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FOULING OF AN 11-FINS-PER-INCH COIL IN AN INTERNAL TANKLESS WATER HEATER

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ABSTRACT

A finned-tube coil operating in a standard tankless hot-water heater was subjected to controlled fouling conditions. Heat transfer tests were made to determine (1) the variation of the fouling with time and (2) the effect of this fouling on the heat transfer performance of the coil.

The results of this investigation indicate that (1) the inside fouling film has a much greater effect on the overall fouling resistance than the outside fouling film and (2) the water flow rate maintained through the inside of the coil influences the internal fouling rate.

OBJECTIVE

The purpose of this investigation was to determine the extent to which fouling affects the heat transfer characteristics of a finned-tube coil in an internal tankless hot-water heater.

I. INTRODUCTION

It has been shown that clean finned-tube coils can be used to definite advantage over comparable plain-tube coils in internal tankless hot-water heaters.[1] Under identical test conditions the amount of heat transferred with a finned-tube coil can be as much as four times that of a comparable plain-tube coil of equal length in which the OD of the plain tube is equal to the root diameter of the finned tube.[1]

This investigation was made in order to determine the extent to which fouling affects the heat transfer characteristics of a finned-tube coil.

The tests were conducted in a standard tankless hot-water heater fabricated in accordance with the Institute of Boiler and Radiator Manufacturers' specifications.[1,2] The coil used in this investigation is identified as test coil number 4 of Report Number 35.[1] The tube and test-coil dimensions are tabulated in Table I.

TABLE I

DIMENSIONS OF TEST COIL NO. 4

D_o = 1.005 in.
D_r = 0.650 in.
D_i = 0.546 in.
Mean fin thickness = 0.0186 in.
Fin height = 0.1761 in.
Fins/in. = 10.925
A_o = 1.032 ft^2/ft
A_o/A_i = 7.21
Total outside area = 26.33 ft^2
No. of straight sections = 20
No. of U bends = 19
Total length = 25.39 ft
Horizontal pitch = 1.005 in.
Vertical pitch = 2.625 in.
D_o of copper leads = 0.875 in.

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[1] References are given on p. 23.

II. THEORETICAL CONSIDERATIONS

The heat transferred through a finned tube can be related to the outside heat transfer area and mean overall temperature difference driving force by

$$Q = U_o A_o (\Delta T)_{mean}, \tag{1}$$

in which

Q = rate of heat transfer, Btu/hr,
U_o = overall heat transfer coefficient, Btu/hr-°F-ft^2 outside surface area,
A_o = total outside surface area, ft^2, and
$(\Delta T)_{mean}$ = mean temperature difference, °F.

The overall heat transfer resistance is related to the individual resistances by

$$\frac{1}{U_o} = \frac{1}{h_o'} + r_o' + r_f + r_m\left(\frac{A_o}{A_m}\right) + r_i\left(\frac{A_o}{A_i}\right) + \frac{1}{h_i}\left(\frac{A_o}{A_i}\right), \tag{2}$$

in which

h_o' = outside film heat transfer coefficient for a finned tube, Btu/hr-°F-ft^2 outside surface area,
r_o' = outside fouling film resistance for a finned tube, hr-°F-ft^2 outside area/Btu,
r_f = fin resistance, hr-°F-ft^2 outside area/Btu (see Equation 3),
r_m = tube root-wall resistance to heat transfer, hr-°F-ft^2 mean metal area/Btu,
A_o = outside tube surface area, ft^2/ft of tube length,
A_m = logarithmic mean metal area between D_i and D_r, ft^2/ft of tube length,
A_i = inside tube surface area, ft^2/ft of tube length,
h_i = inside film heat transfer coefficient, Btu/hr-°F-ft^2 inside surface area, and
r_i = inside fouling film resistance, hr-°F-ft^2 inside area/Btu.

The fin resistance[3] is defined by

$$r_f = \left(\frac{1}{h_o'} + r_o'\right)\left(\frac{1 - E_f}{\frac{A_r}{A_f} + E_f}\right), \tag{3}$$

in which E_f = fin efficiency.

The effect of fouling on the performance of a finned-tube coil can be established by (1) determining the variation of the heat transfer characteristics of the coil with time, under fouling conditions, and (2) determining the values of r_i and r_o'.

III. FOULING MECHANISMS

Fouling mechanisms in general are among the least understood of all heat transfer phenomena. The mechanisms of the fouling of heated or cooled surfaces from water are, however, believed to be qualitatively known.

Scale formation or fouling from water may be divided into two types if the pH is controlled to 7.0 or above: (1) that due to temporary water hardness and (2) that due to permanent hardness.[4]

The mechanism of fouling caused by temporary hardness of the water involves the decomposition of calcium bicarbonate or magnesium bicarbonate upon heating. As water temperature rises, the bicarbonates liberate CO_2 according to the equations

$$Ca(HCO_3)_2 \longrightarrow CaCO_3 + H_2O + CO_2 \tag{4}$$

$$Mg(HCO_3)_2 \longrightarrow MgCO_3 + H_2O + CO_2 \tag{5}$$

The resulting carbonates precipitate as a chalky white powder, which tends to form scale.

The formation of scale due to water containing permanent hardness salts, such as calcium and magnesium sulfate, is not in general due to decomposition but to the decreasing solubility of the salts with increasing temperature. As shown in Fig. 1, the solubility of $CaSO_4$ reaches a maximum at about 40°C, after which it steadily decreases. For example, at 100°C the solubility of $CaSO_4$ is 77% of the solubility at 40°C and 84% of the solubility at 10°C. Permanent hardness scale is harder and more adherent than the carbonate scale caused by temporary hardness.

If the pH is permitted to drop below 7.0, another fouling mechanism involving corrosion of the iron walls of the container vessel is encountered. At high water temperatures, several salts become somewhat unstable. This instability leads to chain reactions typified by the following:

