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OVERALL HEAT TRANSFER COEFFICIENTS FOR STANDARD CONDENSER TUBES. EXPLANATION OF EXPERIMENTAL PROCEDURE, EVALUATION OF DATA AND PRESENTATION OF RESULTS

By

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This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

15 March 1950

Darrel E. Mack
Professor in Charge

H A Neville
Head of Department of
Chemical Engineering

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Clarence F. Mazurkiewicz
Clarence F. Mazurkiewicz
Lieut. Comdr. U. S. Navy

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Appendix:

SUMMARY

This paper presents overall heat transfer coefficients for the following standard condenser tubes:

Admiralty: 1 in., 7/8 in., 3/4 in., 5/8 in., 1/2 in. and 3/8 in., OD, 18 BWG. 7/8 in., OD, 16 BWG.

Muntz: 7/8 in., OD, 18 BWG.

Arsenical Copper: 7/8 in., OD, 18 BWG.

Aluminum Brass: 7/8 in., OD, 18 BWG.

Aluminum Bronze: 7/8 in., OD, 18 BWG.

Copper-Nickel: 7/8 in., and 5/8 in., OD, 18 BWG.

The limits of the tests on these tubes are as follows:

Steam temperature: 100°F.

Inlet water temperature: 80°F.

Water velocity: 2 to 10 feet per second.

Active tube length: 61.56 inches.

Graphs showing the variation of overall heat transfer coefficients with change in water velocity are presented. The effect of diameter, wall thickness and conductivity is noted.

Relative correction factors for the Admiralty tubes are presented as an explanation for the variations between the experimental values and the values calculated by the general equations. Differences in steam-film coefficients among the various metals, calculated from experimental values of the overall heat transfer coefficients of these tubes are also presented. These relative correction factors for the Admiralty series and the calculated steam-film coefficient for 7/8 in., OD, 18 BWG Copper-Nickel tube are used to predict overall coefficients for 5/8 in., and 1/2 in., OD, 18 BWG Copper-Nickel tubes to within a deviation of four percent from actual experimental values.

Details are given of the apparatus.

OBJECT

The object of this thesis is the determination of "pure" heat transfer coefficients from the "raw" data compiled for the Heat Exchange Institute at Lehigh University from February 1946 to August 1947 and the evaluation of this data to determine if it is in agreement with theoretical considerations based on the generally accepted concept that the overall resistance to the flow of heat from one fluid to another is equal to the sum of the resistances of the two fluid films and the resistance of the tube wall.

PROCEDURE

The data contained in this paper was compiled for the Heat Exchange Institute at Lehigh University from February 1946 to August 1947. A total of 419 runs were accumulated in which the effect of steam temperature and inlet water temperature were studied.

A data survey was made to determine which of these runs presented useful information. Criteria were set up by which all but 167 runs were eliminated. The criteria and a summary of the runs is as follows:

Criteria:	Steam temperature 100°F.	
	Inlet water temperature 80°F.	
	At equilibrium, water rate constant and no excessive variations in steam or inlet water temperature during a run.	
Summary of runs:	Steam other than 100°F. and/or inlet water other than 80°F.	124
	Not at equilibrium, water rate etc.	63
	Unknown metal tube.	65
	Total excluded	252

Of the remaining runs, 117 were used in this report as they presented a useful range of data on the effect of tube diameter and conductivity.

The exclusion of runs at steam temperatures other than 100°F. and/or 80°F. was made as not enough data was compiled for any given condition.

Steam temperatures recorded in the original data were measured both by a platinum resistance and a mercury thermometer. Variations of the order of a degree were found between these readings. Investigation found that the platinum resistance thermometer deteriorated during the period of operation. In cases of disagreement in readings, the mercury thermometer was favored in calculations used in this report.

DESCRIPTION OF EQUIPMENT

A schematic diagram of the equipment is shown in Figure 1, and an end view of the calorimeter in Figure 2. The equipment is most easily described by considering the two separate recycling systems--steam and circulating water.

Steam System

Steam generated under vacuum in the evaporator passes through the calorimeter around the condenser tube. The steam condensate which forms and drips from the tube is collected and returned to the evaporator. That portion of the steam not condensed is also returned to the evaporator. The vacuum pump removes any non-condensables from the vapors in the condenser and maintains the system at a pressure considerably below atmospheric (about 28 inches of mercury vacuum). Control of the vacuum, and consequently, of steam temperature, is obtained by regulating the rate of cooling water flow through the condenser.

Circulating Water System

Circulating water flows from a constant head tank through the condenser tube in the calorimeter to a multiple-orifice tank flowmeter. Details of construction of the multiple-orifice tank flowmeter are shown in Figure 3. A valve adjacent to this flowmeter serves for adjusting the flow rate and holding it constant during a run.

Circulating water leaving the multiple-orifice tank flowmeter falls into a weigh tank, used for calibration, and then passes through the circulating water cooler to the supply tank.

Regulating the rate of cooling water flow to this cooler controls the temperature of the circulating water at the inlet to the condenser tube in the calorimeter.

The circulating pump takes suction from the supply tank and returns the water to the constant head tank. The overflow from the constant head tank may be cooled in the overflow cooler before returning to the supply tank. In order to obtain higher velocities through the condenser tube the constant head tank is by-passed, and circulating water enters the tube directly at pump pressure.

SCHEMATIC DIAGRAM OF EQUIPMENT

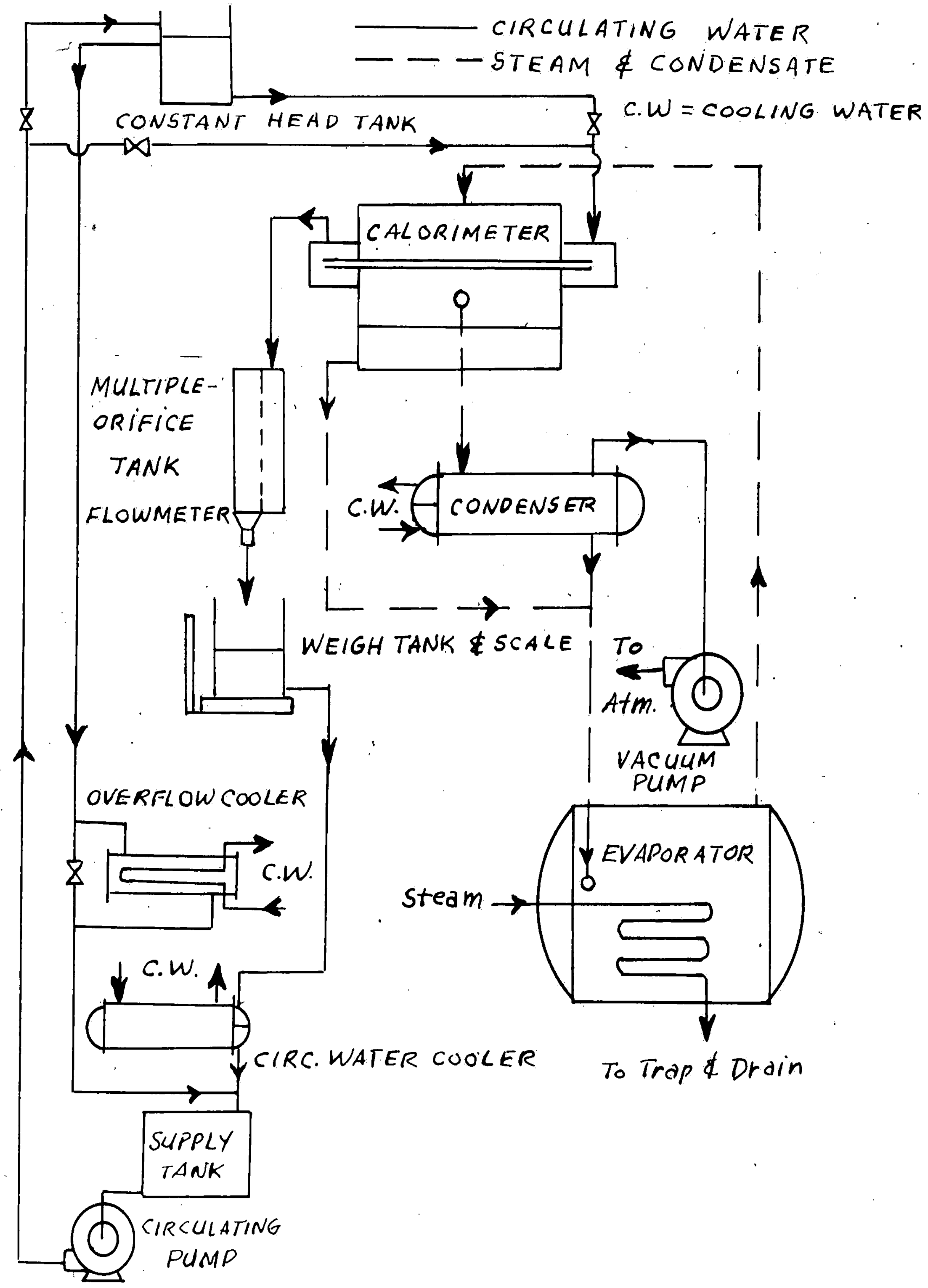


FIG. 1

DETAILS OF THE EQUIPMENT

Calorimeter

The calorimeter is a steel chamber (14" x 36" x 64") with internal baffles so arranged that the entire volume of steam passing through the system flows across the condenser tube under test.

A single condenser tube about two feet longer than the calorimeter is inserted horizontally. The extra length of tube extends into the two end fittings where a baffle arrangement causes the water entering and leaving to pass over the exterior surface of the tube ends. This prevents any radiation effects upon the tube ends and limits the heat transfer surface of the tube to the interior length of the calorimeter.

Multiple-Orifice Tank Flowmeter

The flowmeter is a sheet aluminum tank (8" x 12" x 42") and sight glass, with a series of 3/8 inch diameter orifices in the vertical dividing wall. The maximum capacity of the flowmeter is 25 gallons per minute.

Actual calibration data, obtained using the weight tank and scale for timed runs and plotted as gauge reading (H cm.) against circulating water flow (w lb./hr.), produced a family of intersecting curves, particularly for the high flow rates; the points of intersection coincided with the position of the orifices.

Evaporator

The evaporator is of the submerged coil type operated from the laboratory steam line. The water level remains constant during a series of runs (one-half full) since all condensate is returned to the evaporator.

A reducing and regulating valve assembly supplies steam for heating the coil at eight pounds per square inch reduced from 120-160 pounds per square inch. This establishes approximately constant steam velocities across the condenser tube for all runs.

Vacuum Pump

Two Nash "Hytor" vacuum pumps, size TS-7, Test Nos. H-1641 and H-1642, in series.

Circulating Pump

Ingersoll-Rand "Motorpump", Model B, Serial No. 0241714, 20 gallons per minute at a head of 50 feet.

