the cooling water used in the present study.

Surface Temperature Effects on the Fouling Characteristics of Cooling Water

by

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INTRODUCTION

In the area of heat transfer, fouling or scaling of heat transfer surface has been referred to as the "major unresolved area" (19). Scaling or fouling is known in the published literature to mean any undesirable deposit on heat transfer surfaces. The main types of fouling found in industry are chemical reaction deposits, crystallization, corrosion, and polymerization, which are described thoroughly by Taborek, et al. (19). Existing references on the subject of fouling are widely scattered in the literature due to the number of different forms fouling may take.

Fouling plays a very decisive role in the design of heat transfer equipment, yet very few information sources exist for the use of design engineers except the TEMA recommendations (20, 21). These are valuable recommendations but they have the disadvantage of existing as constant numbers and thus make little allowance for heat exchanger operating conditions.

Cooling water has had a long and important role in the power and process industries. In recirculating cooling tower systems, the evaporation of water leads to a build-up of minerals in the water, which increases the concentration of scale forming ions (3). Foulant control in cooling water systems has become more and more important in the last several years. Two reasons responsible for this are longer operating periods between cleanings and higher water temperatures and heat transfer rates are being utilized. Fouling problems have also increased considerably due to the use of poor quality water, the use of waste waters, and environmental control agency pressure to use closed recirculatory systems (17).

The primary fouling constituents of cooling water are inverse solubility salts, such as calcium carbonate. Crystallization is the main type of fouling found on heat transfer surfaces in contact with cooling water which has no suspended solids. The present research is directed strictly towards the study of crystallization fouling involving inverse solubility salts.

The purpose of this study was to build a cooling tower system in which could be formulated a cooling water comparable to industrial cooling water coming from a wet cooling tower, and to study the fouling of a heated tubular surface under controlled conditions. The water contained a known concentration of inverse solubility salts, and it is hoped to establish a relation between the fouling observed and various parameters which describe the water quality.

BACKGROUND INFORMATION AND LITERATURE SURVEY

Heat Transfer Equation

The overall heat transfer coefficient for a heat exchanger is found from the following fundamental equation:

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{A_o}{A_i}\frac{1}{h_i} + (R_f)_o + \frac{A_o}{A_i}(R_f)_i + R_w \qquad (1)$$

where

U_o = overall heat transfer coefficient based on outside area

h_i, h_o = local convective heat transfer coefficients, inside and outside

A_i, A_o = surface area, inside and outside

$(R_f)_i, (R_f)_o$ = fouling resistance, inside and outside

R_w = thermal resistance of wall

This equation provides the basis for design of heat transfer equipment, and it shows the effect of fouling resistances on the overall heat transfer coefficient.

The convective heat transfer coefficients, h_i and h_o, and the thermal resistance of the wall can be determined with reasonable accuracy, but the fouling resistances are selected from tables of limited accuracy or from experience based sources which often do not fit the design operating conditions (19, 20).

Although fouling resistances increase with time during a process operation, the tendency in industry has been to use a predicted maximum resistance value for design of heat transfer equipment. Kern and Seaton (10, 11), describe how this procedure can actually enhance the fouling rate. The allowance for fouling often accounts for one-half of the surface area specified in a heat exchanger design. These facts combined with the lack of a systematic predictive procedure indicate the potential benefits in studying fouling rates.

Fouling Mechanism

This discussion will be restricted to the deposition of inverse solubility salts. The mechanism of fouling refers to the process in which dissolved salts contained in cooling water are deposited on heated surfaces. As mentioned, there are many different fouling mechanisms known, but the mechanism of fouling involved in cooling water is a complex crystallization process. The main constituents of the deposition scale, $CaCO_3$ and $Mg(OH)_2$, have solubilities which decrease with increasing temperature. Thus the solution in contact with the heat transfer surface has the lowest equilibrium solubility and the scale will deposit when local supersaturation conditions occur at the heated surface.

In studying the scale deposition of CaCO3, Hassen, et al. (5), lists four rate processes that determine crystal growth: nucleation, diffusion, chemical reaction, and molecular ordering of the scale crystal lattice. It was found that the diffusion of Ca^{+2} and HCO_3^- ions was the rate controlling step in scale growth. Taborek, et al. (19), found that cooling water crystalline deposits build up in irregular patterns during fouling, and that these deposits are sensitive to both flow velocity and layer thickness, which combine to cause an asymptotic fouling-time curve. The surface material has little effect on the final asymptotic fouling resistance value since once the surface is covered all deposits are placed on the existing crystalline structure. Of the parameters controllable in the industrial process, salt concentration, water quality, temperature of heat transfer surface, and flow velocity have all been observed to play an important role in cooling water fouling. However, little is known of their exact roles.

Predictive Methods

Recent attempts to mathematically model the fouling process have been based on a material balance. The accumulation of the fouling layer is equal to the rate of deposit minus the rate of removal:

$$\frac{d(t_f/k_f)}{d\theta} = \Phi_d - \Phi_r \qquad (2)$$

where

θ = time

t_f = fouling layer thickness

k_f = effective thermal conductivity of deposit

Φ_d = rate of deposition function

Φ_r = rate of removal function

The deposition rate function depends upon the mechanism of fouling, the surface temperature, the flow conditions, and the water quality. With physical and geometric conditions remaining constant, the deposit rate will remain essentially constant. The removal rate function depends upon the strength of the crystalline structure and the shear stress resulting from the flow of the fluid over the scale layer. When the removal rate increases with the fouling layer thickness due to the deteriorating stability of the deposit, the deposition and removal rate ultimately become equal resulting in an asymptotic fouling resistance value. Recent models have been developed based on Equation (2), and they will be discussed in the following paragraphs.

a) Kern Seaton Model (10). This model predicts an asymptotic fouling curve and was derived to obtain curves which could describe fouling data obtained by Katz (9). The deposition rate function is proportional to the concentration of the foulant and the liquid flow rate. The removal rate function is proportional to the shear stress and the deposit layer thickness.

b) Watkinson-Epstein Model (23). In this model the deposition rate is proportional to the concentration gradient of the foulant and the Arrhenius temperature function and inversely proportional to the mass flow rate squared. The removal rate function is essentially the same as the one found in the Kern Seaton Model.

c) HTRI (19). Heat Transfer Research Incorporated has developed an empirical type of model based on large amounts of data obtained in studying cooling water fouling. The deposition rate is proportional to the residence time in the reaction zone, a water quality factor, and an Arrhenius reaction rate function based upon the deposition surface temperature. The removal rate function is proportional to the shear stress and inversely proportional to the bond resistance of the scale. The semi-empirical model which resulted predicted asymptotic fouling resistances with a standard deviation of ± 40 percent.

d) Walker and Bott (21) proposed a very simple fouling model based on an integrated form of Equation (2).

$$U_\theta = R_f + R_f^* C^\theta \qquad (3)$$

where

U_θ = overall heat transfer resistance at time θ

R_f = fouled tube heat transfer resistance

R_f^* = asymptotic fouling resistance

C = time independent variable

θ = time

The model is used by fitting existing data to Equation (3) by the method of least squares. Predictions of fouling resistances for future runs at different temperatures and velocities can be made using this model.

e) Other models, initiated by McCabe and Robinson (15) in 1924, have been developed but were not based on relations similar to Equation (2). The theory of simultaneous heat and mass transfer was used by Hoffman (8) in developing a model of the fouling process. Using solubility data and heat and mass transfer coefficients predicted from the fluid system, a fouling rate could be predicted from Hoffman's relationships. The model was not compared with experimental data. Hasson, et al. (5,6), studied calcium carbonate and calcium sulfate fouling. The separate effects of flow velocity, scale, surface temperature, and water composition were examined. It was determined that the deposition rate of calcium carbonate was controlled by the diffusion rate of calcium and bicarbonate ions, and in certain cases by the backward diffusion rate of dissolved CO_2. It was also found by Hasson, et al. (5) that the growth rate of the calcium carbonate deposit increased slowly and linearly with increased surface temperature. Gonionskiy, et al. (4) developed a model for predicting heat transfer coefficients as a function of time when solutions containing inverse solubility salts were heated. The rate of scale formation was assumed to be proportional to some power of the concentration driving force, and the model was checked experimentally by studying the fouling characteristics of a saturated calcium sulfate solution. An interesting result of this study was that the fouling rate was found to be independent of the fluid velocity, which contradicts most other findings.

Scaling Indexes

The composition or quality of cooling water depends upon many parameters. The significant ones appear to be pH, hardness, calcium hardness, alkalinity, temperature, and total solids. It has been attempted in the literature to lump these parameters together into one parameter, termed a scaling index, which will indicate the scaling tendency of water. Langelier (12, 13) introduced an important term for scaling indexes in 1936 called the saturation pH, or pH_s. It is shown in Equation (4):

$$pH_s = (pK'_2 - pK'_s) + pCa + pAlk \tag{4}$$

where

K'_2 and K'_s are thermodynamic functions of temperature, dissolved solids, and ionic strength pCa is the negative logarithm of the calcium ion concentration

pAlk is the negative logarithm of the total alkalinity of the water

A more convenient expression for pH_s was developed by Larson and Buswell (14), shown in Equation (5).

$$pH_s = 9.30 + A + B - C - D \tag{5}$$

In this equation, A is a function of total dissolved solids in the water, B is a function of the water temperature, C is a function of the calcium hardness, and D is a function of the alkalinity. These functions will be described later. The algebraic difference between the actual pH of a sample of water and its calculated pH_s is the measure of the degree of calcium carbonate saturation and has been called the saturation index. A plus value for the saturation index indicates a tendency to dissolve calcium carbonate, and a minus value indicates a scaling tendency. This index is only qualitative, however, and Ryznar (18) modified this index into the following equation, creating the Ryznar Stability Index (RSI).

$$RSI = 2pH_s - pH = 2(9.30+A+B-C-D) - pH \tag{6}$$

This index is particularly useful in industry as calculated values of 7 or more for this index indicate corrosion, while calculated values of 6 or less mean a scaling water (2,3). Also, the lower the number the more scale should form. Most industrial cooling systems that use a pH control system are based on the scaling and corrosion predictions of the Ryznar Stability Index. All water quality figures for this study are converted into the Ryznar Stability Index. Program INDEX, a computer program listed in Appendix D, applies the complicated functions A, B, C, and D to calculate a Ryznar Stability Index for a sample of water with known composition.

Recently, Feitler (3) has proposed a new qualitative guide for the scaling nature of water termed a critical pH, pH_c. The critical pH is determined by adding NaOH to a water sample until a precipitate appears. The measured pH at that point is the critical pH and usually runs about 1.7 to 2.0 pH above pH_s. Although easy to determine, the critical pH has not yet been established in the literature as a reliable predictor of scale formation.

EXPERIMENTAL PROGRAM

The literature surveyed indicates a wide variety of methods and models used in the predictions of heat transfer fouling. Clearly, no one model has been developed that is used extensively. No model has been developed which allows design engineers to predict the most economical heat exchanger when extensive fouling is involved.

The research described in this report is part of a project being conducted at Oregon State University to study the fouling characteristics of water under controlled conditions. By operating a cooling water system in a laboratory environment, many factors difficult to control in the industrial environment are more easily held constant, and a systematic study of fouling characteristics of water can be accomplished.

A portable fouling unit which will be described later is on loan from Heat Transfer Research Incorporated. The study in this thesis is the initial phase of the fouling project. There were three major goals for this initial study. The first goal was to build a cooling water system that would simulate an industrial cooling tower circulation process. This would be connected to the portable fouling unit to study fouling characteristics. The second goal was to determine if a typical cooling water can be formulated for controlled studies. The third goal was to isolate and study the effect of surface temperature on cooling water fouling characteristics. The realization of these goals will allow a more thorough identification of the effects of other parameters on the fouling behavior of cooling water.

EXPERIMENTAL EQUIPMENT

The apparatus used in this experimental investigation consisted of two distinct sections. The first section was a closed cooling tower system. The second section was a portable fouling unit which contained the devices essential in measuring the fouling characteristics of the water. Together they comprised the experimental apparatus through which the studied experimental water circulated. A schematic layout of the system is shown in Figure 1.

Cooling Tower System

Supply Tank and Pump

The water was stored and formulated in a 180 gallon stainless steel supply tank. The tank was cylindrical in shape with a diameter of 33.9 inches and a height of 4 feet. The water was drawn out of the supply tank by a Pacific Pumping Co, bronze turbine pump, model number R9AB, driven by a three horse power electric motor. The pump had a speed of 1750 RPM and delivered a steady flow, but required a bypass line as shown in Figure 1 to relieve high pressures obtained at low flow rates. The bypass line also served as a mixer and agitator in the supply tank. In the piping system the maximum achievable water flow rate was about 16 gallons per minute.

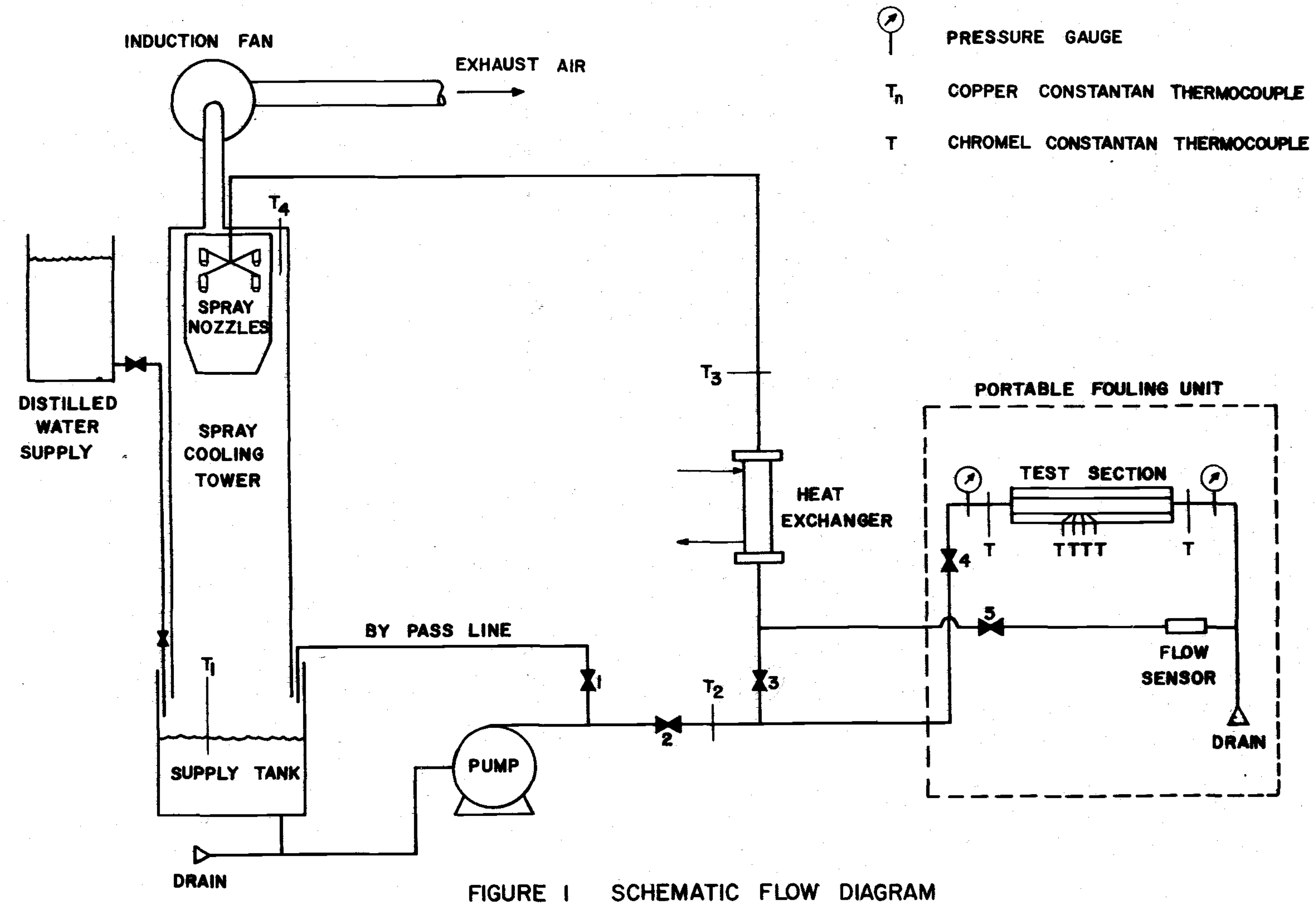

FIGURE I SCHEMATIC FLOW DIAGRAM

Piping System

The entire piping system in the cooling tower section was made up of PVC piping with the exception of one inch flexible plastic tubing leading to and from the portable fouling unit. No corrosive materials were in contact with the water. All threaded connections were sealed with teflon tape, and all glued connections were sealed with IPS 711 Plastic Pipe Cement. These methods successfully prevented water leakage or air intake into the water system. Valve one is brass, valves two through five are stainless steel, and all unions in the system are either PVC or stainless steel.

After the water passed through the portable fouling unit, it passed immediately through a heat exchanger. The heat exchanger was a small Dupont shell and tube teflon exchanger, with steam in the shell passing countercurrent to water in the teflon tubes. The heat exchanger was used only to a limited extent in controlling the bulk temperature of the cooling water.

Downstream from the heat exchanger the water entered the cooling tower. The cooling tower was two feet square and 20 feet high. The sides were made of quarter inch plexiglass, and the tower rested directly upon the 180 gallon supply tank. The water entered the tower through four spraying nozzles. The nozzles were Spraying Systems Co. model number 1590 Fulljet spray nozzles. The nozzles were placed in a square arrangement, eight inches on a side, one foot from the top of the tower and centered. To prevent much of the water spray from running down the sides of the tower, a two and one-half foot long open ended cylindrical piece of sheet metal was hung around the spray nozzles. This device successfully cut down the side angled spray of the nozzles and forced most of the water to fall in drops down the center of the tower. The top of the tower was a two foot square piece of plexiglass in which two openings had been cut. One was for the one inch pipe leading to the spray nozzles. The other opening, a six inch diameter hole, contained the bottom of an air duct leading to an induction fan situated above the cooling tower. The fan was a Clarage Fan Co. size No. 9 NHV fan with a speed of 1750 RPM and was driven by a three-quarter horse power electric motor. The humid air inducted up through the tower was blown out a window through a six inch diameter sheet metal duct.

Four copper-constantan thermocouples were located throughout the cooling tower system. Number one measured the tank water temperature, number two measured the temperature of the water directly before it entered the fouling unit, number three measured the water temperature directly after it left the fouling unit, and number four measured the temperature of the air at the top of the tower. The four thermocouple leads were connected to a 12 position rotary switch, and the cold leads were connected to a thermocouple immersed in a thermos bottle filled with crushed ice in equilibrium with water. All voltages from the cooling tower section and the portable fouling unit were read by a Digitec model 268 millivoltmeter. The copper-constantan thermocouple system was used in preliminary runs to determine the temperature characteristics of the cooling tower system. In actual runs involving fouling resistance measurements the four temperatures were not needed for data points because the portable fouling unit had sufficient temperature measuring devices as shown later. The cooling tower system thermocouple readings were monitored for water temperature control purposes only and will not be listed in the tabulated data section of Appendix F.

Distilled Water Supply

The water level in the supply tank was kept constant by the addition of distilled water to make up the loss of the evaporated water in the cooling tower. A standard toilet float placed in the tank triggered a Safe Flight Instrument Co. Lift Detector, part number 147, when the water level dropped below a level of two feet. The Lift Detector in turn electrically triggered a solenoid valve located on the tubing from the distilled water supply. The distilled water was gravity fed to the water supply tank.

Portable Fouling Unit

The fouling unit on loan from HTRI is a Portable Fouling Unit Model I and is shown in Figure 2. It was designed for measuring fouling resistances as a function of flow velocity and wall temperature. The fluid to be studied flows in an annulus formed by a 3/8 inch diameter stainless electrically heated rod and a 3/4 inch inside diameter glass tube.

Thermocouple Setup

Four chromel-constantan thermocouples imbedded in the heated rod were used to measure the temperature of the rod. Two other chromel-constantan thermocouples, inserted into the flow stream immediately up and downstream from the heated rod, were used to determine the temperature of the water. The cold junction leads from these thermocouples were connected to an electronic thermocouple reference junction compensator, Consolidated Ohmic Devices Model JRSP-248. The six thermocouple leads were connected to a Barber-Colman selector switch, model 810S-20. The voltages from the thermocouple were read on the Digitec millivoltmeter described previously. The thermocouple system was standardized using a standard thermometer and a water bath. The cold reference junction had an adjustable resistor which allowed the millivolt reading to be adjusted

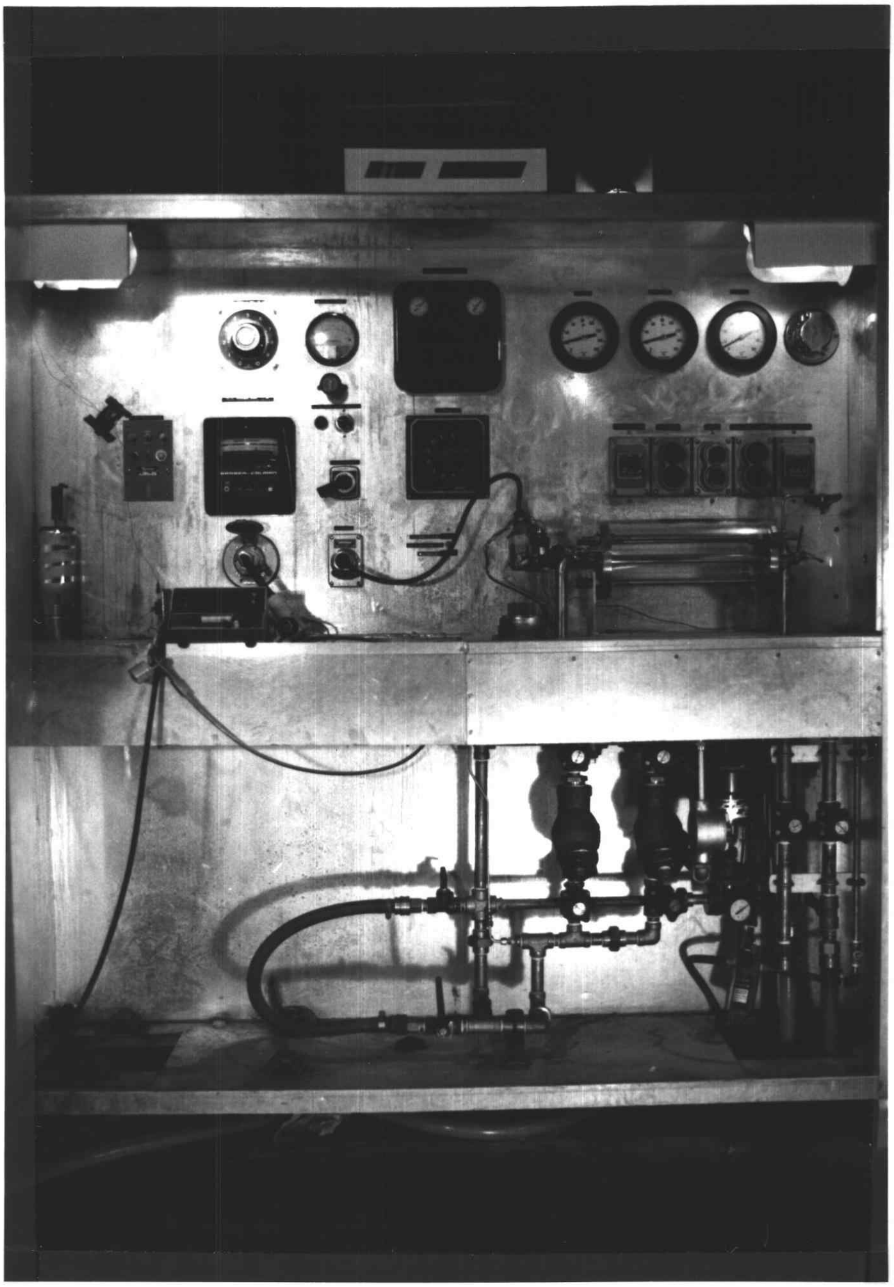

Figure 2. Portable fouling unit.

so that the same calibration curve could be used every run. Each standardization had to be done with the entire fouling unit in steady state operation. The calibration curve is given in Appendix B.