1. $MgCl_2 + 2H_2O \longrightarrow \underline{Mg(OH)_2} + 2HCl$

$$2HCl + Fe \longrightarrow FeCl_2 + H_2$$

$$FeCl_2 + 2H_2O \longrightarrow \underline{Fe(OH)_2} + 2HCl$$

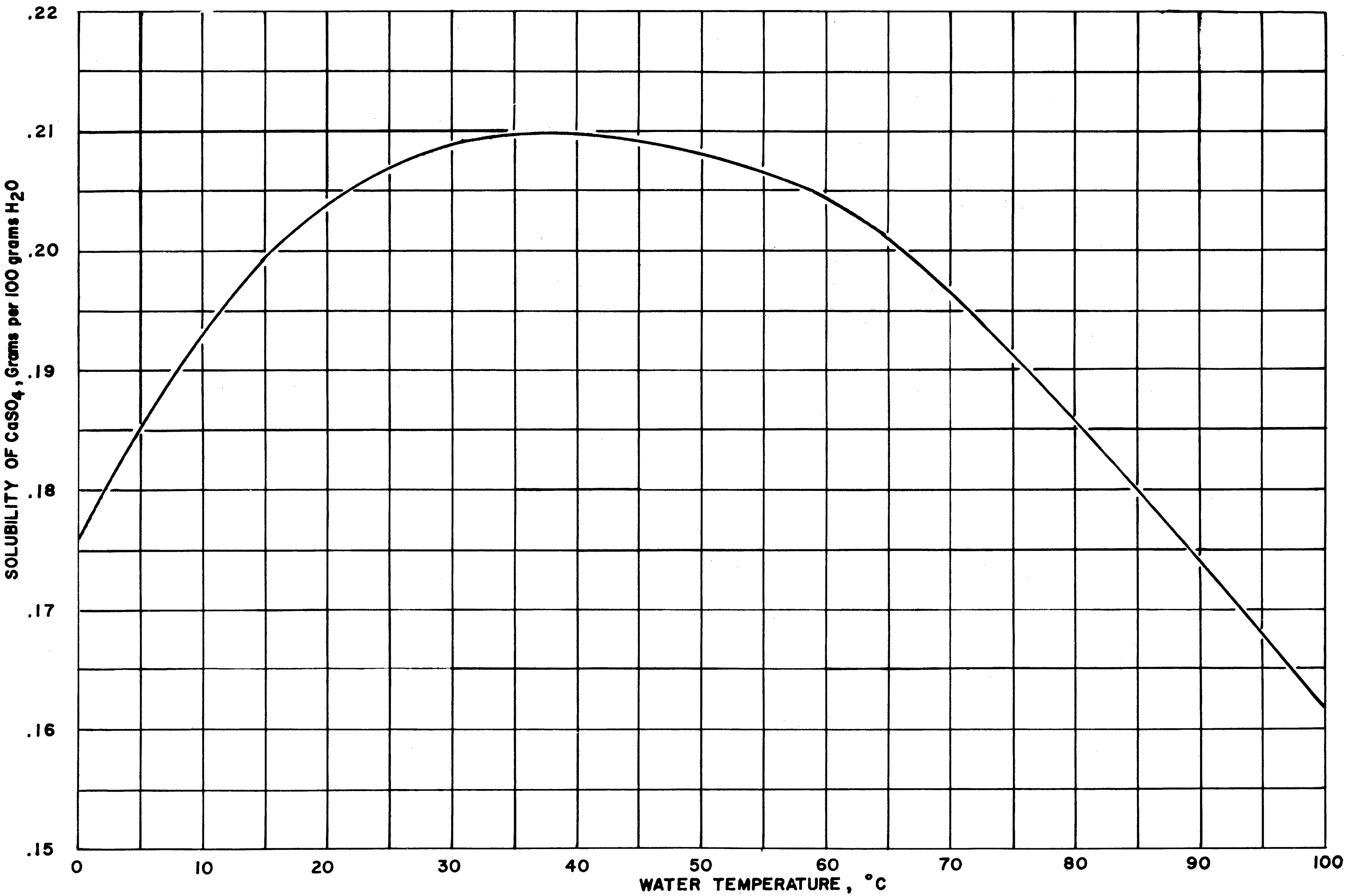

Fig. 1. Solubility of calcium sulfate as a function of temperature.

2. $Mg(NO_3)_2 + 2H_2O \longrightarrow \underline{Mg(OH)_2} + 2HNO_3$

$2HNO_3 + Fe \longrightarrow Fe(NO_3)_2 + H_2$

$Fe(NO_3)_2 + 2H_2O \longrightarrow Fe(OH)_2 + 2HNO_3$

3. $MgSO_4 + 2NaCl \rightleftharpoons MgCl_2 + Na_2SO_4$

$Mg_2Cl_2 + 2H_2O \longrightarrow$ reaction 1.

The $Mg(OH)_2$ and $Fe(OH)_2$ precipitate out of solution, causing scale. However, if the pH is maintained above 7.0 (such as by addition of NaOH), the acids formed in the above reactions are neutralized, stopping the chain reaction.

In order to avoid the above reactions, the pH of the fin-side water was carefully controlled to a value of not less than 8.0 during the tests by adding sodium hydroxide to the tank water when necessary. In addition, the temporary and permanent hardness of the tank (fin-side) water was carefully controlled. The water flowing through the inside of the tubes was taken from the Ann Arbor municipal mains without further treatment.

IV. TEST APPARATUS AND PROCEDURE

The test apparatus described in Report No. 35[1] was used in this investigation. The procedure followed involved (1) the Wilson Plot method and (2) the I.B.R.[2] capacity method. Both procedures are described in Report 35, pages 7-15.

After initial Wilson Plot test data had been accumulated and analyzed, it was found desirable to add three copper-constantan thermocouples below the coil in the tank in order to obtain more exact Wilson Plots. Only the Wilson Plot data obtained after the addition of the thermocouples are presented in this report.

The tank water was maintained at a pH of 8.0 or above and the total hardness was held at about 300 ppm. The pH was adjusted by the addition of a concentrated NaOH solution to the tank. The water hardness was maintained by the addition of $CaCO_3$, $CaSO_4$, $MgSO_4$, and $Mg(NO_3)_2$ to the water when necessary.

In order to maintain a constant tank water temperature throughout the test runs, a self-acting temperature controller was placed in the steam-heating lines. The temperature-measuring bulb of this controller was inserted through the side of the tank at a distance of 3 ft above the steam-heating coil. This measuring bulb actuated a control valve, regulating the amount of steam flowing to the heating coil.

Two series of fouling tests were made on the test coil during the investigation. The clean coil was first allowed to foul for 75 days, with test data being taken throughout the test period. After modification of the test apparatus and acid cleaning of the test coil, a second, 27-day, test period was begun. The Wilson Plot data presented in this report were obtained during this second test period.

After the accumulation of fouling during a test period, the test coil was acid cleaned. This treatment consisted of first removing the fouling film with a 5% sulfuric acid solution and then brightening the surface by treatment with a 5% $K_2Cr_2O_7$ solution. The purpose of the acid cleaning was (1) to determine if the test coil could be restored to its original heat transfer performance by cleaning, (2) to determine if the test coil would refoul at the same rate, and (3) to make possible the separate determination of the inside and outside fouling resistances.

To separate the inside and outside fouling resistances, the following procedure was used:

1. A Wilson Plot was made on the coil in the fouled condition.
2. The coil was removed from the tank, acid cleaned and brightened on the inside only, and replaced in the tank.
3. A Wilson Plot was immediately made on the partially cleaned coil.
4. The coil was again removed from the tank and the outside acid cleaned and brightened.
5. The coil was replaced in the tank, and a Wilson Plot was immediately made on the completely cleaned coil.

The data obtained in this manner were analyzed as indicated in Section V of this report. A typical Wilson Plot test run is presented in Table II. The Wilson Plot test results are tabulated in Appendix A.

TABLE II

TYPICAL WILSON PLOT TEST RUN (Run No. 224)

Inlet H_2O Temp. (°C)	Outlet H_2O Temp. (°C)	Tank Temperatures					
		T_A* (°C)	T_B (°C)	T_C (°C)	Thermocouples		
					A(mv)	B(mv)	C(mv)
21.1	79.1	87.6	88.0	87.8	3.62	3.62	3.60
21.1	78.8	87.6	88.0	87.7	3.60	3.61	3.63
21.1	79.0	87.7	88.1	87.8	3.63	3.63	3.61
21.0	79.0	87.9	88.1	87.9	3.62	3.62	3.61
21.1	79.3	87.9	88.1	88.0	3.63	3.63	3.63
Avg 21.08	79.04	87.74	88.06	87.84	3.620	3.622	3.616

Lb of H_2O = 140; Time = 7 min 37 sec

*See Fig. 4, p. 9, Report No. 35[1].

A typical I.B.R. capacity test run is presented in Table III. The capacity results are tabulated in Appendix B.

TABLE III

TYPICAL I.B.R. TEST RUN
(Run No. 68)

Inlet H_2O Temp. (°C)	Outlet H_2O Temp. (°C)	Tank Temperature		
		T_A(°C)*	T_B(°C)	T_C(°C)
16.60	72.35	86.95	86.90	86.80
16.65	72.70	86.60	86.90	86.80
16.65	72.80	86.80	86.90	86.80
16.70	73.70	86.85	87.10	87.00
16.75	72.40	86.40	86.85	86.85
Avg 16.67	72.99	86.82	86.95	86.69

Lb of H_2O = 75; Time = 3 min 2.7 sec

*See Fig. 4, p. 9, Report No. 35[1].

