ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR

EFFECT OF ROOT WALL THICKNESS ON BOND RESISTANCE TO HEAT TRANSFER OF BIMETAL TUBES

REPORT NO. 34

EDWIN H. YOUNG
Assistant Professor of Chemical Engineering

VERN W. WEEKMAN, JR.

GAREN BALEKJIAN
Research Assistants

DENNIS J. WARD

STEVE G. GODZAK

SHAMSHER S. GROVER
Graduate Students

Project No. 1592

WOLVERINE TUBE DIVISION
CALUMET AND HECLA, INC.
DETROIT, MICHIGAN

July, 1954

ABSTRACT

This investigation of variations in aluminum root-wall thickness on the bond resistance and heat-transfer performance of Al-Cu Bimetal tubes with copper liners indicates no significant effect or consistent trend between the four experimental tubes at the conditions under which they were investigated.

The performance of an equivalent all-aluminum tube under identical test conditions was used as a basis of comparison for evaluation of heat-transfer performance and bond resistance of the four Bimetal tubes having nominal aluminum root-wall thicknesses of 0.02, 0.03, 0.04, and 0.05 inch. In general, the magnitude and effect of bond resistance on heat transfer determined by two test methods--one with steam condensing inside the tube and the other with cold water flowing inside the tube--are in agreement with results expected on the basis of thermal-expansion considerations.

TABLE OF CONTENTS

LIST OF TABLES

EFFECT OF ROOT-WALL THICKNESS ON BOND RESISTANCE TO HEAT TRANSFER OF BIMETAL TUBES

INTRODUCTION

Bond resistance is defined as the resistance to heat transfer at the contact surfaces between the liner metal and the fin-root metal of a Bimetal finned tube. It is believed that an extremely thin film of air in the metal-to-metal bond zone constitutes an additional resistance to heat transfer which varies with the particular use of the tube. The variation in bond resistance is due to the thermal contraction and expansion of the two dissimilar metals due to the difference in thermal-expansion coefficients of the two metals, e.g., the thermal-expansion coefficient of a copper liner is 66 percent of that of aluminum so that, depending on the relative temperatures of the inner and outer surfaces of the bond zone, the clearance constituting the bond resistance may expand or contract, resulting in a corresponding variation in bond resistance. Although it may appear that the thickness variations of the air gap are slight, the effect of the variation on heat transfer is great because the thermal conductivity of air is approximately one ten-thousandth that of copper.

The heat-transfer performance of a finned tube is related to the outside heat-transfer area and mean overall temperature difference driving force by the following relationship:

$$Q = U_o A \, \Delta T \quad , \tag{1}$$

where Q = Heat transferred, Btu per hour
U_o = Overall heat-transfer coefficient Btu/(hr)(°F)(ft^2) outside surface
A = Total outside heat-transfer area, sq ft
ΔT = Mean temperature difference, °F.

If no fouling is present, the heat-transfer coefficient, U_o, is further defined as follows:

$$\frac{1}{U_o} = \frac{1}{h_o} + r_m + \frac{1}{h_i}\left(\frac{A_o}{A_i}\right), \qquad (2)$$

where h_o = Outside film coefficient for a finned tube, Btu/(hr)(°F)(ft^2)
h_i = Inside film coefficient, Btu/(hr)(°F)(ft^2)
A_i = Inside tube-surface area, ft^2/ft of tube length
A_o = Outside tube-surface area, ft^2/ft of tube length.

The resistance of the tube-metal wall to heat transfer, r_m, may be defined as follows:

(a) for monometal finned-tube construction:

$$r_m = \frac{X_e}{k_m}\left(\frac{A_o}{A_{me}}\right), \qquad (3)$$

where X_e = equivalent finned-tube wall thickness based on the equivalent tube diameter, ft (see nomenclature list)
k_m = Thermal conductivity of the metal wall, Btu/(ft)(hr)(°F)
A_{me} = Average tube-metal area between d_i and d_e, ft^2/ft

(b) for copper-aluminum Bimetal tube construction:

$$r_m = \frac{(X_e)_{al}}{k_{al}}\left(\frac{A_o}{A_{me}}\right)_{Al} + R_b\,\frac{(A_o)}{(A_o)_{Cu}} + \left(\frac{X}{k}\right)_{Cu}\frac{(A_o)}{(A_m)_{Cu}} \qquad (4)$$

where R_b = Bond resistance, (ft^2)(hr)(°F)/Btu.

The bond resistance of a Bimetal finned tube may be determined by assuming that the outside film coefficient at infinite inside water velocity is the same as the outside film coefficient of the all-aluminum tube (computed from a Wilson plot intercept using equation (2)), and by using this value of h_o as the value for the Bimetal tube in equation (2). The inside water film resistance $(A_o/A_i h_i)$ in equation (2) is zero at infinite water velocity. When Wilson plot data cannot be obtained for Bimetal and all-aluminum tubes, the bond resistance of the Bimetal tube may be determined from the overall heat-transfer coefficient of the Bimetal tube and the corresponding overall heat-transfer coefficient of an equivalent all-aluminum tube under duplicate test conditions by assuming the inside and outside film coefficients of the Bimetal tube to be respectively equal to the inside and outside film coefficients of the all-aluminum tube, and then using the following relationship:

$$\left(\frac{1}{U_o}\right)_{Bimetal} - \left(\frac{1}{U_o}\right)_{all\text{-}aluminum} = R_b\,\frac{A_o}{(A_o)_{Cu}} \qquad (5)$$

A correction may be applied for the difference in the tube-wall resistance of the Bimetal and all-aluminum tubes by combining the answer obtained in equation (5) with equations (3) and (4).

Information on the relative performance of Al-Cu Bimetal, all-copper and all-aluminum tubes had been compiled from test data provided by eleven organizations on thirty different units for crossflow of air on the outside of tube banks[1]. Except for a few Bimetallic units, heat-transfer data on the all-copper, all-aluminum and the Al-Cu tubes were correlated satisfactorily. The correlation indicates no appreciable difference in the heat-transfer performance of monometallic and Bimetallic tubes for applications of low heat flux.

It was proposed to investigate the effect of the aluminum root-wall thickness on the bond resistance to heat transfer of four Bimetal tubes having aluminum fins and copper liners over a range of heat fluxes. The four tubes were to have nominal root-wall thickness of 0.02, 0.03, 0.04, and 0.05 inch. The heat-transfer performance of a similar all-aluminum tube was to be used as a basis of comparison. Table I gives the characteristics of the all-aluminum tube and four Bimetallic finned tubes.

APPARATUS AND PROCEDURE

Two test procedures were used to cover the range of heat fluxes in this investigation. The basic difference between the two test arrangements was that of reversing the temperature gradient directions. In one arrangement, cold water was passed through the inside of the copper liner and a hot-water bath was maintained on the fin side of the tube. Under this condition the air-gap thickness increased, since the thermal-expansion coefficient of aluminum is considerably greater than that of copper. In the other arrangement, steam was condensed inside the copper liner and a water bath was maintained on the fin side. This reversal of temperature gradient resulted in a decrease in the thickness of the air gap with a corresponding decrease in bond resistance. Both of the above tests were repeated on the all-aluminum tube to obtain comparable performance with a tube having no bond resistance.

Wilson plots were obtained by varying the water flow rates through the tubes in order to evaluate the outside film coefficients of heat transfer and the bond resistance of the Bimetallic tubes.

---

[1] Katz, D. L., et al. "Correlation of Heat Transfer and Pressure Drop for Air Flowing Across Banks of Finned Tubes", University of Michigan Engineering Research Institute Project Report for Wolverine Tube Division of Calumet and Hecla, Inc., August, 1953.

TABLE I

TUBE CHARACTERISTICS

Characteristic	Bimetallic Finned Tubes Nominal Aluminum Root-Wall Thickness				All-Aluminum Tube
	0.02 in.	0.03 in.	0.04 in.	0.05 in.	
Aluminum Root-Wall Thickness, in.	0.0291	0.0348	0.0401	0.0571	0.0730
Average Fin Thickness, in.	0.0198	0.0198	0.0164	0.0174	0.0190
Inside Diameter, Cu Liner, in.	0.928	0.928	0.928	0.928	1.010
Outside Diameter, Copper Liner, in.	0.988	0.987	0.988	0.988	--
Aluminum Root Diameter, in.	1.046	1.057	1.068	1.102	1.156
Diameter over Fins, in.	1.989	2.010	2.001	2.014	1.999
Fins per inch	9.15	9.15	9.15	9.10	9.28
Length of Finned Section, in.	66.0	66.0	66.0	66.0	64.75
Finned Area/ft, ft^2/ft	3.709	3.781	3.705	3.684	3.538
Equivalent Diameter, d_e, in.	1.217	1.230	1.208	1.246	1.305
Total Heat-Transfer Area in Bath, ft^2	20.89	21.25	20.85	20.64	19.78

A. Test Procedure for Steam Condensing Inside the Tube

The equipment used in the present experiment was that originally developed for preliminary bond-resistance tests, completed at an earlier date. As shown in Figure 1, the apparatus consisted of a steam supply to a finned tube submerged in a water trough. The steam was first passed through a condensate separator prior to feeding to the finned tube in order to insure a dry saturated steam feed. The steam was condensed on the inside of the tube, the rate of condensate formation being a measure of the rate of heat transfer.

The inlet steam-pressure gage was calibrated within ± 0.1 psi, and the outlet gage within ± 0.05 psi. The water-bath temperature was measured at three points by thermometers which were calibrated to ± 0.1°C. The rate of heat transfer was measured by timing the collection of 1000 ml of condensate.

Water was admitted to the trough at a constant rate, and was drained through underflows at the opposite end of the trough. A five-foot-long steam sparger, resting on the tank bottom, was used to maintain the bath water at a constant temperature. The sparger provided agitation of the bath water resulting in a more uniform bath temperature.

The condensate from the finned tube was run through a Jerguson gage in which a constant liquid level was maintained. The condensate was bled from the Jerguson gage outlet through a subcooling coil and then collected in a 1000-ml volumetric flask. The subcooling of the condensate prevented partial flashing as the condensate pressure was dropped to atmospheric. Before each run, steam was bled from the steam purge valve located at the base of the downstream compound gage to remove noncondensable gas accumulation.

A test run consisted essentially of timing the collecting of 1000 ml of condensate after the equipment had reached a steady state of operation. During the test run the inlet and outlet steam pressures and the three water-bath thermometers were read at regular intervals.

Two series of test runs were carried out at different steam pressure levels, one series with an inlet steam pressure of 25 psig and the other with an inlet steam pressure of 35 psig. Table II presents typical test data obtained in test run No. 54 on the 0.03-inch-thick root-wall tube with steam at an inlet pressure of 26 psig condensing inside the tube.

TABLE II

TYPICAL TEST DATA OBTAINED ON THE 0.03-INCH ROOT-WALL TUBE WITH STEAM CONDENSING INSIDE THE TUBE (RUN NO. 54)

Steam Pressure to Tube, psig	Steam Condensate Pressure, psi	Water Bath Temperature, °C		
		T_1	T_2	T_3
26.0	4.2	62.8	65.0	69.2
26.0	4.3	62.5	65.8	69.2
26.0	4.3	64.2	65.0	69.2

Time to collect 1000 ml of condensate = 1.280 minutes.

B. Test Procedure with Cold Water Flowing Inside the Tube

The equipment previously described was converted from a steam feed to a cold-water feed to the tube under test. Figure 2 shows the apparatus as modified for the cold-water test procedure. The cold-water inlet and outlet temperatures were measured by thermometers which had been calibrated to ± 0.1°F. A pressure gage on the upstream end of the tube provided a visual means for controlling the water flow rate. A weigh barrel was used to measure accurately the tube-side water flow rate. Provisions were made for preheating the inlet cold water to the tube by direct steam sparging in a separate surge tank. This arrangement permitted Wilson plot tests to be carried out, since a constant average water temperature could be maintained on the tube side.

The trough was filled with water to the overflow level and steam was sparged to heat and maintain the bath water at the desired temperature level. The bath-water temperature was measured by the three calibrated centigrade thermometers used in the previous test procedure.

A test run consisted of adjusting the inlet cold-water temperature to such a level that the average of the inlet and outlet temperatures resulted in the desired average temperature level. In flowing through the tube, the cold-water temperature was increased by heat transferred from the bath, which was maintained at a higher temperature level by sparging steam into it. After the system had been operating at constant conditions for approximately 15 minutes, a test run was made. The test run consisted of timing the collecting of a quantity of water in the weigh barrel. During this period all thermometers were read and recorded at regular intervals. Table III presents typical test data obtained in test run No. 93 on the 0.03-inch-thick root-wall tube.

TABLE III

TYPICAL TEST DATA OBTAINED ON THE 0.03-INCH ROOT-WALL TUBE WITH WATER FLOWING INSIDE THE TUBE (RUN NO. 93)

Inlet Water Temperature, °F	Outlet Water Temperature, °F	Bath Temperatures, °C T_1	T_2	T_3
63.30	81.40	81.5	82.9	83.1
63.10	81.40	81.7	83.0	83.6
62.70	81.50	81.8	83.1	83.4
63.50	81.50	81.7	83.1	83.3
63.70	81.70	81.5	83.2	83.6

Time to collect 230 lb of water = 1.948 minutes.

ANALYSIS OF RESULTS

A. General Discussion

The characteristics of the tubes investigated were summarized in Table I. The calculations of the characteristics for the 0.03-inch tube and the all-aluminum tube are given in Appendices A and B respectively.

Table IV summarizes the bond-resistance-test results obtained with steam condensing inside the tubes, and Table V summarizes the bond-resistance test results obtained with water flowing through the finned tubes.

B. Analysis of Test Results with Steam Condensing Inside the Tube

Table VI contains a summary of test results obtained by condensing steam inside the tubes at 25 and 35 psig inlet steam pressures. A sample calculation for the 0.03-inch root-wall tube with steam condensing at 25 psig is given in Appendix C. Figure 3 graphically compares the overall coefficients given in Table VI as a function of the nominal root-wall thickness. It may be seen that the 0.03- and 0.04-inch nominal root-wall tubes did not perform as well as the 0.02- and 0.05-inch root-wall tubes. The all-aluminum tube, of course, gave the best performance.