MULTIPLE-ORIFICE TANK FLOWMETER

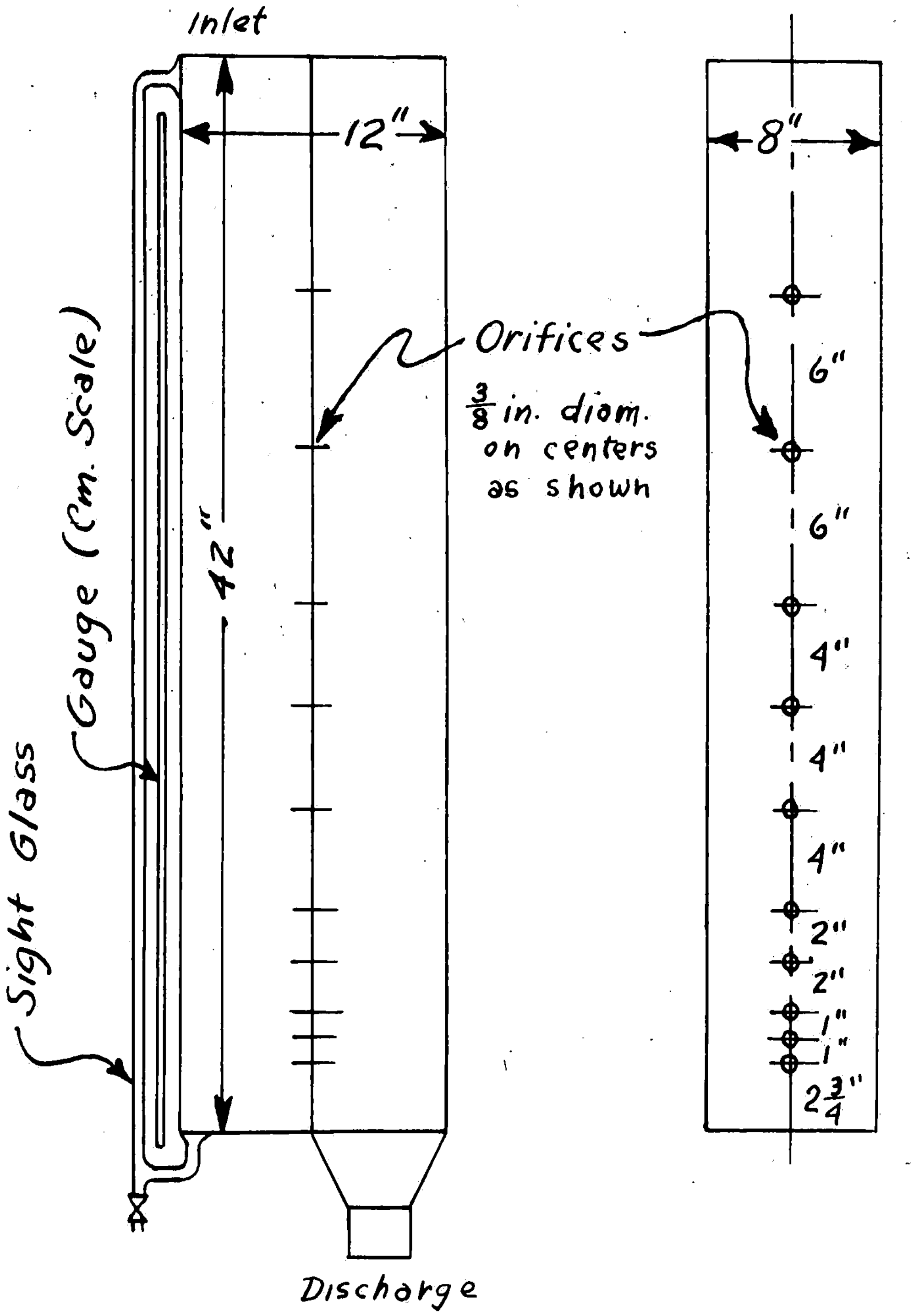


FIG. 3

THEORETICAL CONSIDERATIONS

It has been generally accepted that the overall resistance to the flow of heat from one fluid to another is equal to the sum of the resistance of the two fluid films, the resistance of the tube wall, and the resistance of any dirt, scale or other films that may intervene. In the case of new condensor tubes this latter resistance may be neglected.

If (U_o) represents the overall heat transfer coefficient based on the outside area, then the resistance to heat flow can be expressed as the sum of the resistances:

$$\frac{1}{U_o} = \frac{1}{h_s} + \frac{LD_o}{kD_a} + \frac{D_o}{D_i h_w} \quad \ldots\ldots\ldots\ldots \quad (1)$$

The resistance of the tube wall, LD_o/kD_a, as defined by Fourier's Law and equation 1, is calculated from the wall thickness, average and outside diameters, and the thermal conductivity of the tube.

The resistance of the water film, $D_o/h_w D_i$, is calculated from tube dimensions and the Dittus-Boelter equation:

$$h_w = 0.0225 \frac{k}{D_i} \left(\frac{D_i V \rho}{\mu}\right)^{0.8} \left(\frac{c\mu}{k}\right)^{0.4} \quad \ldots\ldots \quad (2)$$

where the properties of k, ρ, μ and c are evaluated at the mean of inlet and outlet temperatures.

The resistance of the steam condensate film for a single horizontal tube is calculated by the equation of Nusselt:

$$H = 0.725 \left(\frac{k^3 \rho^2 g \lambda}{D_o \mu \Delta t} \right)^{1/4} \quad \ldots\ldots\ldots\ldots \quad (3)$$

in which the properties k, ρ, μ and λ are evaluated at the average temperature of the condensate film.

SAMPLE CALCULATION

The equation, $q = UA\Delta tm$, was used to calculate U_o, the overall heat transfer coefficient based on the outside tube area. The heat transfer rate q, was calculated from the temperature rise and flow rate of process water through the condenser tube, A was measured, and Δtm was the log mean temperature difference between the steam and the water.

The data taken for a single typical run is shown below:

Run Number 33

Time	t_s	t_1	t_2	H
0	99.0	80.5	84.0	41.2
5	99.5	80.0	84.0	41.2
10	99.5	80.0	84.0	41.2
15	99.5	80.0	84.0	41.2
20	100.0	80.0	84.0	41.2

As three consecutive readings were identical these were used in the determination. In cases where three consecutive readings were not identical, only those which showed a constant temperature difference between t_1 and t_2 were considered and then the arithmetical average was taken. Slight steam variations were also averaged.

Water Flow Rate (W)

The water rate over the range H = 25 - 50 cm. was calculated from the linear relationship $W = 144 (H) - 941.6$ derived by previous investigators. Measured water rates were used below H = 25 cm.

Example:

$H = 41.2$ cm. $W = 4990$ lb./hr.

From the tube dimension the 4990 pounds per hour was converted to $V = 4.99$ feet per second.

Total Heat Transfer Rate (q)

The total heat transferred from the tube to the circulating water was calculated from the value of (W) found above, the difference between the heated water and inlet water temperature, and the specific heat of the water, which was taken as 1.0 BTU per pound - °F. in this example, by means of the equation:

$$q = w(t_2 - t_1)c$$

$$q = 4990(84.0 - 80.0)(1.0) = 19960 \text{ BTU/hr.}$$

Outside Tube Area (A)

Run number 33 was made on a 1 in., 18 BWG tube, 61.56 in., effective tube length.

$$A = (3.1416)(1)(61.56)/144 = 1.353 \text{ sq. ft.}$$

Log Mean Temperature Difference (Δt_m)

The log mean temperature difference was used:

$$\Delta t_m = \frac{t_2 - t_1}{\ln \frac{t_s - t_1}{t_s - t_2}} = \frac{4.0}{\ln \frac{19.5}{15.6}} = 17.35^\circ\text{F.}$$

Overall Heat Transfer Coefficient (U_o)

$$U_o = q/A\,\Delta t_m = \frac{19960}{1.343 \times 17.35}$$

$$= 855 \text{ BTU/hr.-sq. ft.-}^\circ\text{F.}$$

TABLES OF DATA

Table I
Tube Size: 1 in. OD, 18 BWG Admiralty

Run	ts	t1	t2	W	q	△tm	V	U
29	99.5	80.3	85.0	3003	14110	16.70	3.0	628
32	99.5	79.9	84.3	3969	17450	17.25	3.97	753
33	99.5	80.0	84.0	4990	19960	17.35	4.99	855
31	100.5	80.1	84.2	5985	24520	18.35	5.99	994
39	100.0	79.83	83.5	6978	25600	18.38	7.0	1035
28	100.0	79.6	83.1	8000	28000	18.60	8.0	1120

Table II
Tube Size: 7/8 in. OD, 18 BWG Admiralty

Run	ts	t1	t2	W	q	△tm	V	U
100	100.2	80.6	87.0	1478	9450	16.20	2.0	496
106	100.2	80.0	86.0	2226	13356	17.05	3.01	666
102	100.0	80.0	84.9	3695	18105	17.40	5.0	885
104	100.0	79.5	83.9	5193	22850	18.10	7.01	1072
101	100.0	80.0	84.0	5927	23708	17.92	8.0	1125

Table III
Tube Size: 7/8 in. OD, 16 BWG Admiralty

Run	ts	t1	t2	W	q	△tm	V	U
272	99.8	80.6	85.9	1935	10250	16.4	2.85	533
269	101.6	80.1	86.3	1965	12190	18.23	2.89	567
268	101.0	79.8	85.3	2642	14550	18.3	3.9	676
267	100.9	79.8	84.9	3420	17450	18.4	5.04	806
266	100.95	79.7	84.5	4160	19950	18.75	6.13	906
265	101.0	80.1	84.6	4825	21700	18.7	7.1	988
263	100.9	80.0	84.2	5510	23160	18.7	8.15	1055
262	101.1	79.9	83.9	6240	24940	19.2	9.18	1105
261	101.15	79.8	83.6	7080	26900	19.45	10.40	1178
260	101.1	79.8	83.3	7740	27100	19.30	11.40	1195

Table IV
Tube Size: 3/4 in. OD, 18 BWG Admiralty

Run	ts	t1	t2	W	q	△tm	V	U
365	101.3	79.8	87.8	1237	9896	17.20	2.37	570
367	101.0	80.3	87.5	1603	11550	16.90	3.08	679
370	100.9	80.0	86.7	1910	12800	17.34	3.66	731
372	101.0	80.3	86.5	2298	14245	17.35	4.41	815
374	101.0	80.3	86.1	2658	15400	17.60	5.1	870
377	100.5	80.07	85.63	3018	16780	17.40	5.8	959
369	101.0	80.3	85.6	3393	18000	17.90	6.51	998
378	100.5	80.5	85.6	3738	19090	17.30	7.17	1097
375	100.9	80.1	85.1	4098	20460	18.25	7.87	1115
376	100.5	79.8	84.7	4458	21850	18.10	8.56	1200
373	100.8	80.0	84.7	4847	22750	18.40	9.3	1230
371	100.8	80.1	84.6	5197	23400	18.30	9.96	1269

Table V
Tube Size: 5/8 in. OD, 18 BWG Admiralty

Run	ts	tl	t2	W	q	Δtm	V	U
94	99.27	79.5	88.0	697	5930	15.05	2.05	468
222*	100.6	80.1	88.4	925	7680	16.0	2.72	570
95	100.0	80.0	88.1	1100	8920	15.6	3.23	680
98	99.9	80.2	87.8	1465	11120	15.6	4.3	850
97	100.0	79.8	87.0	1830	13320	16.3	5.37	974
96	100.0	80.0	86.6	2230	14700	16.5	6.55	1040
213*	100.1	80.0	86.0	2700	15950	16.8	7.92	1130
220*	100.5	79.8	85.8	2745	16450	17.45	8.05	1125
219*	100.5	80.1	85.1	3724	18650	17.75	10.91	1250

* Indicates Tube No. 2

Table VI
Tube Size: 1/2 in. OD, 18 BWG Admiralty

Run	ts	tl	t2	W	q	Δtm	V	U
427A	100.5	80.4	89.9	740	7030	14.85	3.93	705
426	100.5	79.95	88.0	1120	9010	16.15	5.55	830
428	100.7	80.1	87.9	1420	11090	16.40	7.16	1005
424	100.5	80.0	87.0	1730	12100	16.70	8.85	1080
423	100.5	80.1	86.5	2040	13060	17.00	10.3	1142
422	100.0	80.0	85.9	2420	14290	16.85	12.2	1260

Table VII
Tube Size: 3/8 in. OD, 18 BWG Admiralty

Run	ts	tl	t2	W	q	Δtm	V	U
429	101.0	80.0	93.4	225	3020	13.20	2.40	452
436	101.0	80.1	92.8	270	3430	13.55	2.87	501
430	101.0	80.1	92.6	332	4150	13.70	3.52	600
435	101.0	80.0	91.9	403	4800	14.20	4.28	669
431	101.0	79.8	91.1	514	5800	14.80	5.45	776
434	101.0	79.9	90.8	600	6540	15.05	6.33	860
432	101.0	79.9	90.7	687	7420	15.15	7.31	970
433	101.0	80.0	90.0	780	7800	15.50	8.30	995

Table VIII
Tube Size: 7/8 in. OD, BWG Arsenical Copper

Run	ts	tl	t2	W	q	Δtm	V	U
166	100.5	80.2	86.2	1467	8800	17.10	1.99	436
165	100.8	80.0	85.7	2284	13050	17.75	3.08	625
163	101.2	80.0	85.2	3047	15860	18.55	4.11	728
162	100.9	80.0	84.9	3695	18100	18.42	5.0	835
154	100.0	80.1	85.0	3695	18100	17.28	5.0	891
159	100.4	80.6	84.96	4430	19300	17.55	5.99	936
155	99.9	80.1	84.53	4440	19650	17.40	6.0	961
161	100.67	80.0	84.82	4451	21400	18.24	6.01	1002
157	100.9	80.0	84.5	5178	23300	18.5	7.0	1070
158	100.85	79.95	84.0	3927	24000	18.85	8.01	1085