V. ANALYSIS OF TEST DATA

A. ANALYSIS OF WILSON PLOT DATA

The Wilson Plot curves obtained with the test coil cleaned, partially cleaned (inside only), and fouled are presented in Fig. 2. The intercepts of these curves can be used to calculate the fouling factors on the inside and outside of the coil as follows:

$$\text{At the intercept, } \frac{1}{h_i} = 0 ,$$

$$\therefore \quad \left[\frac{1}{U_o A_o}\right]_{\text{intercept}} = \frac{1}{h_o' A_o} + \frac{r_o'}{A_o} + \frac{r_f}{A_o} + \frac{r_i}{A_i} + \frac{r_m}{A_m} . \qquad (6)$$

For the line corresponding to the tube cleaned on the inside only, $r_i = 0$, the intercept $(1/U_oA_o) = 0.000217$. Substituting into Equation 6,

$$0.000217 = \frac{1}{h_o' A_o} + \frac{r_o'}{A_o} + \frac{r_m}{A_m} + \frac{r_f}{A_o} . \qquad (7)$$

Similarly, for the line corresponding to the tube cleaned on both sides, $r_i = 0$, $r_o' = 0$, the intercept $(1/U_oA_o) = 0.000205$. Again, substituting into

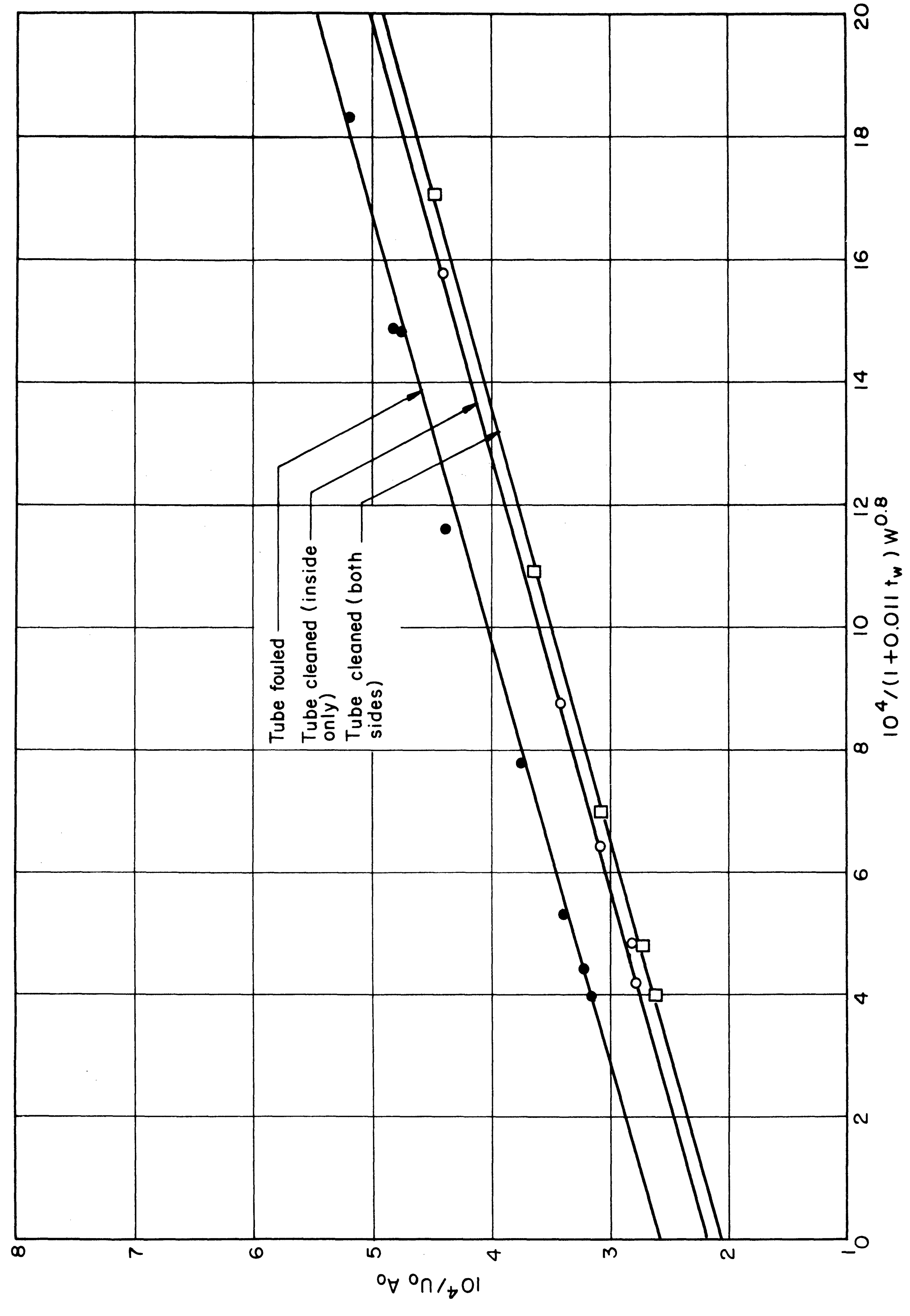

Fig. 2. Wilson Plots for various fouling conditions.

Equation 6,

$$0.000205 = \frac{1}{h_o'A_o} + \frac{r_m}{A_m} + \frac{r_f}{A_o} . \tag{8}$$

Assuming h_o' is the same for both the fouled and unfouled conditions, and combining Equations 7 and 8,

$$0.000217 = .000205 + \frac{r_o'}{A_o} . \tag{9}$$

Solving $r_o' = .000012\ A_o$.

For the line corresponding to no cleaning of the tube, the intercept $(1/U_oA_o) = 0.000257$. Substituting into Equation 6,

$$0.000257 = \frac{1}{h_o'A_o} + \frac{r_o'}{A_o} + \frac{r_i}{A_i} + \frac{r_m}{A_m} + \frac{r_f}{A_o} . \tag{10}$$

But,

$$\frac{r_o'}{A_o} = .000012$$

and

$$\frac{r_f}{A_o} + \frac{r_m}{A_m} + \frac{1}{h_o'A_o} = .000205 .$$

Substituting these values into Equation 10

$$0.000257 = .000205 + .000012 + \frac{r_i}{A_i} . \tag{11}$$

Solving,

$$r_i = .000040\ A_i \text{ (after 27 days)}.$$

From Table I,

$$\text{Total } A_o = 26.33 \text{ ft}^2$$

$$\frac{A_o}{A_i} = 7.21 .$$

Therefore,

$$\text{Total } A_i = \frac{26.33}{7.21} = 3.65 \text{ ft}^2 .$$

Solving for the fouling,

$$r_o' = .000012 \times 26.33 = .000316 \text{ hr-°F-ft}^2 \text{ outside area/Btu}$$

$$r_i = 0.000040 \times 3.65 = 0.000146 \text{ hr-°F-ft}^2 \text{ inside area/Btu.}$$

Taking the ratio of the fouling factors,

$$\frac{r_i}{r_o'} = \frac{0.000146}{0.000316} = 0.462$$

or

$$r_i = 0.462\, r_o' ,$$

the amount of fouling on the inside of the coil is less than half of that on the outside. However, taking the ratio of the actual fouling resistances to heat transfer,

$$\frac{r_i/A_i}{r_o'/A_o} = \frac{0.000040}{0.000012} = 3.33,$$

the inside fouling resistance to heat transfer is over three times the outside fouling resistance. Thus, the inside fouling constitutes

$$\frac{3.33}{3.33 + 1} \times 100 = 77\%$$

of the overall fouling resistance to heat transfer.