Heater Rod

The electric current to the heating coil imbedded in the stainless steel rod was controlled by a "Variac" W10 Autotransformer. A Weston Model 432 Wattmeter was used to record the heat input to the test section. The stainless steel rod together with its imbedded heating coil and four imbedded thermocouples comprised the heater on which fouling occurred. The heaters were made by HTRI and calibrated by HTRI to find the metal resistance (x/k) between each thermocouple and the surface of the rod. Due to the occasional burning out of thermocouples and heating element in the heater, different heating rods were used to replace damaged ones. A summary of the characteristics of each heating rod used is presented in Table 1. A photograph of the fouling test section is shown in Figure 3. Figure 4 shows the thermocouple and heating element location in the heater.

Flow Meter

The flow velocity through the test section was measured by a Ramapo Flow Meter, model Mark V-3/4-SSX. This instrument measures the velocity head by sensing the drag force on a specifically contoured body of revolution suspended in the flow stream. The flow meter was accurately calibrated by HTRI (11) and spot checked at various times during this investigation. The calibration curve of the flow meter is given in Appendix B.

Table 1. Heater specifications.

	Heater Number		
	58	74	21
Rod outside diameter, in	.424	.424	.424
Annular flow area, ft^2	.00208	.00208	.00208
Heated length of rod, L, inches	4.0	4.0	4.0
Heating element resistance, ohms	27.6	25.3	28.8
Thermocouple A k/x, Btu/ft^2-hr-°F	3200.	2900.	25,000.
Thermocouple B k/x, Btu/ft^2-hr-°F	2900.	--	14,300.
Thermocouple C k/x, Btu/ft^2-hr-°F	2200.	3200.	100,000.
Thermocouple D k/x, Btu/ft^2-hr-°F	2300.	2200.	33,000.
Distance Y of thermocouple A, inches	3	3	3
Distance Y of thermocouple B, inches	3	3	1
Distance Y of thermocouple C, inches	3	3	3
Distance Y of thermocouple D, inches	3	3	1

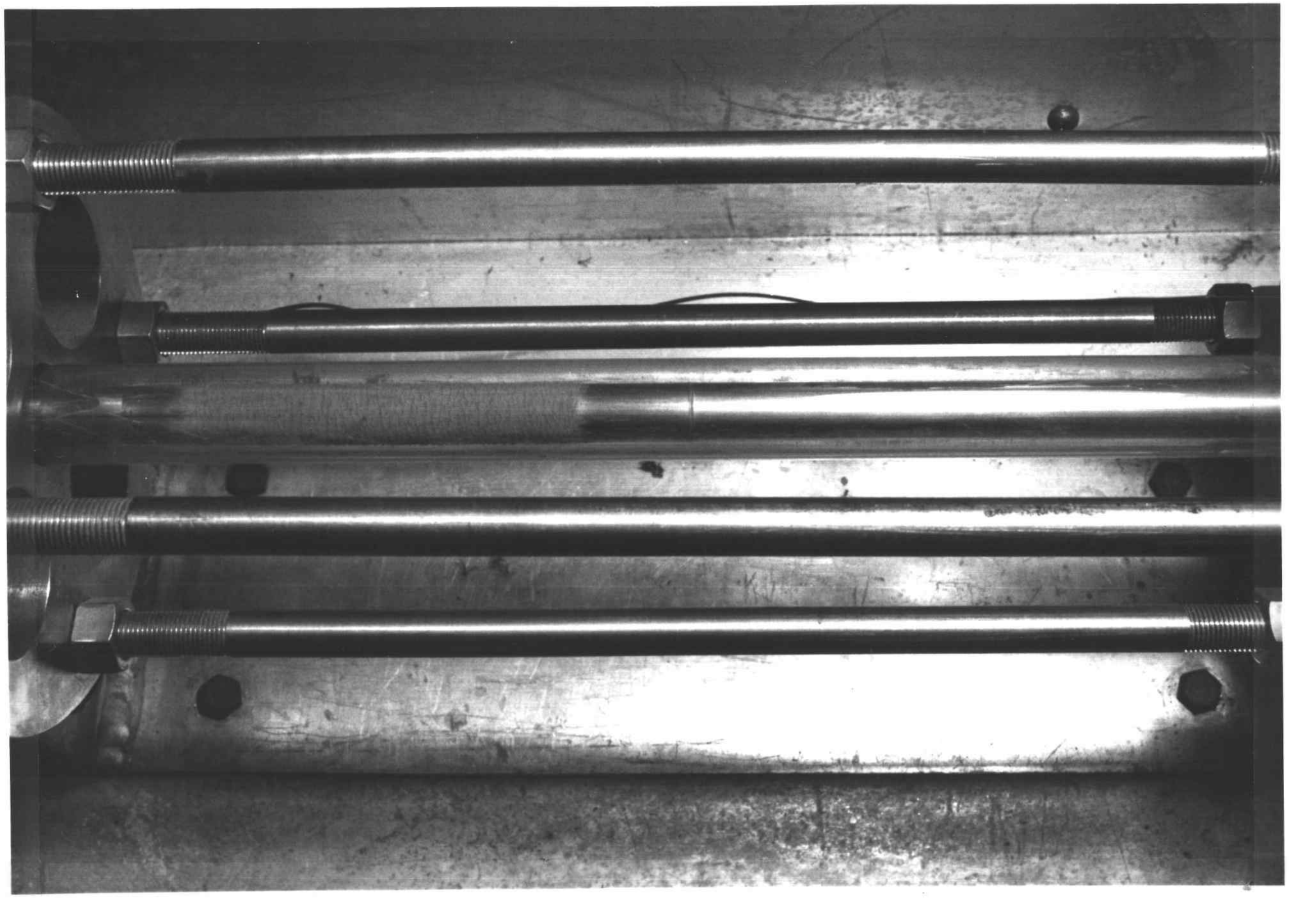

Figure 3. Fouling unit test section.

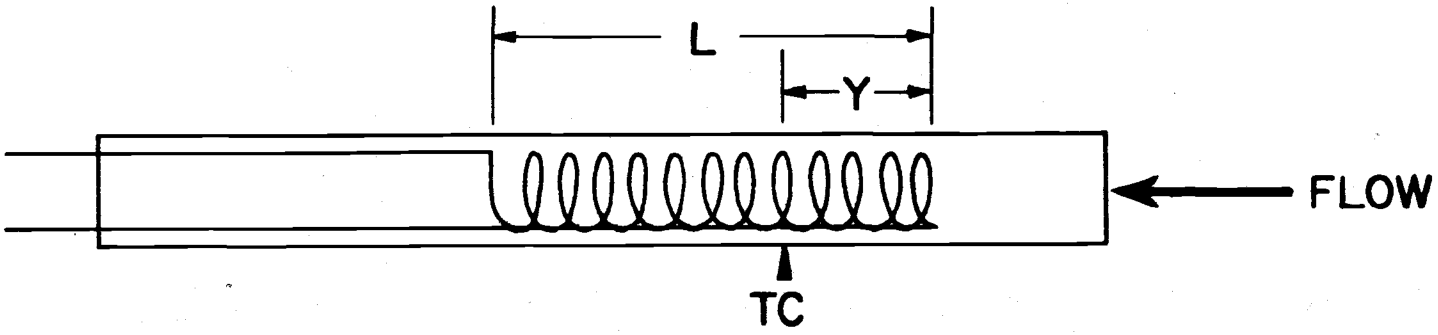

FIGURE 4 Thermocouple and heating element locations

EXPERIMENTAL PROCEDURE

After the cooling tower section was constructed and connected to the portable fouling unit, runs were made to determine the fouling resistance of a given sample of water at constant flow rate and constant surface temperature conditions.

A run began with the preparation in the supply tank of the water to be used for the run. The treatment of the water varied in the beginning runs. This was done in an attempt to find a typical cooling water that could be synthetically reproduced in the laboratory environment. In the later runs where surface temperature-asymptotic fouling resistance correlations were made, the water quality was brought about by adding $CaCl_2$ and $MgCO_3$ to tap water. A summary of preliminary treatment for each run is presented in Table 2.

During an actual run, the water was sampled at least once every other day and analyzed to insure that the composition characteristics of the water were not changing. Distilled water was added through an automatic switch-valve described earlier to keep the water level constant, and chemicals were added periodically to compensate for any change in water composition. The chemical analysis was done or supervised by the author, and a summary of the analysis technique is presented in Appendix C.

Table 2. Summary of water formulation procedures.

Run Number	Formulation Procedure
1	Tap water was evaporated down until it reached a concentration of approximately 460 ppm total solids.
2	The concentrated tap water from run 1 was raised to 2100 ppm total solids by addition of 600 gms $CaCl_2$.
3	710 gms of $CaCl_2$ were added to tap water in the supply tank (354 liters) to raise total solids concentration to 2000 ppm.
4	800 gms of $CaCl_2$ were added to tap water in the supply tank to raise total solids concentration to 2200 ppm. Midway through run 4, 100 gms of $NaHCO_3$ were added to the water.
5-11	521 gms of $CaCl_2$ and 187 gms of $MgCO_3$ were added to 354 liters of tap water which raised the total solids concentration to 1650 ppm.

The test section heating rod was thoroughly cleaned between each run to remove any fouling scale from a previous run. Light steel wool and water were used as cleaning agents, and it was insured before each run that the deposit surface of the rod was smooth and entirely free of foreign matter.

At the start of each run, the water was allowed to circulate throughout the entire system before applying a current to the heating element. This allowed the water to reach a stable bulk temperature and all electronic devices to sufficiently warm up. The run started with the application of an electric current to the heating rod which produced a desired surface temperature of the rod. Data was taken immediately after the heat was applied, and in varying multiple hour intervals thereafter. Runs were from 100 to 600 hours in length and the runs were terminated when the fouling resistance had obviously reached an asymptotic value. Data recorded for each run is found in Appendix F. Data taken on each run included all thermocouple readings, the flow meter reading, the heat input reading, the day and time of the run, and the suction and discharge pressure of the water flowing through the portable fouling unit.

It was essential that the flow velocity and heat input remain constant during a run. The flow rate was kept constant by adjustments of the bypass valve. The heat input was kept constant by small necessary adjustment of the Variac. It was also necessary to keep the bulk temperature of the water relatively constant. The ambient air temperature dictated the equilibrium bulk temperature of the water. Therefore the induction fan in the cooling tower and the heat exchanger were manually manipulated during each run to keep the water bulk temperature as constant as possible. As a general rule, the water temperature had about a six degree temperature range during each run.

CALCULATION PROCEDURES

Development of Equations

Equations for the calculation of the fouling resistance are based on the fact that the velocity flow rate and the heat flux from the heated rod remain constant. Heat flux is proportional to the products of the various heat transfer resistances and their corresponding temperature differences as shown by the following equation.

$$Q/A = h(t_s - t_b) = 1/R_f(t_w - t_s) \qquad (7)$$

Figure 5 shows a cross section of a clean and fouled test section rod, and the outer tube shown is a glass tube forming the outer portion of the flow annulus. For Equation (7) and Figure 5:

t_s = surface temperature

t_w = wall temperature at surface of rod

t_b = water bulk temperature

Q/A = heat flux

h = convective heat transfer coefficient

R_f = fouling resistance

For a clean heating rod, t_w and t_s are obviously equal values. Assuming h is constant and the bulk temperature is constant, t_s

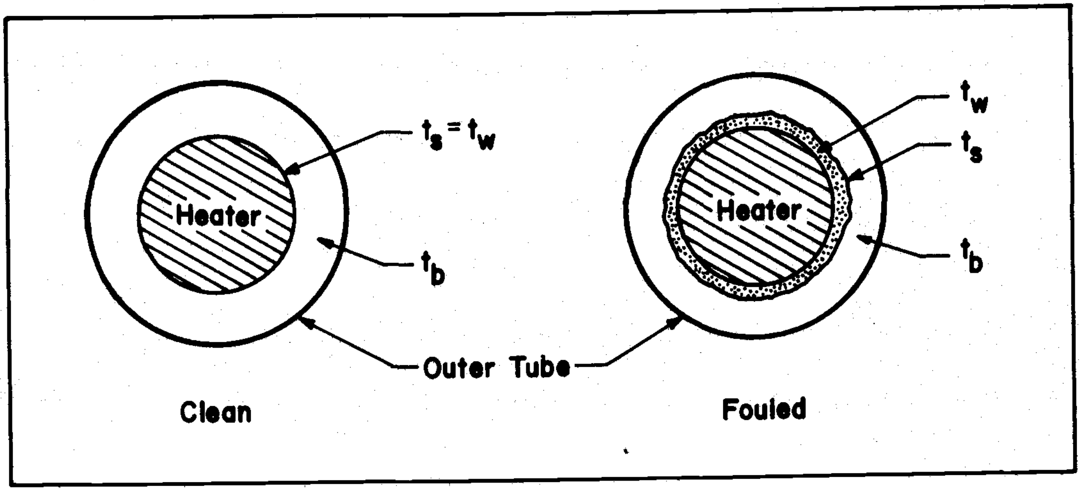

FIGURE 5 Clean and Fouled Test Section Tube

must remain the same at constant heat flux. The surface temperature may be corrected for small changes in bulk temperature by the following equation according to HTRI (11) when velocity is constant.

$$t_{s\ \text{corrected}} = t_{b\ \text{fouled}} + [(t_s - t_b)_{\text{initial}}] \qquad (8)$$

By substituion of Equation (8) into Equation (7) and solving for R_f,

$$R_f = \frac{(t_w - t_b)_{\text{fouled}} - (t_s - t_b)_{\text{initial}}}{Q/A} \qquad (9)$$

It is impossible to measure the wall temperature t_w, but by knowing the temperature indicated by a thermocouple imbedded just below the surface, t_w can be found by Equation (10);

$$(t_c - t_w) = (Q/A)\ (x/k) \qquad (10)$$

where

t_c = thermocouple temperature

x/k = metal resistance between the thermocouple junction and the surface of the rod

therefore

$$t_{s\ \text{initial}} = t_{c\ \text{initial}} - (Q/A)\ (x/k) \qquad (11)$$

and

$$t_w = t_{c\ \text{fouled}} - (Q/A)\ (x/k) \qquad (12)$$

Substituting these values into Equation (9),

$$R_f = \frac{(t_{c\ \text{fouled}} - t_{c\ \text{initial}}) + (t_{b\ \text{initial}} - t_{b\ \text{fouled}})}{Q/A} \tag{13}$$

The bulk temperature was calculated from the average of the water inlet and outlet thermocouple readings. All necessary calculation procedures to obtain the fouling resistance and other significant parameters were carried out by the use of computer program Fouling, listed in Appendix D.

Estimation of Error

The error in R_f is due to the error in the measured quantities in Equation 13. To find the relative percentage error in R_f, the differential method is used. The relative error is the ratio of the absolute error, dR_f, to R_f. dR_f is found by simple differentiation of Equation 13. Making an initial substitution for the numerator in Equation 13, the following equations are developed:

$$\xi = (t_{c\ \text{fouled}} - t_{c\ \text{initial}}) + (t_{b\ \text{initial}} - t_{b\ \text{fouled}}) \tag{14}$$

$$R_f = \frac{\xi A}{Q} \tag{15}$$

$$dR_f = \frac{A d\xi}{Q} + \frac{\xi dA}{Q} - \frac{\xi A dQ}{Q^2} \tag{16}$$

Dividing Equation 16 by Equation 15 and changing the signs to plus or minus signs, the relative error of the fouling resistance, R_f is given in Equation 17.

$$\frac{dR_f}{R_f} = \pm \frac{d\xi}{\xi} \pm \frac{dA}{A} \pm \frac{dQ}{Q} \tag{17}$$

Using the same procedure, the relative error of ξ can be found.

$$d\xi = \frac{dt_{c\ \mathrm{fouled}} \pm dt_{c\ \mathrm{initial}} \pm dt_{b\ \mathrm{initial}} \pm t_{b\ \mathrm{fouled}}}{(t_{c\ \mathrm{fouled}} - t_{c\ \mathrm{initial}}) + (t_{b\ \mathrm{initial}} - t_{b\ \mathrm{fouled}})} \tag{18}$$

The heat flux area A is calculated in terms of the diameter of the heated rod, D, and the length of the heated portion of the rod, L:

$$A = \pi DL \tag{19}$$

Finding the relative error in the heat flux area, A, yields Equation 20.

$$\frac{dA}{A} = \pm \frac{dD}{D} \pm \frac{dL}{L} \tag{20}$$

Q is measured directly from a wattmeter.

The relative error of the surface temperature, t_s is also important, as a later correlation contains t_s as the independent variable. Although slightly affected by water bulk temperature changes, the surface temperature is very close to constant and will be given the value of the initial unfouled wall temperature. Applying the same differential method as described in Equation 11, the relative error of t_s is shown in Equation 21.

$$\frac{dt_s}{t_s} = \left\{ \frac{\pm(x/k)Q}{A} \left(\frac{dQ}{Q} + \frac{dA}{A} + \frac{d(x/k)}{(x/k)} \right) \pm dt_{c\ \mathrm{initial}} \right\} \frac{1}{t_{c\ \mathrm{initial}} - (Q/A)(x/k)} \tag{21}$$

x/k was measured by HTRI and was given as one measurement for each heater.

The last parameter that needs error estimation attention is the Ryznar Stability Index. Since RSI values varied only slightly during the course of each run, only the absolute error need be found. Taking the simple differential of Equation 5 yields the following equation.

$$dRSI = \pm dA \pm dB \pm dC \pm dD \pm dpH \tag{22}$$

Larson and Buswell (14) give expressions for A, B, C, and D, which are also listed by Program Index in Appendix D. Equations 23 through 34 develop the absolute error of each function, A, B, C, and D.

$$A = \frac{2.5A1}{(1 + 5.3A1 + 5.5A1^2)} \tag{23}$$

$$dA = \frac{2.5dA1(1+5.3A1+5.5A1^2) - 2.5A1(5.3dA1+11A1dA1)}{(1+5.3A1+5.5A1^2)^2} \qquad (24)$$

A1 is a dummy variable and is a function of total solids, TS, as shown in Equation 25.

$$A1 = (TS/40000.)^{.5} \qquad (25)$$

$$dA1 = (dTS/80000.)(TS/40000)^{-.5} \qquad (26)$$

$$B = 10^{(BLOG)} \qquad (27)$$

$$dB = 10^{(BLOG)}\log(10)dBLOG \qquad (28)$$

BLOG is a dummy variable which is a function of the absolute temperature of the water, TABS, as shown in Equations 29 through 30.

$$BLOG = -1.37864 + \frac{1040.92}{TABS} - \frac{75,500}{(TABS)^2} \qquad (29)$$

$$dBLOG = +\frac{1040.92}{TABS^2}dTABS + \frac{151,000}{(TABS)^2}dTABS \qquad (30)$$

$$C = \frac{\log(.4CH)}{2.30259} \qquad (31)$$

$$dC = \frac{dCH}{2.30259 \times CH} \qquad (32)$$

$$D = \frac{\log(ALK)}{2.30259} \qquad (33)$$

$$dD = \frac{dALK}{2.30259\ ALK} \qquad (34)$$

In Equations 31 through 34, CH represents measured calcium hardness and ALK represents measured alkalinity.

The magnitude of the errors will be brought out in the following section by a sample calculation.

Sample Calculation

The following numerical sample calculation demonstrates the calculational method used to obtain the fouling resistance, the surface temperature, and the Ryznar Stability Index. The data are from run number 5, using thermocouple A data taken on day 6 at 19:21 hours. The chemical analysis was performed on January 8, and all data listed below is found in Appendix E.

$t_{b\ initial}$ (initial water bulk temperature) = 74.52° F

$t_{c\ initial}$ (initial thermocouple temperature) = 183.63° F

$t_{b\ fouled}$ (fouled water bulk temperature) = 77.80° C

$t_{c\ fouled}$ (fouled thermocouple temperature) = 246.21° F

L (length of heated rod area) = 4 inches

D (heater diameter) = .424 inches

x/k (resistance from thermocouple A to surface)

$$= 3.125 \times 10^{-3}\ (\text{Btu/ft}^2\text{-hr-°F})^{-1}$$

Q1 (wattmeter reading) = 0.96 kilowatts

From Equation 19

$$A = \frac{3.14159 \times .424 \times 4}{144}$$

Converting Q1 to proper units:

$$Q = Q1 \times 3413$$

$$Q = 0.96 \times 3413 = 3276.5 \text{ Btu/hr}$$

Substituting appropriate values into Equation 13 yields the calculated value of the fouling resistance.

$$R_f = \frac{(246.2-183.6) + (74.5-77.8)}{3276.5/.037}$$

$$R_f = 6.69 \times 10^{-3}$$

Substitution of the appropriate values into Equation 11 yields the calculated value for surface temperature, t_s.

$$t_s = 183.6 - 3276.5/.037 \times 3.125 \times 10^{-3}$$

$$t_s = 155.9°F$$

In calculation of the RSI, the following data are used which are listed in Appendix F.

t_b (water bulk temperature) = 77.8° F

TS (total solids) = 1489 ppm

ALK (alkalinity) = 67 ppm $CaCO_3$

CH (calcium hardness) = 794 ppm $CaCO_3$

pH = 8.3

From Equation 25

$$A1 = \left(\frac{1489}{40,000} \right)^{.5}$$

$$A1 = .19294$$

From Equation 23

$$A = \frac{2.5 \times .19294}{1 + 5.3 \times .19294 + 5.5 \times .19294^2}$$

$$A = .21656$$

Converting t_b into TABS (absolute temperature) gives

$$TABS = 77.8 + 459.7 = 537.5°R$$

From Equation 29

$$BLOG = -1.37864 + 1040.92/537.5 - \frac{75,500}{(537.5)^2}$$

$$BLOG = .2966$$

From Equation 27

$$B = 10^{0.2966} = 1.9798$$

From Equation 31

$$C = \frac{\log(.4 \times 794)}{2.30259} = 2.5019$$

From Equation 33

$$D = \frac{\log(67)}{2.30259} = 1.8261$$

Substituting all appropriate values into Equation 5 gives the calculated value of the Ryznar Stability Index:

$$RSI = 2(9.30 + .2166 + 1.9798 - 2.5019 - 1.8261) - 8.3$$

$$RSI = 6.03$$

The error involved in each of these calculations may be found by using the equations developed in the previous section along with the estimated magnitude of error for each measured quantity. The following list shows the estimated error for each measured parameter, and the list is followed by the error calculation for the fouling resistance, the surface temperature, and the Ryznar Stability Index.