Table IX
Tube Size: 7/8 in. OD, 18 BWG Muntz

Run	ts	t1	t2	W	q	Δtm	V	U
116	99.9	79.8	86.0	1478	9150	16.85	2.0	462
111	100.0	79.6	85.1	2226	12400	17.5	3.01	595
114	99.8	80.4	85.2	2961	14200	16.85	4.05	718
115	99.8	79.0	83.83	3695	17850	18.15	5.0	837
118	99.7	79.6	83.9	4430	19050	18.0	5.98	902
113	100.0	79.58	83.98	4440	19550	18.1	6.0	919
112	100.0	80.25	84.4	5178	21500	17.65	7.0	1033
110	100.0	79.95	84.12	5178	21600	17.62	7.0	1041
117	100.0	80.0	83.8	5913	22500	18.0	8.0	1065

Table X
Tube Size: 7/8 in. OD, 18 BWG Aluminum-Brass

Run	ts	t1	t2	W	q	Δtm	V	U
198	100.0	80.08	86.25	1434	8860	16.65	1.94	452
199	100.53	80.0	86.4	1478	9300	17.15	2.0	468
193	100.8	80.4	86.7	1550	9760	17.0	2.09	488
188	100.5	80.0	85.1	2961	15050	17.9	4.05	718
187	100.9	80.1	85.0	3702	18100	18.2	5.01	848
192	100.0	80.0	84.8	3810	18300	17.5	5.15	890
186	100.9	79.8	84.4	4451	20500	18.62	6.01	937
190	101.0	80.0	84.0	5855	23400	18.95	7.91	1051
184	101.23	80.0	84.0	5936	23700	19.25	8.02	1050
197	101.0	80.0	84.0	6546	26180	18.95	8.84	1177
195	101.5	80.0	83.52	7886	27700	19.65	10.65	1200

Table XI
Tube Size: 7/8 in. OD, 18 BWG Aluminum-Bronze

Run	ts	t1	t2	W	q	Δtm	V	U
211	100.8	79.8	86.5	1477	9890	17.45	2.0	482
208	100.7	80.1	86.6	1492	9700	17.20	2.01	480
207	100.6	80.0	85.3	2255	11980	17.85	3.05	570
204	100.4	80.0	84.9	2961	14500	17.80	4.05	694
203	100.8	80.0	84.6	3695	17000	18.45	5.0	784
210	100.6	80.0	84.6	3695	17000	18.25	5.0	792
202	100.8	80.0	84.2	4430	18600	18.70	5.98	847
201	100.75	80.0	84.2	5121	21500	18.47	6.92	990
209	100.8	80.0	84.0	5884	23550	18.80	7.95	1065
200	100.8	80.0	84.0	5884	23550	18.80	7.95	1065

Table XII
Tube Size: 7/8 in. OD, 18 BWG Copper-Nickel

Run	ts	t1	t2	W	q	Δtm	V	U
138	100.3	80.0	86.0	1478	8850	17.1	2.0	441
147	100.1	80.0	84.9	2226	10900	17.5	3.01	530
122	101.0	79.7	85.4	2226	12700	18.3	3.01	589
131	100.0	80.6	85.5	2586	12680	16.81	3.5	640
125	100.0	80.6	85.0	2961	13050	17.25	4.05	642
128	100.1	80.0	84.1	3695	15150	18.0	5.0	716
148	100.1	80.0	84.0	3724	14900	18.0	5.05	705
139	99.57	80.4	84.0	4444	15960	17.25	6.0	780
126	100.2	80.05	83.98	4444	17450	18.25	6.0	814
132	100.1	80.0	83.7	4818	17820	18.20	6.52	834
133	99.9	80.0	83.3	5337	17600	18.10	7.2	827
121	100.2	80.1	83.3	5927	18920	18.40	8.01	878

Table XIII
Tube Size: 5/8 in. OD, 18 BWG Copper-Nickel

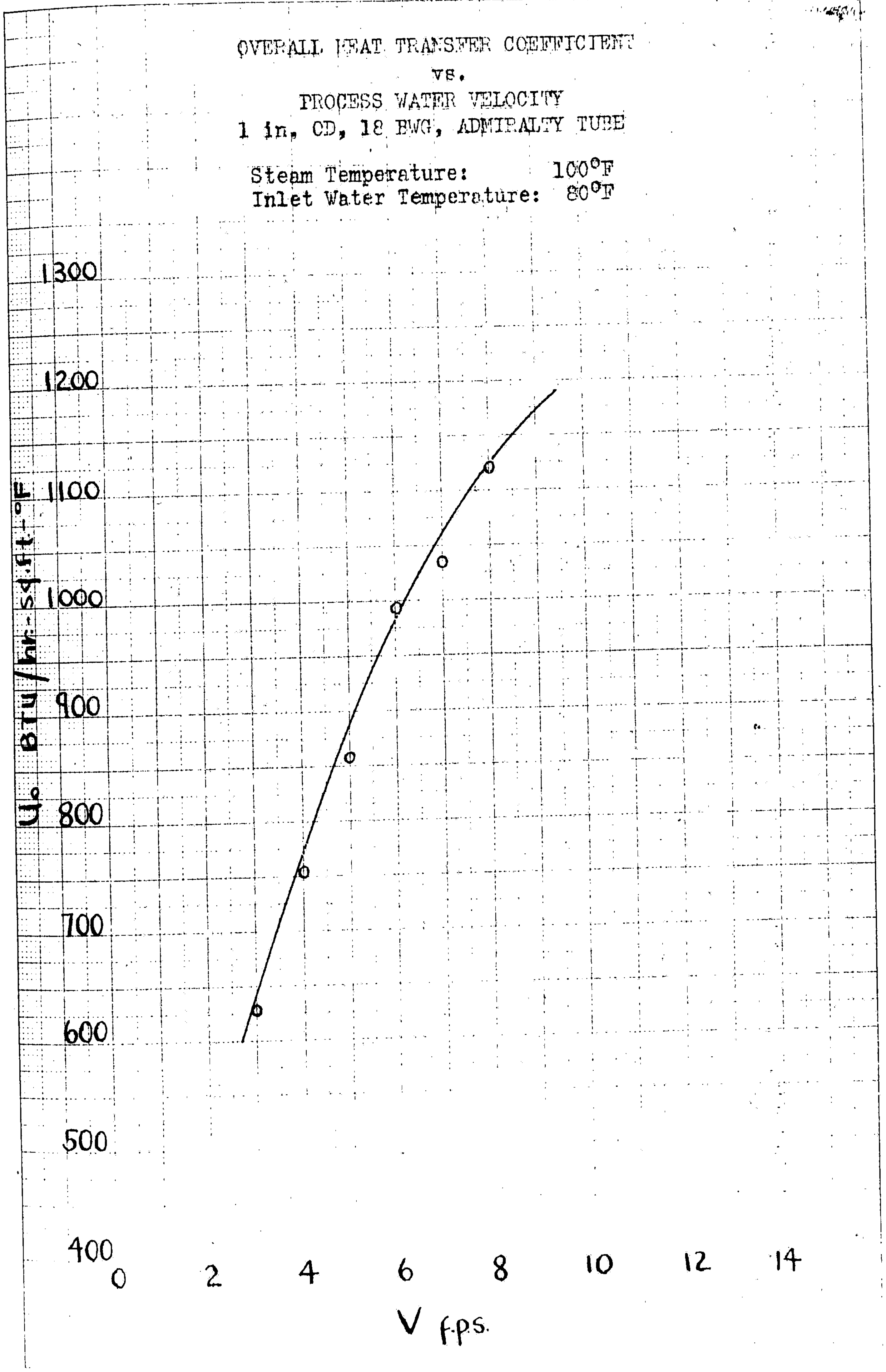
Run	ts	tl	t2	W	q	△tm	V	U
239	100.6	80.2	87.7	930	6970	16.38	2.73	506
235	100.0	80.0	86.7	1370	9200	17.42	4.03	627
232	101.0	80.3	85.8	2140	11770	17.9	6.27	783
231	100.4	80.0	84.9	2615	12810	17.85	7.68	854
230	100.7	80.1	84.8	2946	13850	18.17	8.65	907
240	100.6	80.1	84.7	3040	14000	18.05	8.93	922
229	100.2	80.2	84.2	3718	14850	17.9	10.9	987
225	99.45	79.95	83.42	4446	15500	17.8	13.15	1035
241	100.9	80.0	83.67	4581	16800	19.2	13.46	1040

The following data in Table XIII and Table XIV from M. S. Thesis, "Overall Heat Transfer Coefficients of Copper-Nickel Tubes", by Lt. Cmdr. R. W. Arey USN and Lt. S. J. Robinson USN, Lehigh University, June 1949.

76	99.7	79.75	84.83	2330	11800	17.27	6.8	817
1	99.30	80.18	85.01	2380	11460	16.59	7.0	824
10	100.85	79.91	85.24	2380	12640	18.22	7.0	827
2	99.18	80.49	84.91	2720	12000	16.38	8.0	874
3	99.20	80.48	84.64	3060	12680	12.50	9.0	915
11	100.58	79.91	84.49	3070	14010	18.05	9.05	925
77	100.1	80.01	84.16	3410	14100	17.97	10.0	937
4	100.28	80.64	84.79	3440	14220	17.43	10.1	973
5	100.48	80.97	84.87	3740	14540	17.48	11.0	993
12	100.41	79.89	83.92	3820	15360	18.39	11.2	996
6	100.01	80.46	84.15	4075	14990	17.70	12.0	1010
78	99.7	79.70	83.22	4390	15410	18.23	12.9	1007
7	100.66	80.47	84.00	4415	15540	18.30	13.0	1013
13	100.53	80.09	83.67	4415	15750	18.55	13.0	1013
8	99.91	80.37	83.65	4755	15540	18.00	14.0	1030
9	99.91	80.25	83.39	5095	15940	18.15	15.0	1048
14	100.29	80.04	83.25	5095	16300	18.62	15.0	1042
16	99.14	79.46	82.61	5120	16100	18.10	15.1	1068
17	99.23	79.61	82.62	5420	16250	18.00	16.0	1076
22	100.16	79.81	82.90	5440	16750	18.69	16.0	1069
79	99.9	79.59	82.61	5440	16380	18.85	16.0	1035
23	100.34	80.20	83.09	5800	16700	18.62	17.1	1069
15	100.05	79.42	82.34	5940	17290	19.11	17.5	1078
118	99.89	79.64	82.54	5940	17160	18.68	17.5	1093

Table XIV
Tube Size: 1/2 in. OD, 18 BWG Copper Nickel

Run	ts	t1	t2	W	q	Δtm	V	U
28	99.57	80.02	86.38	1380	8750	16.17	7.0	806
49	100.17	79.75	86.42	1400	9300	16.84	7.1	823
46	100.77	80.12	86.54	1580	9960	16.97	8.0	875
29	100.10	79.97	86.23	1600	10000	16.84	8.1	886
50	99.83	79.91	85.59	1780	10080	16.87	9.0	890
47	100.18	79.96	85.32	1980	10580	17.39	10.0	907
32	100.20	79.67	84.88	2190	11370	17.80	11.1	952
33	100.20	79.65	84.69	2360	11870	17.90	11.9	988
45	100.45	80.24	85.05	2570	12300	17.75	13.0	1032
34	100.61	80.14	84.93	2610	12450	17.90	13.2	1031
35	100.75	80.42	84.90	2720	12370	17.98	14.0	1025
51	99.55	79.96	84.33	2770	12080	17.32	14.0	1038
36	100.62	80.45	84.78	2890	12490	18.04	14.6	1032
52	99.60	79.88	84.07	2960	12370	17.52	15.0	1051
37	99.33	79.89	84.07	2980	12400	17.20	15.1	1074
38	99.97	79.78	83.94	3170	13150	18.07	16.1	1085
39	100.43	79.94	84.01	3360	13640	18.39	17.0	1107
40	99.97	79.99	83.76	3560	13390	18.08	18.0	1103
44	100.56	79.99	83.92	3560	13930	18.58	18.0	1118
41	100.19	79.26	83.08	3750	14200	19.03	19.0	1111
53	99.63	79.88	83.50	3760	13580	18.05	19.0	1120
42	100.18	79.29	83.01	3950	14660	18.78	20.0	1161
43	100.20	79.80	83.33	4150	14570	18.59	21.0	1168