TABLE IV

SUMMARY OF TEST RESULTS WITH STEAM CONDENSING INSIDE TUBES

Nominal Al Root-Wall Thickness, in.	Run No.	Average Bath Temp, °F	Overall ΔT °F	Time to Collect 1000 ml, sec	Total Heat Transfer Btu/hr		Overall Heat-Transfer Coefficient, U_o Btu/(hr)(°F)(ft^2)(outside)
					25 psig steam (267°F)	35 psig steam (280.5°F)	
.05	34	149.9	106.7	74.0	100,900		45.8
.05	35	151.0	105.9	73.6	101,900		46.3
.05	36	151.7	104.9	74.0	100,800		46.6
.05	37	150.2	105.7	74.8	100,000		45.7
.05	38	150.0	105.9	74.4	100,200		45.9
.05	39	149.0	120.4	59.5		124,500	50.1
.05	40	149.2	120.1	61.0		122,000	49.1
.05	41	150.6	118.9	61.5		120,500	49.1
.05	42	152.0	117.5	61.4		120,500	49.6
.04	43	151.3	105.7	76.7	97,200		44.1
.04	44	151.3	105.8	76.7	97,200		44.0
.04	45	151.9	104.9	77.1	96,700		44.1
.04	46	149.7	121.4	63.5		116,000	45.8
.04	47	148.4	122.5	63.7		115,500	45.2
.04	48	149.9	120.8	62.5		117,900	46.8
.04	49	151.3	119.7	62.2		118,500	47.5
.04	50	150.6	119.8	62.0		120,000	48.0
.04	51	150.5	119.7	62.9		118,700	47.6
.03	53	151.1	104.9	77.2	99,200		44.5
.03	54	150.6	105.5	76.8	99,700		44.5
.03	55	150.7	105.5	76.1	100,300		44.7
.03	56	151.2	104.9	77.0	99,700		44.8
.03	57	150.9	115.6	61.5		123,500	49.0
.03	58	150.6	119.1	61.5		123,000	48.5
.03	59	151.6	118.1	61.4		123,500	49.1
.02	61	151.5	104.1	74.4	102,800		46.7
.02	62	151.4	103.5	75.6	102,000		46.6
.02	63	151.0	104.0	77.2	102,500		46.7
.02	64	150.6	104.4	75.7	100,800		45.7
.02	65	150.9	104.6	74.8	102,200		46.4
.02	66	152.0	117.6	61.1		124,000	50.0
.02	67	149.0	120.5	61.1		124,100	48.8
.02	68	151.9	118.1	61.4		123,500	49.5
.02	69	152.4	117.4	61.5		123,000	49.6
All-Aluminum Tube	155	153.3	104.5	81.8	93,500		46.0
	156	150.8	104.4	79.6	96,400		46.6
	157	149.9	105.3	78.6	97,400		46.9
	158	149.9	104.7	78.6	97,500		47.1
	159	151.2	119.7	64.0		117,900	50.0
	160	151.5	119.7	61.8		121,800	51.5
	161	151.3	118.9	63.0		120,000	51.1
	162	150.1	120.9	62.5		120,500	50.4

TABLE V

SUMMARY OF TEST RESULTS FOR WATER FLOWING INSIDE TUBES

Nominal Al Root-Wall Thickness, in.	Run No.	Average Bath Temp., °F	Inlet Water, °F	Outlet Water, °F	Overall ΔT, °F	Flow-Rate, lb/hr	Flow-Rate, ft/sec	Total Heat Transfer, Btu/hr	Overall Heat-Transfer Coefficient, U_o Btu/(hr)(°F)(ft^2)(outside)
.02	121	181.4	56.08	87.62	109.5	2545	2.42	80,200	34.7
.02	122	181.7	55.42	87.15	110.4	2495	2.37	79,300	33.9
.02	123	181.3	58.06	86.34	109.1	3110	2.95	88,000	37.9
.02	124	181.9	58.43	84.82	110.3	3590	3.41	94,800	40.6
.02	125	181.8	58.98	85.03	109.8	3600	3.42	93,800	40.5
.02	70	183.3	60.08	86.62	109.9	3700	3.51	98,100	42.3
.02	71	180.7	59.51	85.92	109.1	3670	3.49	97,000	42.1
.02	72	182.8	60.70	83.95	111.6	4940	4.69	115,000	48.8
.02	73	181.1	60.98	83.48	110.0	4980	4.73	112,000	48.3
.02	74	180.7	62.21	81.64	109.9	6250	5.94	121,500	52.4
.02	75	181.0	62.85	79.35	109.9	7980	7.58	131,800	56.9
.02	76	181.4	63.18	79.97	109.8	7640	7.25	128,200	55.4
.02	77	181.0	63.73	78.54	109.9	9440	8.96	139,900	60.3
.02	126	182.0	64.50	78.92	110.3	9680	9.20	139,000	59.6
.02	127	181.4	65.27	78.35	109.6	10,890	10.32	142,200	61.5
.02	128	181.9	65.72	78.73	109.7	10,900	10.35	142,200	61.4
.02	205	181.8	90.18	109.58	81.9	3295	3.13	63,900	37.3
.02	206	181.9	92.01	108.50	81.7	4295	4.08	70,800	41.4
.02	207	181.8	92.93	107.06	81.8	5320	5.05	75,300	44.0
.02	208	181.9	93.34	106.34	82.1	6200	5.88	80,600	46.9
.02	209	181.9	94.03	105.80	82.0	7350	6.98	86,500	50.4
.02	210	182.0	95.00	105.03	82.0	9240	8.77	92,600	54.1
.02	211	181.3	94.95	104.67	81.5	9200	8.73	89,500	52.6
.02	212	181.8	86.36	113.36	82.0	1838	1.74	49,600	28.9
.02	213	181.5	88.84	110.52	81.8	2690	2.56	58,400	34.2
.03	88	181.8	53.35	91.80	109.2	1945	1.85	74,800	32.3
.03	89	182.0	51.10	90.17	111.4	1960	1.86	76,500	31.9
.03	96	181.5	54.80	88.21	110.0	2415	2.29	80,700	34.5
.03	97	181.5	55.13	88.63	109.6	2420	2.30	81,100	34.8
.03	98	182.5	58.04	86.32	110.3	3340	3.17	94,500	40.3
.03	99	181.4	58.08	86.13	109.3	3340	3.17	93,700	40.3
.03	90	182.3	59.28	84.90	110.2	3965	3.77	101,800	43.4
.03	91	182.3	58.70	84.61	110.7	3880	3.69	100,600	43.0
.03	92	180.8	61.15	82.11	109.2	5430	5.16	113,800	48.9
.03	93	181.9	62.98	81.30	109.8	7090	6.74	130,000	55.7
.03	94	182.6	62.32	80.79	110.0	7060	6.71	130,500	55.8
.03	95	182.4	64.14	80.51	110.2	8450	8.03	138,200	58.8
.03	100	182.6	62.98	79.41	111.4	8670	8.23	142,400	60.1
.03	101	180.8	63.91	78.62	109.5	9670	9.19	142,300	61.2
.03	102	181.9	64.76	78.43	110.3	10,950	10.40	149,800	63.7
.03	103	181.7	64.89	78.26	110.1	11,010	10.46	147,100	62.8

TABLE V (cont.)

SUMMARY OF TEST RESULTS FOR WATER FLOWING INSIDE TUBES

Nominal Al Root-Wall Thickness, in.	Run No.	Average Bath Temp., °F	Inlet Water, °F	Outlet Water, °F	Overall ΔT, °F	Flow-Rate, lb/hr	Flow-Rate, ft/sec	Total Heat Transfer, Btu/hr	Overall Heat-Transfer Coefficient, U_o Btu/(hr)(°F)(ft^2)(outside)
.04	104	182.1	53.11	91.08	110.0	2040	1.94	77,500	33.9
.04	105	182.1	52.50	90.41	110.7	2050	1.95	77,600	33.7
.04	106	181.8	56.26	86.96	110.2	2885	2.74	88,500	38.4
.04	107	181.9	57.50	84.80	110.7	3520	3.34	96,200	41.6
.04	108	181.7	58.61	84.09	110.3	3965	3.77	101,000	43.9
.04	109	182.0	60.58	82.85	110.3	4920	4.66	109,800	47.7
.04	110	181.8	60.25	82.81	110.3	5220	4.96	116,200	50.5
.04	111	181.5	62.98	81.52	109.3	6590	6.25	122,200	53.5
.04	112	181.8	63.02	81.58	109.3	6560	6.24	121,900	53.4
.04	113	181.8	64.05	80.08	109.7	8200	7.78	131,500	57.5
.04	114	182.0	63.93	79.67	110.2	8360	7.95	131,800	57.3
.04	117	181.6	64.68	80.40	109.1	8480	8.05	133,500	58.5
.04	118	181.5	64.74	78.96	109.7	9700	9.22	138,000	60.2
.04	115	182.2	65.99	79.21	109.6	10,960	10.40	145,000	63.4
.04	116	181.6	65.50	78.55	109.6	10,980	10.43	143,000	62.5
.04	119	182.0	65.26	78.41	110.2	10,970	10.43	144,000	62.5
.05	78	181.0	53.58	90.63	108.9	2100	1.99	77,900	34.7
.05	79	181.5	53.52	90.44	109.5	2100	1.99	77,500	34.4
.05	129	181.6	55.43	87.76	110.0	2400	2.38	77,600	34.2
.05	130	181.6	58.71	85.28	109.6	3420	3.25	90,800	40.2
.05	131	181.3	59.95	83.18	109.7	4270	4.05	99,200	43.8
.05	80	182.5	60.71	83.90	110.2	4480	4.26	103,800	45.5
.05	81	182.4	60.36	83.60	110.4	4470	4.25	104,000	45.6
.05	132	181.5	62.15	82.00	109.4	5640	5.35	112,000	49.5
.05	133	181.3	62.13	79.51	110.5	6860	6.52	119,200	52.2
.05	134	181.9	62.91	80.41	110.3	6840	6.49	119,600	52.5
.05	83	181.5	63.44	79.86	109.9	7720	7.33	126,900	55.9
.05	84	181.3	64.58	79.03	109.2	9220	8.75	133,000	58.9
.05	85	181.5	64.84	79.21	109.5	9450	8.98	135,800	60.0
.05	86	181.4	65.67	78.50	109.3	10,950	10.40	140,500	62.2
.05	87	181.1	65.69	78.51	109.0	10,850	10.31	139,200	61.9
All-Aluminum Tube	135	181.9	61.62	95.87	103.2	2400	1.92	82,450	40.4
	136	182.0	61.69	95.71	103.3	2410	1.93	82,100	40.1
	137	181.9	61.71	91.92	105.1	2950	2.36	89,400	42.9
	138	182.1	61.71	91.90	105.3	2950	2.36	89,000	42.7
	139	181.8	61.73	89.32	106.3	3450	2.76	95,200	45.3
	140	181.7	61.79	88.34	106.6	3710	2.97	98,500	46.7
	141	181.7	61.71	84.08	108.8	4920	3.94	110,000	51.1
	142	182.3	61.69	84.20	109.4	4890	3.91	110,000	50.8
	143	181.6	61.99	82.10	109.6	5890	4.71	118,400	54.7
	144	182.3	61.91	82.31	110.2	5980	4.79	122,000	55.9
	145	182.4	62.30	80.94	110.8	6900	5.52	128,500	58.6
	146	182.4	62.36	81.14	110.7	6910	5.53	129,600	59.1

TABLE V (concl.)

SUMMARY OF TEST RESULTS FOR WATER FLOWING INSIDE TUBES

Nominal Al Root-Wall Thickness, in.	Run No.	Average Bath Temp., °F	Inlet Water, °F	Outlet Water, °F	Overall ΔT, °F	Flow-Rate, lb/hr	Flow-Rate, ft/sec	Total Heat Transfer, Btu/hr	Overall Heat-Transfer Coefficient, U_o Btu/(hr)(°F)(ft^2)(outside)
All-Aluminum Tube	147	181.8	61.71	80.82	110.5	6810	5.45	130,000	59.5
	148	182.0	63.26	81.40	109.7	7330	5.86	133,000	61.3
	149	182.2	63.49	80.18	110.4	8550	6.84	142,500	65.2
	150	182.1	64.03	80.01	110.1	9000	7.20	143,700	65.9
	151	182.1	63.77	79.71	110.4	9020	7.22	143,800	65.8
	152	181.9	64.50	78.53	110.4	10,450	8.37	146,800	67.2
	153	182.1	64.53	78.79	110.4	10,550	8.45	150,500	68.6
	154	181.7	65.10	78.55	109.9	11,400	9.13	153,500	70.4
	195	181.9	94.71	105.44	81.8	9490	7.67	102,000	63.0
	196	182.0	94.21	105.91	81.9	8360	6.76	97,900	60.4
	197	182.6	93.45	106.88	82.4	6840	5.53	92,000	56.4
	198	181.8	93.52	107.28	81.4	6390	5.16	88,000	54.6
	199	181.6	93.42	106.41	81.7	7040	5.69	91,500	56.6
	200	181.9	92.77	107.71	81.6	5420	4.39	81,000	50.1
	201	182.0	91.65	108.54	81.9	4660	3.77	78,700	48.6
	202	182.1	91.29	109.15	81.9	4220	3.42	75,400	46.5
	203	182.3	87.80	112.46	82.2	2380	1.92	58,700	36.1
	204	182.1	90.03	110.08	82.1	3420	2.77	68,600	42.2

TABLE VI

SUMMARY OF TEST RESULTS OBTAINED BY CONDENSING STEAM INSIDE THE TUBES

Tube Al-Root Thick, in.	Runs Averaged	Average Bath Temp, °F	Average ΔT_{av}, °F	Average Time (1000 ml), sec	Average Q, Btu/hr	Average U_o Btu/hr-°F-ft^2 out
25 psig steam inside tubes						
0.02	61 - 65	151.0	104.1	75.5	102,060	46.4
0.03	53 - 56	150.9	105.2	76.8	99,730	44.6
0.04	43 - 45	151.5	105.5	76.8	97,030	44.7
0.05	34 - 38	150.8	105.8	74.2	100,760	46.1
All Al	155 - 158	151.0	104.7	79.6	96,200	46.7
35 psig steam inside tubes						
0.02	66 - 69	151.3	118.4	61.3	123,650	49.5
0.03	57 - 59	151.0	117.6	61.5	123,330	48.9
0.04	46 - 51	150.1	120.6	62.8	117,770	46.8
0.05	39 - 42	150.2	119.2	60.9	121,870	49.5
All Al	159 - 162	151.0	119.8	62.8	120,000	50.75

The relative performance of the Bimetal tubes compared to the all-aluminum tube is given in Table VII. The bond resistance was determined by comparing the performance of the four Bimetal tubes with the performance of the all-aluminum tube by the use of equation (5) under identical conditions. The calculation of the bond resistance for the nominal 0.03-inch root-wall tube with 25 psig steam condensing inside the tube is given in Appendix D. Figure 4 graphically presents the variation of the bond resistance of the four Bimetal tubes with condensing steam pressure. A comparison of this performance with that obtained from the Wilson plot results made with water flowing through the inside of the tubes is also given in this figure, a discussion of which is given in section C.

TABLE VII

PERCENTAGE PERFORMANCE OF BIMETAL TUBES COMPARED TO THE ALL-ALUMINUM TUBE FOR CONDENSING STEAM

Nominal Root-Wall Thickness, in.	25 psig Steam	35 psig Steam
0.02	99.4	97.5
0.03	95.5	96.2
0.04	95.7	92.1
0.05	98.6	97.5

C. Analysis of Test Results Obtained with Water Flowing Inside the Tube

Figures 5 through 9 present the Wilson plots for the all-aluminum and Bimetal finned tubes. Appendix E presents a sample calculation of a Wilson plot point for the nominal 0.03-inch tube utilizing the test data given in Table III (Run No. 93 of Table V). The intercepts of the Wilson plots are tabulated along with the computed overall coefficients in Table VIII. The bond resistances are also presented in this table and were obtained by first computing the outside film coefficient for the all-aluminum tube, second, assuming that this same coefficient existed on the outside of the four Bimetal tubes at an infinite water velocity inside the tube, and third, back calculating the bond resistance by use of equations (2) and (4). Appendix F contains the calculation of bond resistance for the nominal 0.03-inch root-wall tube by this method. It should be emphasized that the calculation of bond resistance by this method is highly sensitive to slight variations of the outside film coefficient from that assumed. There is, therefore, some question as to how significant the decimal digits 0.38 are in the value 0.000138 for the 0.02-inch tube for the 71.9°F water in Table VIII.