The error magnitude of all temperature measurements, $dt = \pm.5°F$

The error magnitude of rod diameter, $dD = \pm.0005$ inches

The error magnitude of heated rod length, $dY = \pm.05$ inches

The error magnitude of rod resistance,

$$d(x/k) = \pm.00001\ (Btu/ft^2\text{-}hr\text{-}°F)^{-1}$$

The error magnitude of total solids, dTS = ±20 ppm

The error magnitude of calcium hardness, dCH = ±10 ppm

The error magnitude of alkalinity, dALK = ±1 ppm

The error magnitude of pH, dpH = ±.1

The error magnitude of wattmeter reading,

dQ1 = ±.002 Kilowatts

From Equation 18,

$$\frac{d\xi}{\xi} = \frac{.5 + .5 + .5 + .5}{(246.21-183.63) + (74.52-77.80)}$$

$$\frac{d\xi}{\xi} = 3.37 \times 10^{-2}$$

From Equation 20

$$\frac{dA}{A} = \frac{.0005}{.424} + \frac{.05}{4} = 1.37 \times 10^{-2}$$

Substituting appropriate values into Equation 17 gives the relative fouling resistance error.

$$\frac{dR_f}{R_f} = 3.37 \times 10^{-2} + 1.37 \times 10^{-2} + \frac{.002}{.96}$$

$$\frac{dR_f}{R_f} = \pm.0495 = \pm 4.95\%$$

Substituting appropriate values into Equation 21 yields the relative error of the surface temperature.

$$\frac{dt_s}{t_s} = \left\{ \frac{3.125 \times 10^{-4} \times 3276.5}{.037} \left[.00208 + .0137 + \frac{1 \times 10^{-5}}{3.125 \times 10^{-4}} \right] + .5 \right\}$$

$$\times \frac{1}{183.6 - \dfrac{3276.5 \times 3.125 \times 10^{-4}}{.037}}$$

$$\frac{dt_s}{t_s} = \pm.0117 = \pm 1.17\%$$

From Equation 26

$$dA1 = \left(\frac{20}{80,000}\right)\left(\frac{1489}{40,000}\right)^{-1/2}$$

$$dA1 = 1.296 \times 10^{-3}$$

From Equation 24

$$dA = \frac{\left[2.5 \times 1.296 \times 10^{-3} (1 + 5.3 \times .19294 + 5.5 \times .19294^2) + 2.5 \times .19294 (5.3 \times 1.29 \times 10^{-3} + 11 \times .19294 \times 1.29 \times 10^{-3}) \right]}{1 + 5.3 \times .19294 + 5.5 \times .19294^2}$$

$$dA = 2.38 \times 10^{-3}$$

From Equation 30

$$dBLOG = \frac{+1040.92 \times .5}{(537.5)^2} + \frac{151,000 \times .5}{(537.5)^3}$$

$$dBLOG = 2.289 \times 10^{-3}$$

From Equation 28

$$dB = 10^{(.2966)} \times \log(10) \times 2.289 \times 10^{-3}$$

$$dB = 1.0434 \times 10^{-2}$$

From Equation 32

$$dC = \frac{10}{2.3026 \times 794} = 5.47 \times 10^{-3}$$

From Equation 34

$$dD = \frac{1}{2.3026 \times 67} = 6.48 \times 10^{-3}$$

Substituting these values into Equation 22 we can find the absolute error involved in calculating the Ryznar Stability Index.

$$dRSI = 2.380 \times 10^{-3} + 1.043 \times 10 + 5.47 \times 10^{-3}$$

$$+ 6.48 \times 10^{-3} + .1$$

$$dRSI = \pm.12$$

Table 4 shows, however, that the Ryznar Stability Index had a standard deviation of ±.39 from its average value for all runs in which an attempt was made to hold the RSI constant. This gives a much larger relative error of the RSI as shown below.

$$dRSI = \frac{.39}{6.32} = \pm 6.17\%$$

Therefore, the 3 parameters calculated in the sample calculation could be read as follows.

$$R_f = 6.69 \times 10^{-4} \ (\mathrm{Btu/hr\text{-}ft^2\text{-}^\circ F})^{-1} \pm 4.95\%$$

$$t_s = 155.9 \quad {}^\circ\mathrm{F} \quad \pm 1.17\%$$

$$RSI = 6.03 \quad \pm 6.17\%$$

RESULTS AND DISCUSSION

A summary of critical fouling parameters found in each run is presented in Table 3. The values presented are the average values for each run and are arranged in order of increasing value of asymptotic fouling resistance. Calculated and tabulated data for each run are listed in Appendix F. Fluid velocity is not listed in Table 3 as it remained constant for all runs at a value of 3.39 feet per second. Fouling resistance versus time in hours is plotted for each run and the graphs are located in Appendix E. These curves show that the cooling water used fouled the heated surfaces very rapidly and then an asymptotic fouling resistance value was achieved. Run number 9 is not included in these results because of a mechanical failure in the heater which gave distorted thermocouple readings. Run number 3 is not shown on a graph because no actual fouling was observed to occur.

Water Quality

In the first four runs, the composition of the water was deliberately varied in an effort to find a cooling water satisfactory for study. The water used in run number 5 was chosen for three main reasons: (1) It was very easy to reproduce this particular water by simple addition of chemicals; (2) The chemical composition

Table 3. Summary of fouling parameters for each run.

Asymptotic Fouling Resistance ($^\circ F$-ft^2-hr/Btu)	Surface Temperature ($^\circ F$)	Ryznar Stability Index	Heat Flux (Btu/ft^2-hr)	Water Bulk Temperature ($^\circ F$)	Run Number	Total Hours of Run
.00000	137.	6.28	55,345.	77.	3	474.
.00011	136.	6.62	56,267.	78.	10	119.
.00012	140.	6.11	59,219.	80.	7	126.
.00019	135.	5.95	55,345.	77.	4	197.
.00024	153.	6.08	75,822.	77.	6	127.
.00047	134.	6.89	55,345.	81.	1	480.
.00063	141.	5.59	55,345.	80.	2	598.
.00078	160.	6.38	88,826.	76.	5	127.
.00107	177.	6.07	101,465.	79.	8	216.
.00196	192.	6.55	101,465.	80.	11	386.

parameters were well within the range of industrial cooling tower water; and (3) The fouling characteristics displayed by the cooling water (asymptotic fouling curve plus a definite scale deposit) were similar to those found by previous investigators, i.e., Taborek, et al. (19), and others.

The variation of the water quality in runs 5 through 11 is given in Table 4.

Table 4. Summary of water analysis.

	Average	Standard Deviation	Range
pH	8.2	.23	7.9-8.5
Calcium hardness (ppm $CaCO_3$)	828.	59.	740.-988.
Total hardness (ppm $CaCO_3$)	1434.	87.	1258.-1620.
Total dissolved solids ppm	1645.	103.	1489.-1937.
Akalinity (ppm $CaCO_3$)	54.	13.	31.-78.
STI	6.32	.39	5.62-6.99

In runs 5 through 11, exactly the same quantity of chemicals and water were used to make the experimental cooling water, but the average Ryznar Stability Index varied from 6.08 to 6.62, which is a 9 percent deviation in the water quality index. The problem in keeping the RSI constant was in keeping the total alkalinity of the system constant, which finally was regarded as a nearly uncontrollable parameter in this experimental set-up. Alkalinity may be considered a result of a large number of ions in solution, but the main three are bicarbonate, carbonate, and hydrate ions. As can be observed from the chemical analysis data in Appendix E, the alkalinity generally increased during a run. An increase in alkalinity causes a decrease in the RSI, which indicates a greater tendency to foul. However, the increase in alkalinity noticed in these runs did not coincide with an increase in fouling resistance, as the fouling resistance asymptote often had already been reached at a time when the chemical analysis showed the alkalinity still increasing. The cause of the alkalinity increase during a run was not determined.

The chemical analysis of the water was done by the author as described in Appendix C. However, one sample per run and scale samples were analyzed by the Agricultural Chemistry Lab at Oregon State University. Samples were analyzed using an atomic absorption spectrophotometer. Only minute traces of corrosive material, such as iron, were found in the water. The scale analysis showed the scale to be approximately 90% $CaCO_3$ and 8% $Mg(OH)_2$. The remaining 2 percent of the constituents of the scale were not determined.

The presence of the chloride ion in the water caused all three heaters used in the study to eventually suffer a mechanical failure. The cause of the failure was determined by HTRI metallurgists to be stress corrosion of the welded areas on the stainless steel surface of the heated rod. An experimental run, conducted after the experimental part of this study was concluded, showed $Ca(NO_3)_2$ to be an excellent replacement for $CaCl_2$ in formulating the cooling water. Future studies with this experimental equipment will use $Ca(NO_3)_2$ instead of $CaCl_2$ in order to eliminate the stress corrosion on stainless steel caused by the chloride ion.

Surface Temperature--Fouling Resistance Correlation

This study considered the effect of surface temperature on fouling resistances. Runs 5 through 11 were conducted with all controllable parameters held constant with the exception of surface temperature, which was varied for each run. Flow velocity, water quality, and bulk water temperature were the parameters held essentially constant. Each thermocouple inbedded in the heater rod measured a significantly different fouling resistance and surface temperature than the other. Therefore, four different surface temperature-fouling resistance relationships can be found in each run.

Before further discussion, it should be explained why four different surface temperatures and fouling were recorded on one heated rod. The primary reason is that an off center position of the imbedded heating coil could easily cause a variation in temperature around a given point in the rod. Also, the distance of each thermocouple

(Y as shown in Figure 4) from the upstream end of the heating coil, has an effect on the recorded surface temperature and thus fouling resistance. It was felt by this author that the assumption of an average surface temperature and an average fouling resistance for all four thermocouples would decrease the accuracy of surface temperature-fouling resistance correlations.

After searching for a model that could best represent the temperature dependency of the fouling mechanism, the type of model chosen for this study was one related to the Arrhenius Temperature function as shown in Equation 35.

$$R_f^* = f(e^{-E/RT_s}) \tag{35}$$

where

R_f^* = asymptotic fouling resistance

E = activation energy

T_s = surface temperature, °R

For an initial correlation, E/R was lumped into one parameter, and an equation of the following type was used for correlation purposes.

$$R_f^* = ae^{-b/T_s} \tag{36}$$

where

a, b = undetermined coefficients

Table 5 contains the 23 pairs of data used in the correlation. The fouling resistance values were taken off the graphs in Appendix E, and the surface temperatures used were the initial wall temperatures of each run. Feeling that this model (Equation 36) could best represent theory and empirical findings, a least squares fit of the data to Equation 36 gave the correlation shown in Equation 37.

Table 5. Fouling resistance asymptotes and corresponding surface temperatures.

R_f^*, $(\mathrm{Btu/hr\text{-}ft^2\text{-}°F})^{-1}$	T_s, °R
.000113	599.3
.000131	599.4
.000131	601.3
.000132	596.3
.000176	598.7
.000196	595.3
.000200	593.1
.000259	609.0
.000293	613.1
.000327	612.8
.000367	616.7
.000734	615.6
.000754	617.5
.000808	619.5
.000808	624.5
.001006	637.0
.001088	642.3
.001091	635.6
.001110	631.5
.001947	659.2
.001953	652.4
.001971	652.7
.001980	642.9

$$\ln R_f^* = 21.491 - 18,027/T_s \qquad (37)$$

The data was fit to Equation (37) with a correlation coefficient of .95 and the data had a standard deviation from Equation 37 of 4.08%. Equation 37 in a more familiar form is shown in Equation (38).

$$R_f^* = (2.155 \times 10^9)\, e^{(-18,027/T_s)} \qquad (38)$$

$\ln R_f^*$ is plotted versus $1/T_s$ in Figure 6. The line in Figure 6 represents Equation 38. As shown in Figure 6 and as indicated by a correlation coefficient of .95 and the standard deviation of 4.08%, Equation 38 represents a good correlation between asymptotic fouling resistances and surface temperatures.

To convert coefficient b in Equation 36 from its present form and into a function of the activation energy E, a meaningful connection has to exist between the mechanism causing an asymptotic fouling resistance and the Arrhenius temperature function. Considering that the asymptotic fouling resistance is reached when the scale growth rate and the scale removal rate are of equal value, an attempt to match activation energy in coefficient b with scale deposit energies would ignore scale removal rate contributions and give a meaningless value to E. To test this assumption, a relationship between a derived activation energy and thermodynamic heats of

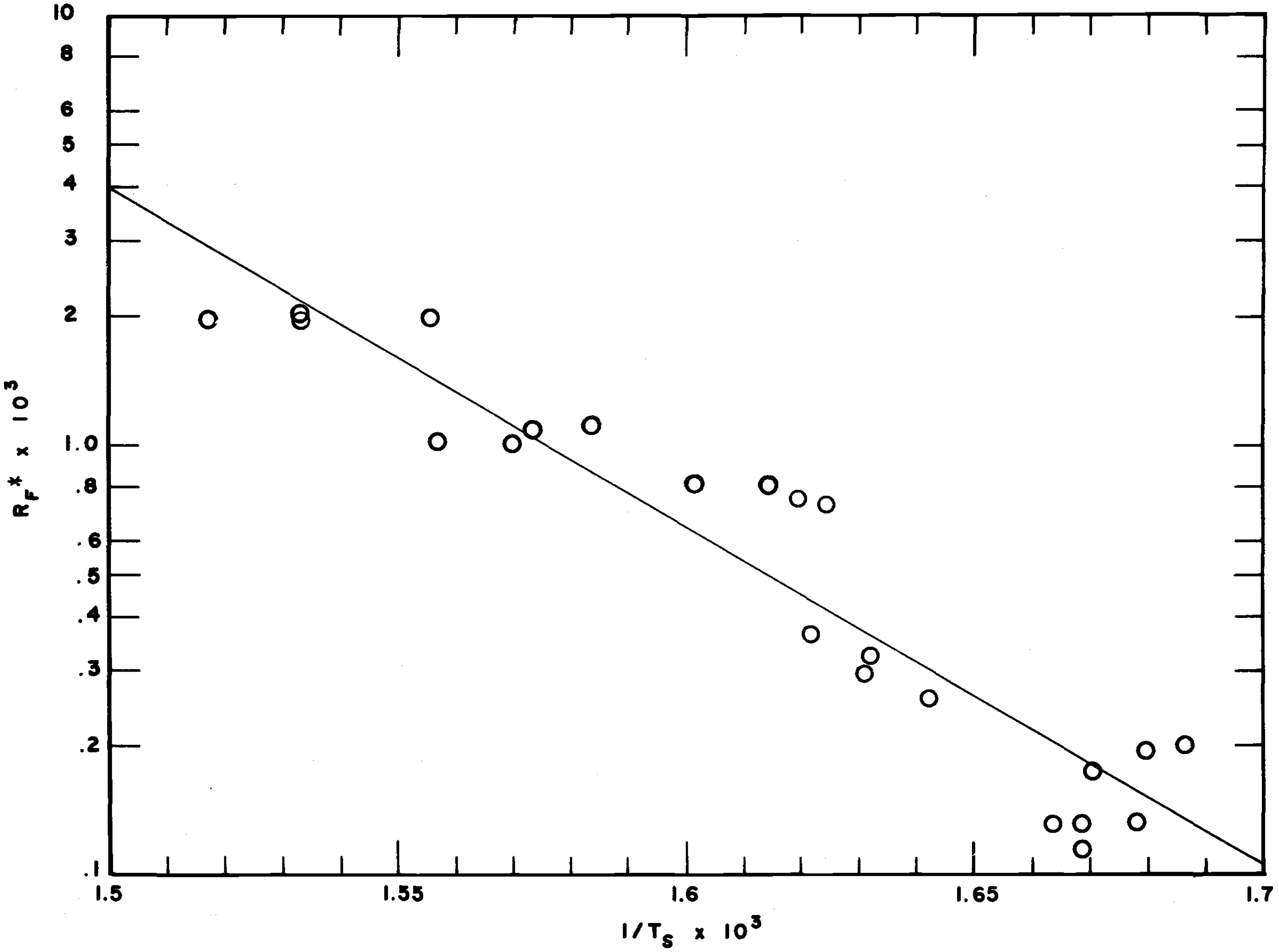

FIGURE 6. R_F^* VERSUS $1/T_S$

formation of the scale was investigated with the following results. With coefficient b = -18,027° F, and using a value of 1.987 Btu/(lb-mole)° R for the gas constant R, the activation energy of Equation 35 is computed to be -9022 Btu/lb-mole. Because the scale is approximately 90% $CaCO_3$, thermodynamic properties of $CaCO_3$, taken from National Bureau of Standards information (22), were used for comparison. The reverse heat of solution for calcium ions and carbonate ions precipitating out of solution as $CaCO_3$ is 5400 Btu/lb-mole. The heat of reaction of the entire crystallization mechanism as described by Hasson (5) in which the carbonate ion is formed by dissassociation from the bicarbonate ion has a heat of reaction of -144,000 Btu/lb-mole. These thermodynamic values do not agree with the -9022 Btu/lb-mole value given by Equation 38. Therefore, it is felt that E/R should be lumped together into one constant for the most meaningful correlation involving asymptotic fouling resistance and surface temperature.

Comparison of Equation 38 with solubility data gives further insight into the mechanism of fouling. Figure 7 shows a plot of $CaCO_3$ solubility in water versus temperature. This graph shows a decreasing slope indicating a decreasing tendency for increasing scale formation from precipitation as temperature increases. Equation 38, however, as evidenced by an Arrhenius temperature type of function, shows an increasing tendency for asymptotic fouling resistance to

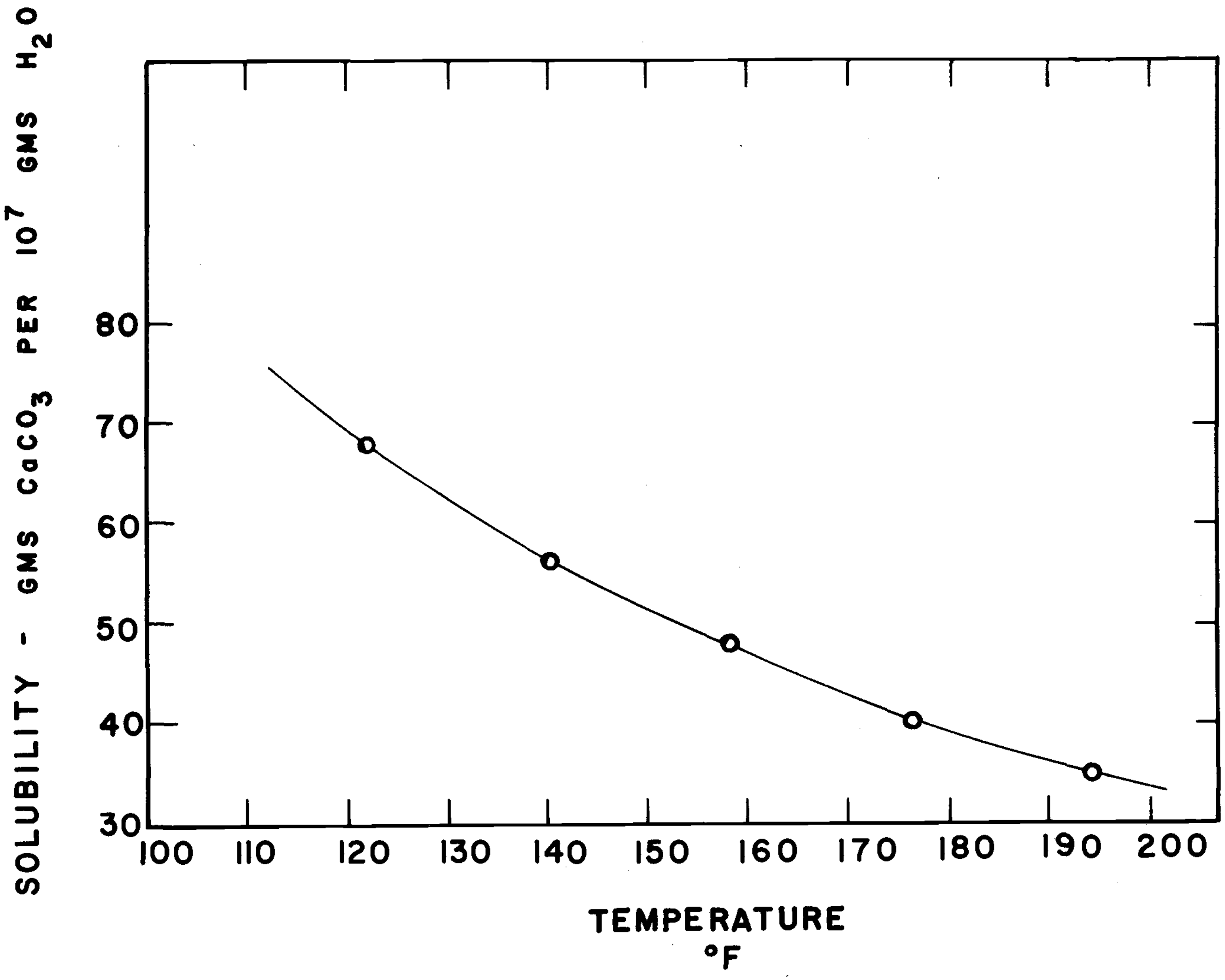

FIGURE 7. $CaCO_3$ SOLUBILITY AS A FUNCTION OF TEMPERATURE

increase with increasing temperature. This comparison indicates that the inverse solubility characteristics of $CaCO_3$ agree in general with fouling data, but fail to account for the exponentially increasing relationship between asymptotic fouling resistance and surface temperature.

Certain assumptions can be made about the coefficients a and b as represented in Equation 36 and which were computed using a least squares analysis. Coefficient b represents the slope of the semi-log plot found in Figure 6, and should be constant for any fouling involving cooling water with the same basic mechanism of fouling. Coefficient a, on the other hand, is not a constant and should contain within it the effects of flow velocity and water quality. Further refinements of the model presented here should correlate coefficient a as a function of both flow velocity and the water quality index.

Double asymptotes were found in the fouling resistance versus time plots in Appendix E for runs 8 and 11. The cause of this is unknown. Effects of this type are usually caused by a mechanical failure or a sudden change in water quality, as shown by Taborek, et al. (19). The thermocouples were in good working order at the end of these two runs, as was the heating coil. The water quality was not altered during the runs.

It is unknown whether the degree of fouling on a specific location of a heated surface is affected by the radial position of the point of observation of fouling--that is, whether or not gravitational effects or flow patterns have an influence. Recognizing some scattering of the data in Figure 6, it is suspected that non-uniform fouling around a horizontal tubular heated surface is being observed.

The Ryznar Stability Index apparently is not a dependable parameter for the quantitative or qualitative prediction of fouling. An obvious example can be taken directly from the results listed in Table 3. Six runs, numbers 1, 2, 3, 4, 7, and 10, were made with their average surface temperatures within 7°F of each other. Therefore, the surface temperature effect should be essentially the same for all runs. With velocity and bulk water temperature essentially constant, the only remaining variable to predict relative amounts of fouling is the Ryznar Stability Index. As shown below, the predicted order of relative amounts of fouling based on the RSI differs greatly from the order of the relative amount of fouling observed. The lowest number corresponds to the lowest amount of fouling.