OVERALL HEAT TRANSFER COEFFICIENT
vs.
PROCESS WATER VELOCITY
1 in, OD, 18 BWG, ADMIRALTY TUBE

Steam Temperature: 100°F
Inlet Water Temperature: 80°F

FIG. 4

OVERALL HEAT TRANSFER COEFFICIENT
vs.
PROCESS WATER VELOCITY
7/8 in. OD, 18 BWG, ADMIRALTY TUBE

Steam Temperature: 100°F
Inlet Water Temperature: 80°F

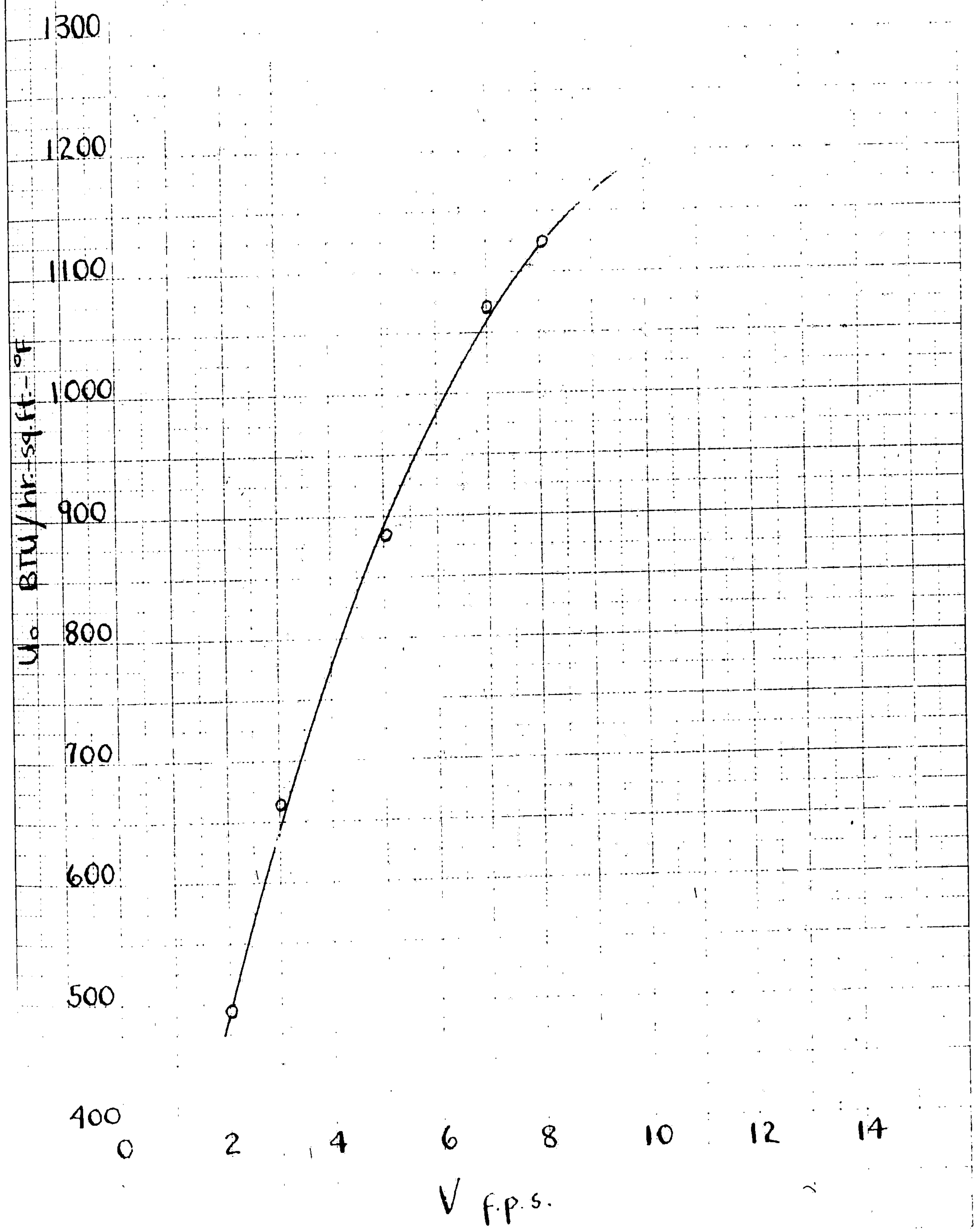
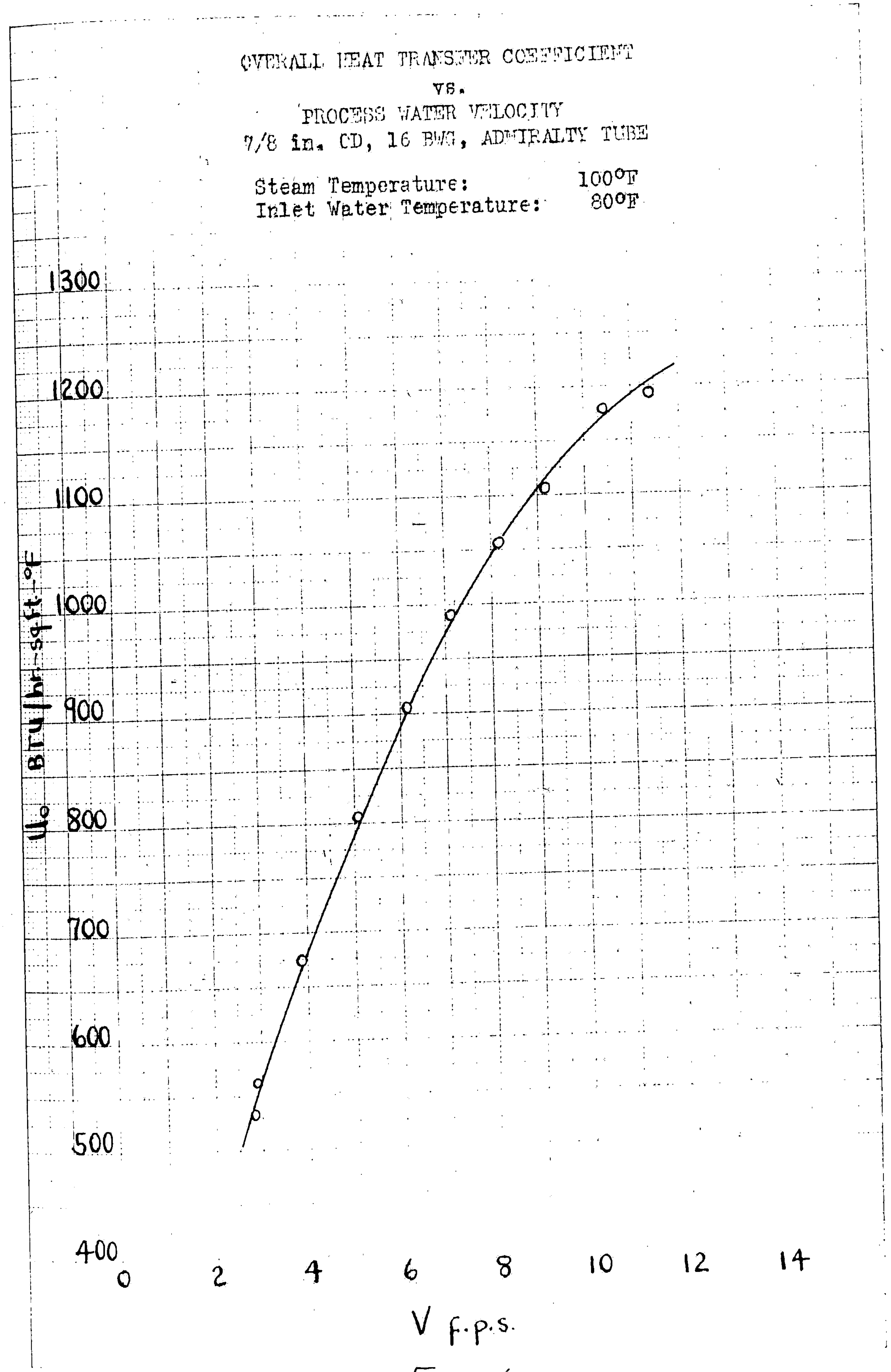