During the course of the investigation it was noted that the Wilson Plot intercepts obtained from the test data tended to shift with variations in experimental procedure. Wilson Plot curves indicating this effect are given in Fig. 3. This variation of the Wilson Plot intercepts is discussed further in Section VI.

The Wilson Plot data obtained during the initial, 75-day, test period using the I.B.R. test methods were not sufficiently accurate to allow direct computation of the fouling factor from the intercepts. Consequently, these runs are not included in this report. The second, 27-day, test was begun after acid cleaning of the test coil and modification of the test apparatus to include thermocouples located below the test coil. The addition of these thermocouples permitted more accurate Wilson Plot test measurements. A typical calculation of a Wilson Plot test run is presented in Appendix C.

B. ANALYSIS OF THE I.B.R. CAPACITY DATA

The I.B.R. capacity data are of a comparative nature and do not directly indicate the fouling resistance present on the tube. However, the variation of the capacity curves with time for a coil provides a qualitative record of the fouling trend. Inasmuch as the Wilson Plots taken during the initial, 75-day, test period were inconclusive, the capacity data were used to determine the fouling trend during this test period. A typical calculation of a capacity-type test run is presented in Appendix D.

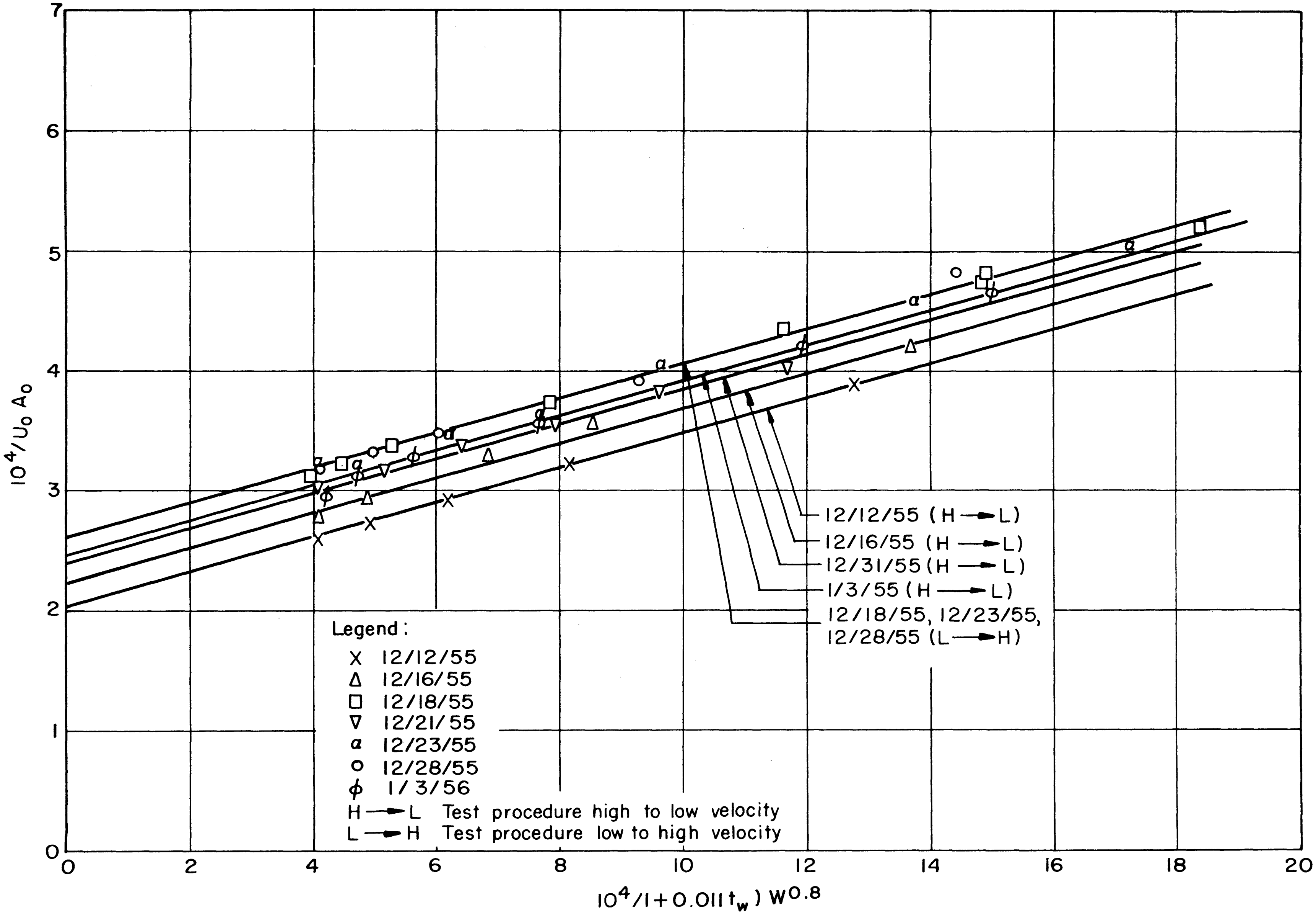

Fig. 3. Effect of test procedure on Wilson Plot intercepts.

The capacity curves for the initial, 75-day, test period, with parameters of days of testing, are presented in Fig. 4. The corresponding capacity curves for the second, 27-day, test period are presented in Fig. 5.

Photographs of the test coil taken after the initial, 75-day, test period and before cleaning are shown in Fig. 6.

VI. DISCUSSION OF RESULTS

The analysis of the Wilson Plot data obtained during the second, 27-day, test period indicated that the inside fouling, although less than half as great as the outside fouling, constituted 77% of the overall fouling resistance to heat transfer. This emphasizes the importance of the inside fouling on the overall fouling resistance to heat transfer. The large outside-to-inside area ratio (7.21/1 for the test coil) greatly increases the effect of the inside fouling. As can be seen by examination of Equation 2, the inside fouling is multiplied by the outside-to-inside area ratio to obtain the inside fouling resistance to heat transfer.

As shown in Section V, the high hardness content of the tank-side water caused the outside fouling to be nearly twice as great as the inside fouling. The water flowing through the inside of the coil was taken directly from the City of Ann Arbor water mains and had a total hardness which varied from 85 to 115 parts per million (ppm). The recirculating-tank water was maintained at about 300 ppm. Thus, although the total hardness on the outside of the test coil was three times the hardness on the inside of the coil, the degree of fouling on the outside of the coil was only about twice that on the inside of the coil. This indicates that the degree of fouling is not directly proportional to the hardness of the water in contact with the metal, but also varies with other factors such as temperature of metal relative to the water, velocity of the water, etc.