Run Number	Observed Order of Degree of Fouling	Predicted Order of Degree of Fouling
3	1	3
10	2	2
7	3	4
4	4	5
1	5	1
2	6	6

Although the RSI was not a parameter studied in depth in this work, surface observations show it to be a poor predictor of the degree of fouling for the type of water used in this study. Perhaps a new index such as the critical pH proposed by Feitler (3) would be more effective for cooling water systems. A comparison between the Ryznar Stability Index and the critical pH was not able to be done in this study. The critical pH involved an extra chemical analysis of each water sample as described earlier, and most of the water analyses had been done and the water discarded before the weakness of the RSI was fully realized.

CONCLUSIONS

A cooling tower system was constructed in which cooling water can be formulated, circulated, and studied in a laboratory environment. With the aid of a HTRI portable fouling unit provided by Heat Transfer Research Incorporated (HTRI), Alhambra, California, fouling resistances were measured as a function of time. With the experimental equipment used, it was possible to control flow velocity, surface temperature, and water quality to allow a comprehensive study of fouling and the significant parameters which affect it.

Maintaining flow velocity and water quality constant, fouling resistances were measured under different surface temperature conditions ranging from 136° F to 199° F. The resulting correlation given in Equations 37 and 38 confirms a direct relationship between surface temperature and asymptotic fouling resistance as predicted by previous studies, but offers a simple model for use in predicting fouling factors at given surface temperatures. The correlation indicates that inverse salt solubility does not alone explain the mechanism of fouling.

The effects of flow velocity and water quality need to be studied in further depth. Scaling tendency in water quality has been judged by the Ryznar Stability Index since 1944, and this particular index was found not to be effective in predictions of fouling for the water used in this study.

Because of the tremendous range of conditions found in industrial cooling water systems, the isolation and study of a water with one quality and one flow velocity appears to be an infinitely small contribution. Isolation of significantly contributing parameters has to start somewhere, however, and it is hoped that the general effect of the surface temperature on fouling resistance asymptotes given in Equation 37 will hold up under these wide range of existing conditions. Further study of fouling is already in progress at Oregon State University, and the experimental equipment built and the model developed in this work easily serves as a starting point for this future research.

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APPENDICES

APPENDIX A

Nomenclature

Symbol	Definition	Units
A	Surface area, function of total dissolved solids	ft^2
A1	Function of total dissolved solids as defined in Equation 25	
ALK	Total alkalinity concentration	ppm $CaCO_3$
B	Function of water temperature in scaling index	
BLOG	Function of absolute water temperature as defined in Equation 29	
C	Function of calcium hardness for scaling index	
Ca	Calcium ion concentration	ppm
CH	Calcium hardness concentration	ppm $CaCO_3$
D	Function of alkalinity for scaling index, heater rod diameter	 inches
h_i	Inside local convective heat transfer coefficient	Btu/hr-ft^2-°F
h_o	Outside local convective heat transfer coefficient	Btu/hr-ft^2-°F
HTRI	Heat Transfer Research Incorporated	
K'_2, K'_s	Thermodynamic function of temperature, dissolved solids, and ionic strength	
L	Length of heated section of rod	inches
ln	Natural logarithm	
pH	Negative logarithm of the hydrogen concentration	
pH_s	Saturation pH	
pH_c	Critical pH	
Q	Heat input into heater	Btu/hr

Symbol	Definition	Units
Q1	Wattmeter reading	Kilowatts
R	Universal gas constant	1.987 Btu/(lb-mole)(° R)
R_f	Fouling rate transfer resistance	$(\text{Btu/hr-ft}^2\text{-° F})^{-1}$
R_f^*	Asymptotic fouling heat transfer resistance	$(\text{Btu/hr-ft}^2\text{-° F})^{-1}$
RSI	Ryznar stability index	
R_w	Thermal heat transfer resistance of wall	$(\text{Btu/hr-ft}^2\text{-° F})^{-1}$
T	Absolute temperature	° R
t_b	Water bulk temperature	° F
t_c	Thermocouple temperature	° F
TC	Thermocouple location	
TH	Total hardness concentration	ppm $CaCO_3$
t_s	Surface temperature	° F
T_s	Absolute surface temperature	° R
TS	Total dissolved solids concentration	ppm
t_w	Wall temperature	° F
U_o	Overall heat transfer coefficient based on outside area of rod	$\text{Btu/hr-ft}^2\text{-° F}$
x/k	Thermal metal resistance in heater wall	$(\text{Btu/hr-ft}^2\text{-° F})^{-1}$
ξ	Dummy variable used in error analysis	° F
θ	Time	hours

APPENDIX B

Calibration Curves

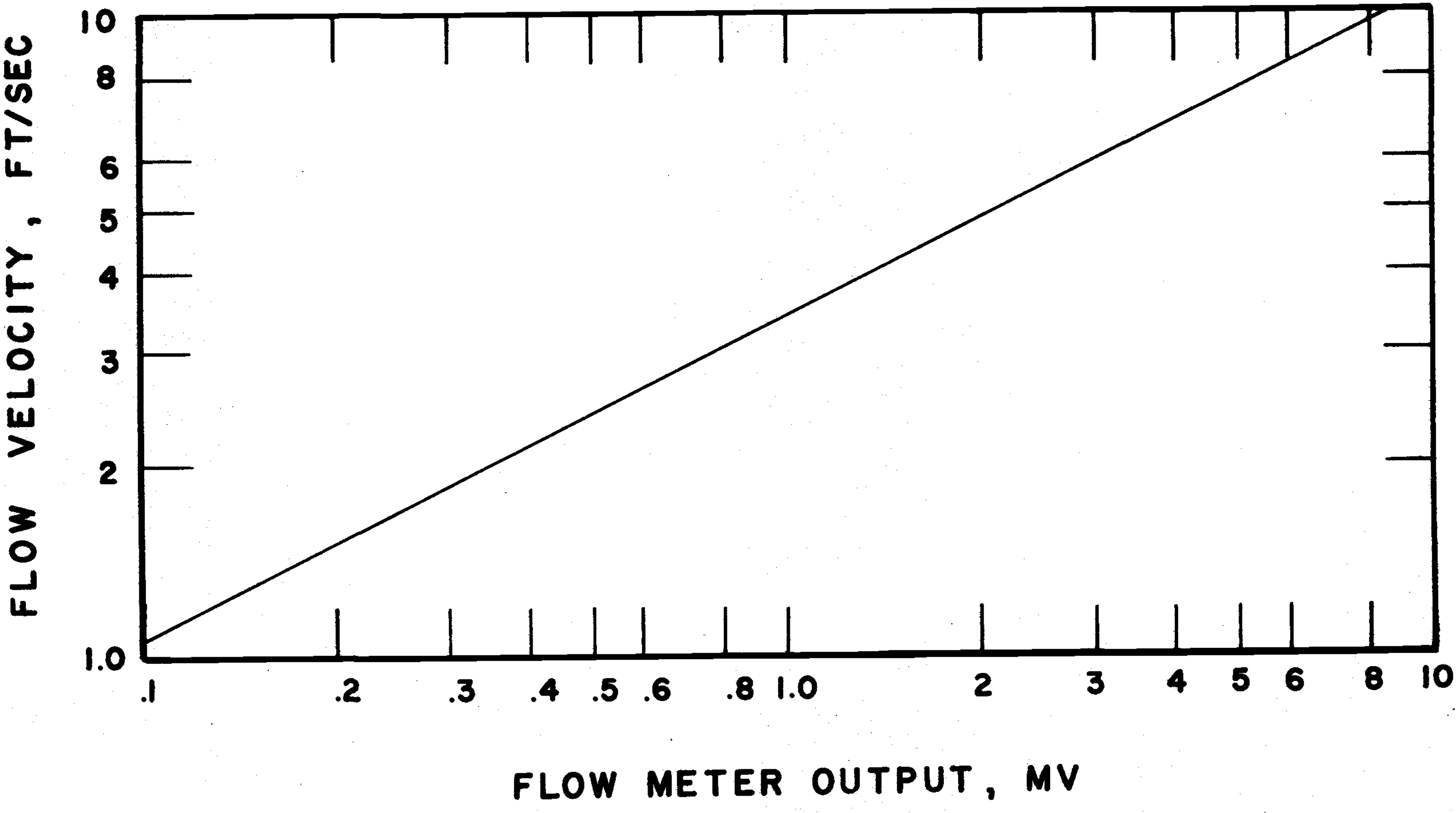


FIGURE 8. FLOW METER CALIBRATION CURVE

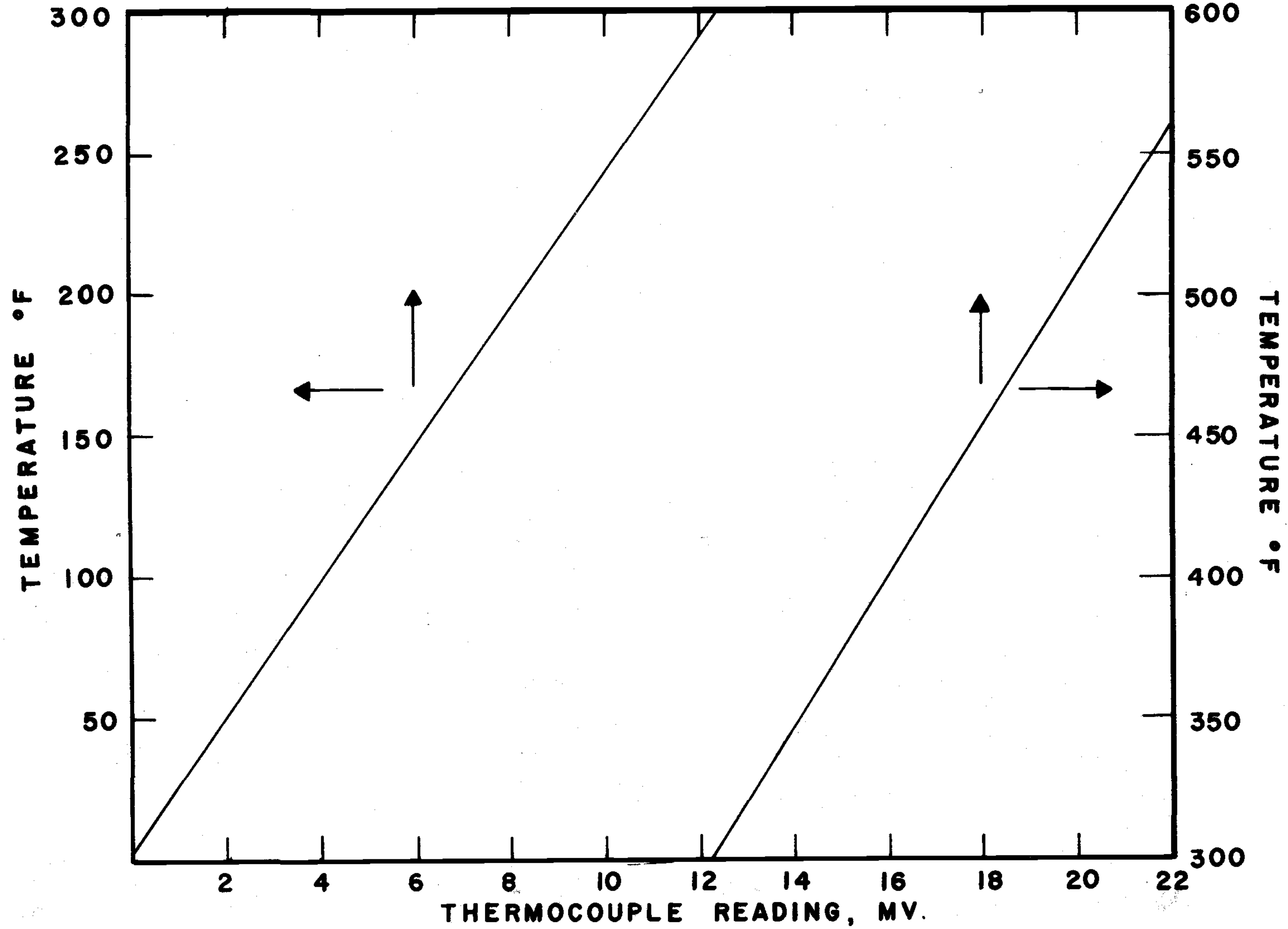


FIGURE 9. THERMOCOUPLE CALIBRATION CURVE

APPENDIX C

Chemical Analysis Procedures

Each water sample taken was analyzed for total hardness, calcium hardness, pH, alkalinity, and total solids. Total hardness and calcium hardness were found by titration with a standard EDTA solution. The procedure followed is outlined in McCoy (16). Results are given in ppm $CaCO_3$. Total alkalinity was found by titration with a standard sulfuric acid solution. The procedure followed is outlined in Standard Methods (1), and the mixed indicator method was used. Results are given in ppm $CaCO_3$.

The pH of each sample was measured with a Beckman "Chem-Mate" pH meter. This meter used a polypropylene combination electrode and has an accuracy of ±.1 pH unit.

The amount of total solids in each sample was determined by using a simple evaporation technique as recommended by Standard Methods (1). Water was dried at 180 degrees centigrade for 24 hours, and the total solids concentration was found by dividing the weight of solids left in the evaporating dish after drying by the weight of the total sample of water.

The purpose of the water analysis was two fold. First, it was necessary to frequently monitor the water content to avert significant changes in water quality. Second, the analyzed parameters were converted to the Ryznar Stability Index, which was needed as a general indicator of the water fouling tendency.

APPENDIX D

Computer Program Listings

Nomenclature Used in PROGRAM INDEX

Symbol	Meaning
A, B, C, D	Function in scaling index as described in Appendix A
ALK	Alkalinity
CH	Calcium hardness
DA	Date of analysis
PH	pH
RN	Run number
SI	Ryznar Stability Index
TABS	Abolute water temperature
TAVG	Average water temperature
TH	Total hardness
TIN	Inlet water temperature
TOUT	Outlet water temperature
TS	Total solids

```
      PROGRAM INDEX
      INTEGER RN
C
C     READ IN RUN NUMBER AND CHEMICAL COMPOSITION DATA
C
      RN=TTYIN(4H RN=)
      WRITE(61,100)RN
  100 FORMAT(1X,'CHEMICAL ANALYSIS OF WATER SAMPLES FOR '
     3'RUN NO. 'I2/2X,'DATE',3X'TEMP'3X'TOTAL SOLIDS  AL'
     1'K  TOT HARD CAL HARD  PH   STI'/8X'(DE'
     2'G F)'4X'(PPM)'5X'(PPM)'3X'(PPM)'3X'(PPM)')
    1 READ(5,101)DA,TH,CH,PH,ALK,TS,TIN,TOUT
  101 FORMAT(A6,6F6.0,1X,F5.0)
      IF(TH.LT.5.)GO TO 2
C
C     CONVERT THERMOCOUPLE READINGS TO TEMPERATURE
C
      T1=32.583*((TIN-4.041)+5.02)**.949
      IF((TIN-4.041).GE.-1.)T1=38.529*((TIN-4.041)+4.72)**.8765
      T2=32.583*((TOUT-4.041)+5.02)**.949
      IF((TOUT-4.041).GE.-1.)T2=38.529*((TOUT-4.041)+4.72)
     3**.8765
      TAVG=(T1+T2)/2.
C
C     COMPUTE  RYZNAR STABILITY INDEX USING FUNCTIONS A,B,C,& D
C
      AID=(TS/40000.)**.5
      A=2.5*AID/(1.+5.3*AID+5.5*AID*AID)
      TABS=TAVG+459.72
      RECIP=1./TABS
      BLOG=-1.37864+1040.92*RECIP-75500.*RECIP*RECIP
      B=10.**BLOG
      C=ALOG(CH*.4)/2.30259
      D=ALOG(ALK)/2.30259
      SI=2.*(9.30+A+B-C-D)-PH
      WRITE(61,102)DA,TAVG,TS,ALK,TH,CH,PH,SI
  102 FORMAT(1X,A6,F6.1,F10.0,F10.0,F8.0,F8.0,F8.1,F6.2)
      GO TO 1
    2 CONTINUE
      END
```

Nomenclature Used in PROGRAM FOULING

Symbol	Meaning
A	Surface area
Del	Difference array
F	Fouling resistance array
FLUX	Heat flux
PD	Discharge pressure
PS	Suction pressure
Q1	Wattmeter reading
Q2	Heat input in Btu/hr
RD	Day of run
RN	Run number
T	Chromel constantan thermocouple readings array
TB	Water bulk temperature
TH, ITIME, TIME, CT	Variables used in measuring total time
T1, T2, T3, T4	Copper constantan thermocouple readings
TI	Time array
TS	Surface temperature array
TW	Wall temperature array
V	Flow velocity
V1	Flow meter reading
XK	Thermal resistance array

```
      PROGRAM FOULING
      INTEGER RN
      DIMENSION T(6),TW(4),TS(4),F(4),XK(4),DEL(4),TI(100),
     1CT(100),DA(100)
C
C     READ IN RUN NUMBER AND HEATER SPECIFICATIONS
C
      RN=TTYIN(4HRN =)
      XK(1)=TTYIN(4HXK1=)
      XK(2)=TTYIN(4HXK2=)
      XK(3)=TTYIN(4HXK3=)
      XK(4)=TTYIN(4HXK4=)
      DO 1 I=1,4
    1 XK(I)=1./XK(I)
      WRITE(10,101)RN
  101 FORMAT(1H1,16X,'CALCULATED DATA FOR RUN NO. 'I2//17X,
     2'HOURS VEL      Q/A     T BLK   TW A    TW B    TW C    TW D'
     3'     FOUL A    FOUL B    FOUL C    FOUL D')
      J=1
C
C     READ IN DATA FILE
C
    5 READ(5,102)ITIME,TIME,T1,T2,T3,T4,T(5),T(6),(T(I),I=1,4),
     5V1,Q1,PS,PD,RD
  102 FORMAT(I2,F3.0,15F5.0)
      IF(T1.LT..001)GO TO 45
C
C     CONVERT KILOWATTS READING TO HEAT FLUX
C
      A=(3.14159*.424/12.)*4./12.
      Q2=Q1*3413.
      FLUX=Q2/A
C
C     CONVERT THERMOCOUPLE READINGS TO FARENHEIT TEMPERATURE
C
      DO 15 I=1,6
      IF((T(I)-4.041).LT.-1.0)GO TO 10
      T(I)=38.529*((T(I)-4.041)+4.72)**.8765
      GO TO 15
   10 T(I)=32.583*((T(I)-4.041)+5.02)**.949
   15 CONTINUE
C
```

```
C     COMPUTE FLOW VELOCITY, WATER BULK TEMPERATURE, ROD
C     WALL TEMPERATURE, DEPOSIT LAYER SURFACE TEMPERATURE,
C     FOULING RESISTANCE, AND TOTAL HOURS AT TIME OF RUN
C
      V=10.*SQRT(V1/10.)*.0022280/.00208
      TB=(T(5)+T(6))/2.
      DO 25 I=1,4
      TW(I)=T(I)-FLUX*XK(I)
      IF(J.GT.1)GO TO 20
      DEL(I)=TW(I)-TB
   20 TS(I)=TB+DEL(I)
   25 F(I)=(TW(I)-TS(I))/FLUX
      DA(J)=RD
      TH=ITIME
      CT(J)=TH+(TIME/60.)*100.
      IF(J.NE.1)GO TO 30
      TI(J)=0.00
      GO TO 35
   30 TI(J)=TI(J-1)+CT(J)-CT(J-1)+24.*(DA(J)-DA(J-1))
   35 DO 40 I=1,4
      IF(TW(I).GT.33.)GO TO 40
      TW(I)=0.
      F(I)=0.
   40 CONTINUE
      WRITE(10,103)TI(J),V,FLUX,TB,(TW(I),I=1,4),(F(I),I=1,4)
  103 FORMAT(16X,F6.2,1X,F4.2,1X,F8.1,1X,F5.2,4F7.2,4F9.6)
      J=J+1
      GO TO 5
   45 CONTINUE
      END
```