FIG. 5


OVERALL HEAT TRANSFER COEFFICIENT
vs.
PROCESS WATER VELOCITY
7/8 in. OD, 16 BWG, ADMIRALTY TUBE

Steam Temperature: 100°F
Inlet Water Temperature: 80°F

FIG. 6

OVERALL HEAT TRANSFER COEFFICIENT
vs.
AVERAGE WATER VELOCITY
3/4 in. OD, 18 BWG, ADMIRALTY TUBE

Steam Temperature: 100°F
Inlet Water Temperature: 50°F

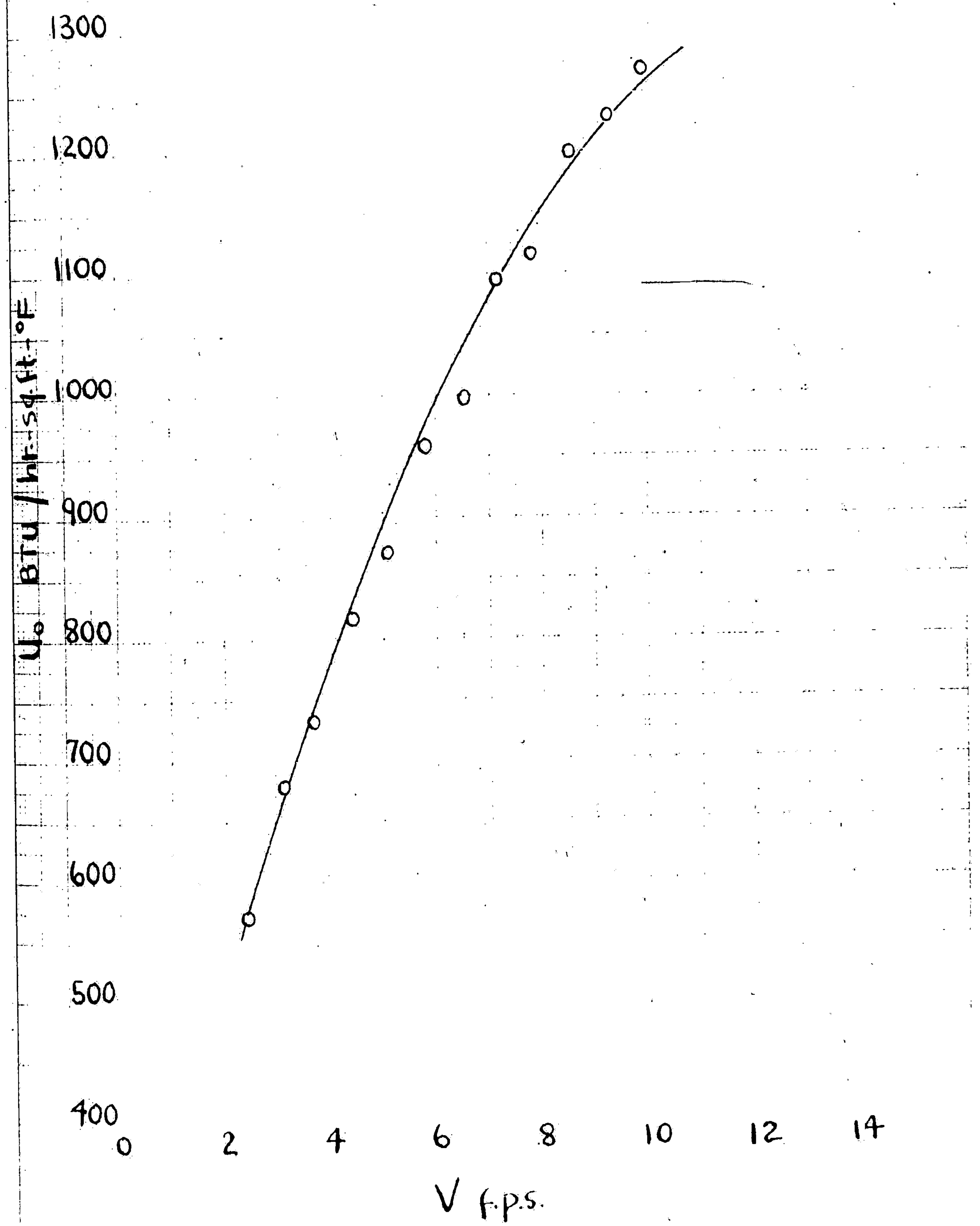


Fig. 7

OVERALL HEAT TRANSFER COEFFICIENT
vs.
COOLING WATER VELOCITY
5/8 In. OD, 18 BWG, ADMIRALTY TUBE

Steam Temperature: 100°F
Inlet Water Temperature: 80°F

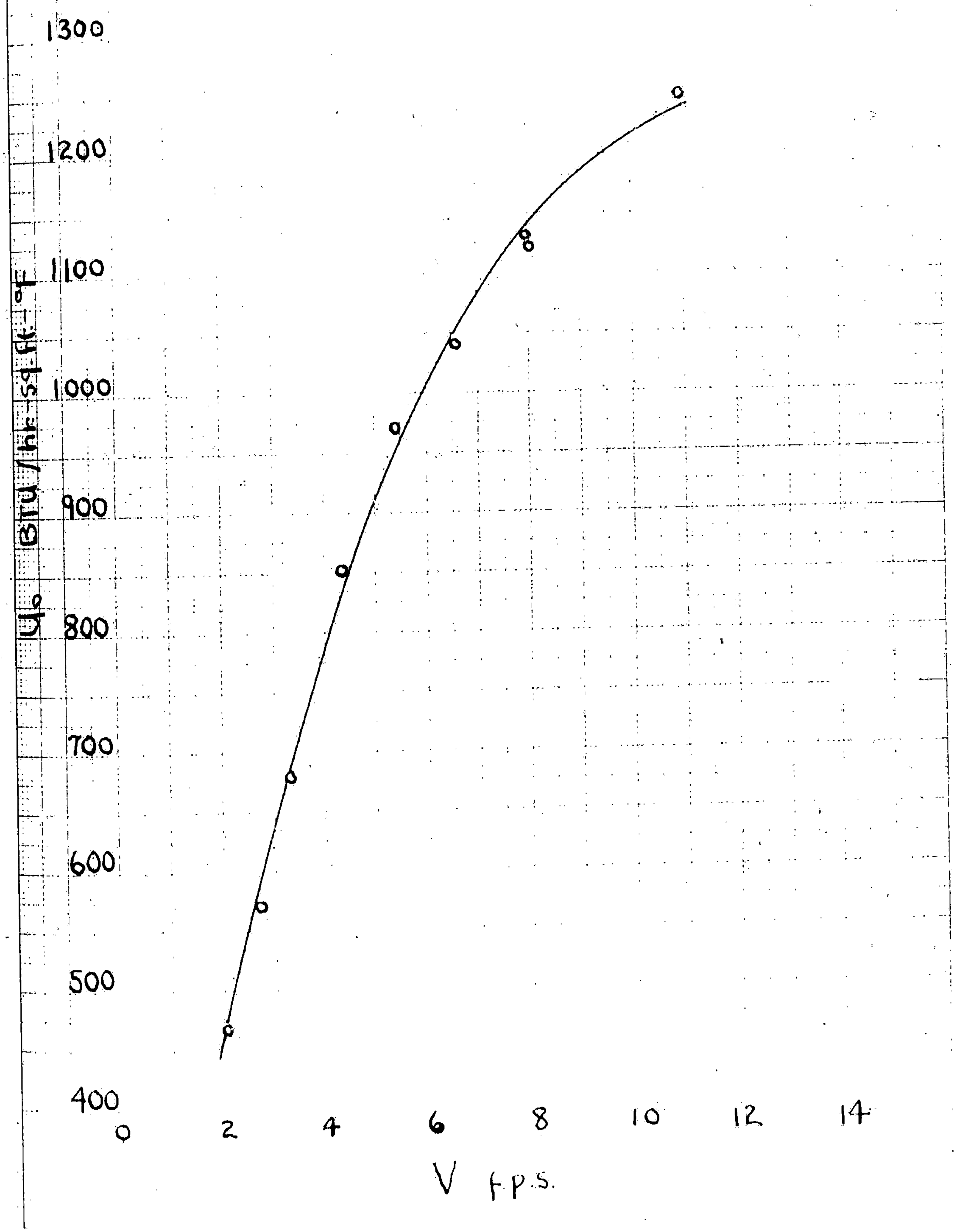


FIG. 8

OVERALL HEAT TRANSFER COEFFICIENT
vs.
PROCESS WATER VELOCITY
1/2 in. OD, 18 BWG, ADMIRALTY TUBE

Steam Temperature: 100°F
Inlet Water Temperature: 80°F

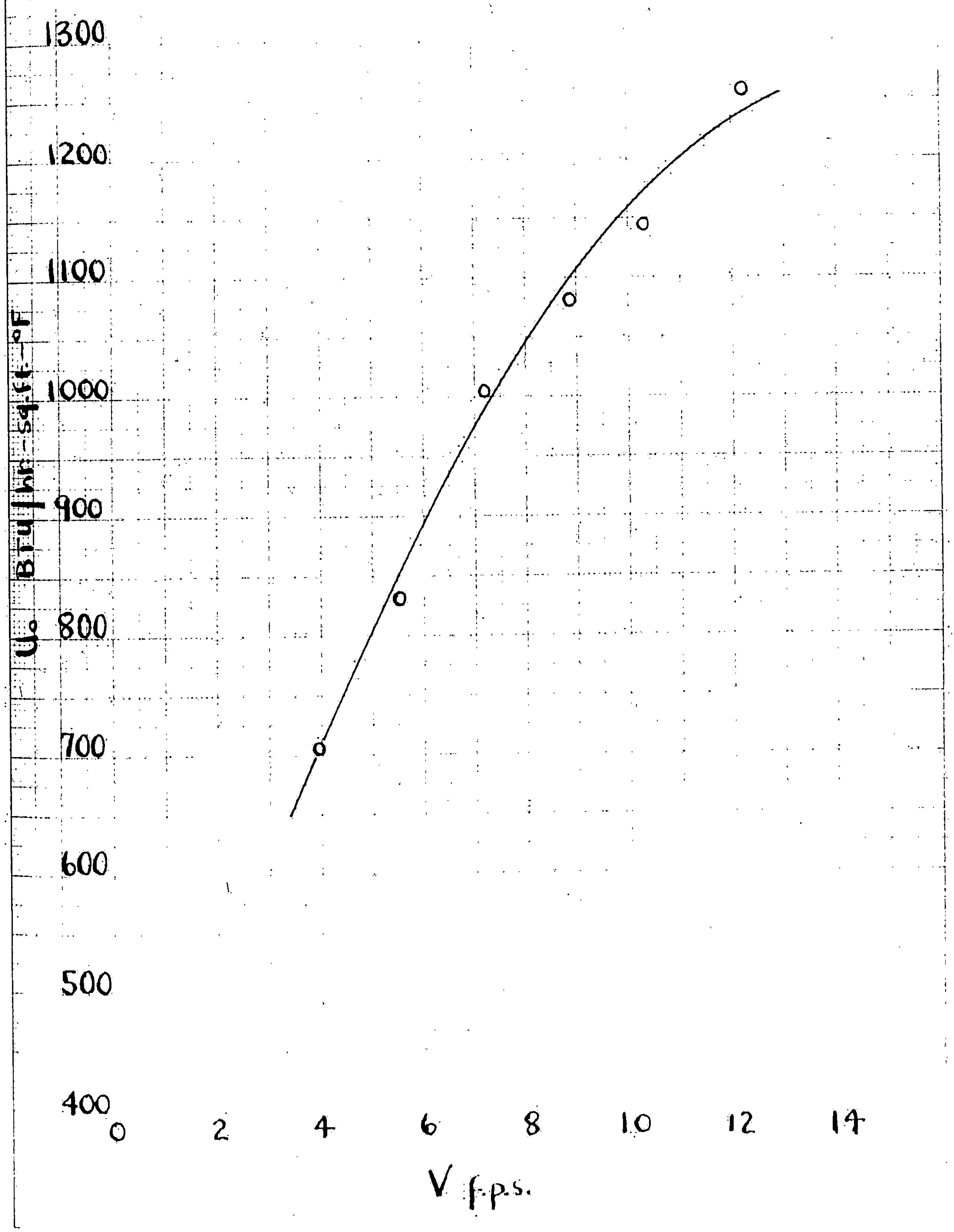


Fig. 9

OVERALL HEAT TRANSFER COEFFICIENT
vs.
[illegible] WATER VELOCITY
3/4 in. OD, 18 BWG, ADMIRALTY TUBE

Steam Temperature: 100°F
Inlet Water Temperature: 80°F

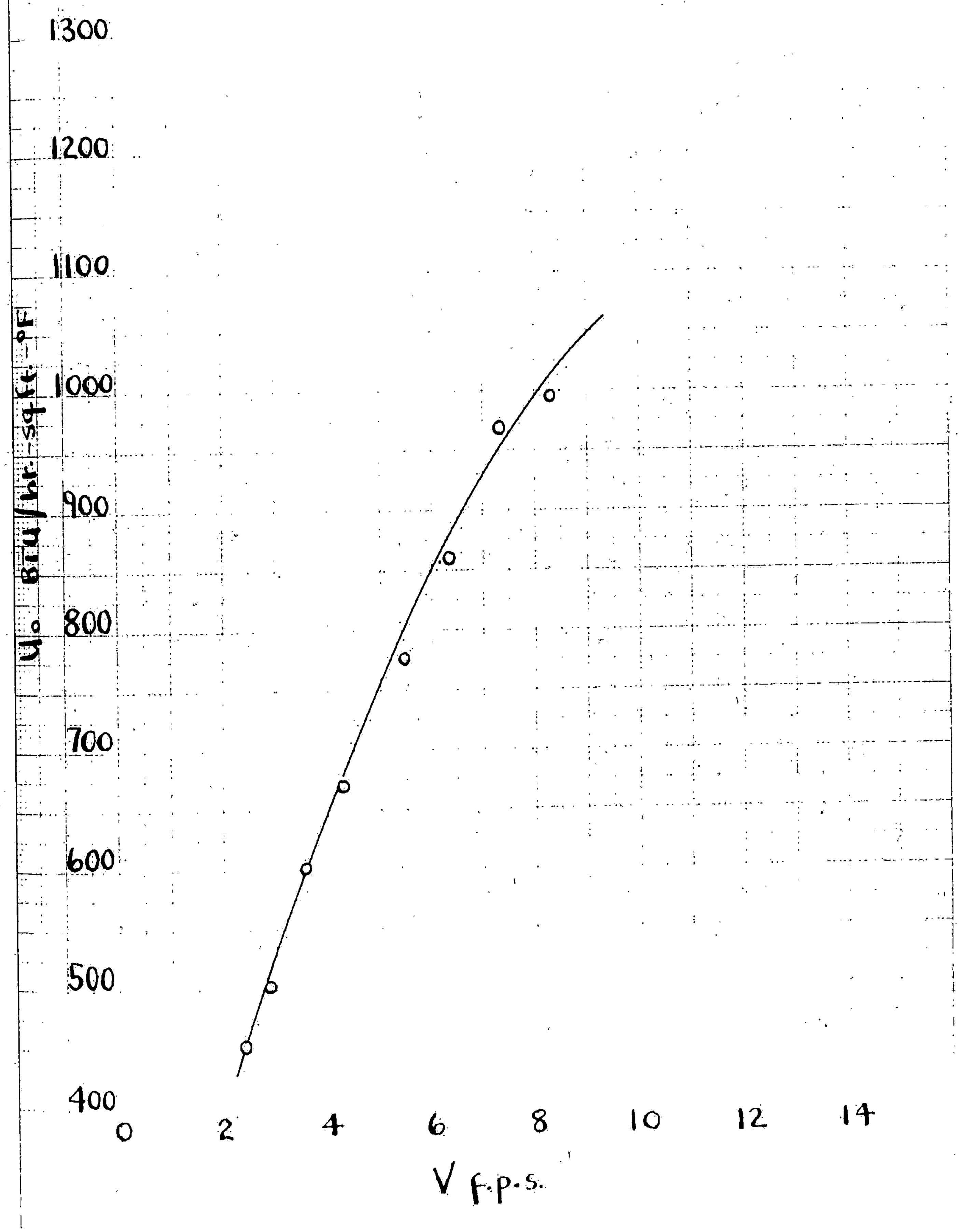


Fig. 10

EFFECT OF DIAMETER

18 BWG ADMIRALTY METAL TUBES

Steam Temperature: 100°F
Inlet Water Temperature: 80°F

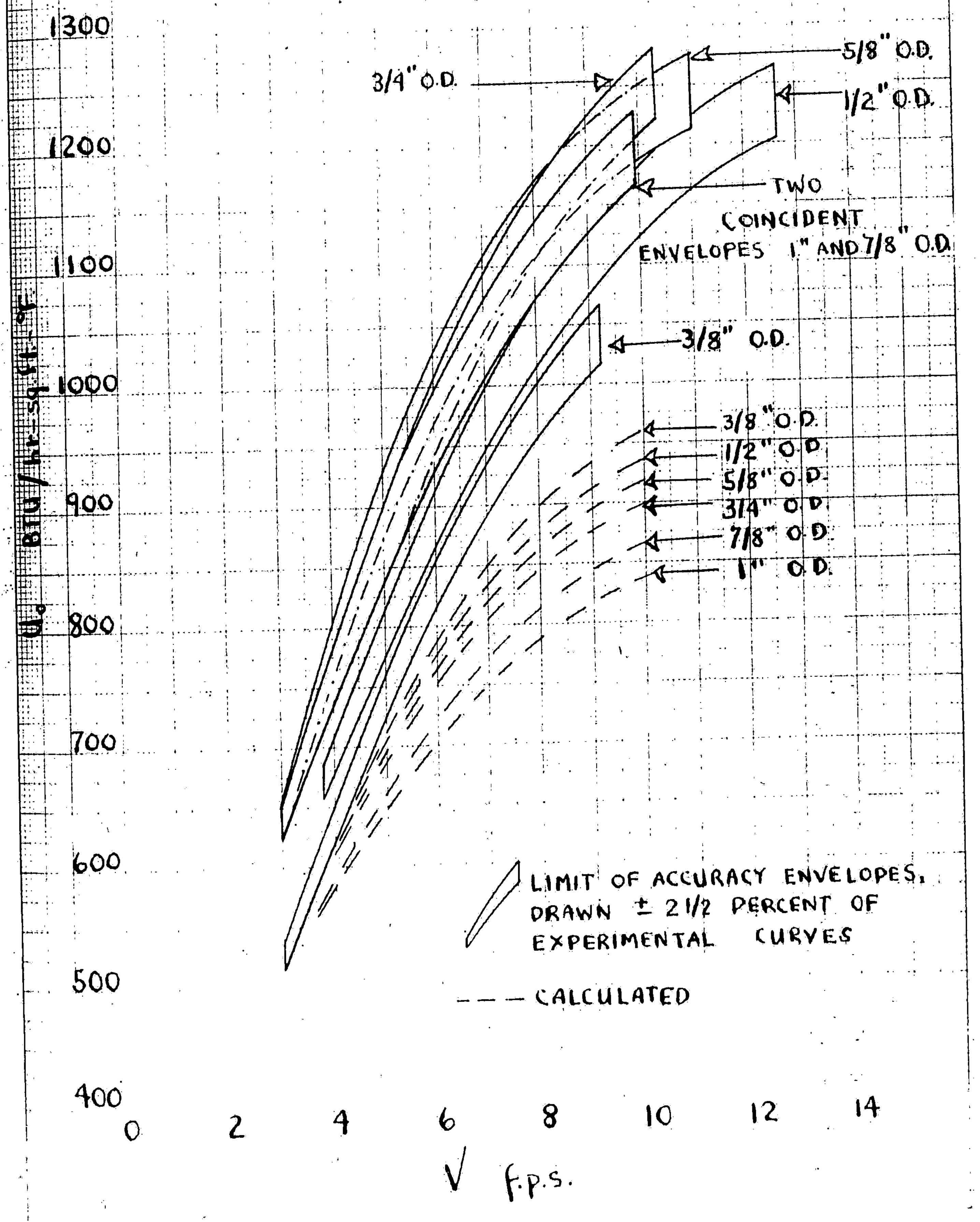


FIG. 11

EFFECT OF WALL THICKNESS

7/8 in. OD, ADMIRALTY TUBES

Steam Temperature: 100°F
Inlet Water Temperature: 80°F

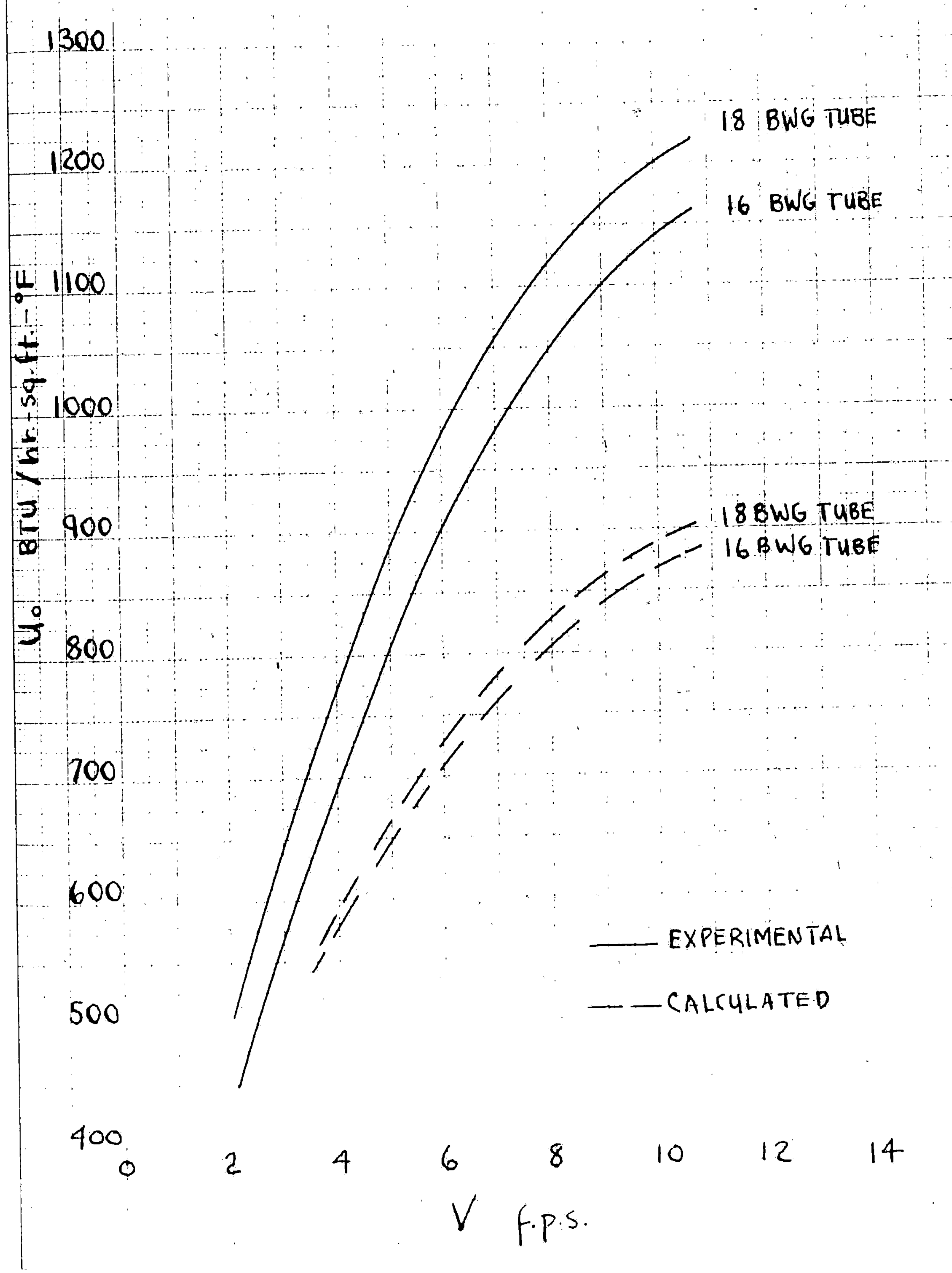


FIG 12

OVERALL HEAT TRANSFER COEFFICIENT
vs.
PROCESS WATER VELOCITY
7/8 in. OD, 18 BWG, ARSENICAL COPPER TUBE

Steam Temperature: 100°F
Inlet Water Temperature: 80°F

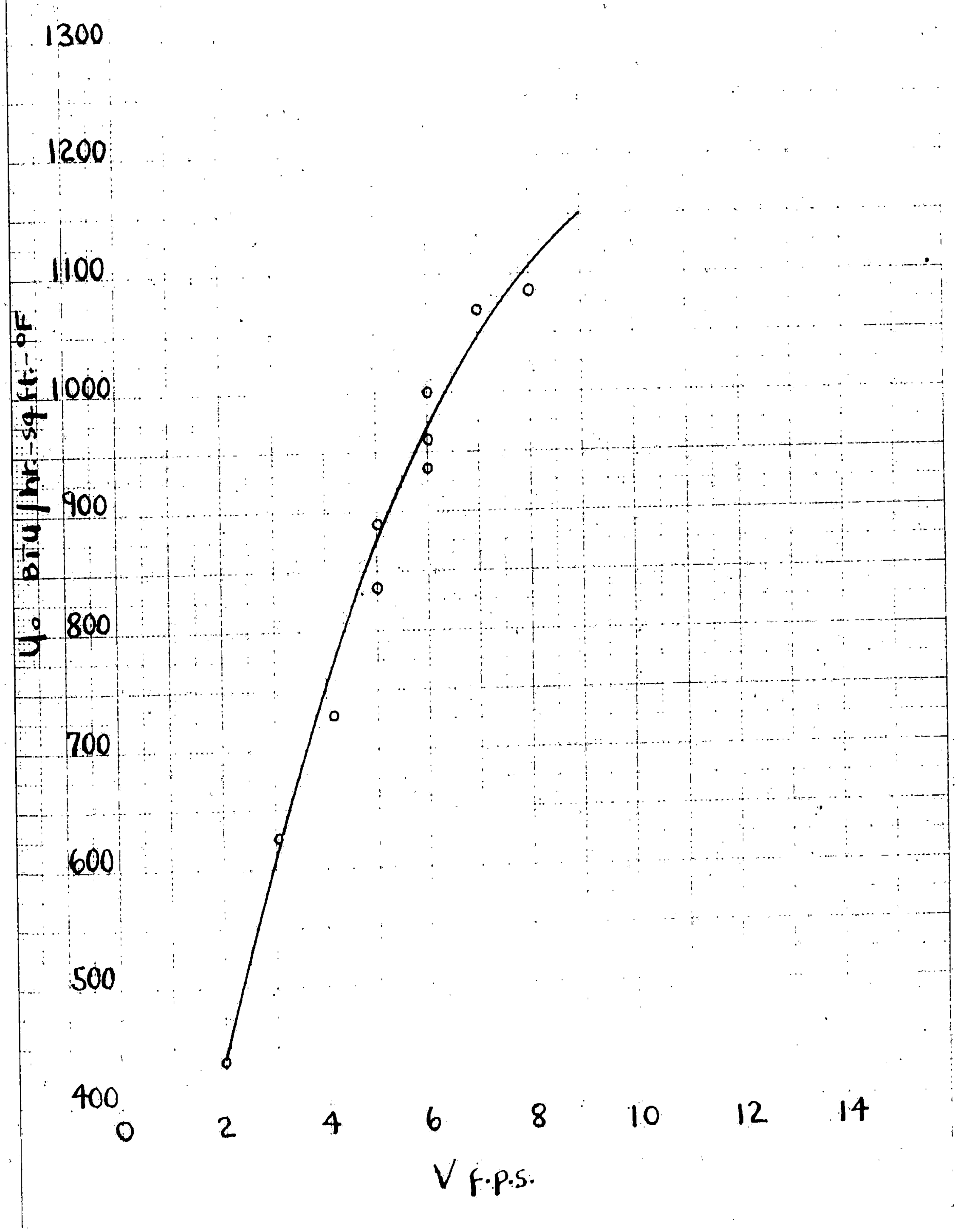


FIG. 13

OVERALL HEAT TRANSFER COEFFICIENT
vs.
PROCESS WATER VELOCITY
7/8 in. OD, 18 BWG, MUNTZ TUBE

Steam Temperature: 100°F
Inlet Water Temperature: 80°F

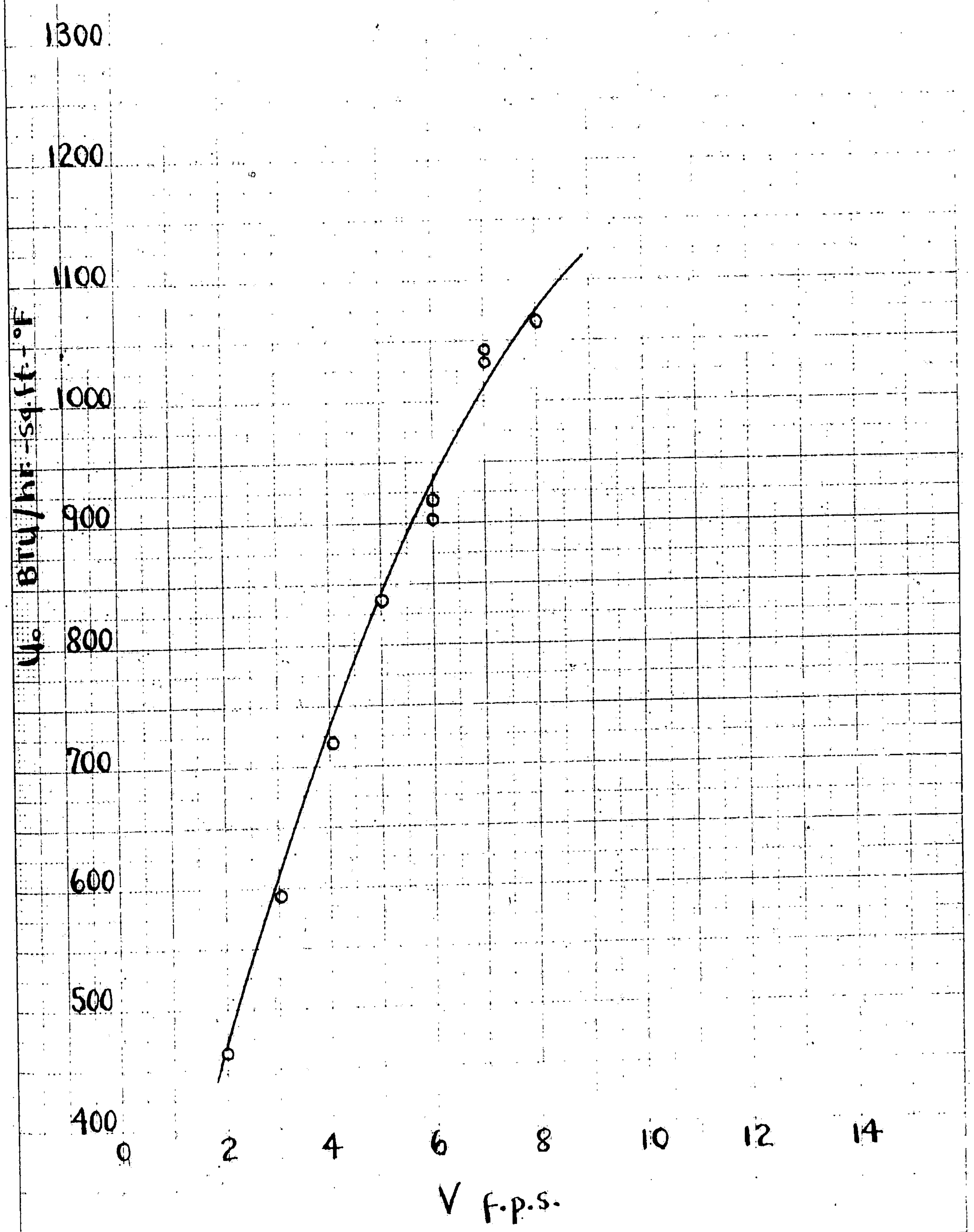


FIG. 14

OVERALL HEAT TRANSFER COEFFICIENT
vs.
PROCESS WATER VELOCITY
7/8 in. OD, 18 BWG, ALUMINUM BRASS TUBE

Steam Temperature: 100°F
Inlet Water Temperature: 80°F