TABLE VIII

WILSON PLOT DATA AND EVALUATED BOND RESISTANCES

Tube Al Root Thickness, in.	$t_w = 71.9$ °F Wilson Plot Intercept hr-°F/Btu	Total Heat-Transfer Area, ft^2	Overall Coefficient at ∞ Water Velocity	Bond* Resistance hr-°F-ft^2/Btu	$t_w = 100.0$ °F Wilson Plot Intercept	U_o at ∞ Velocity	Bond Resistance
0.02	0.00049	20.89	97.6	0.000138	0.00064	74.8	0.00023
0.03	0.000492	21.85	95.5	0.000148	--	--	--
0.04	0.00052	20.85	92.2	0.000185	--	--	--
0.05	0.00051	20.64	95.0	0.000158	--	--	--
All-Al Tube	0.000418	19.78	121.0	--	0.00051	99.3	--

---

*Calculated on the assumption that the outside coefficient between fins and bath water are the same for Bimetal and all-aluminum tubes; at 71.9°F, $h_o = 142$, and at 100°F, $h_o = 113$ Btu/hr-°F-sq ft.

Figures 10 through 13 present the individual experimental overall coefficients as a function of water velocity for the four Bimetal finned tubes. Figure 14 again presents the four curves given in Figures 11 through 13 for ease of comparison. This figure indicates that the effect of variation of root-wall thickness on bond resistance is of minor importance. At low heat fluxes the performances tend to merge, while at high heat fluxes the effect of root-wall thickness becomes more appreciable. Figure 15 presents a comparison of the performance of the four Bimetal tubes with the performance of the all-aluminum tube with an average tube-side water temperature of 71.9°F. This figure clearly depicts the influence of bond resistance on heat-transfer performance. Figure 16 presents a similar comparison at an average tube-side water temperature of 100.0°F for the 0.02-inch tube. The 100.0°F tests were made to determine the effect of increasing the inside water temperature on bond resistance. Increasing the inside water temperature by 28°F resulted in bond resistances of 0.000138 and 0.00023 at 71.9°F and 100.0°F for the 0.02-inch tube as indicated in Table VIII. This corresponds to a 67 percent increase in the numerical value of the bond resistance, but the overall performance remained about the same.

Figure 17 graphically indicates the relative performance of the 0.02-inch tube as indicated in Figures 15 and 16. It should be pointed out that the difference between the two curves of Figure 17 is due to the 28°F difference in temperature level between the average tube-side water temperatures. The bath-water temperature was the same for both curves. It is interesting to note that the relative effect of bond resistance decreased with decreasing water flow rates below 5 ft/sec. On the other hand, the curves indicate that for velocities of 5 ft/sec and higher, the relative effect of bond resistance levels off to a constant performance of 85 percent for 71.9°F water and 82.5 percent for 100.0°F water.

TABLE IX

CALCULATED BOND RESISTANCES FOR TESTS WITH STEAM INSIDE TUBE AND COMPARISON WITH TESTS WITH WATER FLOWING INSIDE TUBE

Nominal Al Root-Wall Thickness, in.	Bond Resistance - hr-°F-ft^2/Btu			
	Steam Inside Tubes		Water Flowing Inside Tubes	
	25 psig	35 psig	t_W = 71.9 °F	t_W = 100.0 °F
0.02	0.00001	0.000035	0.000138	0.00023
0.03	0.000068	0.000051	0.000148	No data obtained for these tubes
0.04	0.000066	0.000115	0.000185	
0.05	0.000013	0.000035	0.000158	

D. Discussion of Results of the Two Tests

An examination of Figure 4 and Table IX indicates the range of bond resistances obtained in the two tests. The steam-condensing bond resistance varied from 0.00001 to 0.000115 hr-°F-ft^2/Btu, whereas the cold water tests resulted in bond resistances varying from 0.000138 to 0.000185 for 71.9°F water. A value of 0.00023 was obtained for the 0.02-inch tube with the 100.0°F water.

The lower bond resistances obtained with steam inside the tube as compared to 71.9°F water inside the tube is what would normally be expected, since the hotter fluid would thermally expand the inner liner and thereby tighten up the bond existing between the liner and the finned-tube metal. A comparison of the value of 0.00023, obtained with 100.0°F water, with the value of 0.000138, obtained with 71.9°F water, indicates an inconsistency, since the 100.0°F water should thermally expand the liner metal and thereby reduce the bond resistance over that obtained with 71.9°F water. The overall coefficients obtained at infinite water velocity from the Wilson plot intercepts of Figures 5 and 6 and tabulated in Table VIII for these two conditions are 74.8 and 97.6 Btu/hr-°F-sq ft, respectively, for the 0.02-inch tube. The corresponding values for the all-aluminum tube are 99.3 and 121.0 respectively. The corresponding outside film coefficients for the all-aluminum tube are 113.0 and 142.0 Btu/hr-°F-ft^2, respectively. The above information, when put together with the computed bond resistances, indicates that the higher inside water temperature resulted not only in a reduced overall ΔT driving force, but also in reduced overall heat-transfer coefficients and reduced outside film coefficients. The net effect was an increase in the bond resistance contrary to what would normally be expected. This discrepancy may be due to the assumption of equal outside film coefficients for the Bimetallic and all-aluminum tubes under the same test conditions. It must be emphasized that a small variation in the value of the outside film coefficient of the Bimetal tube appreciably affects the magnitude of the corresponding bond resistance.

CONCLUSIONS AND RECOMMENDATIONS

This investigation of the effect of the aluminum root-wall thickness on bond resistance to heat transfer for the tubes studied at the conditions under which they were investigated does not indicate any significant trend or effect. This is clearly indicated by Figures 14 and 15 which show the relative performances decreasing in the following order: 0.03, 0.04, 0.02, with the 0.05 giving the poorest performance. It should be emphasized, however, that the differences in performance are of a minor nature, as the overall coefficients for the four Bimetal tubes corresponding to any fixed water velocity have the same order of magnitude. This is further substantiated by Figure 3 for the condensing-steam tests, which do not indicate a consistent performance order for the four Bimetal tubes at the two steam condensing pressures. The lower bond-resistance values from steam-condensing tests compared to the cold-water tests are in agreement with the results expected from thermal-expansion considerations.

The effect of decreasing the overall temperature difference by raising the inside water temperature resulted in a decrease in the overall coefficient as indicated in Figures 15 and 16, and an increase in the bond resistance as indicated in Table VIII, for the 0.02-inch tube. It should be emphasized that the relative performance of the 0.02-inch tube to the all-aluminum tube at these two water temperatures and at normal water flow rates is approximately 84 percent as shown in Figure 17. It was not possible to develop a general correlation for predicting bond resistance for Bimetal tubes over a wide range of temperature levels and heat fluxes on the basis of the above observation.

The need for a correlation for predicting vond resistances over a wide range of temperature levels and heat fluxes has been established. It is recommended that an investigation be undertaken to establish a method for predicting bond resistances under these conditions and that such an investigation be made a part of the investigation of cyclic operation on bond resistance.

APPENDICES

APPENDIX A

SAMPLE CALCULATIONS
DETERMINATION OF TUBE CHARACTERISTICS FOR 0.03-INCH TUBE

Data from Table I:

Aluminum root-wall thickness = 0.0348 in.
Aluminum root diameter = 1.057 in.
Diameter over fins = 2.010 in.
Fins per inch = 9.15
Length of finned section = 66.0 in.
Length of bare copper section = 6 in.
Length of bare iron pipe = 16 in.

$$A_o = \frac{\pi(1.057)}{12} + \frac{(2)(\pi)(\overline{2.010}^{2} - \overline{1.057}^{2})9.15}{(4)(12)} = 3.781 \text{ ft}^2/\text{ft}$$

Total outside area, finned section:

$$\frac{3.781 \times 66}{12} = 20.75 \text{ ft}^2$$

Outside area of bare sections:

OD Copper liner = 0.988 in. (6 in. long)

$$\frac{3.14 \times 0.988}{12} \times \frac{6}{12} = 0.1295 \text{ ft}^2$$

OD Iron-pipe sections = 1.050 in. (16 in. long)

$$\frac{3.14 \times 1.050}{12} \times \frac{16}{12} = 0.367 \text{ ft}^2$$

Total heat-transfer area (outside):

$$A = (20.75 + 0.1295 + 0.367) = 21.247 \text{ ft}^2$$

APPENDIX B

SAMPLE CALCULATIONS
DETERMINATION OF TUBE CHARACTERISTICS FOR ALL-ALUMINUM TUBE

Data from Table I:

ID = 1.010 in.
Root diameter = 1.156 in.
Root-wall thickness = 0.073 in.
Diameter over fins = 1.999 in.
Average fin thickness = .019 in.
Length of finned section = 64.75 in.
Fins per inch = 9.28

$$A_o = \frac{\pi \times 1.156}{12} + \frac{2\pi\,[(1.999)^2 - (1.156)^2]\,9.28}{4 \times 12} = 3.538 \text{ ft}^2/\text{ft}$$

$$A_i = \frac{\pi \times 1.01}{12} = 0.264 \text{ ft}^2/\text{ft}$$

$$A_o/A_i = \frac{3.538}{.264} = 13.4$$

Total nonfinned heat-transfer area in bath was measured and computed to be 0.680 ft^2.

Total area of finned section:

$$3.538 \times \frac{64.75}{12} = 19.10 \text{ ft}^2$$

Total heat-transfer area in bath:

$$19.10 + 0.68 = 19.78 \text{ ft}^2$$

Equivalent diameter:

$$d_e = 1.156 + .019\,(1.999 - 1.156)\,9.28 = 1.305 \text{ in.}$$

Average aluminum diameter:

$$\frac{1.305 + 1.01}{2} = 1.157 \text{ in.}$$

Average aluminum conduction length:

$$x_e = \frac{1.305 - 1.010}{2} = 0.148 \text{ in.}$$

APPENDIX C

SAMPLE CALCULATIONS FOR RUN NO. 93 WITH STEAM CONDENSING INSIDE THE TUBE

The calculations are based on the data contained in Tables II and IV. The values in Table IV are the values in Table II corrected by the appropriate calibrations.

Data:

Average bath temperature = 150.6°F
Inlet steam pressure = 39.70 psia (266.8°F)
Outlet steam pressure = 18.67 psia (224.3°F)
Enthalpy of vapor in = 1169.6 Btu/lb
Enthalpy of liquid condensate out = 192.5 Btu/lb

Calculation of the water flow rate:

$$\frac{1000 \text{ ml} \times 60 \text{ min} \times .987 \text{ gm/ml}}{1.280 \text{ min} \times 1 \text{ hr} \times 453.6 \text{ gm/lb}} = 102.0 \text{ lb/hr}$$

Calculation of heat transfer:

$$\Delta H = 1169.6 - 192.5 = 977.1 \text{ Btu/lb}$$
$$Q = (977.1)(102) = 99{,}770 \text{ Btu/hr}$$

Calculation of average overall ΔT:

To determine the effective average overall ΔT it was necessary to make a preliminary calculation for the tube under a specific set of conditions. It was assumed that the inlet steam entered at 25 psig and 267°F. The condensing length was divided into eight zones as shown in Figure 18. The effective ΔT existing at the end of each zone was computed by a trial-and-error procedure so that the heat duty in each zone could be matched by the corresponding heat-transfer rate, zone area, and ΔT driving force. Figure 18 indicates the effective ΔT's for each zone. Figure 19 was prepared to indicate the variation of the metal area available for condensing as a result of condensate buildup.

It was found that the effective ΔT could be determined by summing up 75 percent of the inlet ΔT and 25 percent of the outlet ΔT.

$$\Delta T = [224.3 + .75\,(266.8 - 224.3)] - 150.6 = 105.6°\text{F}$$

Calculation of the overall coefficient:

Using equation (1),

$$U_o = \frac{99{,}700}{(21.247)(105.6)} = 44.5 \text{ Btu/hr-°F-ft}^2 .$$

Note: all overall coefficients are based on the total area in the bath; i.e., finned-tube plus bare-tube areas.

APPENDIX D

SAMPLE CALCULATION OF BOND RESISTANCE FOR 25-PSIG STEAM CONDENSING INSIDE THE 0.03-INCH TUBE

From Table VI the overall heat-transfer coefficient, U_o, for the all-aluminum tube is 46.7 Btu/hr-ft^2-°F, and the U_o for the 0.03-inch tube is 44.6 Btu/hr-ft^2-°F. From equation (5) the bond resistance is obtained as follows:

$$R_b = \frac{1}{44.6} - \left(\frac{1}{46.7}\right) \frac{0.259}{3.781} = 0.0000684 \text{ hr-°F-ft}^2\text{/Btu.}$$

APPENDIX E

SAMPLE CALCULATION OF A WILSON PLOT POINT FOR FIGURE 7

The following calculations are based on the data for Run No. 93 contained in Tables III and V. All temperatures listed have been corrected by the appropriate calibration.

Calculated data:

T_{av} = average bath temperature = 181.9°F (corrected)
Average inlet water temperature = 62.98°F (corrected)
Average outlet water temperature = 81.30°F (corrected)
Flow rate = 7090 lb/hr
Average H_2O temperature = 72.14°F

Calculation of Wilson plot coordinates:

$$y = \frac{10^4}{U_o A} \qquad x = \frac{10^4}{[1 + .011\ t_w]\ W^{0.8}}$$

where:

U_o = overall coefficient
A = total outside area (finned and bare)
t_w = average tube-side water temperature, °F
W = flow rate lb/hr

Overall temperature difference:

$$\Delta T = 181.9 - 72.14 = 109.8°F$$

Tube-side Δt:

$$\Delta t = 81.30 - 62.98 = 18.32\ °F$$

Total heat transferred:

$$Q = W\ C_p\ \Delta t$$
$$Q = 7090\ (1)(18.32) = 130{,}000\ \text{Btu/hr}$$

$$y = \frac{10^4}{U_o A} = \frac{\Delta T \times 10^4}{Q} = \frac{109.8 \times 10^4}{130{,}000} = 8.45$$

$$x = \frac{10^4}{[1 + .011\ t_w]\ W^{0.8}} = \frac{10^4}{[1 + .011(72.14)]7090^{0.8}} = 4.62$$

Calculation of the overall coefficient, U_o, for Figure 11:

$$U_o = \frac{Q}{A\Delta T} = \frac{130{,}000}{(21.247)(109.8)} = 55.7\ \text{Btu/hr-°F-ft}^2.$$

APPENDIX F

SAMPLE CALCULATION OF BOND RESISTANCE FOR WATER FLOWING INSIDE 0.03-INCH TUBE

Computation of Outside Heat-Transfer Coefficient Based on All-Aluminum Tube for Water Flowing Inside Tube

From Figure 5 (Wilson plot for the all-aluminum tube), the intercept at infinite water velocity is 4.18 with 71.9°F tube-side water

$$\frac{10^4}{U_oA} = 4.18 .$$

Therefore,

$$U_o = \frac{10^4}{(19.78)(4.18)} = 121 \text{ Btu/hr-°F-ft}^2$$

At infinite water velocity the following equation holds:

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{(X_e)_{Al}\ A_o}{k_{Al}(A_m)_{Al}} \tag{6}$$

$$\frac{1}{h_o} = \frac{1}{121} - \frac{(.0123)(3.538)}{117(.303)} = .00704 .$$

Therefore $h_o = 142$ Btu/hr-ft²-°F.