APPENDIX E

Fouling Resistance Versus Time Graphs

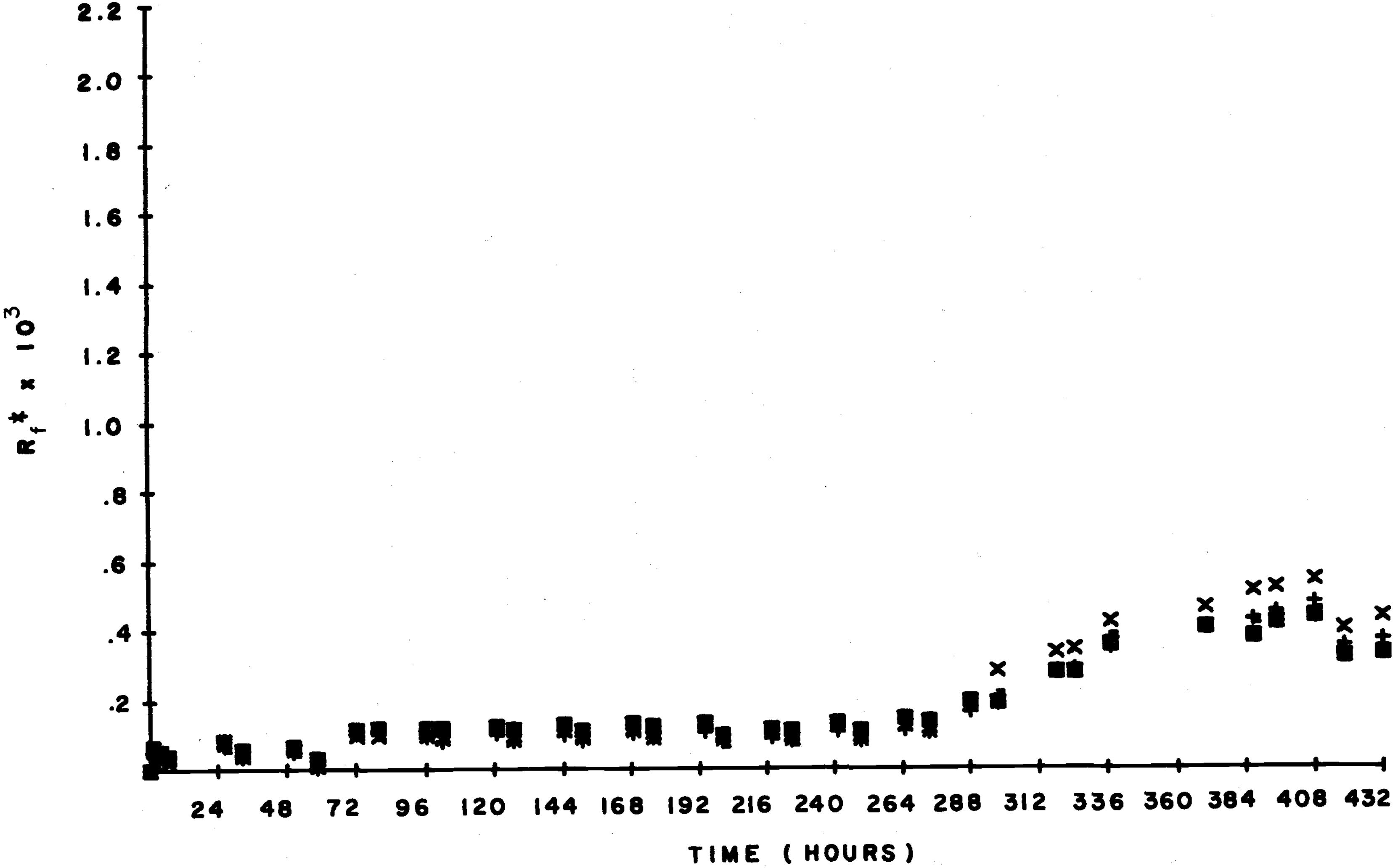


FIGURE 10. RUN NO. 1, FOULING VS. TIME

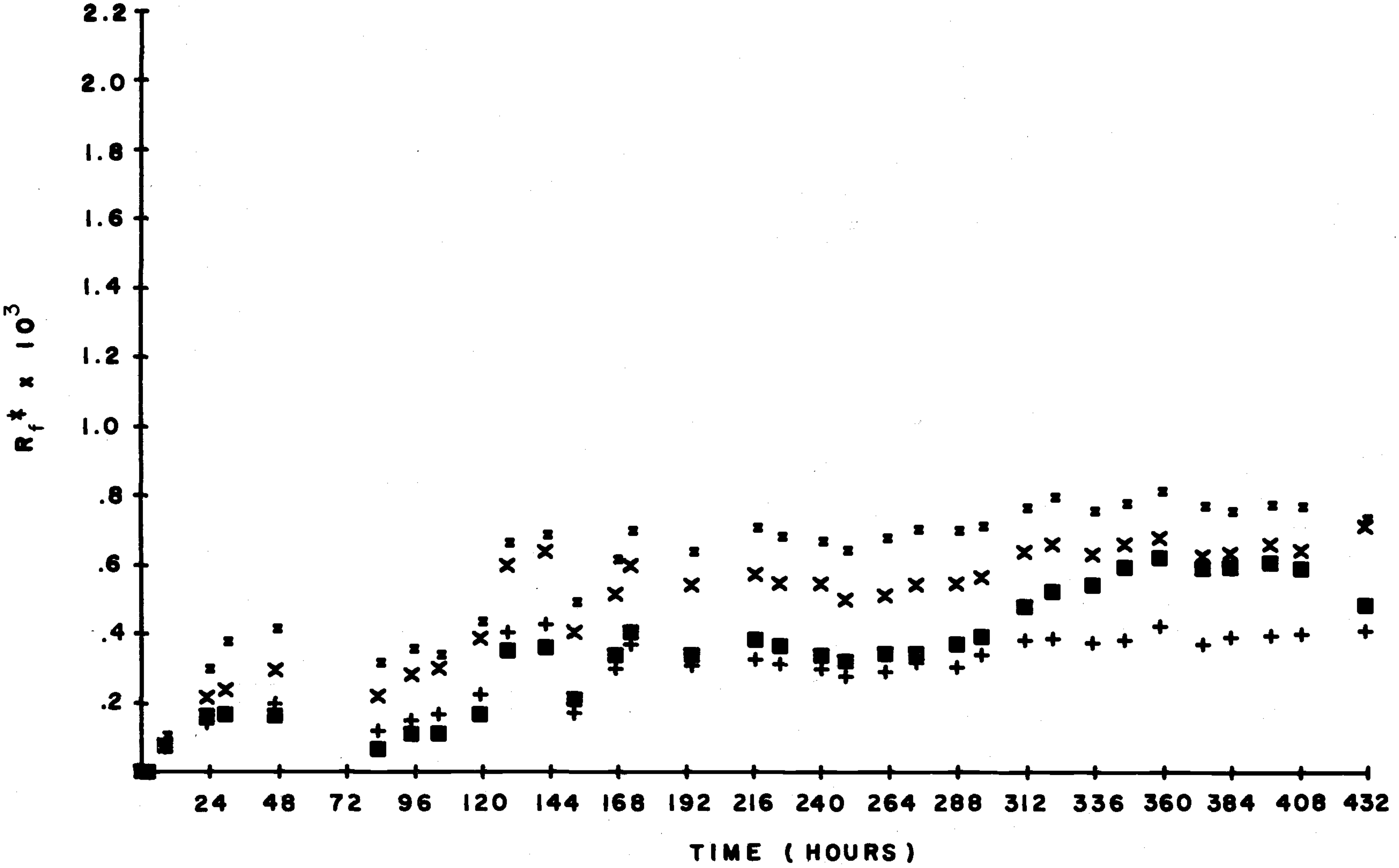


FIGURE 11. RUN NO. 2, FOULING VS. TIME

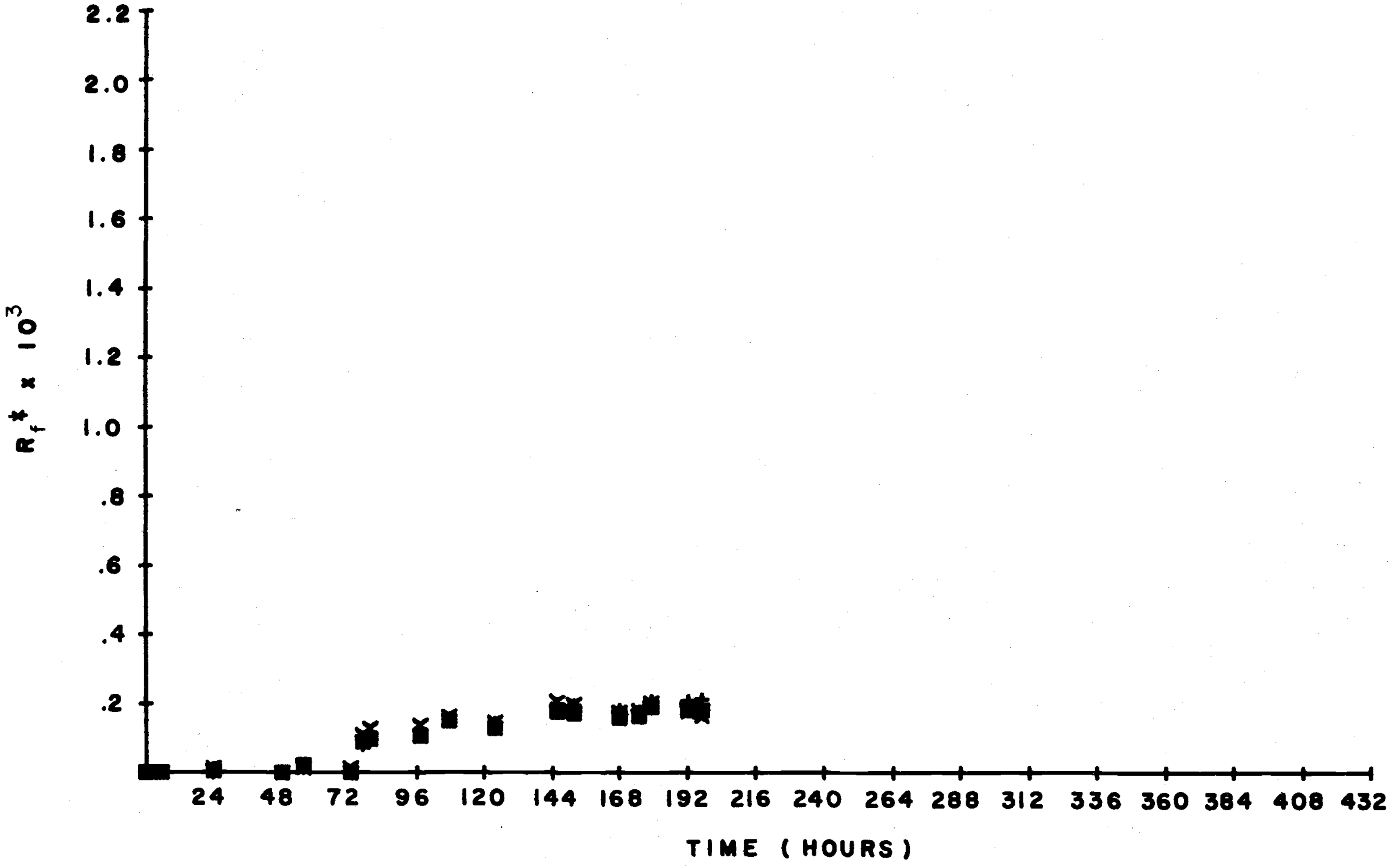
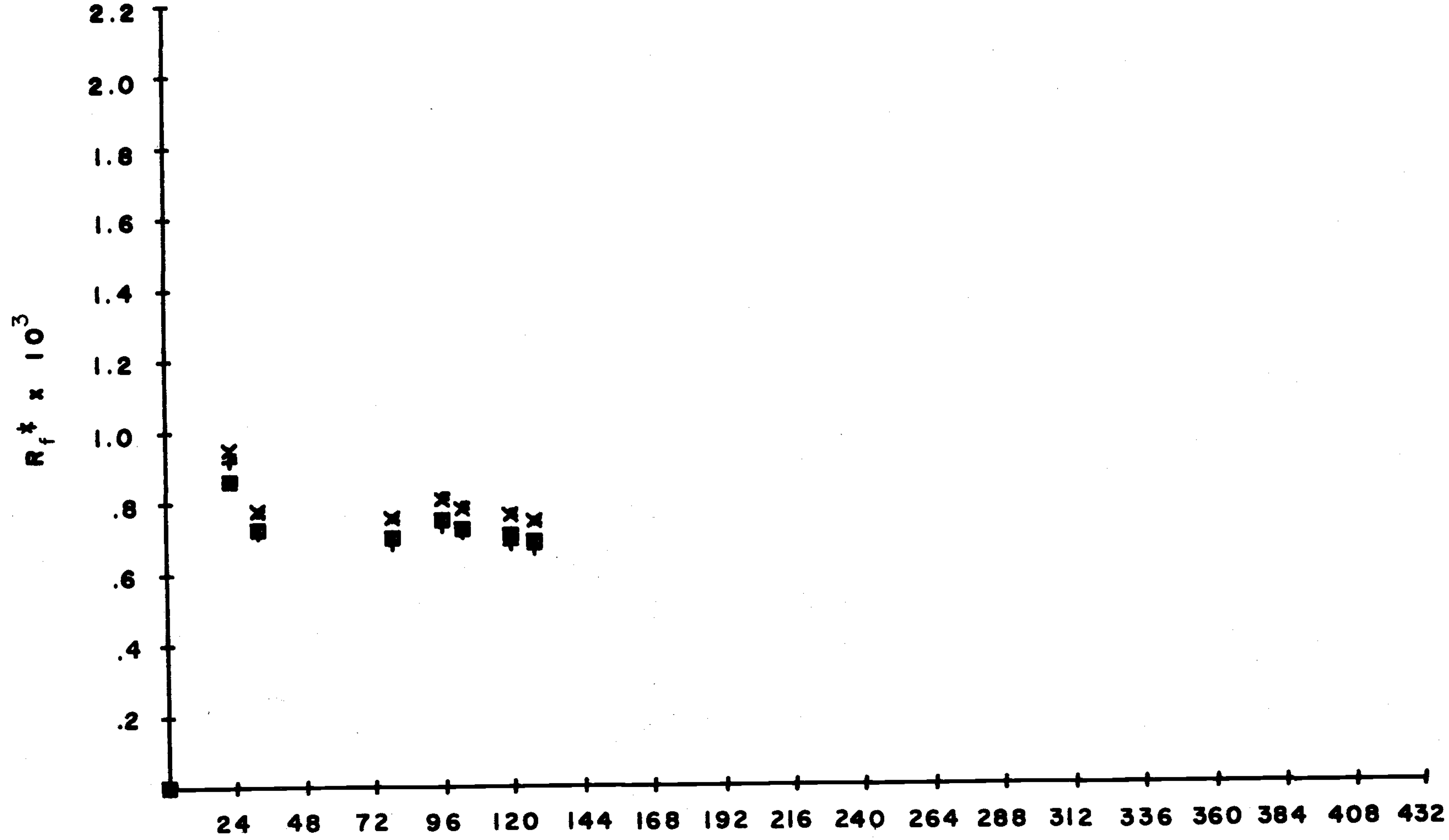


FIGURE 12. RUN NO. 4, FOULING VS. TIME



TIME (HOURS)