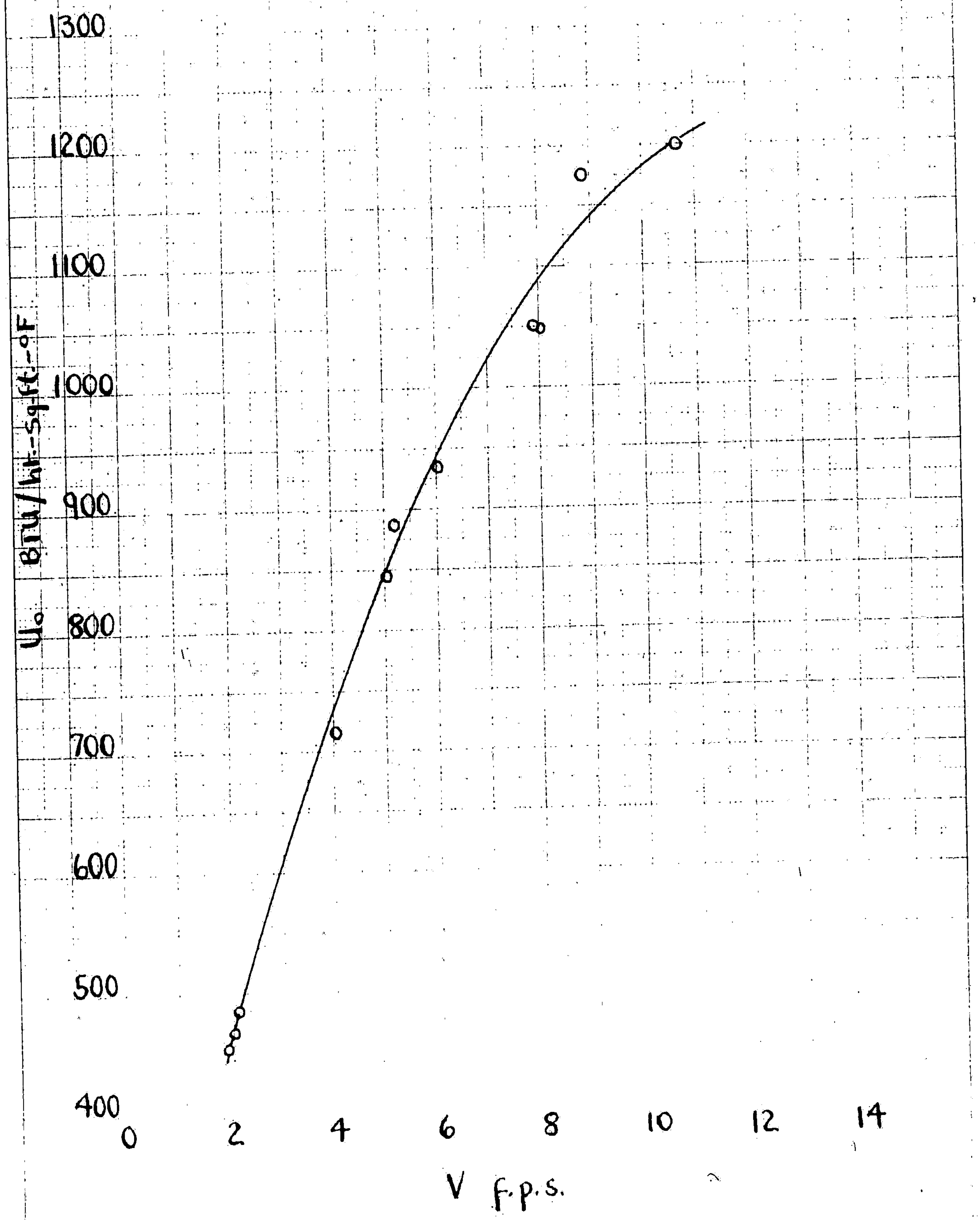


FIG. 15

OVERALL HEAT TRANSFER COEFFICIENT
vs.
INSIDE WATER VELOCITY
7/8 in. OD, 18 BWG, ALUMINUM BRONZE TUBE

Steam Temperature: 100°F
Inlet Water Temperature: 80°F

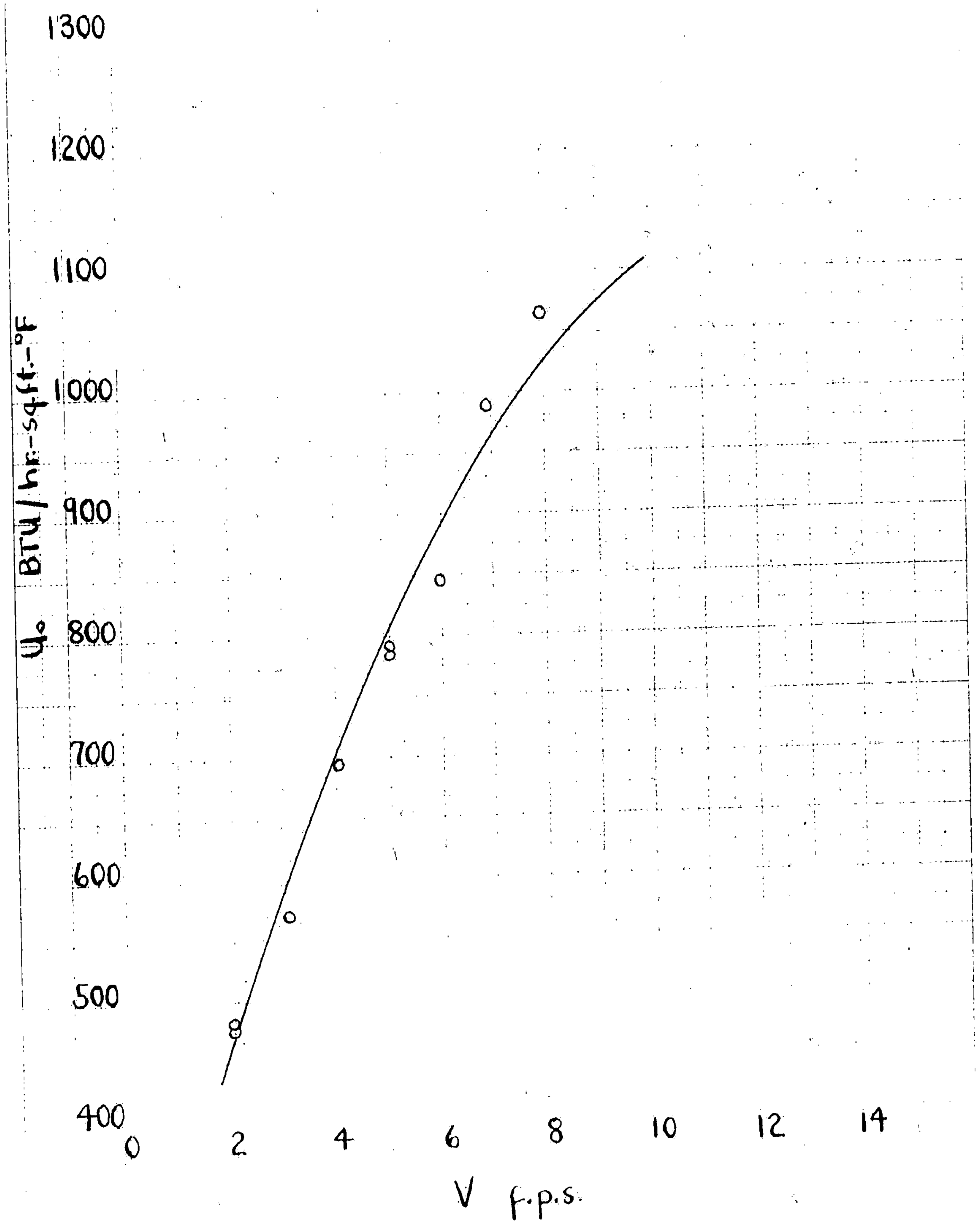


FIG. 16

OVERALL HEAT TRANSFER COEFFICIENT
vs.
PROCESS WATER VELOCITY
7/8 in. OD, 18 BWG, 70-30 COPPER-NICKEL TUBE

Steam Temperature: 100°F
Inlet Water Temperature: 80°F

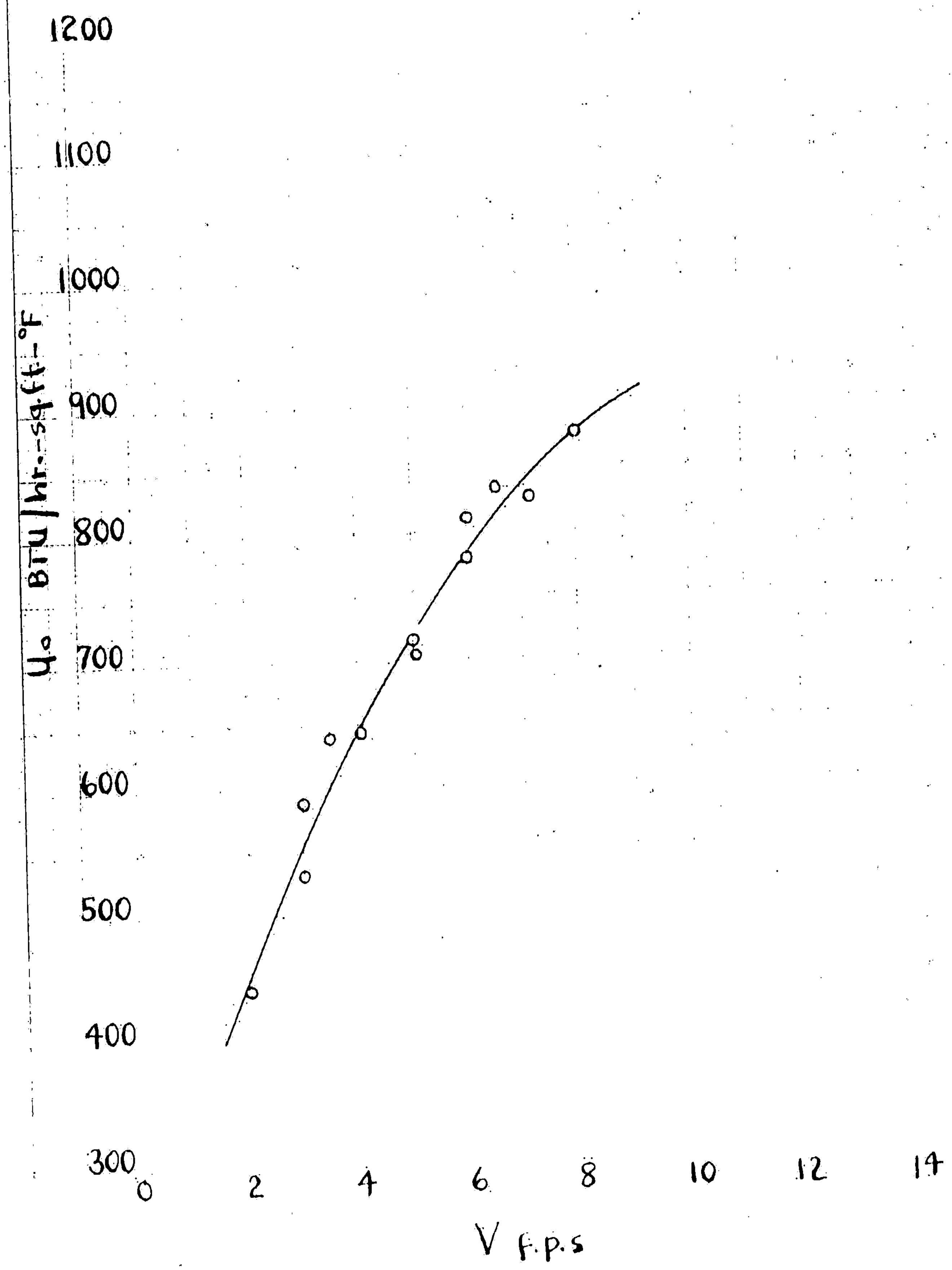


FIG. 17

EFFECT OF CONDUCTIVITY

7/8 in. OD, 18 BWG, TUBES

Steam Temperature: 100°F
Inlet Water Temperature: 80° F

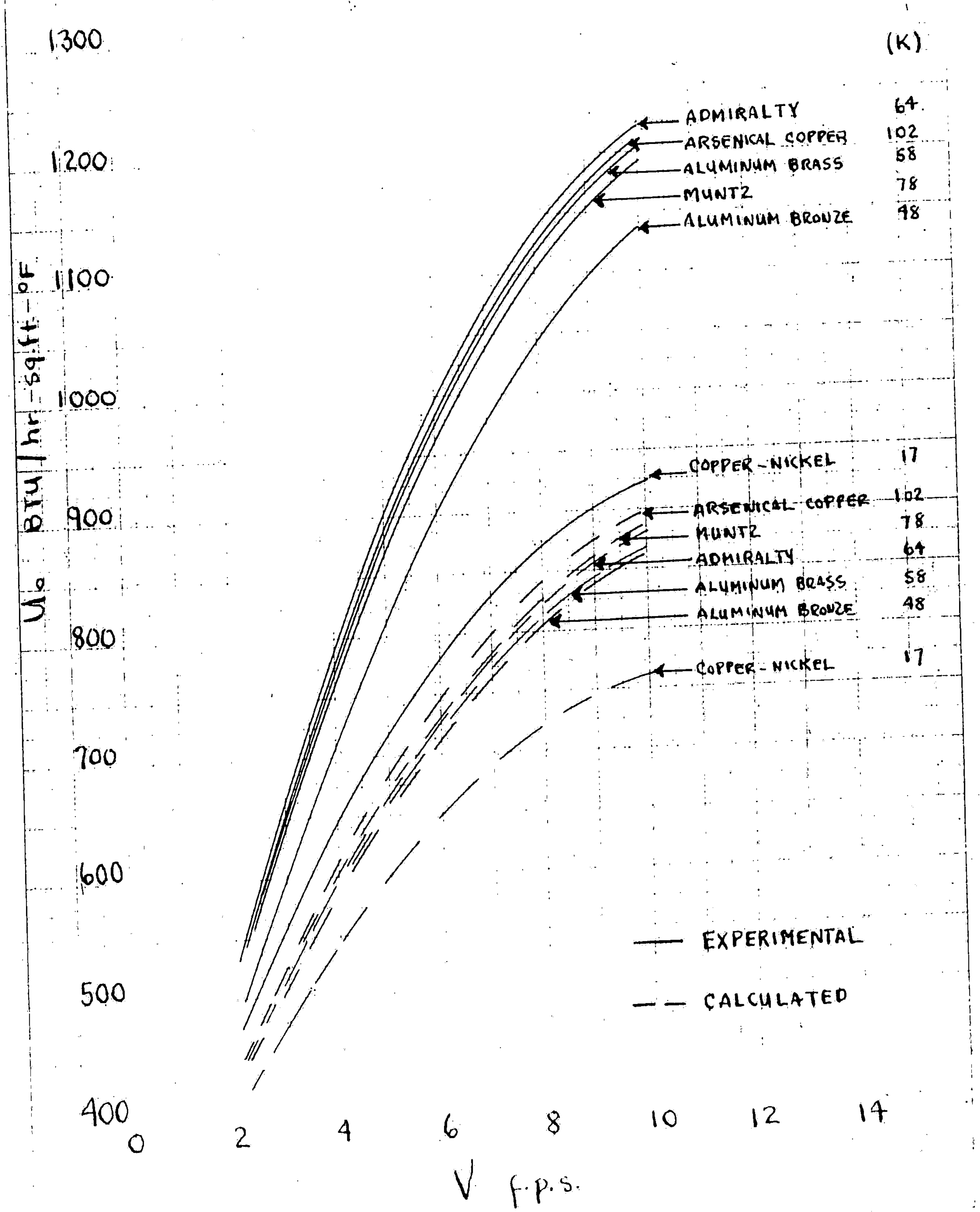


FIG. 18

ANALYSIS OF RESULTS

The experimental values of the overall heat transfer coefficients (U_o) calculated from the "raw" data obtained for the Heat Exchange Institute are displayed in Figs. 4 to 10, 13 to 17, and 20 as a function of the process water velocity (V). The range of the 5/8 in., OD, 18 BWG, 70-30 Copper-Nickel tube, Fig. 20 was extended by use of data as noted in Table XIII. Fig. 21, 1/2 in., OD, 18 BWG, 70-30 Copper-Nickel tube was included to illustrate a method of predicting overall coefficients using relative corrections to be advanced further in this paper.

The accuracy of the results was calculated using the limits to which the measured variables were read. The deviation of the coefficients from their mean based on these limits was found to be five percent and indicates the magnitude of any nonsystematic experimental errors.

Effect of Tube Diameter

Fig. 11 is a plot of the overall heat transfer coefficients (U_o) versus the water velocity (V) for the various sizes of 18 BWG Admiralty metal tubes (i.e. 1 in., 7/8 in., 3/4 in., 5/8 in., 1/2 in., and 3/8 in., OD). This plot is presented as a family of envelopes, the limits of which were drawn ± 2.5 percent from the mean values shown in Figs. 4 to 10. Calculated values of the overall coefficient as