Figure 3 presents the effect of the test procedure on the Wilson Plot intercept values. The Wilson Plot curves which were obtained starting with the low-velocity runs and increasing the velocity for additional runs tend to be higher than the Wilson Plot curves obtained using the opposite experimental procedure (starting with a high-velocity run and decreasing the velocity for each additional run). This effect of shifting the Wilson Plot curves is probably attributable to the removal of part of the fouling scale on the inside of the tube due to the erosive action of the water during the high-velocity runs. For the series of runs starting with high velocities, part of the fouling film would be removed during the first high-velocity run and would not be present throughout the remainder of the Wilson Plot test. For the series of runs starting with low velocities, the fouling film would be present during the majority of the runs and would not be removed until the

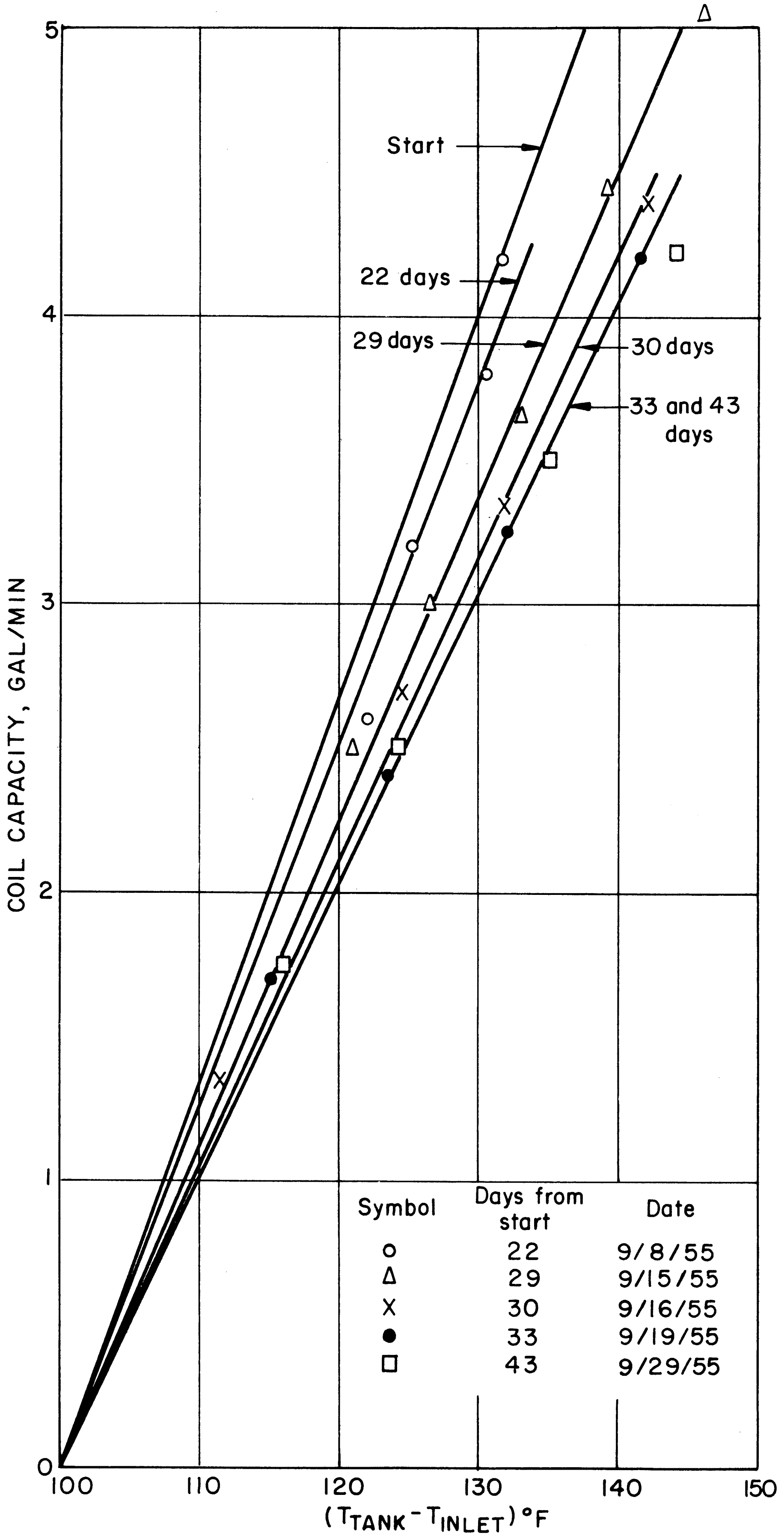

Fig. 4. I.B.R. capacity curves during 75-day test period.

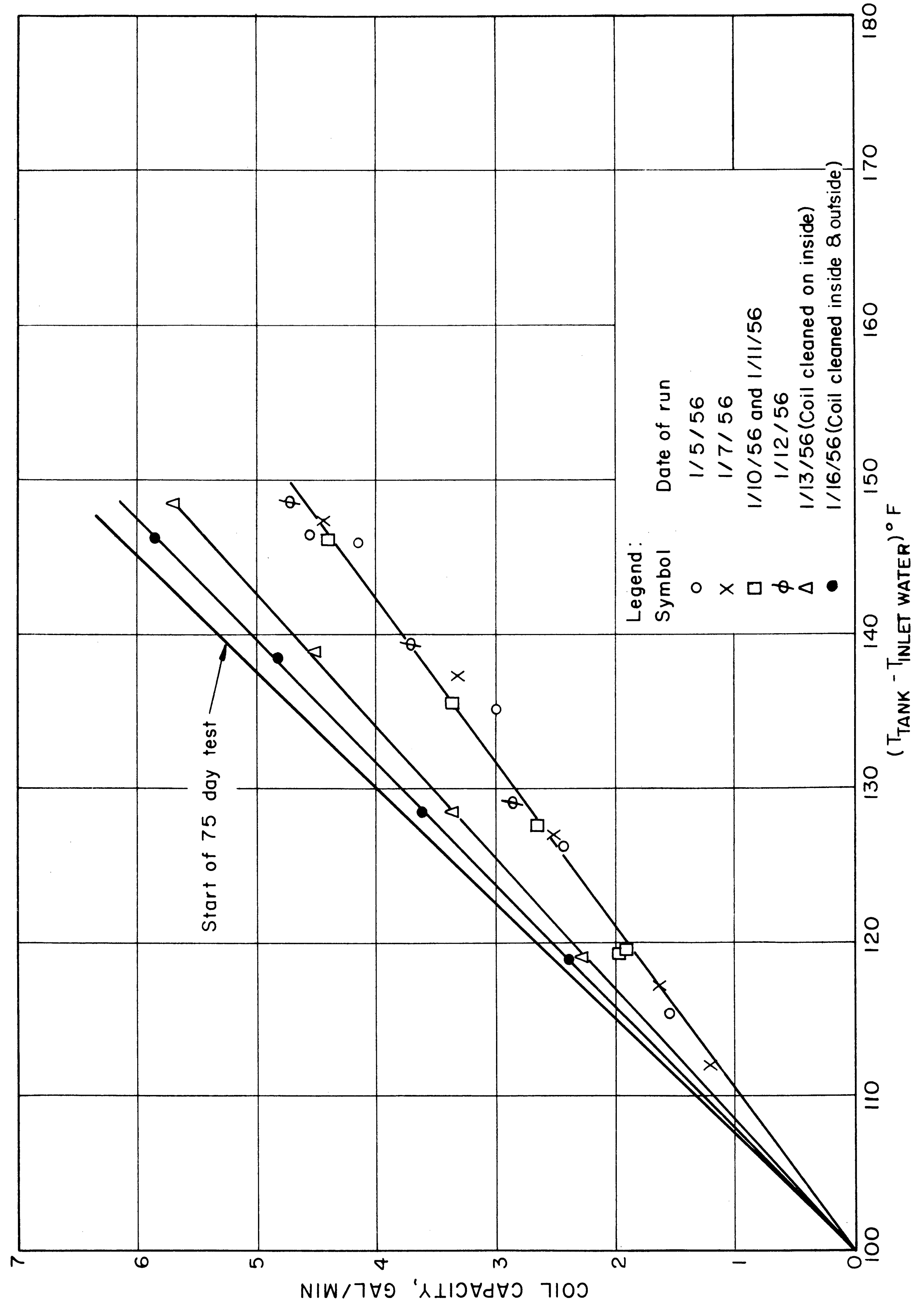

Fig. 5. I.B.R. capacity curves during 27-day test period.