FIGURE 13. RUN NO. 5, FOULING VS. TIME

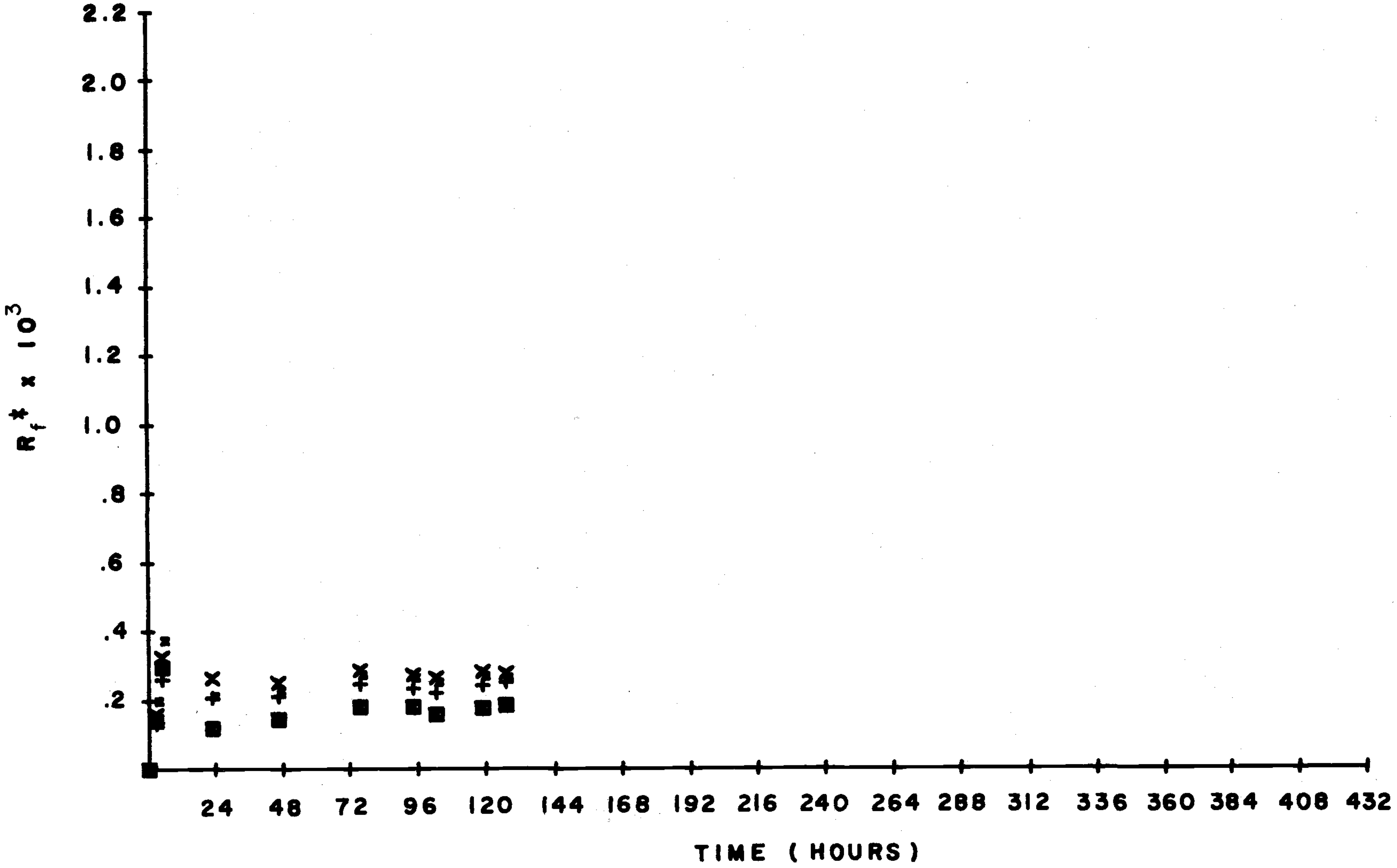


FIGURE 14. RUN NO. 6, FOULING VS. TIME

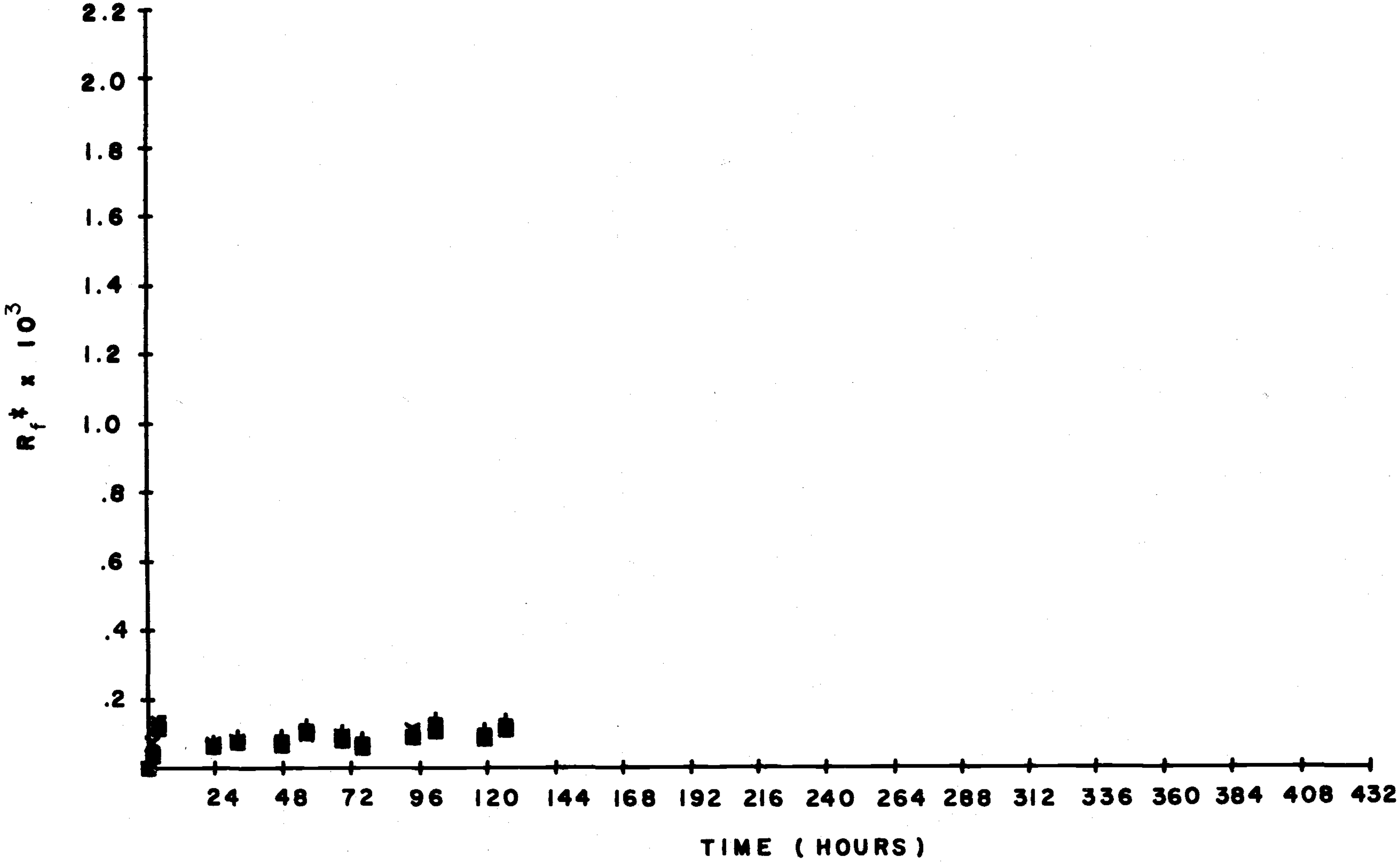


FIGURE 15. RUN NO. 7, FOULING VS TIME

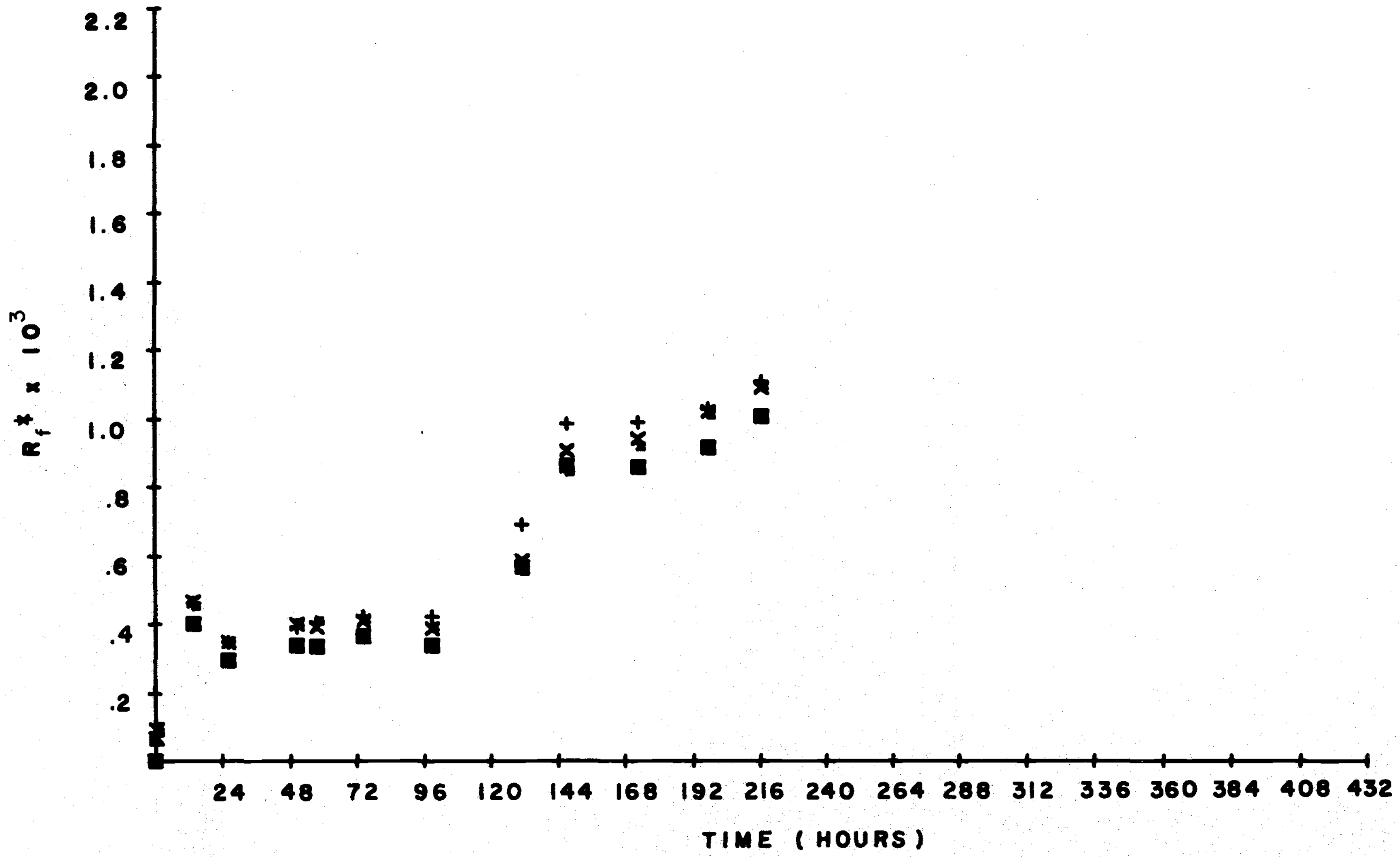


FIGURE 16. RUN NO. 8, FOULING VS. TIME

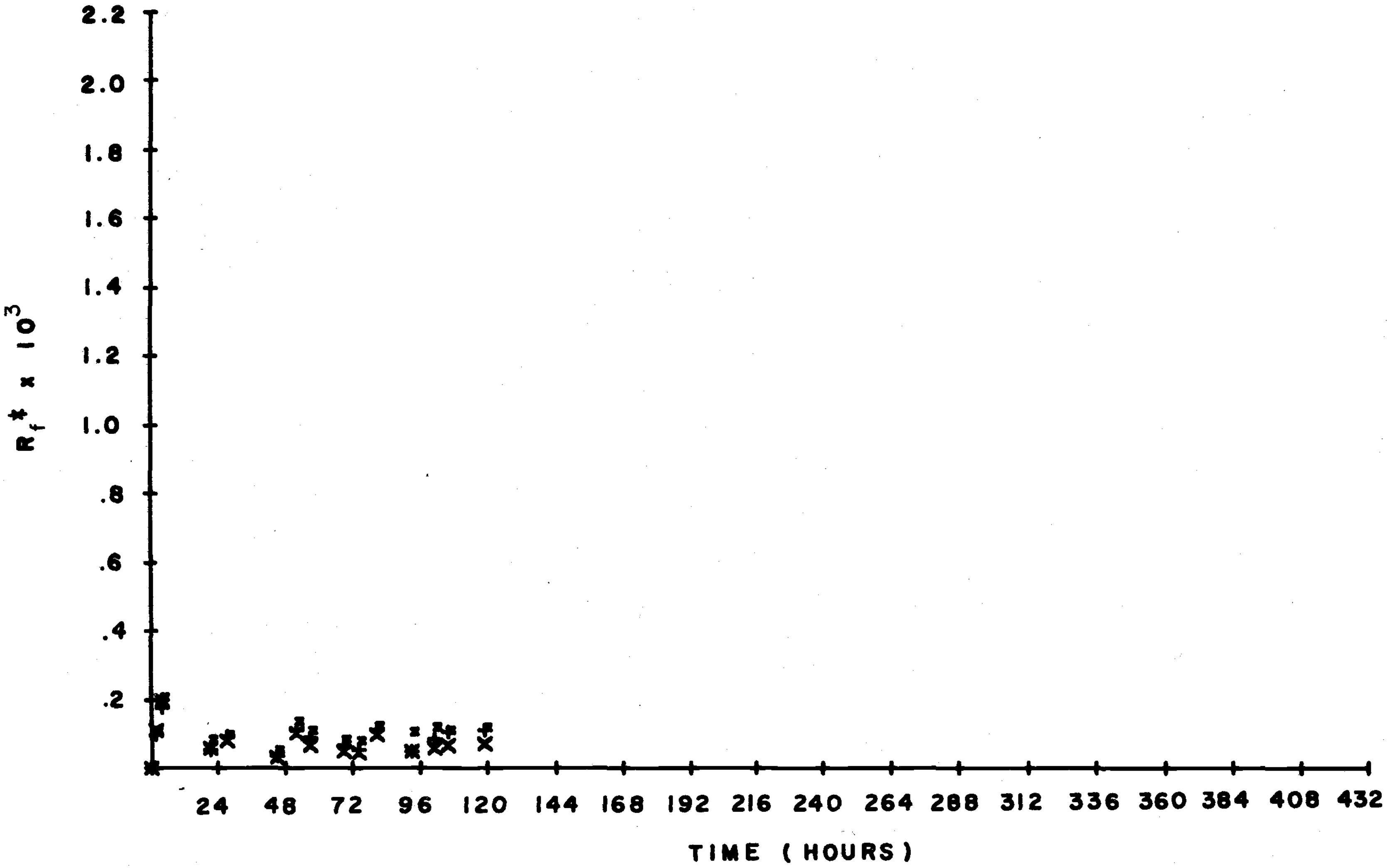


FIGURE 17. RUN NO. 10, FOULING VS. TIME

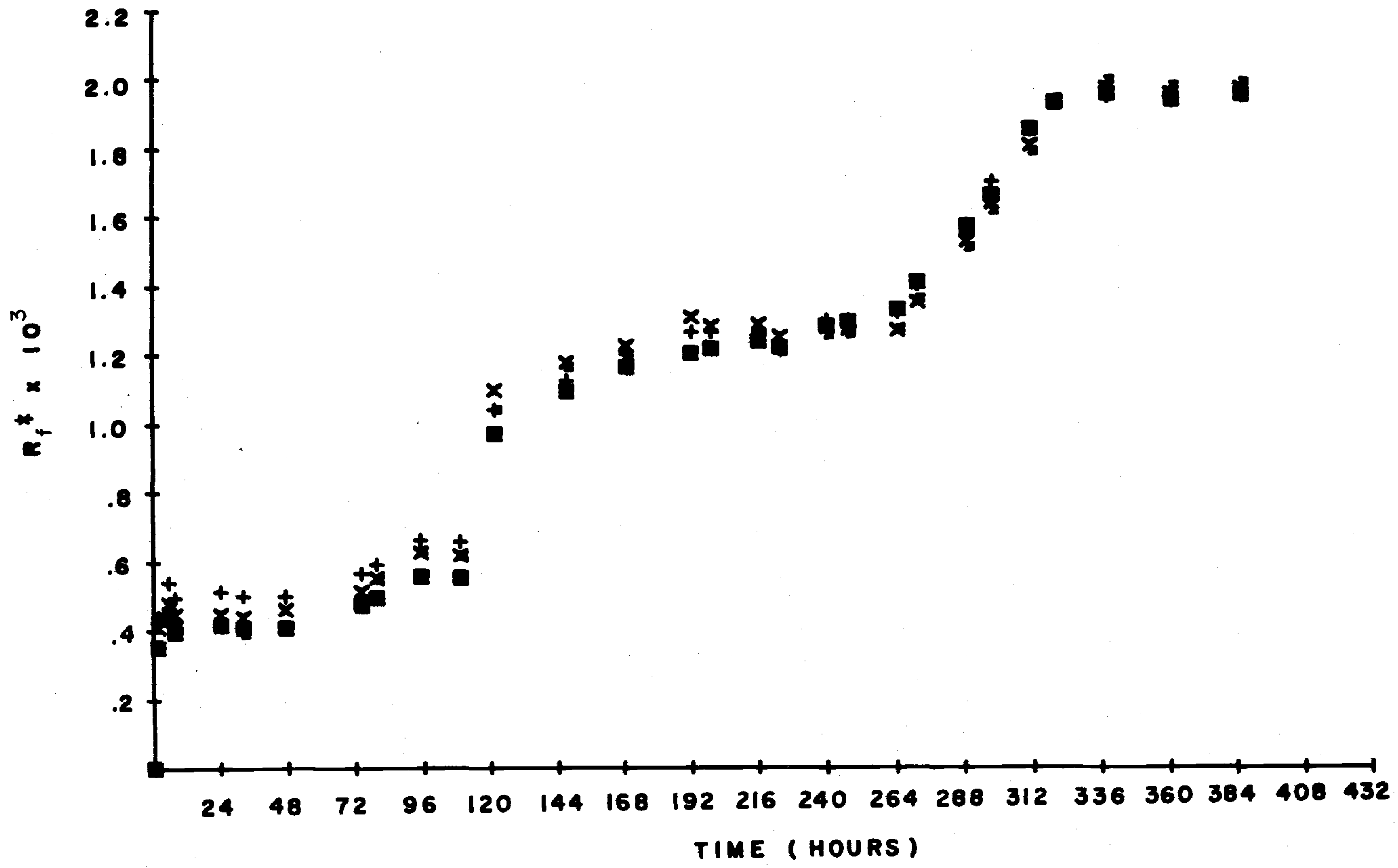


FIGURE 18. RUN NO. 11, FOULING VS. TIME

APPENDIX F

Tabulated Data

```
OBSERVED DATA FOR RUN NO.  1
HEATER NUMBER 58
DA TIME   T IN T OUT  T A   T B   T C   T D   FLO HEAT P IN  P OUT
 1  9.15 1.398 1.440 4.07  4.04  4.43  4.44  1.00  .60 18.50 18.20
 1 10.17 1.516 1.564 4.31  4.30  4.61  4.62  1.00  .60 19.20 19.00
 1 13.10 1.641 1.690 4.42  4.41  4.75  4.77  1.00  .60 18.30 18.20
 1 15.40 1.728 1.776 4.49  4.47  4.82  4.84  1.00  .60 18.30 18.10
 2 11.00 1.616 1.666 4.45  4.44  4.77  4.83  1.00  .60 18.30 18.20
 2 17.40 1.754 1.804 4.52  4.54  4.87  4.91  1.00  .60 18.30 18.20
 3 11.35 1.617 1.667 4.40  4.41  4.75  4.79  1.00  .60 18.30 18.20
 3 19.24 1.713 1.761 4.42  4.44  4.77  4.80  1.00  .60 18.30 18.20
 4  9.05 1.647 1.699 4.54  4.54  4.88  4.91  1.00  .60 18.30 18.20
 4 16.40 1.703 1.757 4.61  4.61  4.94  4.97  1.00  .60 18.30 18.20
 5  9.25 1.538 1.589 4.41  4.43  4.77  4.79  1.00  .60 18.70 18.50
 5 15.00 1.699 1.752 4.55  4.60  4.92  4.95  1.00  .60 18.60 18.40
 6  9.25 1.562 1.615 4.45  4.47  4.81  4.85  1.00  .60 18.60 18.50
 6 15.40 1.713 1.765 4.57  4.61  4.93  4.95  1.00  .60 18.60 18.50
 7  9.30 1.598 1.651 4.48  4.51  4.88  4.88  1.00  .60 18.50 18.40
 7 15.40 1.690 1.742 4.54  4.58  4.91  4.94  1.00  .60 18.50 18.40
 8  9.30 1.518 1.570 4.40  4.44  4.77  4.80  1.00  .60 18.50 18.30
 8 16.35 1.629 1.681 4.50  4.54  4.85  4.87  1.00  .60 18.30 18.20
 9 11.00 1.552 1.605 4.45  4.47  4.82  4.88  1.00  .60 18.40 18.30
 9 17.40 1.699 1.749 4.54  4.56  4.88  4.94  1.00  .60 16.50 16.40
10 11.00 1.672 1.725 4.54  4.57  4.90  4.94  1.00  .60 16.50 16.30
10 18.00 1.724 1.775 4.58  4.61  4.92  4.96  1.00  .60 16.50 16.30
11 10.00 1.597 1.648 4.50  4.52  4.88  4.92  1.00  .60 16.50 16.30
11 18.00 1.745 1.796 4.60  4.63  4.96  4.99  1.00  .60 16.50 16.30
12 10.00 1.591 1.642 4.50  4.54  4.89  4.90  1.00  .60 16.50 16.30
12 18.25 1.679 1.730 4.58  4.62  4.94  4.96  1.00  .60 16.80 16.20
13  9.10 1.521 1.573 4.53  4.56  4.91  4.94  1.00  .60 16.30 16.20
13 18.35 1.628 1.677 4.69  4.67  5.09  5.26  1.00  .60 16.30 16.20
14 15.15 1.549 1.602 4.79  4.76  5.13  5.29  1.00  .60 16.20 16.00
14 22.00 1.592 1.644 4.86  4.81  5.20  5.35  1.00  .60 16.00 16.00
15 10.00 1.479 1.530 4.86  4.85  5.27  5.39  1.00  .60 16.00 16.00
16 19.15 1.501 1.552 5.00  4.97  5.35  5.49  1.00  .60 16.00 15.80
17 12.00 1.454 1.505 4.99  4.86  5.33  5.54  1.00  .60 17.00 16.40
17 20.00 1.566 1.615 5.16  5.06  5.48  5.68  1.00  .60 16.80 16.20
18  9.20 1.409 1.460 5.04  4.93  5.34  5.56  1.00  .60 16.80 16.20
18 20.00 1.524 1.573 4.92  4.82  5.20  5.39  1.00  .60 16.50 16.10
19  9.10 1.468 1.517 4.89  4.78  5.17  5.40  1.00  .60 16.60 16.10
19 20.40 1.508 1.556 4.56  4.47  4.91  5.16  1.00  .60 17.80 17.00
20 10.00 1.374 1.425 4.50  4.42  4.86  5.08  1.00  .60 17.80 17.00
20 17.00 1.504 1.553 4.55  4.49  4.92  5.11  1.00  .60 17.80 17.00
21  9.18 1.441 1.493 4.52  4.45  4.87  5.08  1.00  .60 17.80 17.40
22 14.05 1.563 1.614 4.57  4.51  4.92  5.08  1.00  .60 17.80 17.40
```

```
OBSERVED DATA FOR RUN NO.  2
HEATER NUMBER 58
DA TIME    T IN T OUT  T A   T B   T C   T D   FLO HEAT P IN  P OUT
 1 11.17 1.576 1.622  4.24  4.29  4.83  4.55 1.00  .60 17.60 16.80
 1 13.35 1.615 1.662  4.25  4.29  4.80  4.54 1.00  .60 17.60 16.80
 1 19.20 1.677 1.728  4.49  4.55  5.14  4.82 1.00  .60 16.40 16.20
 2  9.55 1.542 1.596  4.49  4.58  5.39  4.95 1.00  .60 18.40 17.60
 2 16.27 1.544 1.597  4.54  4.59  5.55  5.00 1.00  .60 17.60 17.60
 3  9.52 1.493 1.548  4.55  4.53  5.57  5.06 1.00  .60 17.80 17.80
 4 22.08 1.688 1.739  4.60  4.54  5.58  5.12 1.00  .60 17.20 17.00
 5 10.02 1.686 1.741  4.66  4.63  5.66  5.24 1.00  .60 17.00 16.80
 5 19.46 1.715 1.767  4.73  4.66  5.66  5.31 1.00  .60 17.00 16.80
 6 10.04 1.535 1.587  4.65  4.58  5.66  5.29 1.00  .60 17.00 16.80
 6 19.43 1.669 1.730  5.16  5.11  6.29  5.88 1.00  .60 16.00 15.80
 7  9.27 1.487 1.548  5.01  4.93  6.13  5.76 1.00  .60 16.00 15.80
 7 19.46 1.637 1.691  4.65  4.78  5.89  5.44 1.00  .60 17.60 16.80
 8 10.17 1.539 1.597  4.81  4.94  6.04  5.56 1.00  .60 16.80 16.20
 8 15.42 1.577 1.636  4.99  5.11  6.26  5.78 1.00  .60 15.00 14.60
 9 13.19 1.528 1.586  4.81  4.93  6.07  5.60 1.00  .60 16.00 15.00
10 11.35 1.515 1.576  4.84  5.00  6.21  5.66 1.00  .60 16.00 15.60
10 20.27 1.525 1.581  4.82  4.98  6.16  5.61 1.00  .60 16.60 16.30
11 11.17 1.507 1.565  4.77  4.90  6.11  5.59 1.00  .60 16.00 15.80
11 19.47 1.607 1.663  4.84  4.98  6.17  5.60 1.00  .60 16.10 15.90
12  9.39 1.527 1.584  4.78  4.93  6.15  5.54 1.00  .60 16.00 15.90
12 20.36 1.612 1.671  4.92  5.03  6.30  5.70 1.00  .60 16.00 15.80
13 10.32 1.528 1.584  4.80  4.99  6.20  5.61 1.00  .60 16.00 15.80
13 19.21 1.572 1.628  4.92  5.08  6.28  5.70 1.00  .60 16.00 15.80
14 10.18 1.550 1.610  4.99  5.24  6.36  5.83 1.00  .60 15.40 15.00
14 19.56 1.559 1.619  5.01  5.34  6.44  5.89 1.00  .60 15.40 15.00
15 10.00 1.561 1.621  4.98  5.38  6.36  5.82 1.00  .60 15.40 15.00
15 21.31 1.587 1.649  5.03  5.51  6.43  5.92 1.00  .60 15.40 15.00
16  9.45 1.514 1.575  5.03  5.49  6.43  5.87 1.00  .60 15.40 15.00
17   .43 1.593 1.653  5.01  5.51  6.42  5.85 1.00  .60 15.60 15.20
17 10.56 1.564 1.625  5.02  5.49  6.36  5.84 1.00  .60 16.60 16.40
18   .31 1.585 1.645  5.06  5.54  6.42  5.91 1.00  .60 17.00 16.60
18 11.44 1.601 1.662  5.08  5.52  6.43  5.90 1.00  .60 17.00 16.60
19 10.02 1.414 1.474  4.90  5.10  6.15  5.83 1.00  .60 17.00 16.00
19 20.03 1.576 1.633  5.01  5.20  6.33  5.98 1.00  .60 17.00 16.00
20 10.12 1.474 1.534  5.01  5.20  6.29  5.99 1.00  .60 16.80 16.00
20 19.36 1.512 1.570  4.98  5.22  6.31  6.01 1.00  .60 16.40 15.80
21  9.56 1.409 1.467  4.93  5.19  6.31  6.00 1.00  .60 16.40 15.80
21 23.17 1.599 1.657  5.03  5.28  6.37  6.12 1.00  .60 16.40 15.90
22  9.54 1.480 1.538  4.96  5.15  6.31  6.06 1.00  .60 16.80 16.00
22 20.07 1.625 1.684  5.09  5.30  6.41  6.19 1.00  .60 16.80 16.00
23  9.55 1.471 1.528  5.00  5.28  6.33  6.10 1.00  .60 16.80 16.00
24 10.43 1.580 1.640  5.08  5.35  6.35  6.18 1.00  .60 16.80 16.00
25 12.23 1.476 1.537  5.00  5.30  6.21  6.10 1.00  .60 16.00 15.00
25 19.58 1.498 1.558  5.05  5.33  6.27  6.13 1.00  .60 16.60 16.00
26  9.16 1.354 1.411  4.91  5.20  6.11  5.98 1.00  .60 16.60 16.00
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OBSERVED DATA FOR RUN NO.  3
HEATER NUMBER 58
DA TIME    T IN T OUT  T A    T B    T C    T D   FLO HEAT P IN  P OUT
 1 14.46 1.428 1.477  4.10   4.09   4.66   4.57 1.00  .60 20.00 19.00
 1 16.23 1.453 1.502  4.11   4.11   4.66   4.56 1.00  .60 20.00 19.00
 1 21.00 1.513 1.561  4.12   4.10   4.66   4.57 1.00  .60 20.00 19.00
 2 14.01 1.580 1.630  4.15   4.15   4.70   4.59 1.00  .60 19.40 18.60
 3 11.20 1.543 1.591  4.15   4.15   4.70   4.60 1.00  .60 19.40 18.60
 3 20.05 1.555 1.603  4.18   4.18   4.72   4.60 1.00  .60 19.50 18.00
 4 10.20 1.439 1.488  4.11   4.09   4.64   4.58 1.00  .60 19.00 18.20
 5 11.30 1.451 1.500  4.11   4.10   4.66   4.57 1.00  .60 19.00 18.20
 6  9.04 1.438 1.483  4.08   4.08   4.61   4.52 1.00  .60 19.00 18.20
 7  8.30 1.403 1.448  4.08   4.08   4.61   4.53 1.00  .60 19.50 19.30
 8  9.17 1.440 1.486  4.12   4.10   4.64   4.59 1.00  .60 19.50 19.00
 8 20.55 1.519 1.569  4.16   4.14   4.70   4.63 1.00  .60 19.80 19.00
10 10.19 1.607 1.656  4.20   4.19   4.74   4.66 1.00  .60 19.80 19.00
10 20.00 1.509 1.566  4.15   4.13   4.67   4.61 1.00  .60 19.80 19.00
11  8.17 1.396 1.443  4.09   4.06   4.62   4.55 1.00  .60 19.80 19.00
11 19.22 1.528 1.578  4.16   4.15   4.70   4.61 1.00  .60 19.80 19.00
12 14.48 1.575 1.625  4.21   4.20   4.75   4.66 1.00  .60 19.80 19.00
12 21.20 1.508 1.558  4.15   4.14   4.67   4.51 1.00  .60 20.20 19.00
13 10.07 1.659 1.707  4.24   4.25   4.76   4.69 1.00  .60 20.20 19.20
13 20.56 1.469 1.515  4.11   4.11   4.64   4.57 1.00  .60 20.00 19.20
14  8.27 1.478 1.524  4.13   4.12   4.66   4.60 1.00  .60 20.20 19.80
15  9.27 1.335 1.382  4.05   4.04   4.63   4.51 1.00  .60 20.20 19.80
16 11.25 1.302 1.350  4.05   4.05   4.60   4.53 1.00  .40 20.20 19.80
16 23.00 1.429 1.475  4.13   4.12   4.68   4.62 1.00  .60 20.20 19.80
17 11.40 1.399 1.446  4.12   4.12   4.67   4.57 1.00  .60 20.00 19.50
18  8.30 1.356 1.403  4.11   4.12   4.67   4.60 1.00  .60 20.00 19.50
18 17.02 1.380 1.429  4.11   4.11   4.66   4.58 1.00  .60 20.00 19.50
19  9.42 1.404 1.450  4.11   4.09   4.66   4.58 1.00  .60 20.00 19.50
20  9.50 1.456 1.505  4.15   4.14   4.70   4.63 1.00  .60 20.00 19.50
21  8.25 1.475 1.523  4.15   4.16   4.69   4.64 1.00  .60 21.50 20.50
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OBSERVED DATA FOR RUN NO.  4
HEATER NUMBER 58
DA TIME    T IN T OUT  T A    T B    T C    T D   FLO HEAT P IN  P OUT
 1  9.30 1.466 1.514  3.99   4.15   4.52   4.35 1.00  .60 22.00 22.00
 1 14.45 1.504 1.550  4.01   4.16   4.52   4.36 1.00  .60 22.00 22.00
 2  9.00 1.485 1.532  4.02   4.18   4.56   4.40 1.00  .60 22.00 21.00
 3  9.40 1.558 1.604  4.07   4.23   4.57   4.45 1.00  .60 22.00 21.00
 3 17.00 1.458 1.504  4.01   4.18   4.53   4.37 1.00  .60 22.00 21.00
 4  9.52 1.543 1.587  4.06   4.20   4.59   4.46 1.00  .60 21.50 20.70
 4 14.07 1.449 1.490  4.13   4.30   4.68   4.55 1.00  .60 21.50 20.70
 4 17.00 1.444 1.489  4.19   4.32   4.69   4.58 1.00  .60 21.50 20.70
 5 10.26 1.558 1.603  4.33   4.46   4.82   4.72 1.00  .60 21.50 20.70
 5 21.10 1.402 1.448  4.23   4.38   4.72   4.61 1.00  .60 21.50 20.70
 6 13.02 1.567 1.614  4.38   4.51   4.85   4.75 1.00  .60 21.50 20.70
 7 11.19 1.426 1.474  4.34   4.46   4.82   4.72 1.00  .60 22.00 21.00
 7 17.05 1.407 1.452  4.31   4.43   4.80   4.68 1.00  .60 22.00 21.00
 8  9.12 1.505 1.551  4.39   4.51   4.85   4.74 1.00  .60 22.00 21.00
 8 16.25 1.522 1.566  4.40   4.53   4.88   4.77 1.00  .60 22.00 21.00
 8 20.48 1.490 1.537  4.43   4.55   4.89   4.78 1.00  .60 22.00 21.00
 9  9.20 1.484 1.531  4.42   4.54   4.87   4.72 1.00  .60 22.00 21.00
 9 14.50 1.524 1.570  4.47   4.57   4.93   4.74 1.00  .60 22.00 21.00
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OBSERVED DATA FOR RUN NO.  5
HEATER NUMBER 58
DA TIME    T IN T OUT  T A    T B    T C    T D    FLO HEAT P IN  P OUT
 1 11.54 1.379 1.445  5.26   5.51   6.06   5.81  1.00  .96 22.00 21.00
 2 10.07 1.342 1.417  8.32   8.38   9.17   9.01  1.00  .96 20.50 19.00
 2 19.50 1.524 1.595  7.83   8.12   8.83   8.62  1.00  .96 22.00 20.20
 4 18.06 1.503 1.572  7.68   8.00   8.74   8.52  1.00  .96 22.00 21.00
 5 11.21 1.387 1.456  7.73   8.06   8.82   8.56  1.00  .96 22.20 20.80
 5 18.41 1.467 1.537  7.76   8.06   8.82   8.56  1.00  .96 22.20 20.80
 6 11.21 1.430 1.500  7.61   7.96   8.70   8.46  1.00  .96 22.20 20.80
 6 19.21 1.489 1.557  7.62   7.96   8.70   8.47  1.00  .96 22.20 20.80

OBSERVED DATA FOR RUN NO.  6
HEATER NUMBER 58
DA TIME    T IN T OUT  T A    T B    T C    T D    FLO HEAT P IN  P OUT
 1 10.40 1.488 1.546  4.87   5.11   5.55   5.35  1.00  .82 22.80 22.00
 1 13.13 1.532 1.592  5.29   5.55   6.13   5.85  1.00  .82 22.80 22.00
 1 15.37 1.546 1.606  5.66   6.00   6.66   6.34  1.00  .82 22.00 21.00
 2  9.32 1.588 1.647  5.56   5.55   6.24   6.20  1.00  .82 22.00 21.00
 3  9.09 1.553 1.612  5.53   5.59   6.24   6.13  1.00  .82 21.50 20.80
 4 14.15 1.495 1.555  5.57   5.63   6.31   6.16  1.00  .82 21.50 20.80
 5  9.10 1.475 1.533  5.50   5.60   6.25   6.10  1.00  .82 21.50 20.80
 5 17.05 1.540 1.600  5.54   5.61   6.29   6.15  1.00  .82 21.50 20.80
 6  9.22 1.500 1.560  5.56   5.62   6.30   6.15  1.00  .82 21.50 20.80
 6 17.27 1.492 1.552  5.57   5.63   6.28   6.14  1.00  .82 21.50 20.80

OBSERVED DATA FOR RUN NO.  7
HEATER NUMBER 58
DA TIME    T IN T OUT  T A    T B    T C    T D    FLO HEAT P IN  P OUT
 1 11.35 1.555 1.607  4.22   4.40   4.77   4.59  1.00  .64 21.00 20.80
 1 13.23 1.497 1.548  4.24   4.41   4.76   4.69  1.00  .64 21.00 20.80
 1 15.32 1.443 1.491  4.38   4.52   4.93   4.75  1.00  .64 21.00 20.80
 2 10.55 1.609 1.660  4.44   4.59   4.95   4.80  1.00  .64 21.00 20.80
 2 19.11 1.565 1.617  4.43   4.57   4.93   4.77  1.00  .64 21.00 20.40
 3 11.08 1.667 1.717  4.54   4.66   5.02   4.86  1.00  .64 21.00 20.40
 3 19.41 1.523 1.574  4.45   4.58   4.95   4.76  1.00  .64 21.00 20.40
 4  8.13 1.612 1.664  4.51   4.63   5.01   4.85  1.00  .64 21.00 20.80
 4 14.55 1.672 1.725  4.52   4.65   5.04   4.86  1.00  .64 21.00 20.40
 5  9.10 1.562 1.614  4.42   4.60   5.00   4.84  1.00  .64 21.00 20.80
 5 16.55 1.520 1.570  4.48   4.59   4.98   4.81  1.00  .64 21.40 21.00
 6 10.33 1.621 1.673  4.53   4.65   5.01   4.85  1.00  .64 21.00 20.80
 6 17.43 1.555 1.609  4.51   4.64   5.01   4.83  1.00  .64 21.60 21.20

OBSERVED DATA FOR RUN NO.  8
HEATER NUMBER 58
DA TIME    T IN T OUT  T A    T B    T C    T D    FLO HEAT P IN  P OUT
 1 10.18 1.437 1.518  6.00   6.33   6.95   6.62  1.00 1.10 20.50 20.00
 1 10.50 1.498 1.579  6.35   6.66   7.38   7.05  1.00 1.10 20.50 20.00
 1 23.34 1.525 1.610  7.89   7.99   8.80   8.54  1.00 1.10 20.50 20.00
 2 12.11 1.672 1.756  7.61   7.73   8.52   8.24  1.00 1.10 20.50 20.00
 3 12.15 1.415 1.498  7.48   7.62   8.48   8.15  1.00 1.10 20.50 20.00
 3 19.37 1.608 1.694  7.76   7.82   8.71   8.34  1.00 1.10 21.50 20.00
 4 12.21 1.395 1.479  7.58   7.69   8.48   8.16  1.00 1.10 22.50 20.00
 5 13.06 1.608 1.695  7.83   7.84   8.64   8.33  1.00 1.10 22.50 20.00
 6 21.37 1.603 1.688  8.88   8.73   9.29   9.10  1.00 1.10 22.50 20.00
 7 13.32 1.510 1.596  9.95   9.80  10.35  10.29  1.00 1.10 22.50 20.00
 8 14.51 1.494 1.580  9.95   9.76  10.63  10.40  1.00 1.10 22.50 20.00
 9 16.05 1.672 1.758 10.32  10.20  11.22  10.93  1.00 1.10 20.20 19.90
10 10.45 1.493 1.581 10.43  10.36  11.35  11.01  1.00 1.10 20.20 19.90
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OBSERVED DATA FOR RUN NO. 10
HEATER NUMBER 74
DA TIME    T IN T OUT  T A   T B    T C    T D    FLO HEAT P IN  P OUT
 1 12.47 1.480 1.528  4.34       0  4.15   4.36 1.00  .61 21.50 20.50
 1 14.14 1.555 1.602  4.62       0  4.43   4.66 1.00  .61 21.50 20.50
 1 16.42 1.435 1.501  4.66       0  4.51   4.73 1.00  .61 20.50 20.30
 2 10.05 1.577 1.623  4.55       0  4.40   4.58 1.00  .61 21.00 20.40
 2 15.35 1.399 1.450  4.44       0  4.24   4.44 1.00  .61 21.00 20.40
 3  9.37 1.598 1.645  4.54       0  4.36   4.55 1.00  .61 21.00 20.40
 3 16.52 1.364 1.415  4.44       0  4.29   4.44 1.00  .61 21.00 20.40
 3 21.32 1.490 1.540  4.53       0  4.37   4.51 1.00  .61 21.00 20.40
 4  9.23 1.526 1.576  4.52       0  4.35   4.51 1.00  .61 21.00 20.40
 4 14.45 1.558 1.608  4.53       0  4.38   4.53 1.00  .61 21.00 20.40
 4 21.07 1.404 1.455  4.48       0  4.30   4.48 1.00  .61 21.50 21.00
 5  9.24 1.554 1.605  4.52       0  4.43   4.54 1.00  .61 21.50 21.00
 5 17.32 1.578 1.629  4.62       0  4.48   4.58 1.00  .61 21.50 20.40