outlined under theoretical considerations are also included to allow comparison with experimental values. As can be noted the calculated values follow the general trend of increasing coefficient with decreasing tube size while the envelopes of the experimental values show a decreasing coefficient beyond the 3/4 in. OD tube. To reiterate, the 5/8 in., 1/2 in. and 3/8 in. show exact reverse order from the calculated values.

At this point it appears that no constant correction factor will bring the calculated and experimental values into close agreement and that some correction such as a function of diameter would have to be introduced to account for the lowered coefficients in the 5/8 in., 1/2 in. and 3/8 in., OD, 18 BWG Admiralty tubes.

Resolution of the experimental curves into individual film resistances and wall resistances was attempted. This presents a solution of one equation (Fourier's) and two unknowns (Dittus-Boelter and Nusselt). As no absolute value of the steam film could be presupposed, any solution would have to be relative among the various tube sizes and metals. The finding of a best combination of water film coefficient and steam film coefficient to duplicate the experimental curves was undertaken. As a starting point it was assumed that the basic method for calculation of these resistances was correct and that correction factors on these resistances would be satisfactory as a solution to the problem.

Study was made of the 7/8 in., OD, 18 BWG Admiralty tube because it also appears in the conductivity series. A correction factor of 1.32 on the water film coefficient as calculated and a constant steam film of 3500 for the 7/8 in. tube were found, by trial, to give values in perfect agreement with experimental values over the complete range of velocity.