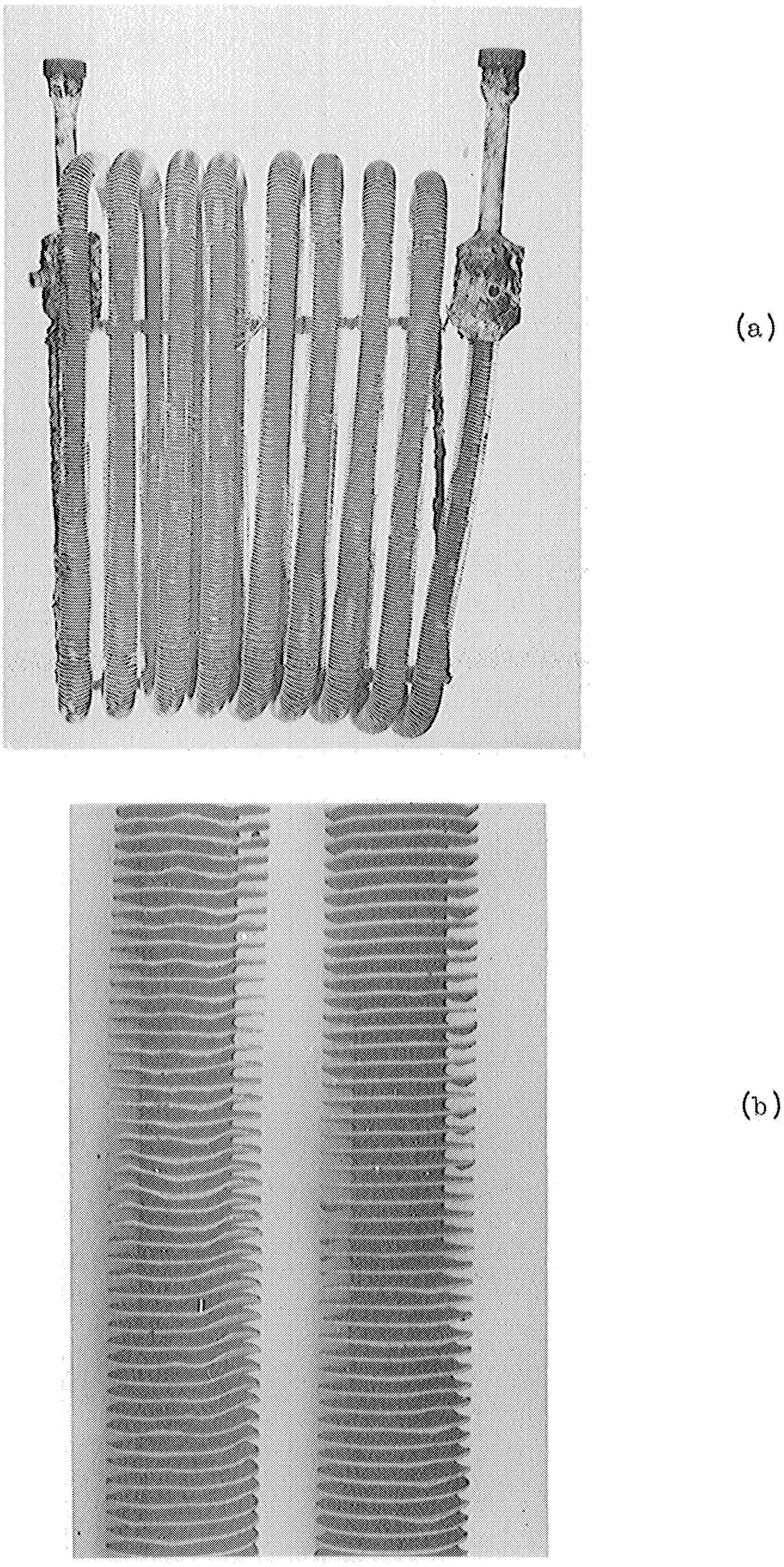

Fig. 6. Test coil after 75-day test period, before cleaning.

higher velocities were reached.

A comparison of Figs. 4 and 5 indicates that the total fouling present after the second, 27-day, test period was greater than that present after the 75-day test period. For example, at $(T_{\text{tank}} - T_{\text{inlet water}}) = 140^\circ\text{F}$ the coil capacity after the initial, 75-day, test period was 4.05 gal/min, whereas after the second, 27-day, test period the capacity was 3.77 gal/min; this decrease in capacity was due to a greater degree of fouling present in the latter case.

Visual observation of the effect of acid cleaning the test coil indicated that the cleaning tended to roughen or pit the surface of the finned tube. Since fouling or scale can adhere more easily to rough surfaces, it would be expected that the fouling rate after cleaning would be greater than that for a new coil.

A comparison of Figs. 4 and 5 indicates that the early stage or initial fouling rate during the second, 27-day, test period was greater than the initial rate during the 75-day test period. During both test periods the coil capacity tended to decrease to a fairly constant, limiting value. However, during the second, 27-day, test period this limiting value was reached much more quickly than in the initial, 75-day, test period.

As shown in Fig. 5, the acid cleaning and brightening treatment of the test coil failed to return the coil to its initial performance condition. This indicates that some of the fouling film was not removed from the coil surfaces during these treatments even though the coil was acid cleaned several times.

VII. CONCLUSIONS

The following conclusions were reached in this investigation:

1. In a finned-tube coil the inside fouling film has a much larger effect on the overall fouling resistance than the outside fouling film, due to the large outside-to-inside area ratio of the finned tube.

2. The degree of fouling of a finned-tube coil is not directly proportional to the hardness of the water in contact with the coil, but also varies with other factors such as the temperature of the metal relative to the water, the velocity of the water, etc.

3. The water flow rate maintained through the inside of the test coil has a large influence on the fouling rate.

4. The total fouling present at the end of the 27-day test period was greater than that present after the earlier, 75-day, test period. This was attributed to the roughening of the surfaces of the test coil during cleaning.

5. The early stage or initial fouling rate during the second, 27-day, test period was greater than the initial rate during the earlier, 75-day, test period.

6. The best acid cleaning and brightening treatment of the test coil failed to return the coil to its initial performance condition.