 5 22.40 1.589 1.638  4.67       0  4.47   4.61 1.00  .61 21.50 20.40
 6 11.44 1.549 1.599  4.64       0  4.45   4.58 1.00  .61 21.50 20.40
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OBSERVED DATA FOR RUN NO. 11
HEATER NUMBER 21
DA TIME    T IN T OUT  T A    T B    T C    T D    FLO HEAT P IN  P OUT
 1  9.28 1.503 1.588  6.00   5.86   5.28   5.72 1.00 1.10 21.80 20.80
 1 11.00 1.599 1.687  7.81   7.32   6.70   7.39 1.00 1.10 21.80 20.80
 1 14.56 1.487 1.574  8.08   7.51   6.92   7.54 1.00 1.10 21.80 20.80
 1 16.50 1.603 1.691  8.04   7.50   6.94   7.56 1.00 1.10 21.80 20.80
 2  9.16 1.483 1.568  7.96   7.45   6.83   7.42 1.00 1.10 22.20 20.80
 2 17.19 1.552 1.634  7.99   7.48   6.78   7.47 1.00 1.10 22.20 20.80
 3  8.40 1.588 1.673  8.04   7.53   6.91   7.58 1.00 1.10 22.20 20.80
 4 11.22 1.615 1.702  8.33   7.81   7.22   7.83 1.00 1.10 21.50 20.80
 4 17.03 1.734 1.822  8.57   8.03   7.60   8.12 1.00 1.10 21.00 20.80
 5  8.35 1.403 1.490  8.47   7.91   7.56   8.03 1.00 1.10 21.50 20.50
 5 22.30 1.645 1.734  8.73   8.16   7.78   8.28 1.00 1.10 21.00 20.50
 6 11.05 1.578 1.668 10.18   9.75   9.38  10.12 1.00 1.10 21.00 20.50
 7 12.39 1.495 1.584 10.42  10.14   9.77  10.34 1.00 1.10 23.80 23.00
 8 10.35 1.506 1.593 10.74  10.45   9.84  10.54 1.00 1.10 22.50 21.90
 9  9.52 1.443 1.528 10.93  10.52   9.91  10.80 1.00 1.10 22.50 21.90
 9 16.30 1.464 1.550 10.96  10.60   9.95  10.73 1.00 1.10 22.50 21.90
10  9.30 1.472 1.557 10.96  10.71  10.03  10.75 1.00 1.10 22.00 21.70
10 17.08 1.693 1.781 11.09  10.89  10.18  10.86 1.00 1.10 22.00 21.70
11  9.21 1.489 1.573 11.12  10.90  10.13  10.74 1.00 1.10 22.00 21.70
11 16.38 1.461 1.548 11.10  10.92  10.13  10.69 1.00 1.10 22.00 21.70
12 10.00 1.580 1.668 11.33  11.20  10.32  10.80 1.00 1.10 22.00 21.70
12 17.06 1.645 1.734 11.73  11.61  10.74  11.23 1.00 1.10 22.00 21.70
13 10.11 1.552 1.634 12.25  12.17  11.24  11.82 1.00 1.10 22.00 21.70
13 18.45 1.552 1.635 12.85  12.53  11.67  12.28 1.00 1.10 22.00 21.70
14  8.20 1.495 1.584 13.40  13.26  12.32  12.91 1.00 1.10 22.00 21.70
14 17.16 1.487 1.574 13.73  13.56  12.95  13.43 1.00 1.10 22.00 21.70
15 11.35 1.507 1.592 13.82  13.70  13.18  13.61 1.00 1.10 22.00 21.70
16 10.21 1.556 1.639 13.81  13.69  13.16  13.61 1.00 1.10 22.00 21.90
17 11.17 1.499 1.586 13.80  13.67  13.14  13.59 1.00 1.10 22.00 21.90
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CHEMICAL ANALYSIS OF WATER SAMPLES FOR RUN NO. 1

DATE	TEMP (DEG F)	TOTAL SOLIDS (PPM)	ALK (PPM)	TOT HARD (PPM)	CAL HARD (PPM)	PH	STI
AUG 3	74.7	443	119	185	126	8.2	7.20
AUG 4	81.3	459	120	191	127	8.2	7.04
AUG 5	81.3	435	124	189	126	8.2	7.01
AUG 6	81.8	437	118	189	126	8.2	7.04
AUG 7	79.0	435	116	184	123	8.3	7.04
AUG 8	79.7	444	118	189	127	8.3	6.98
AUG 9	80.8	432	117	184	124	8.3	6.98
AUG 10	78.4	450	117	192	129	8.3	7.01
AUG 11	79.4	466	122	191	127	8.4	6.87
AUG 12	83.0	467	124	193	129	8.4	6.76
AUG 13	80.7	471	125	194	130	8.5	6.69
AUG 14	80.6	471	128	197	134	8.4	6.75
AUG 15	78.5	462	123	194	130	8.5	6.76
AUG 16	79.3	465	123	196	129	8.5	6.75
AUG 17	77.3	462	125	197	131	8.5	6.77
AUG 19	76.5	490	126	199	132	8.5	6.78
AUG 20	75.2	487	128	202	135	8.5	6.78
AUG 21	76.9	485	127	203	135	8.5	6.74
AUG 22	74.1	488	127	202	135	8.4	6.91
AUG 23	76.1	492	125	201	135	8.4	6.88

CHEMICAL ANALYSIS OF WATER SAMPLES FOR RUN NO. 2

DATE	TEMP (DEG F)	TOTAL SOLIDS (PPM)	ALK (PPM)	TOT HARD (PPM)	CAL HARD (PPM)	PH	STI
SEP 6	81.2	2157	85	1435	1358	8.2	5.41
SEP 7	78.7	2072	87	1422	1334	8.2	5.46
SEP 8	79.2	2212	84	1430	1332	8.1	5.59
SEP 10	83.4	2182	84	1427	1331	8.2	5.39
SEP 11	83.0	2121	77	1389	1331	8.1	5.57
SEP 12	79.1	2100	82	1409	1320	8.1	5.61
SEP 13	79.1	2150	83	1429	1342	8.0	5.69
SEP 14	79.0	2238	83	1453	1366	8.1	5.58
SEP 15	78.3	2225	82	1441	1349	8.1	5.62
SEP 17	80.3	2318	83	1441	1366	8.1	5.55
SEP 18	79.3	2231	80	1436	1366	8.1	5.60
SEP 19	79.5	2185	81	1450	1368	8.2	5.49
SEP 20	79.7	2230	79	1459	1362	8.1	5.61
SEP 21	78.2	2104	80	1459	1347	8.2	5.54
SEP 22	79.8	2080	80	1458	1363	8.1	5.59
SEP 24	78.2	2055	79	1459	1361	8.0	5.74
SEP 28	77.3	2011	77	1473	1364	7.9	5.88
SEP 30	77.3	1975	80	1470	1363	8.0	5.75

CHEMICAL ANALYSIS OF WATER SAMPLES FOR RUN NO. 3

DATE	TEMP (DEG F)	TOTAL SOLIDS (PPM)	ALK (PPM)	TOT HARD (PPM)	CAL HARD (PPM)	PH	STI
OCT 20	80.2	1917	54	1084	981	7.6	6.70
OCT 23	76.4	2068	57	1173	1099	8.1	6.15
OCT 25	75.5	1860	58	1068	988	8.1	6.24
OCT 29	74.7	2107	61	1174	1056	8.1	6.17
NOV 2	72.9	1909	59	1140	990	8.1	6.29
NOV 5	73.6	1881	63	1110	1024	8.1	6.19
NOV 8	77.8	1802	61	1110	976	8.0	6.25

CHEMICAL ANALYSIS OF WATER SAMPLES FOR RUN NO. 4

DATE	TEMP (DEG F)	TOTAL SOLIDS (PPM)	ALK (PPM)	TOT HARD (PPM)	CAL HARD (PPM)	PH	STI
NOV 27	77.9	2310	62	1385	1312	7.9	6.10
NOV 29	77.9	2232	60	1384	1301	7.9	6.13
NOV 30	76.2	2330	100	1274	1203	7.9	5.80
DEC 2	79.8	2209	80	1210	1138	8.0	5.85
DEC 4	77.9	2242	81	1226	1171	8.0	5.86

CHEMICAL ANALYSIS OF WATER SAMPLES FOR RUN NO. 5

DATE	TEMP (DEG F)	TOTAL SOLIDS (PPM)	ALK (PPM)	TOT HARD (PPM)	CAL HARD (PPM)	PH	STI
JAN 4	78.9	1683	41	1495	860	8.2	6.47
JAN 6	76.7	1498	41	1519	740	8.2	6.65
JAN 8	77.8	1489	67	1349	794	8.3	6.03

CHEMICAL ANALYSIS OF WATER SAMPLES FOR RUN NO. 6

DATE	TEMP (DEG F)	TOTAL SOLIDS (PPM)	ALK (PPM)	TOT HARD (PPM)	CAL HARD (PPM)	PH	STI
JAN 14	78.9	1696	52	1340	790	8.5	6.04
JAN 16	79.6	1637	55	1370	817	8.3	6.15
JAN 18	79.6	1670	55	1430	808	8.4	6.06

CHEMICAL ANALYSIS OF WATER SAMPLES FOR RUN NO. 7

DATE	TEMP (DEG F)	TOTAL SOLIDS (PPM)	ALK (PPM)	TOT HARD (PPM)	CAL HARD (PPM)	PH	STI
JAN 21	79.5	1575	50	1460	780	8.3	6.28
JAN 23	78.5	1646	54	1480	812	8.5	6.00
JAN 25	78.5	1640	56	1480	830	8.4	6.05

CHEMICAL ANALYSIS OF WATER SAMPLES FOR RUN NO. 8

DATE	TEMP (DEG F)	TOTAL SOLIDS (PPM)	ALK (PPM)	TOT HARD (PPM)	CAL HARD (PPM)	PH	STI
FEB 15	79.1	1506	31	1340	780	8.0	6.99
FEB 17	81.6	1744	58	1448	883	8.4	5.90
FEB 20	78.2	1937	78	1620	988	8.4	5.62
FEB 22	78.2	1830	75	1550	882	8.4	5.76

CHEMICAL ANALYSIS OF WATER SAMPLES FOR RUN NO. 10

DATE	TEMP (DEG F)	TOTAL SOLIDS (PPM)	ALK (PPM)	TOT HARD (PPM)	CAL HARD (PPM)	PH	STI
MAR 26	76.2	1657	33	1310	886	7.9	6.99
MAR 28	78.6	1598	47	1421	903	8.0	6.53
MAR 30	79.3	1632	64	1504	893	7.9	6.35

CHEMICAL ANALYSIS OF WATER SAMPLES FOR RUN NO. 11

DATE	TEMP (DEG F)	TOTAL SOLIDS (PPM)	ALK (PPM)	TOT HARD (PPM)	CAL HARD (PPM)	PH	STI
APR 9	79.9	1621	39	1258	794	7.9	6.87
APR 12	82.7	1666	46	1504	787	7.9	6.67
APR 14	78.3	1601	57	1383	796	7.9	6.57
APR 16	77.3	1595	67	1402	781	7.9	6.46
APR 19	80.8	1630	75	1421	781	8.0	6.19

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CALCULATED DATA FOR RUN NO.  1

HOURS VEL     Q/A     T BLK  TW A   TW B   TW C   TW D    FOUL A   FOUL B   FOUL C   FOUL D
     0 3.39  55344.5 74.73 133.65 131.03 135.78 137.15  .000000  .000000  .000000  .000000
  1.03 3.39  55344.5 78.30 140.32 138.25 140.74 142.10  .000056  .000066  .000025  .000025
  3.92 3.39  55344.5 82.00 143.36 141.30 144.58 146.22  .000044  .000054  .000028  .000033
  5.42 3.39  55344.5 84.54 145.29 142.95 146.49 148.14  .000033  .000038  .000016  .000021
 25.75 3.39  55344.5 81.26 144.19 142.12 145.13 147.86  .000072  .000082  .000051  .000075
 32.42 3.39  55344.5 85.33 146.12 144.88 147.86 150.05  .000034  .000059  .000027  .000041
 50.33 3.39  55344.5 81.30 142.81 141.30 144.58 146.77  .000047  .000067  .000040  .000055
 55.15 3.39  55344.5 84.10 143.36 142.12 145.13 147.04  .000006  .000031-0.000000  .000009
 71.83 3.39  55344.5 82.22 146.67 144.88 148.13 150.05  .000100  .000115  .000088  .000098
 79.42 3.39  55344.5 83.89 148.60 146.81 149.77 151.69  .000104  .000119  .000087  .000097
 96.17 3.39  55344.5 78.99 143.09 141.85 145.13 146.77  .000093  .000118  .000092  .000097
101.75 3.39  55344.5 83.76 146.95 146.53 149.23 151.14  .000077  .000117  .000080  .000090
120.17 3.39  55344.5 79.73 144.19 142.95 146.22 148.41  .000100  .000125  .000098  .000113
125.42 3.39  55344.5 84.16 147.50 146.81 149.50 151.14  .000080  .000115  .000078  .000082
144.25 3.39  55344.5 80.79 145.02 144.05 148.13 149.23  .000096  .000126  .000114  .000109
150.42 3.39  55344.5 83.48 146.67 145.98 148.95 150.87  .000077  .000112  .000080  .000090
168.25 3.39  55344.5 78.42 142.81 142.12 145.13 147.04  .000099  .000134  .000102  .000112
175.33 3.39  55344.5 81.69 145.57 144.88 147.31 148.96  .000089  .000125  .000083  .000088
193.75 3.39  55344.5 79.43 144.19 142.95 146.49 149.23  .000105  .000130  .000109  .000133
200.42 3.39  55344.5 83.72 146.67 145.43 148.13 150.87  .000073  .000098  .000061  .000085
217.75 3.39  55344.5 82.97 146.67 145.71 148.68 150.87  .000086  .000116  .000084  .000099
224.75 3.39  55344.5 84.47 147.77 146.81 149.23 151.41  .000079  .000109  .000067  .000082
240.75 3.39  55344.5 80.73 145.57 144.33 148.13 150.32  .000107  .000132  .000115  .000130
248.75 3.39  55344.5 85.08 148.32 147.36 150.32 152.23  .000078  .000108  .000076  .000085
254.75 3.39  55344.5 80.55 145.57 144.88 148.41 149.78  .000110  .000145  .000123  .000123
273.17 3.39  55344.5 83.14 147.77 147.08 149.77 151.41  .000103  .000138  .000101  .000106
287.92 3.39  55344.5 78.51 146.40 145.43 148.95 150.87  .000162  .000192  .000170  .000180
297.33 3.39  55344.5 81.61 150.79 148.46 153.86 159.57  .000185  .000190  .000202  .000281
318.00 3.39  55344.5 79.35 153.53 150.92 154.95 160.38  .000276  .000276  .000263  .000336
324.75 3.39  55344.5 80.60 155.45 152.29 156.85 162.01  .000288  .000278  .000275  .000343
336.75 3.39  55344.5 77.25 155.45 153.39 158.75 163.09  .000348  .000358  .000369  .000423
370.00 3.39  55344.5 77.90 159.27 156.66 160.91 165.79  .000405  .000406  .000397  .000460
386.75 3.39  55344.5 76.51 159.00 153.66 160.37 167.14  .000426  .000377  .000412  .000510
394.75 3.39  55344.5 79.79 163.62 159.12 164.42 170.90  .000450  .000416  .000426  .000518
408.08 3.39  55344.5 75.18 160.36 155.57 160.64 167.67  .000474  .000435  .000441  .000543
418.75 3.39  55344.5 78.55 157.09 152.57 156.85 163.09  .000354  .000320  .000312  .000400
431.92 3.39  55344.5 76.90 156.27 151.47 156.03 163.36  .000369  .000330  .000327  .000434
443.42 3.39  55344.5 78.06 147.22 142.95 148.95 156.86  .000165  .000155  .000178  .000296
456.75 3.39  55344.5 74.15 145.57 141.57 147.59 154.68  .000226  .000201  .000224  .000327
463.75 3.39  55344.5 77.96 146.95 143.50 149.23 155.50  .000182  .000167  .000185  .000273
480.05 3.39  55344.5 76.14 146.12 142.40 147.86 154.68  .000200  .000180  .000193  .000291
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CALCULATED DATA FOR RUN NO.  2

HOURS  VEL     Q/A    T BLK  TW A    TW B    TW C    TW D    FOUL A    FOUL B    FOUL C    FOUL D
    0 3.39  55344.5 80.04 138.38 137.98 146.77 140.18         0         0         0         0
  2.30 3.39  55344.5 81.20 138.66 137.98 145.95 139.90-0.000016-0.000021-0.000036-0.000026
  8.05 3.39  55344.5 83.08 145.29 145.16 155.22 147.59   .000070   .000075   .000098   .000079
 22.63 3.39  55344.5 79.15 145.29 145.98 161.99 151.14   .000141   .000161   .000291   .000214
 29.17 3.39  55344.5 79.20 146.67 146.26 166.31 152.50   .000165   .000165   .000368   .000238
 46.58 3.39  55344.5 77.72 146.95 144.61 166.85 154.14   .000197   .000162   .000405   .000294
 82.85 3.39  55344.5 83.41 148.32 144.88 167.12 155.77   .000119   .000064   .000307   .000221
 94.75 3.39  55344.5 83.41 149.97 147.36 169.27 159.03   .000149   .000109   .000346   .000280
104.48 3.39  55344.5 84.22 151.89 148.18 169.27 160.92   .000169   .000109   .000331   .000299
113.78 3.39  55344.5 78.92 149.70 145.98 169.27 160.38   .000225   .000165   .000427   .000385
128.43 3.39  55344.5 83.00 163.62 160.48 186.11 176.27   .000403   .000353   .000657   .000599
142.17 3.39  55344.5 77.63 159.54 155.57 181.85 173.05   .000426   .000361   .000677   .000637
152.48 3.39  55344.5 81.95 149.70 151.47 175.44 164.44   .000170   .000209   .000484   .000404
167.00 3.39  55344.5 79.12 154.08 155.85 179.45 167.67   .000300   .000339   .000607   .000513
172.42 3.39  55344.5 80.26 159.00 160.48 185.31 173.59   .000369   .000403   .000692   .000600
194.03 3.39  55344.5 78.80 154.08 155.57 180.25 168.75   .000306   .000340   .000627   .000539
216.30 3.39  55344.5 79.46 154.90 157.48 183.98 170.37   .000327   .000381   .000701   .000574
225.17 3.39  55344.5 78.68 154.36 156.94 182.65 169.02   .000313   .000367   .000673   .000546
240.00 3.39  55344.5 78.16 152.99 154.75 181.32 168.48   .000298   .000337   .000658   .000545
248.50 3.39  55344.5 81.10 154.90 156.94 182.92 168.75   .000279   .000323   .000634   .000497
262.37 3.39  55344.5 78.76 153.26 155.57 182.38 167.14   .000292   .000341   .000667   .000510
273.32 3.39  55344.5 81.29 157.09 158.30 186.37 171.44   .000315   .000345   .000693   .000542
287.25 3.39  55344.5 78.77 153.81 157.21 183.71 169.02   .000302   .000370   .000690   .000544
296.07 3.39  55344.5 80.07 157.09 159.66 185.84 171.44   .000338   .000391   .000705   .000564
311.02 3.39  55344.5 79.48 159.00 164.01 187.97 174.93   .000383   .000480   .000755   .000638
320.65 3.39  55344.5 79.74 159.54 166.71 190.09 176.53   .000388   .000525   .000788   .000662
334.72 3.39  55344.5 79.80 158.73 167.80 187.97 174.66   .000372   .000543   .000749   .000627
346.23 3.39  55344.5 80.60 160.09 171.31 189.82 177.34   .000382   .000592   .000768   .000661
358.47 3.39  55344.5 78.43 160.09 170.77 189.82 176.00   .000421   .000621   .000807   .000676
373.43 3.39  55344.5 80.75 159.54 171.31 189.56 175.46   .000370   .000589   .000760   .000625
383.65 3.39  55344.5 79.91 159.82 170.77 187.97 175.20   .000390   .000595   .000747   .000635
397.23 3.39  55344.5 80.51 160.90 172.11 189.56 177.07   .000398   .000608   .000765   .000658
403.45 3.39  55344.5 81.00 161.45 171.57 189.82 176.80   .000400   .000590   .000761   .000644
430.75 3.39  55344.5 75.46 156.54 160.20 182.38 174.93   .000411   .000484   .000726   .000711
440.77 3.39  55344.5 80.20 159.54 162.92 187.17 178.94   .000379   .000448   .000727   .000697
454.92 3.39  55344.5 77.24 159.54 162.92 186.11 179.21   .000433   .000501   .000761   .000756
464.32 3.39  55344.5 78.33 158.73 163.46 186.64 179.74   .000399   .000491   .000751   .000746
478.65 3.39  55344.5 75.29 157.36 162.65 186.64 179.48   .000429   .000532   .000806   .000796
492.00 3.39  55344.5 80.89 160.09 165.09 188.23 182.68   .000377   .000474   .000734   .000752
502.62 3.39  55344.5 77.38 158.18 161.56 186.64 181.08   .000406   .000474   .000768   .000787
512.93 3.39  55344.5 81.67 161.72 165.63 189.29 184.54   .000392   .000470   .000739   .000772
526.63 3.39  55344.5 77.10 159.27 165.09 187.17 182.14   .000431   .000543   .000783   .000811
551.43 3.39  55344.5 80.36 161.45 166.98 187.70 184.28   .000411   .000518   .000734   .000791
577.10 3.39  55344.5 77.31 159.27 165.63 183.98 182.14   .000427   .000549   .000722   .000808
584.68 3.39  55344.5 77.94 160.63 166.44 185.58 182.94   .000440   .000552   .000739   .000811
597.98 3.39  55344.5 73.65 156.82 162.92 181.32 178.94   .000449   .000566   .000740   .000816
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CALCULATED DATA FOR RUN NO.   3

 HOURS  VEL      Q/A     T BLK  TW A    TW B    TW C    TW D     FOUL A     FOUL B     FOUL C     FOUL D