Evaluation of Bond Resistance

From Figure 7 (Wilson Plot for 0.03-inch tube), the intercept at infinite water velocity is 4.92.

$$\frac{10^4}{U_oA} = 4.92$$

Therefore,

$$U_o = \frac{10^4}{(21.247)(4.92)} = 95.5 \text{ Btu/hr-ft}^2\text{-°F}$$

Again, at infinite water velocity the following equation may be written for the 0.03-inch Bimetallic tube:

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{(X_e)_{Al}}{(k)_{Al}}\left(\frac{A_o}{A_{me}}\right)_{Al} + \frac{R_bA_o}{(A_o)_{Cu}} + \frac{X_{Cu}A_o}{k_{Cu}(A_m)_{Cu}} \tag{7}$$

Since the all-aluminum tube has approximately the same total outside area and the tests were controlled under the same conditions, h_o calculated for the all-aluminum tube is assumed to be the same as that of the Bimetallic tubes tested. Therefore,

$$R_b = \frac{.259}{3.781}\left(\frac{1}{95.5} - \frac{1}{142} - \frac{(.0101)(3.781)}{(117)(.290)} - \frac{.0025(3.781)}{(220)(.290)}\right)$$

$$= .000148 \text{ hr-°F-ft}^2\text{/Btu.}$$

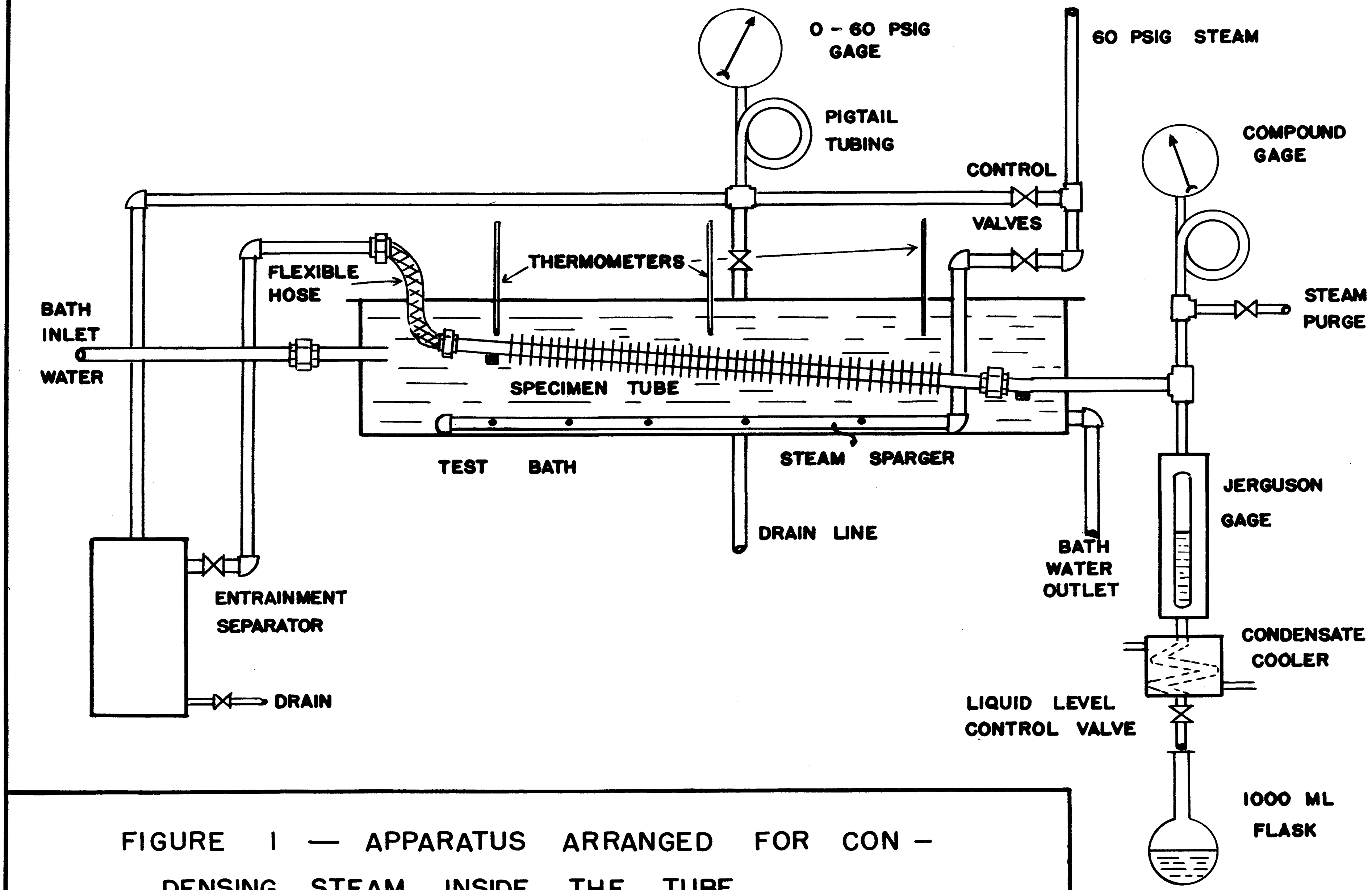


FIGURE 1 — APPARATUS ARRANGED FOR CONDENSING STEAM INSIDE THE TUBE

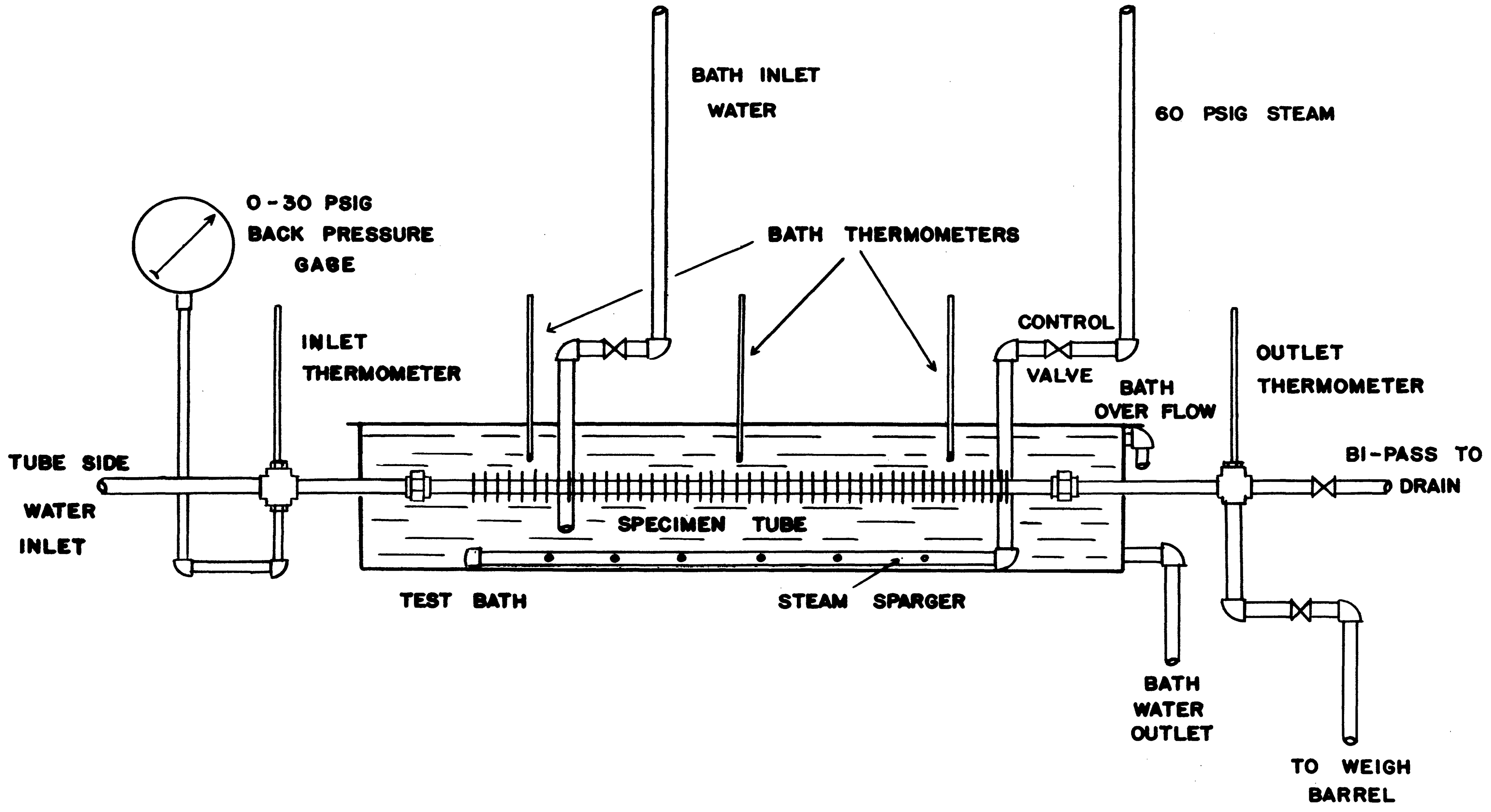


FIGURE 2 — APPARATUS ARRANGED FOR COLD WATER FLOWING INSIDE THE TUBE

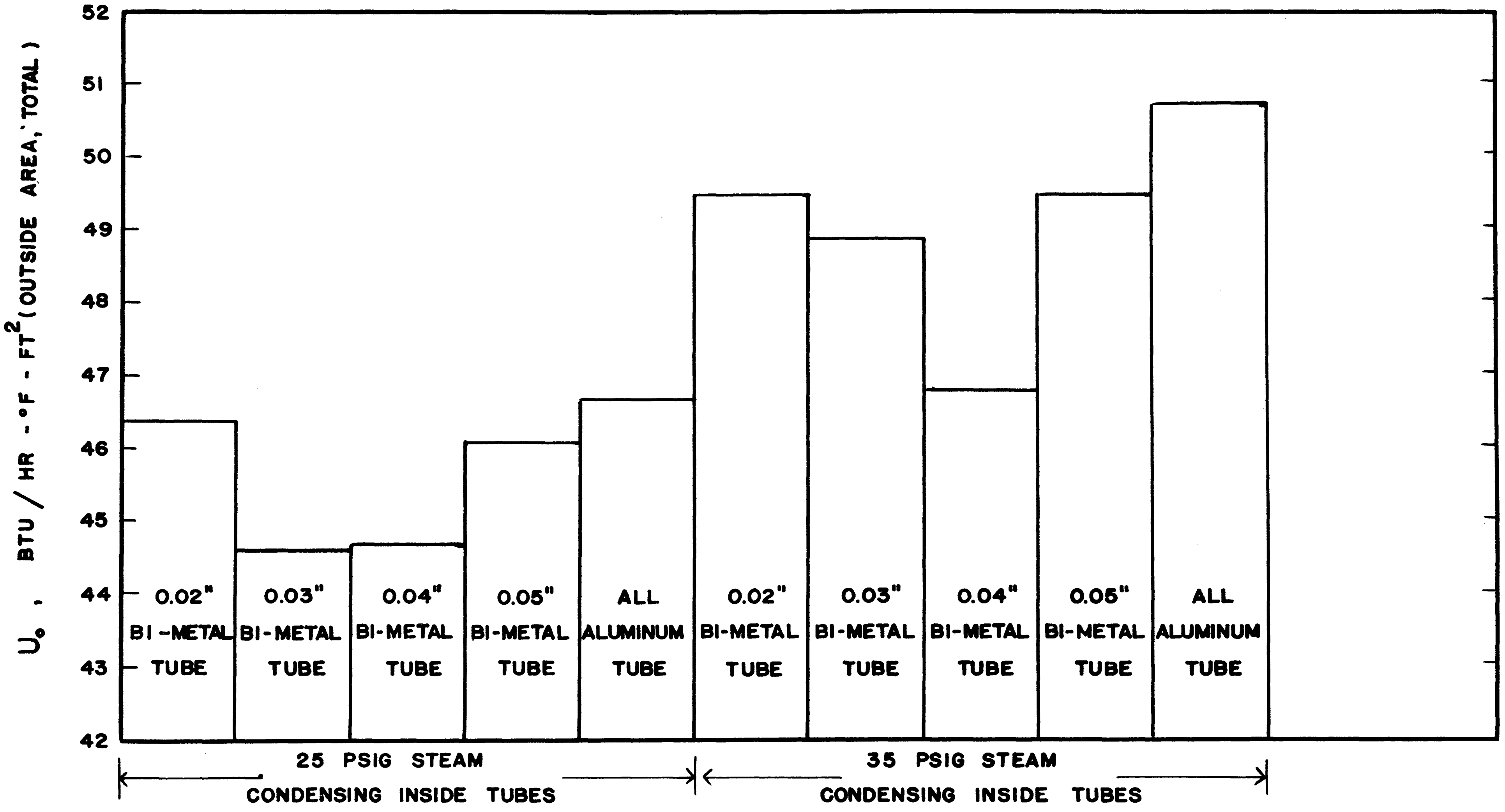


FIGURE 3 - COMPARISON OF OVERALL HEAT TRANSFER COEFFICIENT FOR ALL TUBES TESTED WITH STEAM CONDENSING INSIDE TUBES

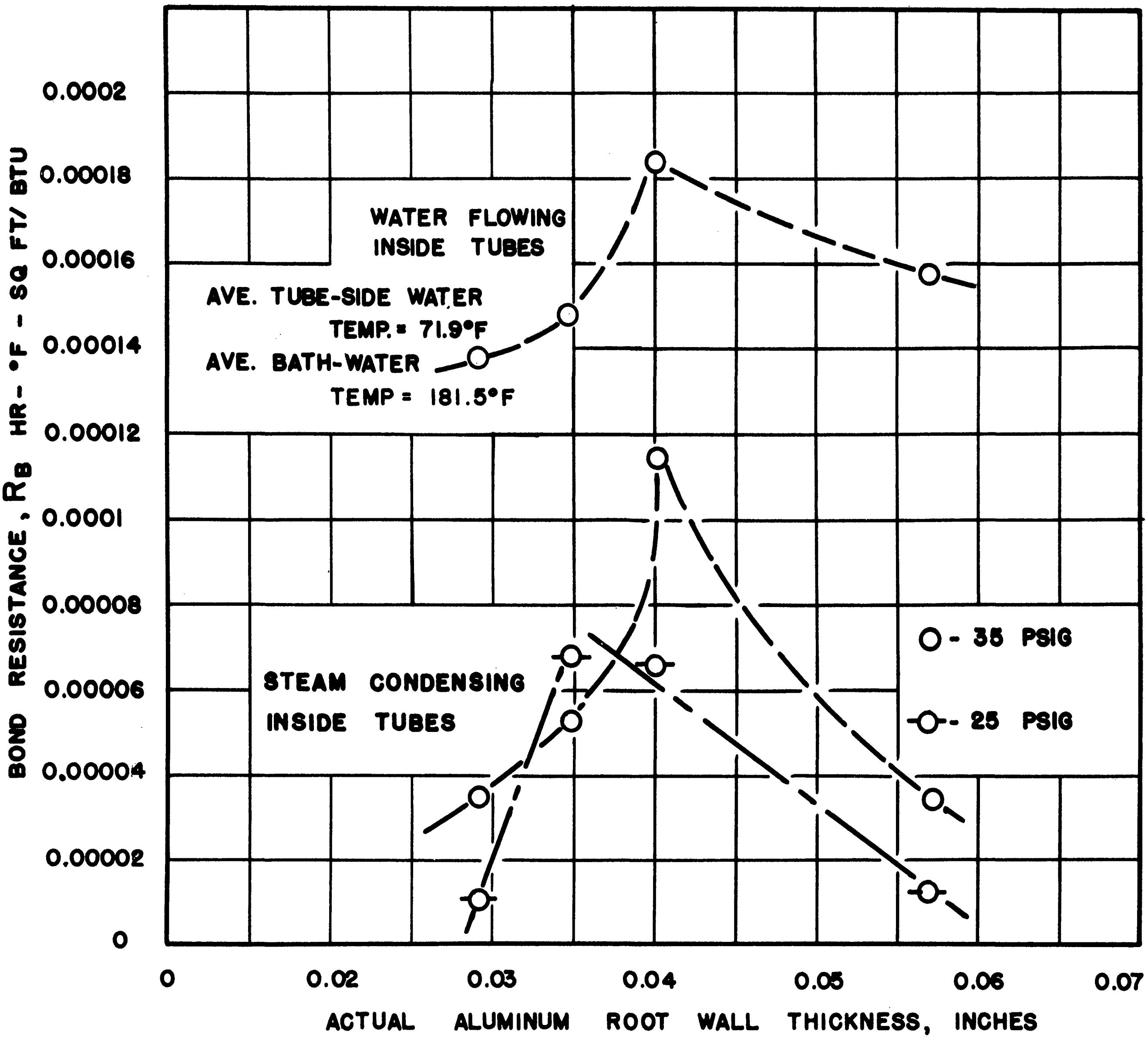


FIGURE 4 — EFFECT OF ALUMINUM ROOT WALL THICKNESS ON BOND RESISTANCE

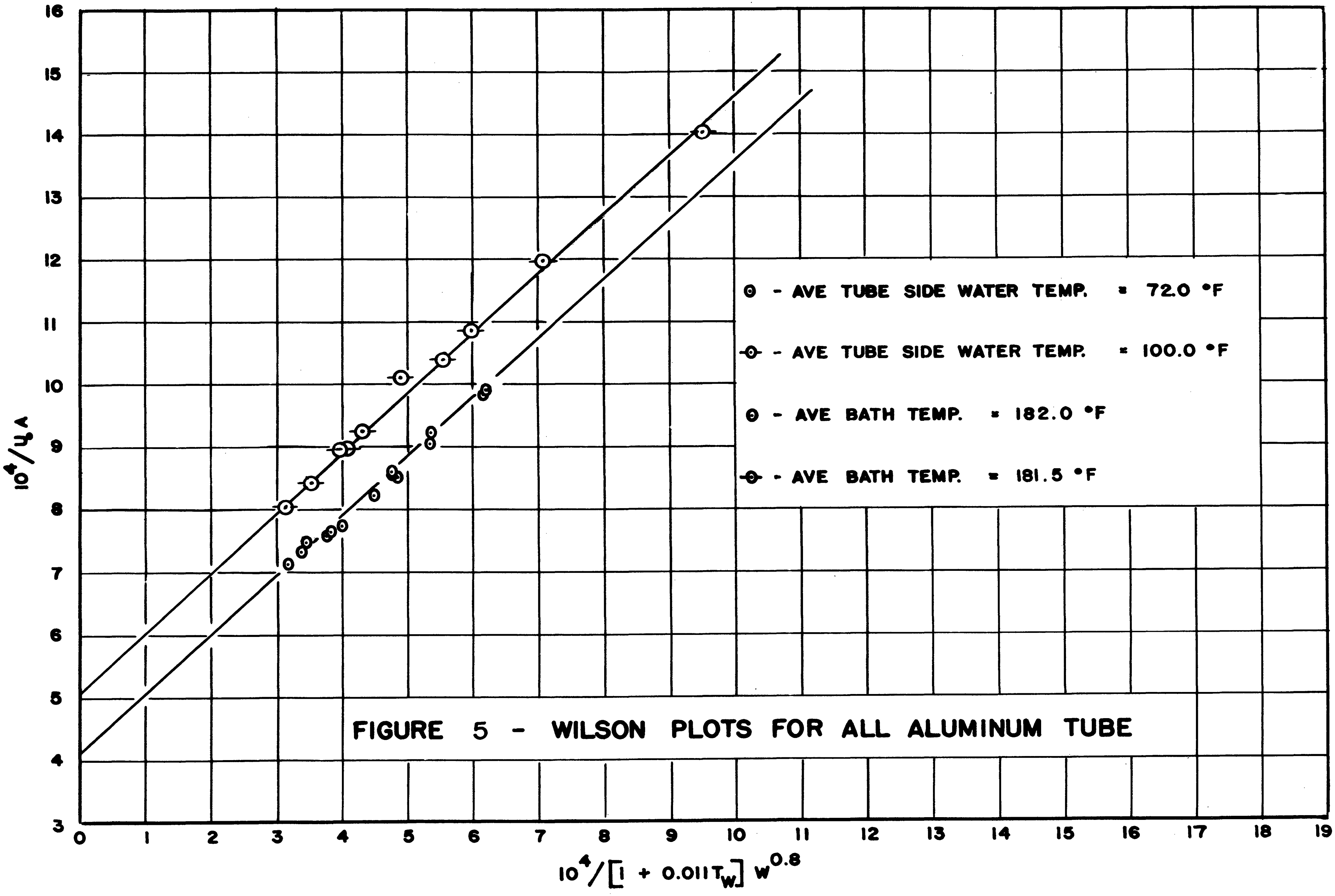


FIGURE 5 - WILSON PLOTS FOR ALL ALUMINUM TUBE

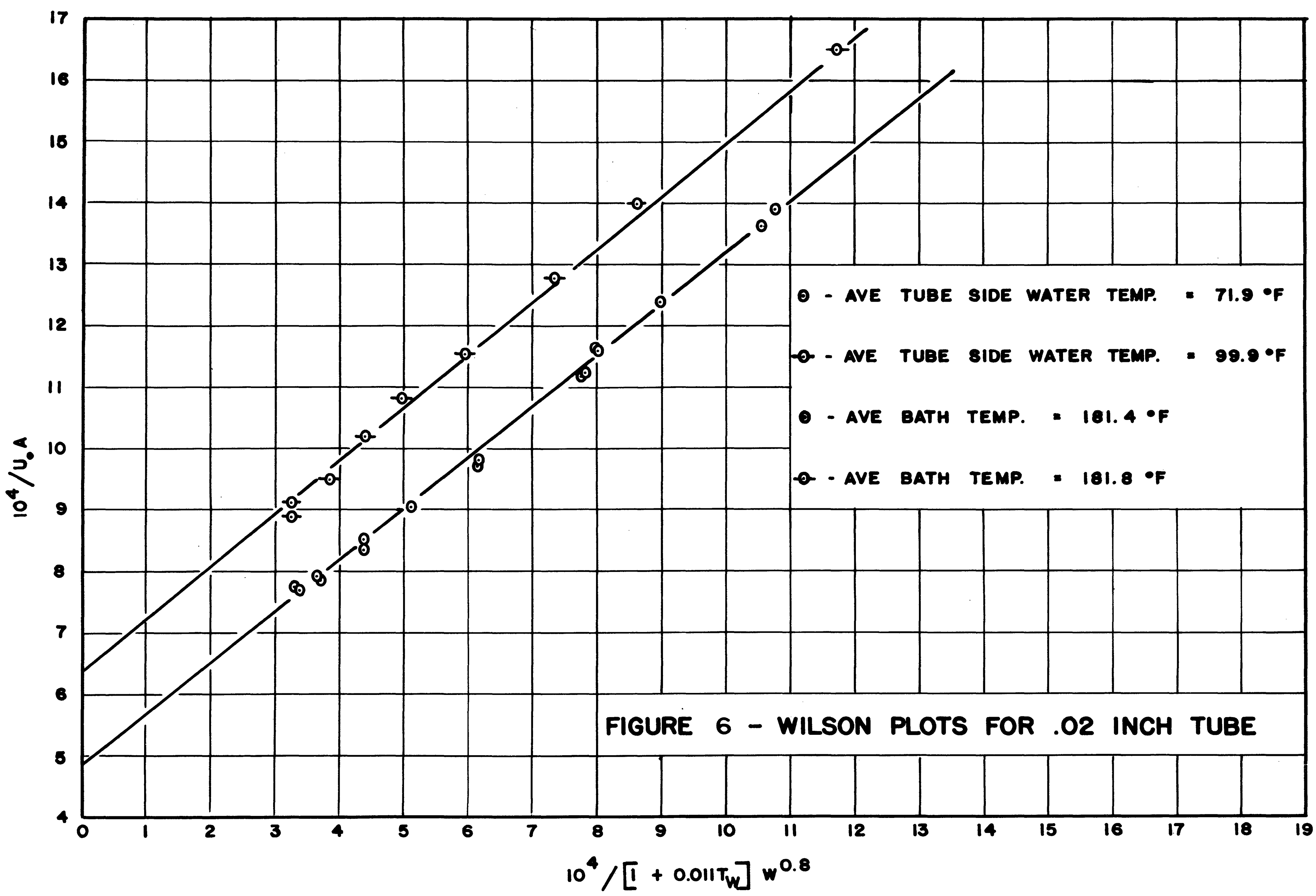
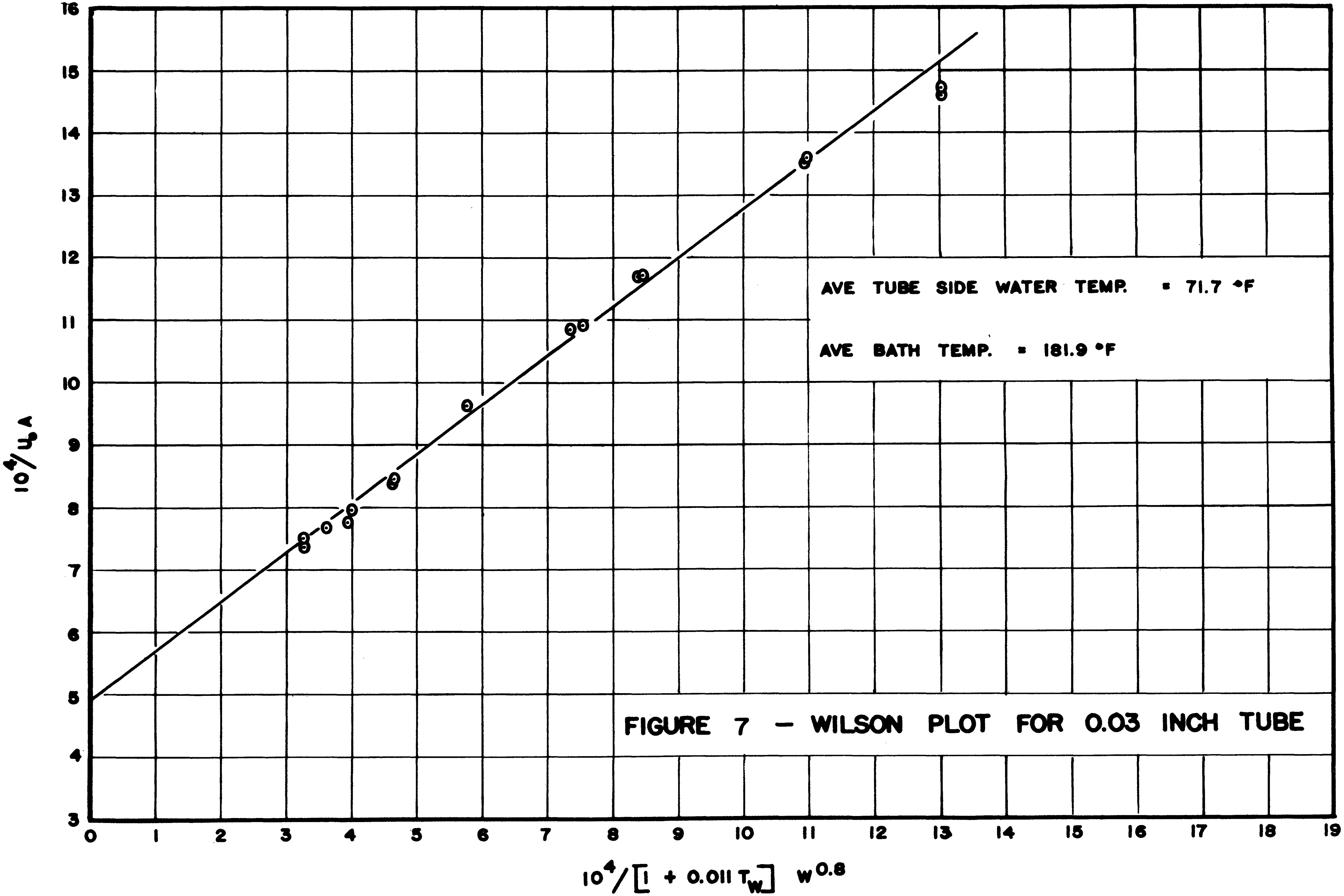