APPENDIX A

SUMMARY OF WILSON PLOT DATA

Date	Run No.	Water Rate (lb/hr)	Avg Tank Temp. to Coil (°F)	Avg Tank Temp. from Coil (°F)	Inlet Coil Water Temp. (°F)	Outlet Coil Water Temp. (°F)	ΔT_{LM} (°F)	Q x 10^{-4} (Btu/hr)	U_o	$\frac{10^4}{U_oA_o}$	$\frac{10^4}{(1 + 0.011\ t_w)W^{0.8}}$	Remarks
12/10/55	149	5510	190.36	183.38	100.48	143.20	62.90	23.55	142.2	2.67	4.40	
	150	4640	190.51	183.75	97.72	146.02	62.30	22.40	136.7	2.78	4.92	
	151	3190	190.12	183.40	91.40	152.81	59.30	19.58	125.3	3.03	6.65	Coil cleaned and placed in tank
	152	2350	190.35	185.40	84.23	159.26	58.20	17.62	115.1	3.30	8.69	
	153	1357	190.29	185.00	73.94	170.15	51.40	13.03	96.5	3.94	13.40	
	154	1930	190.65	185.40	80.42	163.44	56.20	16.01	108.1	3.52	11.80	
12/12/55	155	6050	190.97	179.30	102.50	141.80	61.80	23.86	146.60	2.59	4.02	
	156	4765	191.30	179.10	98.10	145.50	61.50	22.64	139.80	2.72	4.90	Two days of fouling
	157	3504	190.95	180.70	92.80	151.80	60.20	20.70	130.60	2.91	6.19	
	158	2500	191.30	182.10	85.20	158.70	59.10	18.40	118.40	3.21	8.18	
	159	1436	191.30	183.50	74.20	170.30	53.60	13.80	97.85	3.88	12.75	
12/16/55	160	6040	191.40	183.40	102.80	141.07	64.20	23.14	136.80	2.77	4.05	
	161	4765	191.10	182.20	99.05	144.57	63.20	21.70	130.40	2.91	4.89	Six days of fouling
	162	3150	190.85	185.80	91.00	152.10	62.70	19.25	116.60	3.26	6.82	
	163	2370	191.10	186.80	85.70	158.20	60.80	17.18	107.40	3.54	8.55	
	164	1315	190.87	187.80	72.75	171.15	54.10	12.94	90.80	4.18	13.70	
12/18/55	165	914	190.30	185.10	69.75	174.80	49.75	9.61	73.30	5.18	18.35	
	166	1180	191.50	186.50	73.20	170.85	54.40	11.54	80.40	4.72	14.85	
	167	1178	191.40	186.40	73.80	170.57	54.40	11.42	79.80	4.77	14.90	
	168	1616	191.30	185.30	81.27	163.43	57.80	13.29	87.40	4.35	11.60	Eight days of fouling
	169	2646	190.60	185.00	90.02	152.83	62.10	16.64	112.00	3.73	7.81	
	170	4300	190.50	183.70	100.05	143.67	63.30	18.80	112.90	3.37	5.30	
	171	5400	190.50	183.20	104.12	140.62	63.20	19.70	117.50	3.21	4.45	
	172	6170	191.00	183.90	104.97	138.52	64.70	20.70	122.00	3.12	3.97	
12/21/55	173	5990	189.80	179.70	104.80	139.00	62.10	20.50	125.20	3.03	4.07	
	174	4425	190.10	179.50	99.80	143.90	61.40	19.45	120.10	3.16	5.20	
	175	3392	189.70	180.60	95.30	148.40	60.70	18.00	112.90	3.37	6.42	Eleven days of fouling
	176	2600	190.10	181.80	89.60	154.30	59.80	16.82	107.00	3.55	7.93	
	177	2046	191.20	182.80	84.50	159.60	58.70	15.35	99.40	3.82	9.60	
	178	1600	190.50	183.20	79.00	165.40	55.60	13.82	94.48	4.02	11.70	
12/23/55	179	3500	190.38	181.29	96.32	147.49	61.60	17.90	110.20	3.45	6.21	
	180	2680	189.71	180.80	91.58	152.47	59.00	16.30	105.00	3.62	7.68	
	181	2015	190.46	182.49	86.11	158.11	58.60	14.50	93.90	4.04	9.67	Thirteen days of fouling
	182	1295	191.09	185.17	76.21	168.56	54.80	11.96	83.00	4.58	13.79	
	183	976	190.81	185.12	70.43	173.52	51.40	10.17	75.20	5.05	17.30	
	184	5960	190.13	180.80	105.40	138.38	62.90	19.58	118.20	3.22	4.08	
	185	4875	190.44	180.80	102.09	141.89	62.30	19.40	118.20	3.21	4.77	
12/28/55	186	701	191.43	186.72	64.00	179.69	47.20	8.10	65.20	5.83	22.60	
	187	1232	191.33	186.93	73.31	170.20	54.90	11.94	79.00	4.81	14.40	
	188	2130	191.06	185.24	84.94	157.82	60.70	15.51	97.30	3.91	9.29	Eighteen days of fouling
	189	3645	190.87	184.01	97.43	146.95	62.70	18.06	104.50	3.47	6.03	
	190	4645	190.85	183.25	102.31	143.21	62.90	19.00	114.85	3.31	4.98	
	191	5920	191.50	183.42	104.07	131.81	65.20	20.55	120.00	3.17	4.11	
1/3/56	192	5890	190.75	177.90	103.17	139.07	62.40	21.18	128.90	2.95	4.14	
	193	4985	191.25	181.00	101.83	142.15	62.80	20.10	121.40	3.13	4.73	
	194	3990	191.40	182.20	97.32	145.85	63.20	19.40	116.60	3.26	5.64	Twenty four days of fouling
	195	2730	190.70	182.50	90.30	152.90	61.00	17.10	106.30	3.57	7.65	
	196	1553	190.75	184.70	79.60	165.40	56.20	13.32	91.00	4.22	11.97	
	197	1170	191.45	186.70	72.62	171.63	53.80	11.58	81.90	4.64	15.00	
	198	731	190.97	187.80	65.48	178.72	48.20	8.28	65.20	5.83	21.90	
1/13/56	220	5820	191.10	181.80	101.85	141.45	63.70	23.03	137.00	2.77	4.16	
	221	4870	191.08	182.60	97.98	144.78	63.70	22.80	136.00	2.79	4.82	Coil cleaned on inside
	222	3395	190.55	182.20	94.50	152.00	59.80	19.54	124.20	3.06	6.40	
	223	2300	190.50	185.10	85.45	160.02	58.30	17.16	111.80	3.40	8.74	
	224	1103	190.58	186.40	69.87	174.57	50.70	11.55	86.50	4.38	15.80	
1/16/56	229	6170	189.30	177.60	103.02	140.70	60.70	23.21	145.50	2.61	3.97	
	230	4900	190.13	180.10	99.45	145.05	61.00	22.34	139.00	2.73	4.79	Coil cleaned, both sides
	231	3055	189.35	180.70	89.58	152.83	59.70	19.33	123.80	3.07	6.98	
	232	1745	190.22	182.00	79.08	165.82	55.65	15.14	104.50	3.64	10.91	
	233	1000	189.90	186.50	68.17	176.40	48.30	10.82	85.00	4.47	17.05	
	234	6025	180.13	172.00	105.44	138.35	53.20	19.84	142.00	2.68	4.03	Coil cleaned, both sides; tank temperature of 180°F
	235	4550	180.03	171.70	102.32	142.60	51.80	18.32	134.20	2.83	5.08	
	236	2143	180.60	174.50	87.70	155.85	49.50	14.60	112.00	3.39	9.27	
	237	957	179.88	176.00	75.21	168.35	41.20	8.91	82.30	4.62	17.60	