     0  3.39   55344.5 75.72 134.49  132.42  142.11  140.73           0          0          0          0
  1.62  3.39   55344.5 76.45 134.77  132.98  142.11  140.45-0.000008-0.000003-0.000013-0.000018
  6.23  3.39   55344.5 78.21 135.05  132.70  142.11  140.73-0.000035-0.000040-0.000045-0.000045
 23.25  3.39   55344.5 80.22 135.88  134.09  143.21  141.28-0.000056-0.000051-0.000061-0.000071
 44.57  3.39   55344.5 79.10 135.88  134.09  143.21  141.55-0.000036-0.000031-0.000041-0.000046
 53.32  3.39   55344.5 79.45 136.71  134.92  143.76  141.55-0.000027-0.000022-0.000038-0.000053
 67.57  3.39   55344.5 76.04 134.77  132.42  141.56  141.00-0.000001-0.000006-0.000016-0.000001
 92.73  3.39   55344.5 76.40 134.77  132.70  142.11  140.73-0.000007-0.000007-0.000012-0.000012
114.30  3.39   55344.5 75.95 133.93  132.14  140.74  139.35-0.000014-0.000009-0.000029-0.000029
137.73  3.39   55344.5 74.92 133.93  132.14  140.74  139.63   .000004    .000009-0.000010-0.000005
162.52  3.39   55344.5 76.03 135.05  132.70  141.56  141.28   .000004-0.000001-0.000016    .000004
174.15  3.39   55344.5 78.42 136.16  133.81  143.21  142.38-0.000019-0.000024-0.000029-0.000019
211.55  3.39   55344.5 81.00 137.27  135.20  144.30  143.20-0.000045-0.000045-0.000056-0.000051
221.23  3.39   55344.5 78.23 135.88  133.53  142.38  141.83-0.000020-0.000025-0.000040-0.000025
233.52  3.39   55344.5 74.74 134.21  131.59  141.01  140.18   .000013    .000003-0.000002    .000008
244.60  3.39   55344.5 78.68 136.16  134.09  143.21  141.83-0.000023-0.000023-0.000034-0.000034
264.03  3.39   55344.5 80.07 137.55  135.48  144.58  143.20-0.000023-0.000023-0.000034-0.000034
270.57  3.39   55344.5 78.09 135.88  133.81  142.38  139.08-0.000018-0.000018-0.000038-0.000073
283.35  3.39   55344.5 82.51 138.38  136.87  144.85  144.03-0.000052-0.000042-0.000073-0.000063
294.17  3.39   55344.5 76.68 134.77  132.98  141.56  140.73-0.000016-0.000011-0.000031-0.000021
305.68  3.39   55344.5 77.15 135.32  133.26  142.11  141.55-0.000011-0.000011-0.000026-0.000011
330.63  3.39   55344.5 72.93 133.10  131.03  141.28  139.08   .000025    .000025    .000035    .000020
356.65  3.39   36896.4 71.97 138.86  137.67  148.85  147.65   .000220    .000244    .000284    .000289
368.23  3.39   55344.5 75.70 135.32  133.26  142.66  142.10   .000015    .000015    .000010    .000025
380.90  3.39   55344.5 74.83 135.05  133.26  142.38  140.73   .000026    .000031    .000021    .000016
401.73  3.39   55344.5 73.56 134.77  133.26  142.38  141.55   .000044    .000054    .000044    .000054
410.27  3.39   55344.5 74.30 134.77  132.98  142.11  141.00   .000031    .000036    .000026    .000031
426.93  3.39   55344.5 74.96 134.77  132.42  142.11  141.00   .000019    .000014    .000014    .000019
431.07  3.39   55344.5 76.54 135.88  133.81  143.21  142.38   .000010    .000010    .000005    .000015
473.65  3.39   55344.5 77.09 135.88  134.37  142.93  142.65   .000000    .000010-0.000010    .000010
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CALCULATED DATA FOR RUN NO.  4

HOURS  VEL      Q/A      T BLK   TW A     TW B     TW C     TW D      FOUL A      FOUL B      FOUL C      FOUL D
    0  3.39   55344.5  76.82  131.42  134.09  138.26  134.66   .000000    .000000    .000000    .000000
  5.25  3.39   55344.5  77.92  131.98  134.37  138.26  134.94-0.000010-0.000015-0.000020-0.000015
 23.50  3.39   55344.5  77.37  132.26  134.92  139.36  136.04   .000005    .000005    .000010    .000015
 48.17  3.39   55344.5  79.51  133.65  136.31  139.63  137.42-0.000008-0.000008-0.000024    .000001
 55.50  3.39   55344.5  76.56  131.98  134.92  138.53  135.21   .000015    .000020    .000010    .000015
 72.37  3.39   55344.5  79.04  133.37  135.48  140.19  137.70-0.000005-0.000015-0.000005    .000015
 76.62  3.39   55344.5  76.22  135.32  138.25  142.66  140.18   .000081    .000086    .000090    .000111
 79.50  3.39   55344.5  76.13  136.99  138.81  142.93  141.00   .000113    .000098    .000097    .000127
 96.93  3.39   55344.5  79.49  140.87  142.68  146.49  144.85   .000123    .000107    .000101    .000136
107.67  3.39   55344.5  74.90  138.10  140.47  143.76  141.83   .000155    .000150    .000134    .000164
123.53  3.39   55344.5  79.79  142.26  144.05  147.31  145.67   .000142    .000126    .000110    .000145
145.82  3.39   55344.5  75.64  141.15  142.68  146.49  144.85   .000197    .000176    .000170    .000205
151.58  3.39   55344.5  75.04  140.32  141.85  145.95  143.75   .000193    .000172    .000171    .000197
167.70  3.39   55344.5  77.94  142.53  144.05  147.31  145.40   .000180    .000160    .000143    .000174
174.92  3.39   55344.5  78.42  142.81  144.61  148.13  146.22   .000177    .000161    .000150    .000180
179.30  3.39   55344.5  77.52  143.64  145.16  148.41  146.49   .000208    .000187    .000171    .000201
191.83  3.39   55344.5  77.34  143.36  144.88  147.86  144.85   .000206    .000186    .000164    .000175
197.33  3.39   55344.5  78.51  144.74  145.71  149.50  145.40   .000210    .000179    .000173    .000164
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CALCULATED DATA FOR RUN NO.  5

HOURS  VEL      Q/A      T BLK   TW A     TW B     TW C     TW D      FOUL A      FOUL B      FOUL C      FOUL D
    0  3.39   88828.0  74.52  155.87  159.76  164.76  159.83   .000000    .000000    .000000    .000000
 22.22  3.39   88828.0  73.56  236.57  235.24  245.71  243.39   .000919    .000861    .000922    .000951
 31.93  3.39   88828.0  78.87  223.91  228.54  237.03  233.41   .000717    .000725    .000765    .000779
 78.20  3.39   88828.0  78.22  220.02  225.44  234.73  230.85   .000680    .000698    .000746    .000758
 95.45  3.39   88828.0  74.80  221.31  226.99  236.78  231.87   .000734    .000754    .000808    .000808
102.78  3.39   88828.0  77.18  222.09  226.99  236.78  231.87   .000716    .000727    .000781    .000781
119.45  3.39   88828.0  76.08  218.20  224.40  233.71  229.31   .000684    .000710    .000759    .000764
127.45  3.39   88828.0  77.80  218.46  224.40  233.71  229.56   .000668    .000691    .000739    .000748
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CALCULATED DATA FOR RUN NO.  6

HOURS  VEL     Q/A     T BLK  TW A    TW B    TW C    TW D     FOUL A   FOUL B   FOUL C   FOUL D
     0 3.39  75822.0  77.62  149.32  153.41  157.00  153.10   .000000  .000000  .000000  .000000
  2.55 3.39  75822.0  78.95  160.75  165.32  172.54  166.56   .000133  .000140  .000187  .000160
  4.95 3.39  75822.0  79.36  170.73  177.39  186.60  179.63   .000259  .000293  .000367  .000327
 22.87 3.39  75822.0  80.58  168.04  165.32  175.47  175.91   .000208  .000118  .000204  .000262
 46.48 3.39  75822.0  79.55  167.23  166.40  175.47  174.04   .000211  .000146  .000218  .000251
 75.58 3.39  75822.0  77.86  168.31  167.48  177.33  174.84   .000247  .000182  .000265  .000284
 94.50 3.39  75637.5  77.24  166.48  166.73  175.82  173.32   .000232  .000181  .000254  .000272
102.42 3.39  75637.5  79.18  167.56  167.00  176.88  174.65   .000220  .000159  .000242  .000264
118.70 3.39  75637.5  78.00  168.10  167.27  177.15  174.65   .000243  .000178  .000261  .000280
126.78 3.39  75637.5  77.77  168.37  167.54  176.62  174.39   .000250  .000185  .000257  .000279
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CALCULATED DATA FOR RUN NO.  7

HOURS  VEL     Q/A     T BLK  TW A    TW B    TW C    TW D     FOUL A   FOUL B   FOUL C   FOUL D
     0 3.39  59218.6  79.51  136.61  139.68  143.36  139.59         0        0        0        0
  1.30 3.39  59218.6  77.78  137.17  139.96  143.09  142.34   .000039  .000034  .000025  .000076
  3.95 3.39  59218.6  76.14  141.05  142.99  147.74  143.99   .000132  .000113  .000131  .000131
 23.33 3.39  59218.6  81.08  142.70  144.92  148.29  145.36   .000076  .000062  .000056  .000071
 31.60 3.39  59218.6  79.80  142.43  144.37  147.74  144.54   .000093  .000074  .000069  .000078
 47.55 3.39  59218.6  82.78  145.46  146.85  150.19  147.00   .000094  .000066  .000060  .000070
 56.10 3.39  59218.6  78.55  142.98  144.65  148.29  144.26   .000124  .000100  .000099  .000095
 68.63 3.39  59218.6  81.19  144.63  146.02  149.92  146.72   .000107  .000079  .000082  .000092
 75.33 3.39  59218.6  82.97  144.91  146.57  150.74  147.00   .000082  .000058  .000066  .000067
 93.58 3.39  59218.6  79.71  142.15  145.20  149.65  146.45   .000090  .000090  .000103  .000112
101.33 3.39  59218.6  78.45  143.81  144.92  149.10  145.63   .000139  .000106  .000115  .000120
113.97 3.39  59218.6  81.45  145.18  146.57  149.92  146.72   .000112  .000083  .000078  .000088
126.13 3.39  59218.6  79.54  144.63  146.30  149.92  146.18   .000135  .000111  .000110  .000111
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CALCULATED DATA FOR RUN NO.  8

HOURS  VEL     Q/A     T BLK  TW A    TW B    TW C    TW D     FOUL A    FOUL B    FOUL C    FOUL D
    0  3.39 101465.0  76.45 203.54  177.34  182.58  175.89   .000000   .000000   .000000   .000000
  .53  3.39 101465.0  78.25 212.86  186.08  193.84  187.21   .000074   .000068   .000093   .000094
13.27  3.39 101465.0  79.11 253.22  220.82  230.52  225.87   .000463   .000402   .000446   .000466
25.88  3.39 101465.0  83.42 245.95  214.08  223.35  218.15   .000349   .000293   .000333   .000348
49.95  3.39 101465.0  75.83 242.57  211.23  222.32  215.83   .000391   .000340   .000398   .000400
57.32  3.39 101465.0  81.57 249.85  216.42  228.22  220.73   .000406   .000335   .000399   .000391
74.05  3.39 101465.0  75.26 245.17  213.05  222.32  216.09   .000422   .000364   .000403   .000408
98.80  3.39 101465.0  81.58 251.67  216.94  226.43  220.47   .000424   .000340   .000382   .000389
131.32 3.39 101465.0  81.41 278.69  239.86  243.02  240.19   .000692   .000567   .000547   .000585
147.23 3.39 101465.0  78.68 305.85  267.08  269.79  270.29   .000986   .000862   .000838   .000908
172.55 3.39 101465.0  78.21 305.85  266.06  276.81  273.06   .000991   .000857   .000911   .000940
197.78 3.39 101465.0  63.45 315.16  277.16  291.53  286.32   .001031   .000915   .001005   .001019
216.45 3.39 101465.0  78.21 317.92  281.18  294.77  288.31   .001110   .001006   .001088   .001091
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CALCULATED DATA FOR RUN NO. 10

HOURS  VEL     Q/A     T BLK  TW A    TW B    TW C    TW D     FOUL A    FOUL B    FOUL C    FOUL D
    0  3.39  56266.9  77.24 139.04       0  135.59  133.42         0         0         0         0
 1.45  3.39  56266.9  79.43 146.76       0  143.35  141.69   .000098         0   .000099   .000108
 3.92  3.39  56266.9  76.17 147.86       0  145.56  143.61   .000176         0   .000196   .000200
21.30  3.39  56266.9  80.07 144.84       0  142.52  139.49   .000053         0   .000073   .000058
26.30  3.39  56266.9  74.69 141.81       0  138.09  135.63   .000091         0   .000086   .000081
44.83  3.39  56266.9  80.70 144.56       0  141.41  138.67   .000037         0   .000042   .000032
52.08  3.39  56266.9  73.85 141.81       0  139.48  135.63   .000109         0   .000129   .000099
56.75  3.39  56266.9  77.56 144.29       0  141.69  137.56   .000087         0   .000103   .000068
68.60  3.39  56266.9  78.62 144.01       0  141.14  137.56   .000064         0   .000074   .000049
73.97  3.39  56266.9  79.57 144.29       0  141.97  138.11   .000052         0   .000072   .000042
80.33  3.39  56266.9  75.04 142.91       0  139.75  136.74   .000108         0   .000113   .000098
92.62  3.39  56266.9  79.46 144.01       0  143.35  138.39   .000049         0   .000098   .000049
100.75 3.39  56266.9  80.17 146.76       0  144.73  139.49   .000085         0   .000110   .000056
105.85 3.39  56266.9  80.47 148.14       0  144.45  140.32   .000104         0   .000100   .000065
118.95 3.39  56266.9  79.30 147.31       0  143.90  139.49   .000110         0   .000111   .000071
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CALCULATED DATA FOR RUN NO. 11

 HOURS  VEL      Q/A      T BLK   TW A    TW B    TW C    TW D      FOUL A     FOUL B     FOUL C     FOUL D
     0  3.39  101465.0  78.46  199.48  192.70  183.16  192.97          0          0          0          0
  1.53  3.39  101465.0  81.33  247.09  231.30  221.11  237.15    .000441    .000352    .000346    .000407
  5.47  3.39  101465.0  78.02  254.08  236.26  226.90  241.06    .000542    .000434    .000435    .000478
  7.37  3.39  101465.0  81.45  253.04  236.00  227.42  241.58    .000498    .000397    .000407    .000450
 23.80  3.39  101465.0  77.67  250.96  234.69  224.53  237.93    .000513    .000420    .000414    .000449
 31.55  3.39  101465.0  79.86  251.75  235.47  223.21  239.23    .000501    .000408    .000381    .000442
 47.20  3.39  101465.0  80.97  253.04  236.78  226.64  242.10    .000503    .000410    .000404    .000460
 73.90  3.39  101465.0  81.79  260.52  244.05  234.77  248.59    .000569    .000473    .000476    .000515
 79.58  3.39  101465.0  85.30  265.69  249.75  244.68  256.09    .000595    .000495    .000539    .000555
 95.12  3.39  101465.0  75.54  264.12  246.64  243.64  253.77    .000666    .000560    .000625    .000628
109.03  3.39  101465.0  82.70  270.79  253.11  249.36  260.22    .000661    .000554    .000611    .000621
121.62  3.39  101465.0  80.74  307.58  293.70  290.41  307.06    .001043    .000973    .001035    .001102
147.18  3.39  101465.0  78.28  313.61  303.54  300.29  312.59    .001127    .001094    .001156    .001181
169.12  3.39  101465.0  78.58  321.63  311.33  302.06  317.61    .001203    .001168    .001171    .001227
192.40  3.39  101465.0  76.69  326.37  313.08  303.83  324.11    .001268    .001204    .001207    .001310
199.03  3.39  101465.0  77.32  327.12  315.09  304.84  322.36    .001269    .001217    .001210    .001286
216.03  3.39  101465.0  77.55  327.12  317.84  306.85  322.86    .001267    .001242    .001228    .001289
223.67  3.39  101465.0  84.10  330.36  322.34  310.63  325.61    .001234    .001222    .001201    .001252
239.88  3.39  101465.0  78.03  331.11  322.59  309.37  322.61    .001301    .001284    .001248    .001282
247.17  3.39  101465.0  77.25  330.61  323.09  309.37  321.36    .001304    .001297    .001256    .001277
264.53  3.39  101465.0  80.77  336.33  330.06  314.15  324.11    .001326    .001331    .001268    .001270
271.63  3.39  101465.0  82.70  346.25  340.24  324.67  334.83    .001405    .001412    .001353    .001356
288.72  3.39  101465.0  79.86  359.08  354.07  337.14  349.46    .001559    .001577    .001504    .001529
297.23  3.39  101465.0  79.88  373.81  362.93  347.81  360.80    .001704    .001664    .001609    .001640
310.87  3.39  101465.0  78.28  387.24  380.79  363.85  376.26    .001852    .001856    .001783    .001808
319.80  3.39  101465.0  78.02  395.27  388.10  379.30  388.96    .001934    .001930    .001937    .001936
333.12  3.39  101465.0  78.58  397.46  391.50  384.92  393.34    .001950    .001958    .001987    .001974
359.38  3.39  101465.0  79.99  397.21  391.26  384.43  393.34    .001934    .001942    .001969    .001960
385.62  3.39  101465.0  78.37  396.97  390.78  383.95  392.85    .001947    .001953    .001980    .001971
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