FIGURE 6 – WILSON PLOTS FOR .02 INCH TUBE



AVE TUBE SIDE WATER TEMP. = 71.7 °F

AVE BATH TEMP. = 181.9 °F

FIGURE 7 – WILSON PLOT FOR 0.03 INCH TUBE

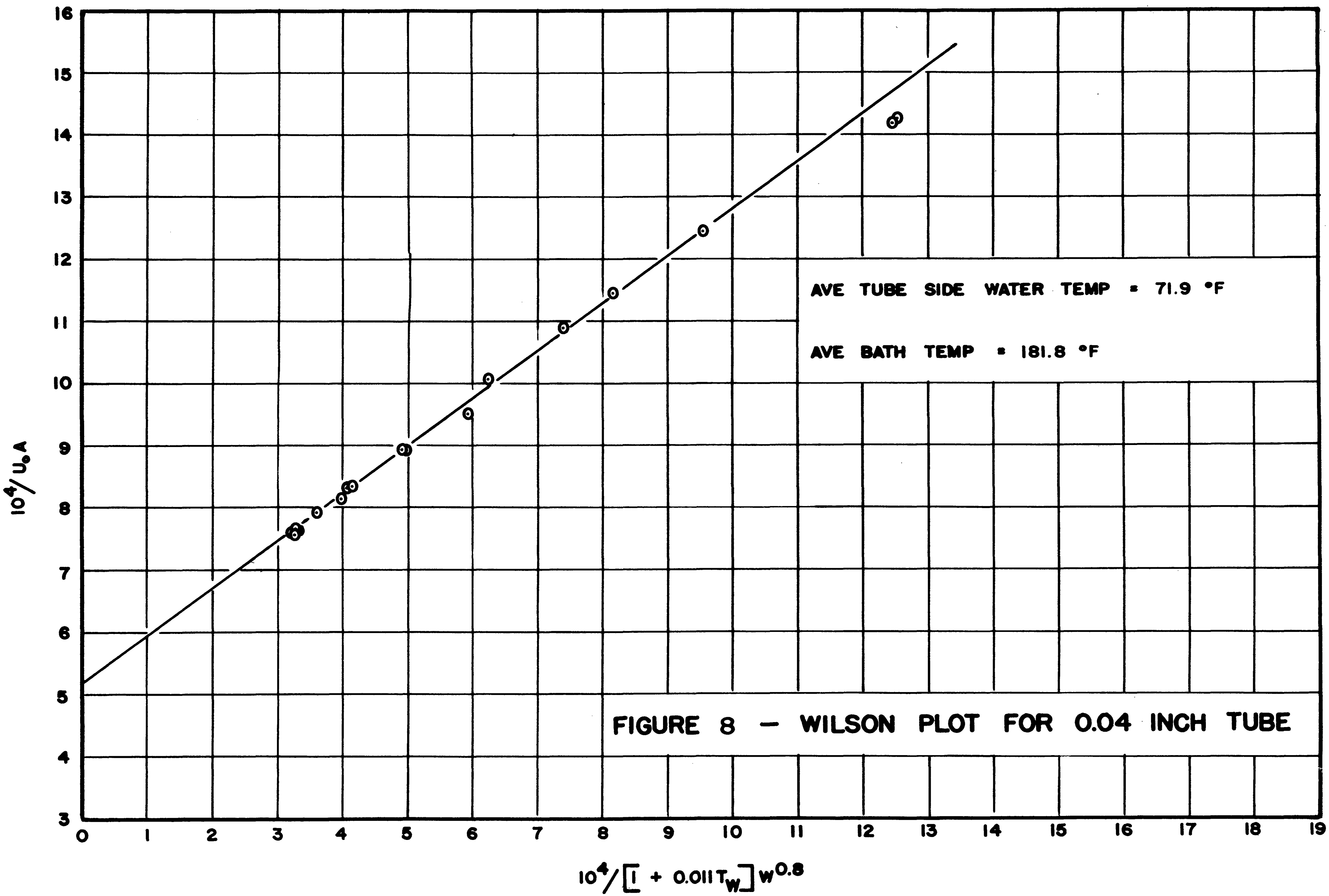


FIGURE 8 — WILSON PLOT FOR 0.04 INCH TUBE

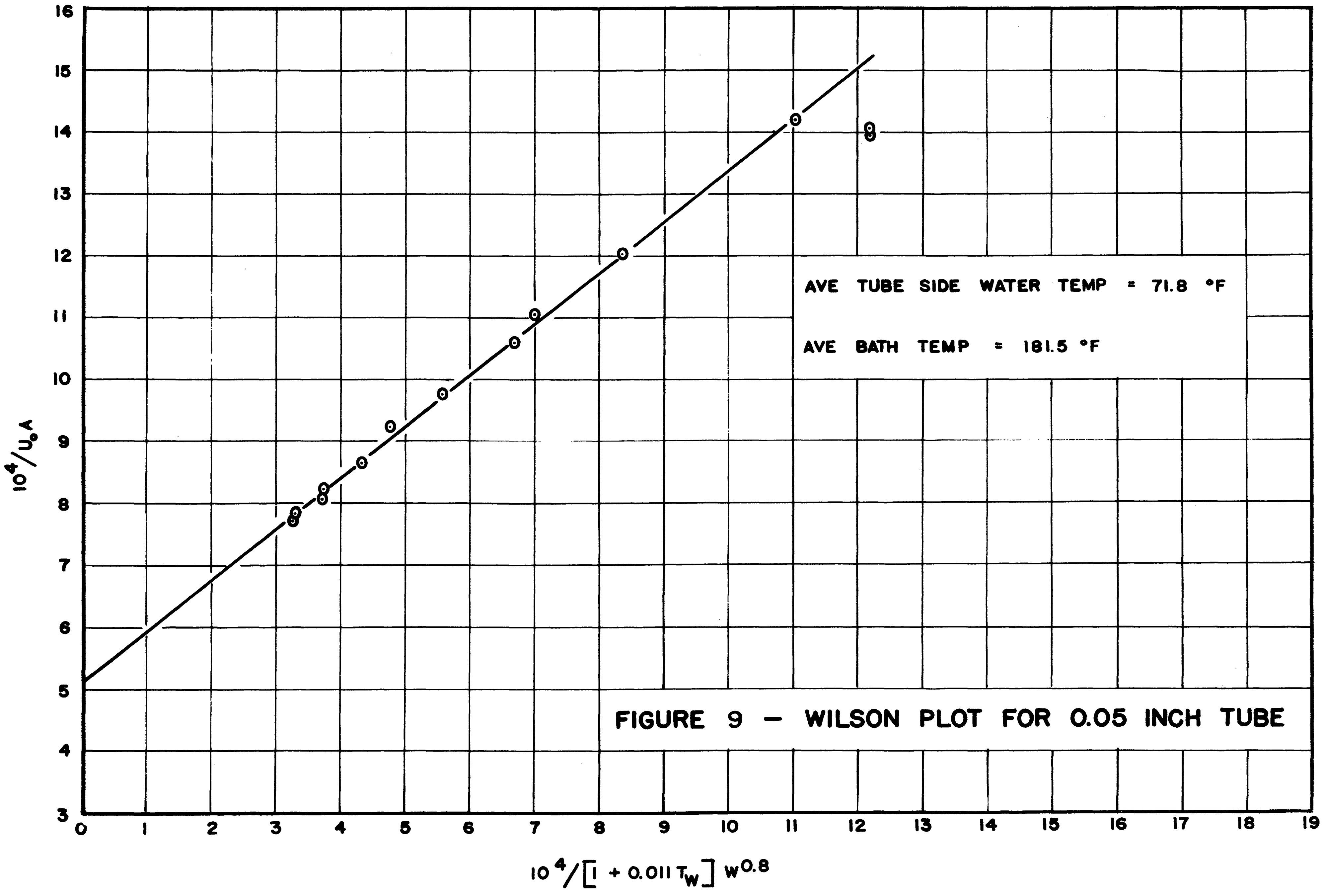
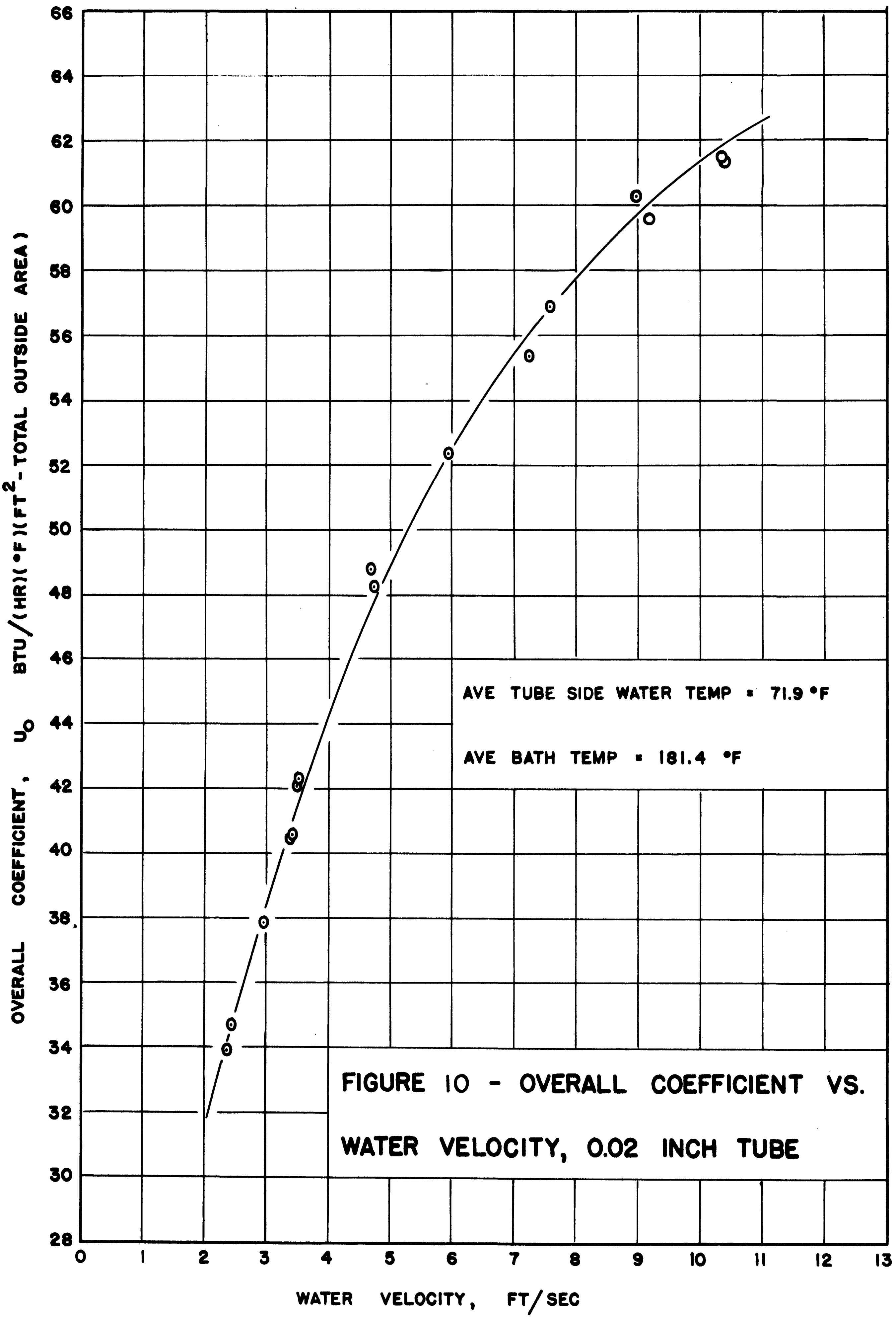


FIGURE 9 – WILSON PLOT FOR 0.05 INCH TUBE



AVE TUBE SIDE WATER TEMP = 71.9 °F

AVE BATH TEMP = 181.4 °F

FIGURE 10 - OVERALL COEFFICIENT VS. WATER VELOCITY, 0.02 INCH TUBE

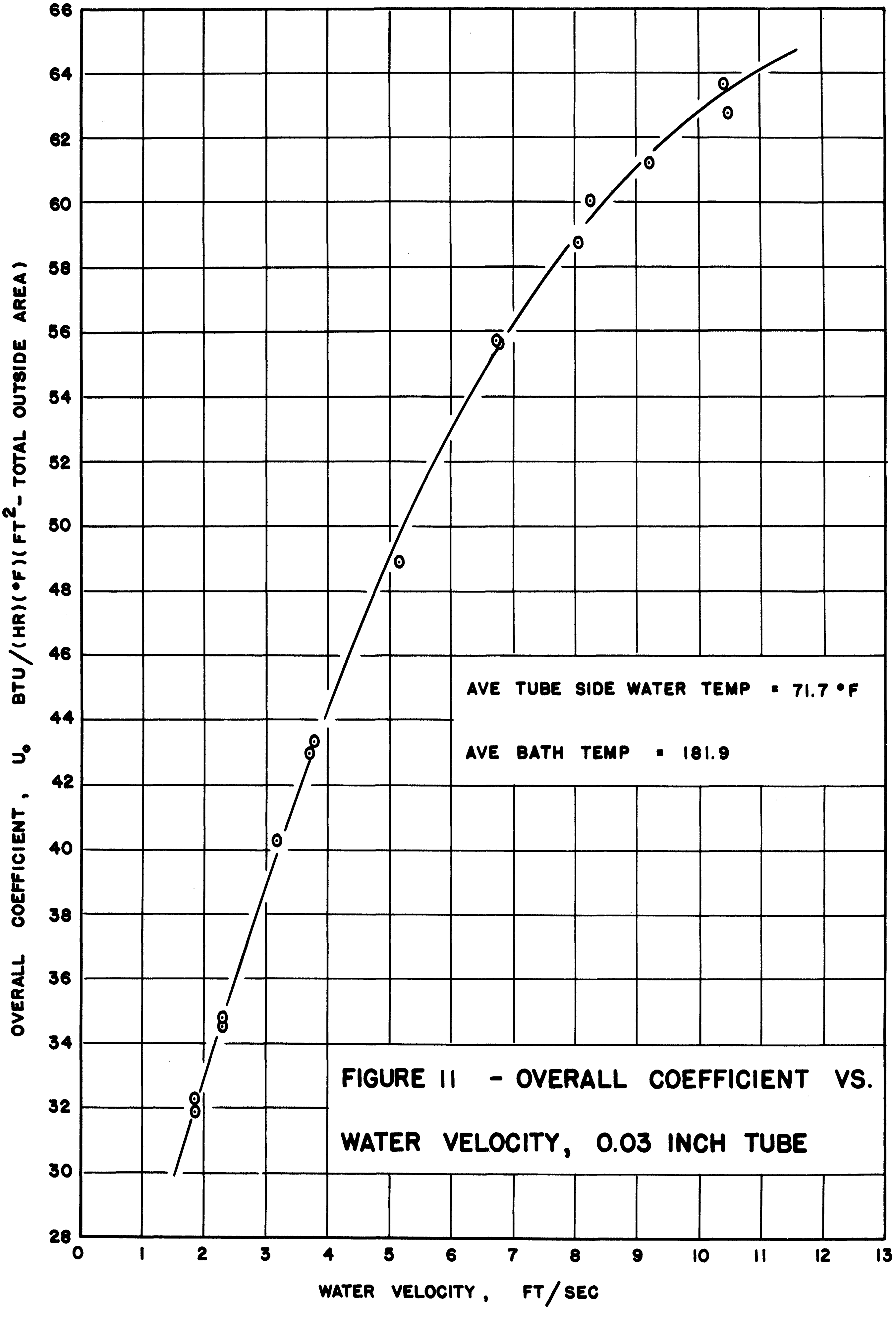
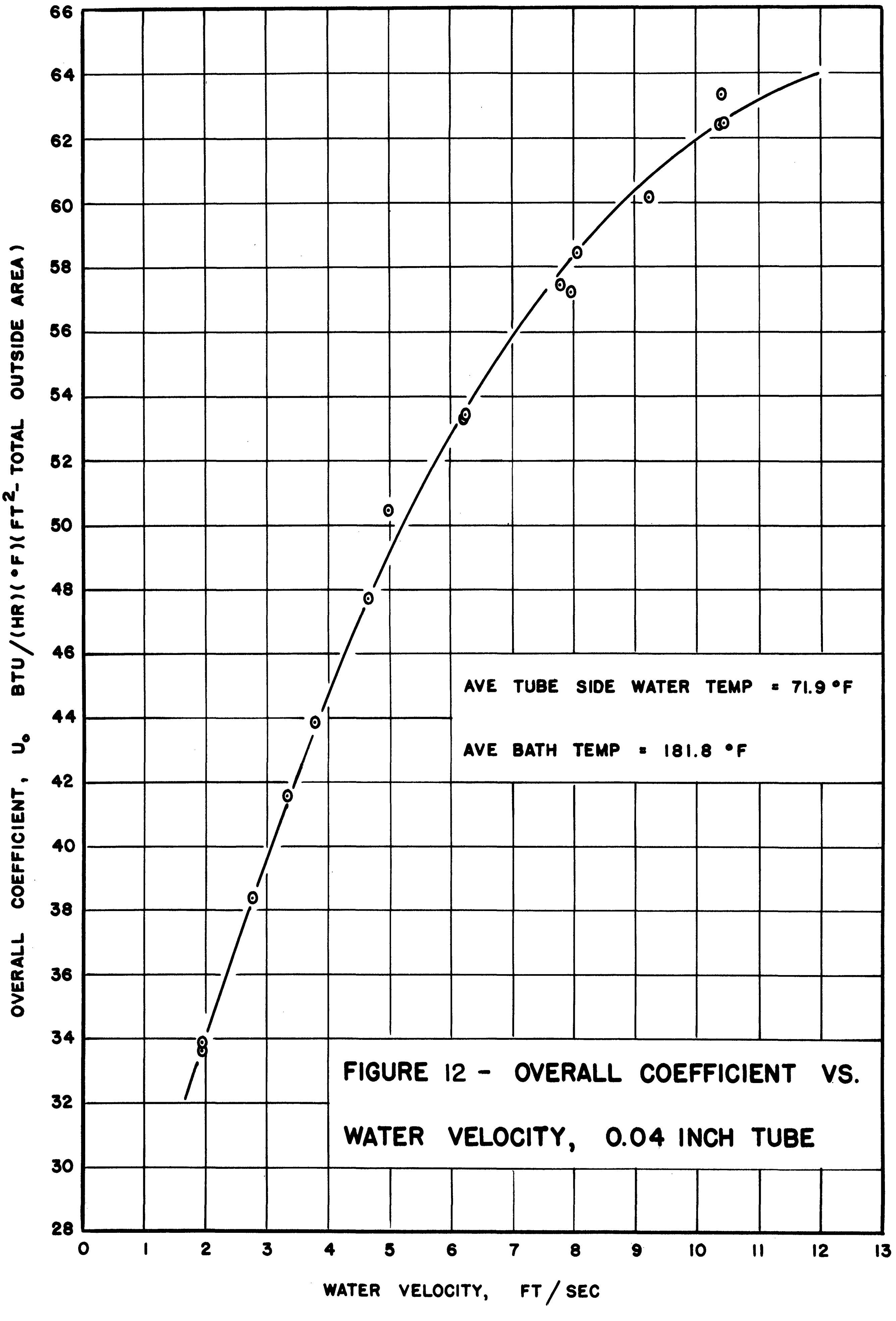