APPENDIX B

SUMMARY OF I.B.R. CAPACITY DATA

Date	Run No.	T_{tank} Average Tank Temp. (°F)	$T_{water\ in}$ Inlet Water Temp. (°F)	$T_{water\ out}$ Outlet Water Temp. (°F)	Δt_{water} (°F)	$T_{tank} - T_{water\ in}$ (°F)	Coil Capacity (gal/min)	Remarks
75-day test period								
9/8/55	58	190.66	68.83	170.01	101.18	121.83	2.59	
	59	188.87	63.35	163.13	99.78	125.52	3.21	
	60	189.23	58.80	158.60	99.80	130.43	3.78	
	61	188.16	56.59	157.00	100.41	131.57	4.22	
9/15/55	67	189.43	68.53	169.26	100.73	120.90	2.52	
	68	188.58	62.00	163.61	101.61	126.58	3.01	
	69	188.12	55.04	156.40	101.36	133.08	3.67	
	70	187.90	48.80	148.79	99.99	139.10	4.46	
	71	187.00	40.92	140.91	99.99	146.08	5.07	
9/16/55	72	160.75	49.12	152.20	103.08	111.63	1.34	
	73	171.15	46.50	146.67	100.17	124.65	2.70	
	74-A	179.25	47.46	148.36	100.90	131.71	3.36	
	74-B	189.56	47.58	148.22	100.64	141.98	4.41	
9/19/55	75	162.44	47.26	146.97	99.71	115.18	1.69	
	76	169.95	46.55	146.84	100.29	123.40	2.42	
	77	178.59	46.27	146.49	100.22	132.32	3.26	
	78	188.53	46.78	146.82	100.06	141.75	4.20	
9/29/55	84	161.80	45.96	146.76	100.80	115.84	1.75	
	85	169.26	45.62	145.75	100.13	123.64	2.54	
	86	178.97	45.16	145.60	100.44	133.81	3.52	
	87	189.45	45.13	145.81	100.68	144.32	4.23	
27-day test period								
1/5/56	199	161.80	46.31	146.59	100.28	115.49	1.55	
	200	171.45	45.35	145.61	100.26	126.10	2.43	
	201	179.94	44.75	146.75	102.00	135.19	3.05	
	202	190.15	44.11	144.52	100.41	146.04	4.17	
	203	190.16	43.76	144.11	100.35	146.40	4.56	
1/7/56	204	160.30	43.55	143.65	100.10	116.75	1.671	
	205-A	154.92	43.13	143.13	100.00	111.79	1.224	
	205-B	189.97	42.67	142.13	99.46	147.30	4.415	
	206-A	169.85	42.98	143.12	100.14	126.87	2.512	
	206-B	179.95	42.65	143.00	100.35	137.30	3.33	
1/10/56	207	161.35	42.13	142.33	100.20	119.23	1.97	
	208	169.72	42.15	142.40	100.25	127.57	2.64	
	209	179.81	44.45	144.34	99.89	135.36	3.37	
	210	189.57	43.53	143.84	100.31	146.04	4.40	
1/11/56	211	160.74	41.53	141.28	99.75	119.46	1.970	
1/12/56	212	159.93	40.83	141.13	100.30	119.10	1.965	
	213	169.78	40.95	140.90	99.95	128.83	2.86	
	214	179.89	40.63	141.15	100.52	139.26	3.70	
	215	189.45	40.90	140.25	99.35	148.55	4.72	
1/13/56	216	160.00	40.98	141.55	100.57	119.02	2.34	
	217	169.97	41.52	142.25	100.73	128.45	3.37	Coil cleaned on inside
	218	189.78	41.25	141.43	100.18	148.53	5.69	
	219	179.87	41.26	141.51	100.25	138.61	4.50	
1/16/56	225	160.05	41.08	140.80	99.72	118.97	2.39	
	226	170.00	41.47	140.35	98.87	128.53	3.58	Coil cleaned on inside and outside
	227	179.95	41.43	141.52	100.09	138.52	4.80	
	228	188.03	41.92	142.05	100.13	146.11	5.86	

APPENDIX C

WILSON PLOT RUN CALCULATION

Run No. 224—coil cleaned on inside

$$W = \frac{(140)(3600)}{(457.2)} = 1103 \text{ lb/hr}$$

$$T_{H_2O \text{ in}} = 21.08 \qquad T_{H_2O \text{ out}} = 79.04$$

$$\text{Correction} = \underline{-1.04} \qquad \text{Correction} = \underline{+.17}$$

$$T_1 = 20.04°C \qquad T_2 = 79.21°C$$

$$= 69.87°F \qquad 174.57°F$$

$$\Delta t_{H_2O} = \begin{array}{r} 174.57 \\ \underline{69.87} \\ 104.70°F \end{array}$$

$$t_{water} = 122.22°F$$

$$W^{0.8} = 270.6$$

$$10^4/(1 + .011\, t_w)W^{0.8} = \frac{10^4}{2.34\, W^{0.8}} = 15.80$$

$$T_A = \begin{array}{r} 87.74 \\ \underline{+.29} \\ 88.03°C \end{array} \qquad T_B = \begin{array}{r} 88.06 \\ \underline{+.23} \\ 88.29°C \end{array} \qquad T_C = \begin{array}{r} 87.84 \\ \underline{+.14} \\ 87.98°C \end{array}$$

$$T_{tank} \text{ before coil} = \frac{T_A + T_B + T_C}{3} = 88.10°C$$

$$= 190.58°F$$

The average thermocouple reading is

$$T_{thermocouple} = \frac{T_{cA} + T_{cB} + T_{cC}}{3}$$

$$= \frac{3.620 + 3.622 + 3.616}{3} = 3.619 \text{ mv (copper constantan)}$$

Therefore,

$$T_{tank} \text{ leaving coil} = 186.40°F$$

$$\Delta T_1 = \begin{array}{r} 190.58 \\ \underline{-174.57} \\ 16.01°F \end{array} \qquad \Delta T_2 = \begin{array}{r} 186.40 \\ \underline{-69.87} \\ 116.53°F \end{array}$$

$$\Delta T_{LM} = \frac{\Delta T_2 - \Delta T_1}{\ln \frac{\Delta T_2}{\Delta T_1}} = 50.7°F$$

$$Q = WC_p \Delta t_{H_2O}$$

$$= 1103 \times 1.0 \times 104.70$$

$$= 115{,}500 \text{ Btu/hr}$$

$$A_o = 26.33 \text{ ft}^2$$

$$U_o = \frac{Q}{A_o \Delta T_{LM}} = \frac{115{,}500}{(26.33)(50.7)} = 86.5 \frac{\text{Btu}}{\text{hr-ft-°F}}$$

$$\frac{10^4}{U_o A_o} = \frac{10^4}{(86.5)(26.33)} = 4.38 \frac{\text{hr-°F}}{\text{Btu}} .$$

APPENDIX D

I.B.R. CAPACITY RUN CALCULATION

Run No. 68

$T_{H_2O\ in} = 16.67$ $\qquad T_{H_2O\ out} = 72.99$

$\text{Correction} = \underline{+\ .01}$ $\qquad \text{Correction} = \underline{+\ .13}$

$T_1 = 16.68°C$ $\qquad T_2 = 73.12°C$

$= 62.00°F$ $\qquad = 163.61°F$

$T_A = 86.82$ $\qquad T_B = 86.95$ $\qquad T_C = 86.69$

$\underline{+0.14}$ $\qquad \underline{+0.15}$ $\qquad \underline{+0.23}$

$86.96°C$ $\qquad 87.10°C$ $\qquad 86.92°C$

$$T_{tank} = \frac{86.96 + 87.10 + 86.92}{3} = 86.99°C$$

$$= 188.58°F$$

$$\Delta T_{coil} = T_2 - T_1 = 163.61 - 62.00 = 101.61°F$$

$$(T_{tank} - T_{water\ in}) = 188.58 - 62.00 = 126.58°F$$

$$W = \frac{75 \times 3600}{182.7} = 1478\ \text{lb/hr}$$

$$Q = WC_p\Delta T_{coil} = 1478 \times 1 \times 101.61 = 150{,}200\ \text{Btu/hr}$$

$$K = \frac{Q}{50{,}000} = 3.01\ \text{gal/min}$$

REFERENCES

1. E. H. Young et al. The Investigation of Heat Transfer and Pressure Drop of 11-Fins-Per-Inch Tubes and Coils. Eng. Res. Inst. Report No. 35, Univ. of Mich., Ann Arbor, February, 1955.
2. "I.B.R. Testing and Rating Code for Indirect-Storage and Tankless Water Heater Tested in Tank," The Institute of Boiler and Radiator Manufacturers, New York, New York, 1952.
3. W. H. Carrier and S. W. Anderson, "The Resistance to Heat Flow Through Finned Tubing," Heating, Piping, and Air Conditioning, May, 1944, pp. 304-318.
4. F. V. Matthews. Boiler Feed Water Treatment, 3rd Edition. New York: Chemical Publishing Co., Inc, 1951.