FIGURE 11 - OVERALL COEFFICIENT VS. WATER VELOCITY, 0.03 INCH TUBE



AVE TUBE SIDE WATER TEMP = 71.9 °F

AVE BATH TEMP = 181.8 °F

FIGURE 12 - OVERALL COEFFICIENT VS. WATER VELOCITY, 0.04 INCH TUBE

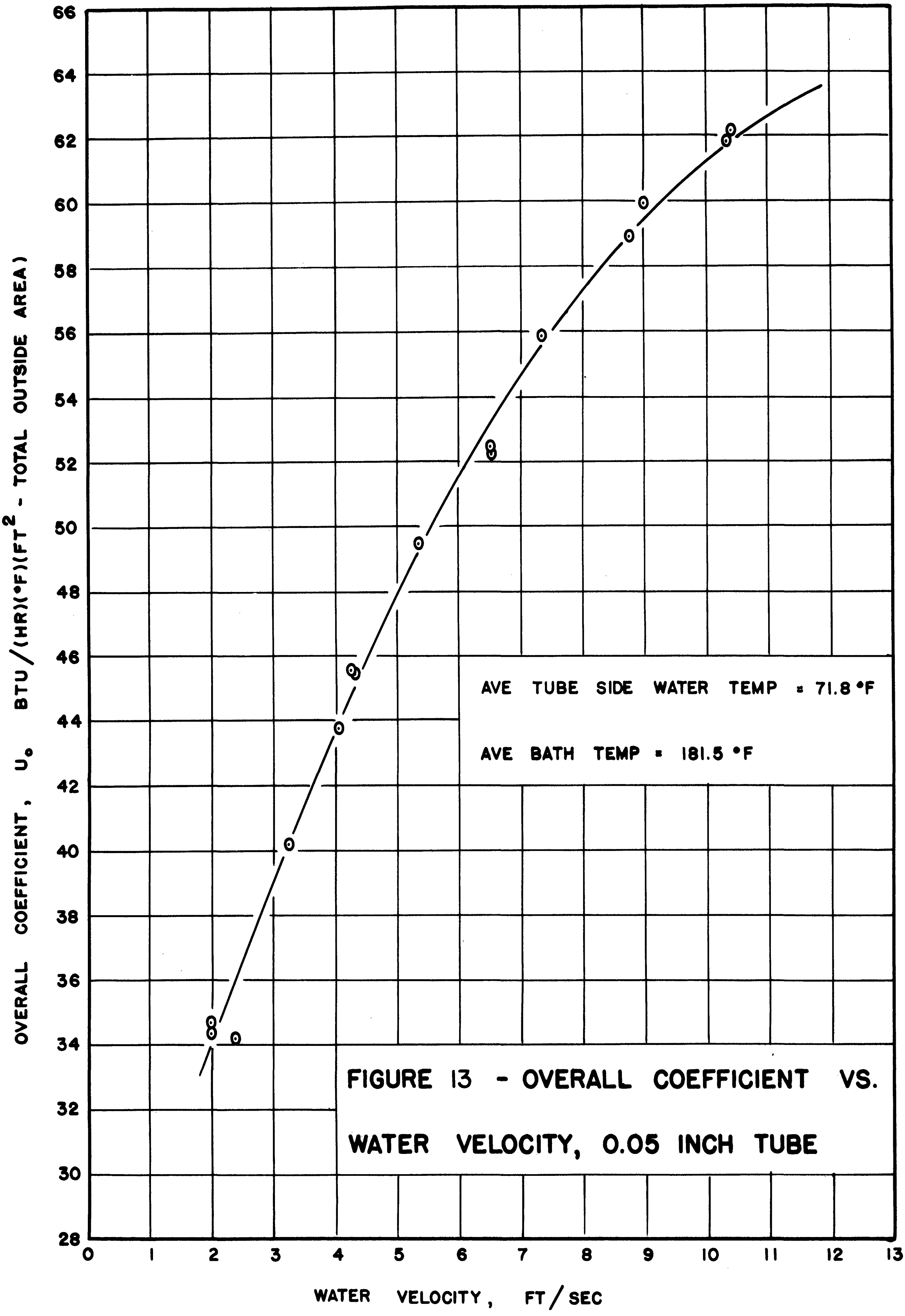


FIGURE 13 - OVERALL COEFFICIENT VS. WATER VELOCITY, 0.05 INCH TUBE

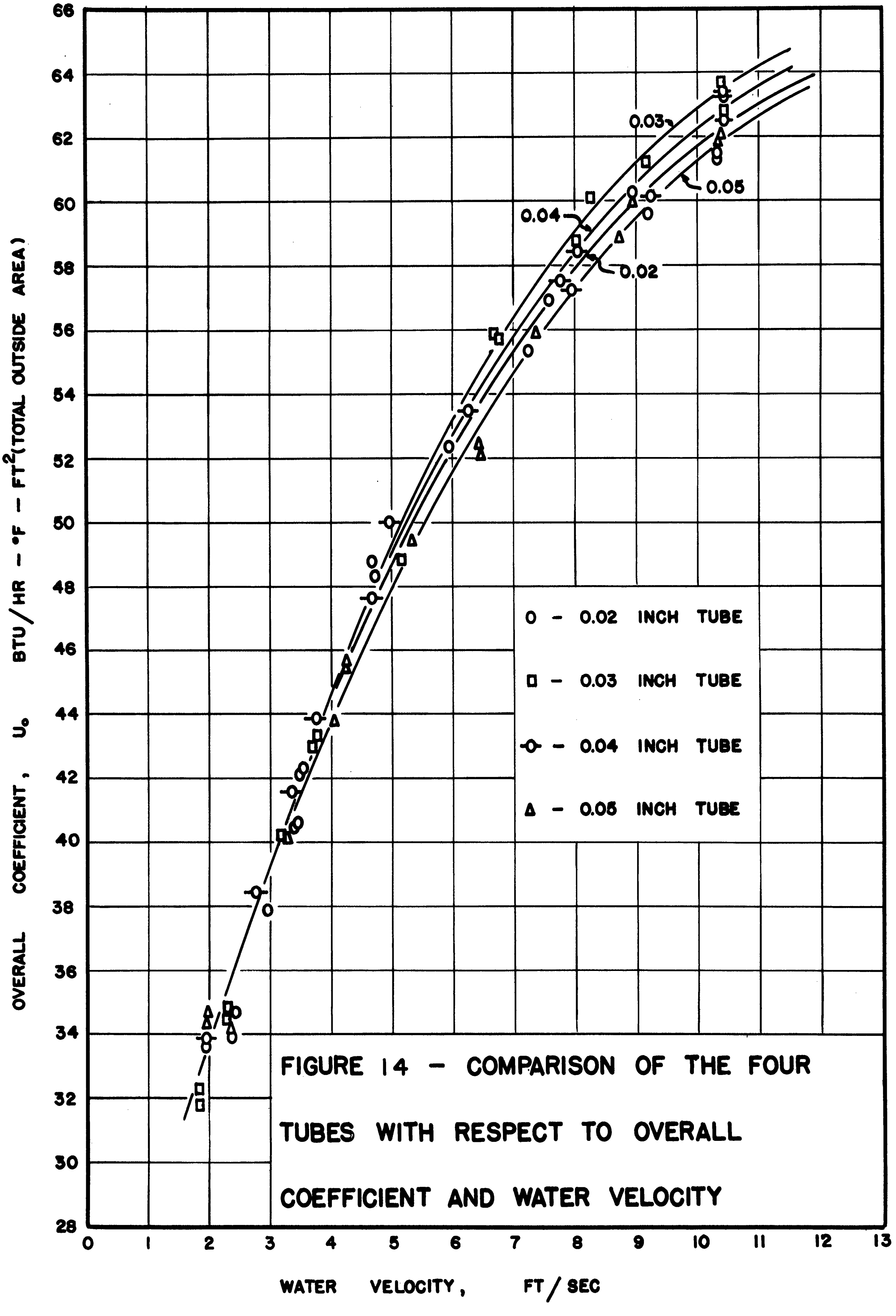


FIGURE 14 – COMPARISON OF THE FOUR TUBES WITH RESPECT TO OVERALL COEFFICIENT AND WATER VELOCITY

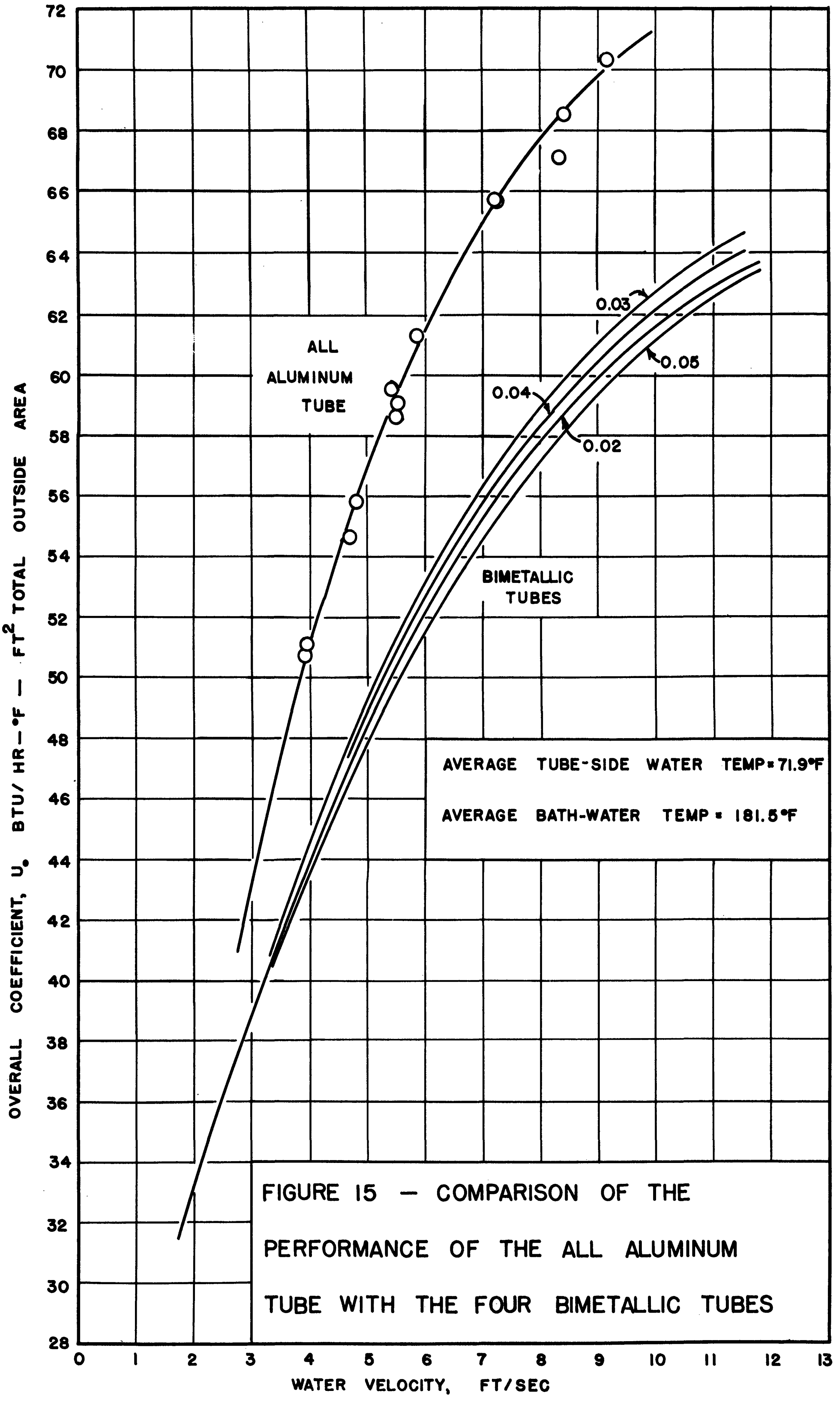


FIGURE 15 — COMPARISON OF THE PERFORMANCE OF THE ALL ALUMINUM TUBE WITH THE FOUR BIMETALLIC TUBES

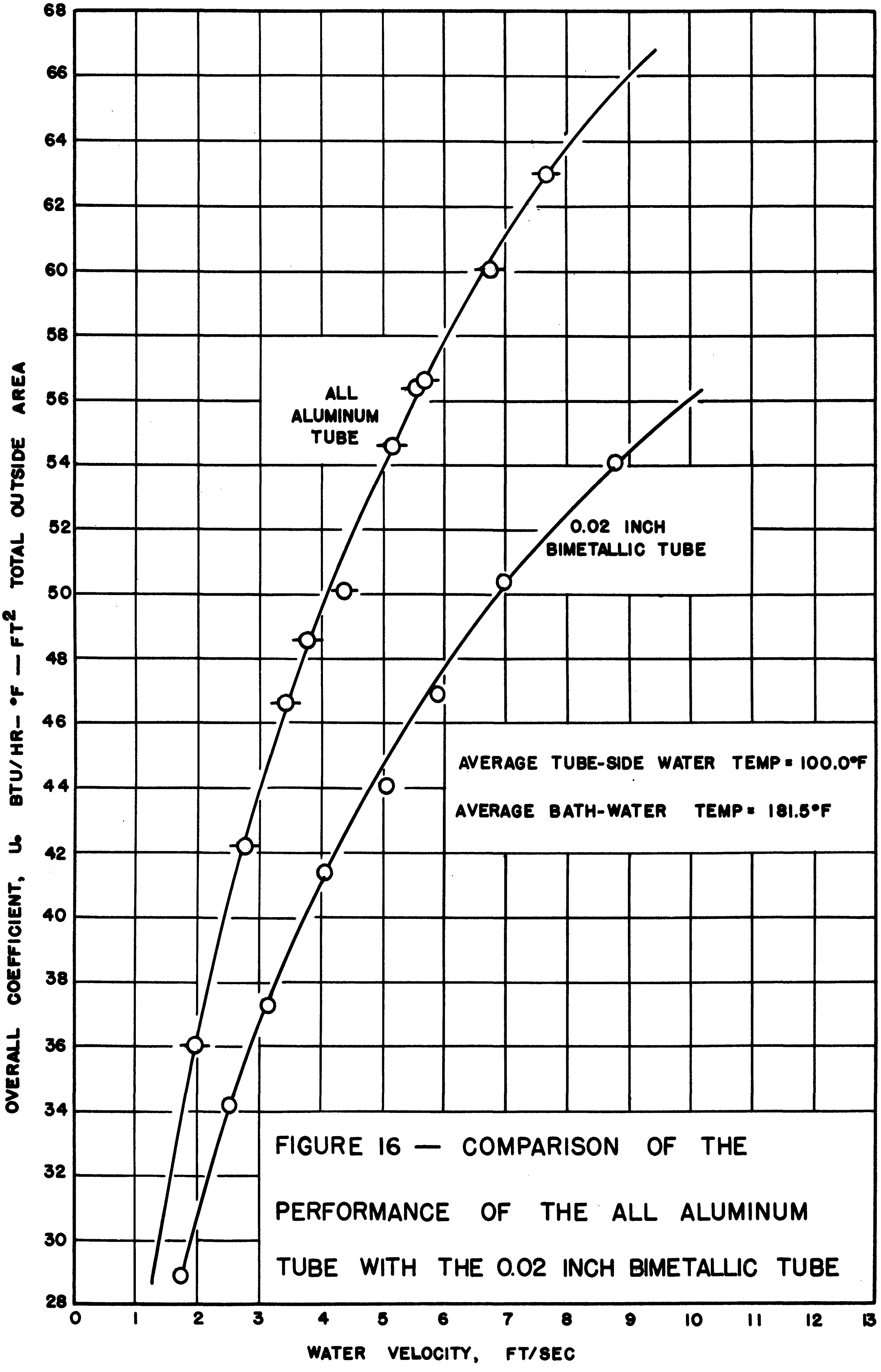


FIGURE 16 — COMPARISON OF THE PERFORMANCE OF THE ALL ALUMINUM TUBE WITH THE 0.02 INCH BIMETALLIC TUBE

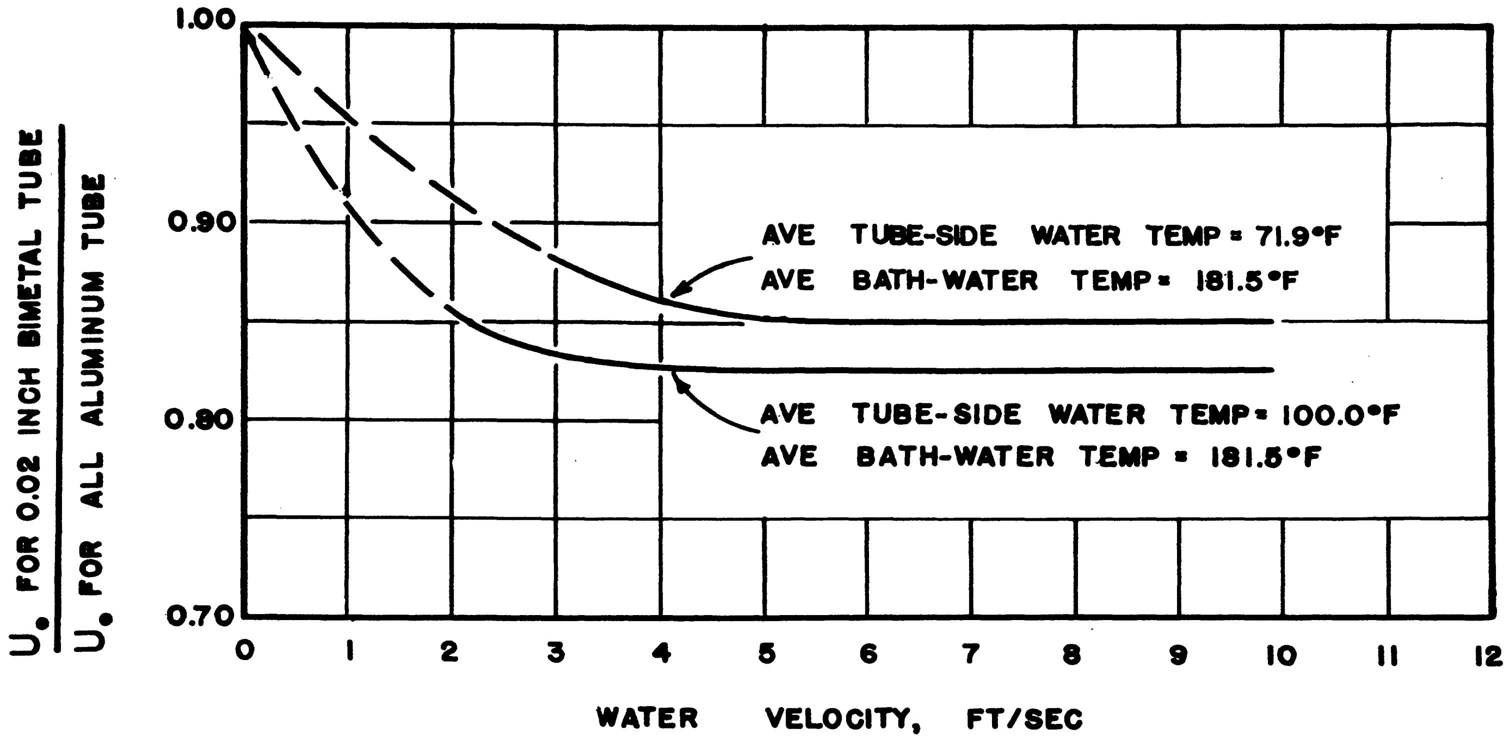


FIGURE 17 — RELATIVE PERFORMANCE OF THE 0.02 INCH TUBE AT TUBE-SIDE WATER TEMPERATURES OF 71.9°F AND 100.0°F

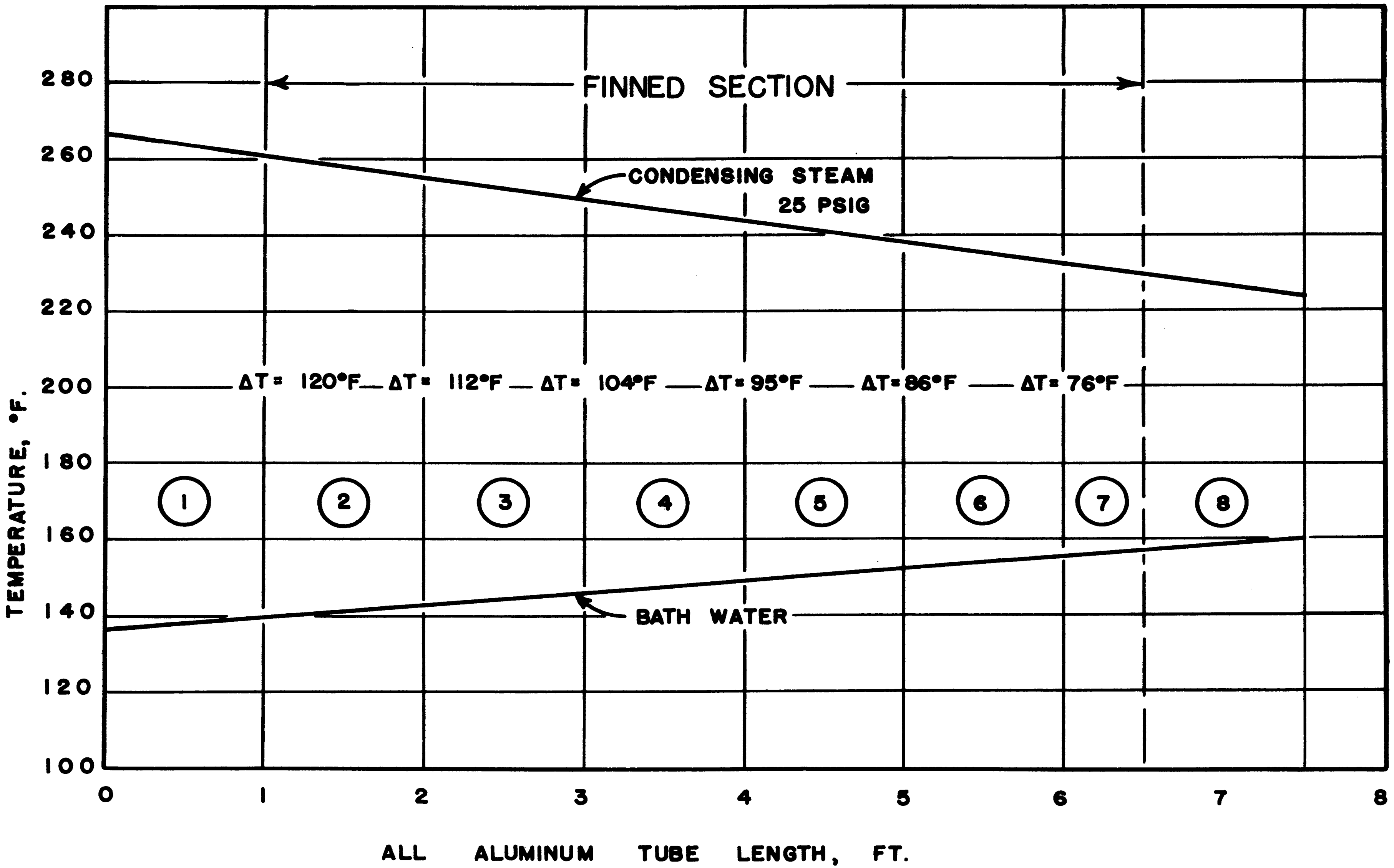


FIGURE 18 — TEMPERATURE GRADIENTS FOR CONDENSING STEAM TESTS

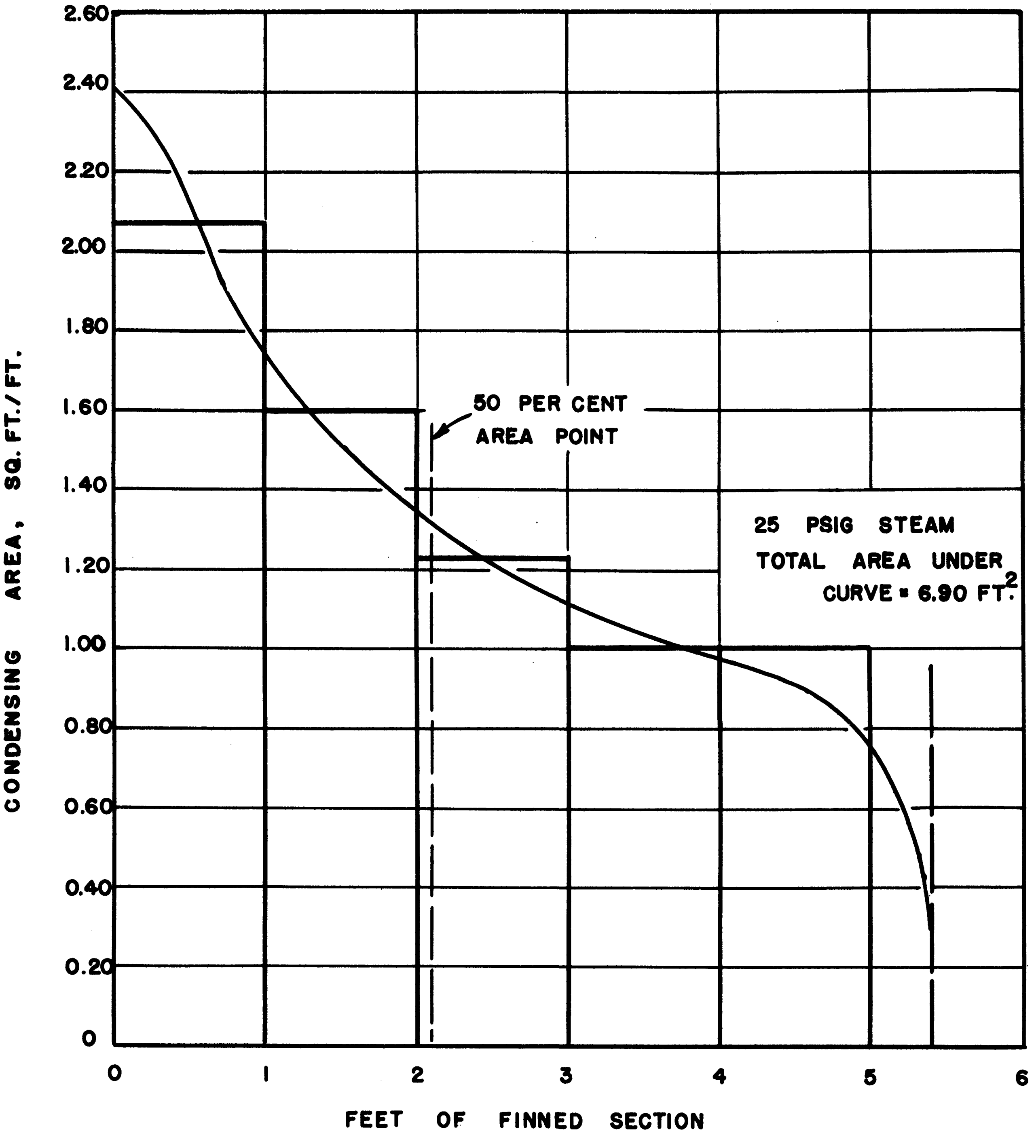


FIGURE 19 — VARIATION OF CONDENSING AREA WITH TUBE LENGTH AS A RESULT OF CONDENSATE BUILDUP

NOMENCLATURE

A	Total outside tube area in heat exchanger, ft^2
A_i	Inside tube area, ft^2/ft of tube length
A_m	Arithmetic mean metal area between D_i and D_o for copper liner, ft^2/ft
A_{me}	Average tube-metal area between D_i and D_e, ft^2/ft
A_o	Outside tube-surface area, ft^2/ft of tube length
A_o/A_i	Ratio of outside to inside surface areas
C_p	Specific heat of fluid, Btu/(lb)(°F)
D_e	A diameter for finned tube equal to the diameter of a hypothetical plain tube with the same volumetric displacement (or with the same plane projection) as the finned tube, ft
d_e	A diameter for finned tubes equal to the diameter of a hypothetical plain tube with the same volumetric displacement (or with the same plane projection) as the finned tubes, in. $d_e = d_r + y(d_o - d_r)N$
D_i	Inside tube diameter, ft
d_i	Inside tube diameter, in.
D_o	Diameter over the fins, ft
d_o	Diameter over the fins, in.
D_r	Finned-tube root diameter, ft
d_r	Finned-tube root diameter, in.
ΔH	Change in enthalpy, Btu/lb
h_i	Inside film coefficient, Btu/(hr)(°F)(ft^2)
h_o	Outside film coefficient corrected to base of fin, Btu/(hr)(°F)(ft^2)
k_m	Thermal conductivity of tube wall, (Btu)(ft)/(hr)(°F)(ft^2)
N	Number of fins per inch
Q	Total heat load, Btu/hr
R_b	Bond resistance, (hr)(°F)(ft^2)/Btu
r_m	Tube metal resistance, (hr)(°F)(ft^2)/Btu
ΔT	Overall temperature difference, °F
Δt	Temperature difference between outlet and inlet fluid on tube side, $(t_2 - t_1)$, °F
T_{av}	Average bulk shell-side temperature, °F
t_w	Average water temperature in tubes, °F
U_o	Overall coefficient of heat transfer, Btu/(hr)(°F)(ft^2)outside surface
W	Total flow through tube side, lb/hr
X_e	Equivalent finned-tube wall thickness, ft, based on equivalent tube diameter D_e, ft
x_e	Equivalent finned-tube wall thickness, in., based on equivalent tube diameter, d_e, in.
y	Mean fin thickness, in.