Relative condensate film coefficients for the other sizes of Admiralty tubes were then calculated using the relationship of $h_s/h_s' = (D_o'/D_o)^{1/4}$ from the equation of Nusselt. Using these values for the steam film resistances, correction factors on the water film coefficients are calculated from the experimental values using the following relationship:

$$1/U_o(\text{Exp.}) - LD_o/kD_a - 1/h_s = D_o/D_i h_w(\text{corr. factor}) \quad . \; . \; . \; (4)$$

A listing of these values is presented in Table XIV and a graphical display in Fig. 19. The correction factor of each tube size appears to be a definite function of the inside diameter.

These variations are attributable to the effect of the ratio of diameter to length, D/L, and the design of the apparatus. It appears that a smaller ratio of D/L would tend to minimize these end effects and from a consideration of the values obtained in Table XIV the critical value would be roughly D/3L.

Effect of Wall Thickness

Fig. 12 is a plot of the overall coefficients versus the water velocity for 7/8 in., OD, Admiralty tubes of varying wall thickness (i.e. 16 and 18 BWG). These follow the calculated values through the velocity range studied. The apparent difference in the ratio of the experimental values to the calculated values for the two tubes can be explained in light of different end effect corrections. The calculated end effect correction for the 16 BWG tube based on a steam film coefficient of 3500 is 1.27, the interpolated value from Fig. 19 is 1.31. Though these values are in close agreement it is felt that a complete study of 16 BWG tubes is necessary to ascertain the possibility of wall thickness effects on these corrections.

It is also noted from a study of the work of Lt. Comdr. R. W. Arcy USN and Lt. S. J. Robinson USN that there is a difference in the ratio of the experimental values to the calculated values for the 1/2 in., OD, 18 and 20 BWG, 70-30 Copper-Nickel tubes.

Effect of Conductivity

Fig. 18 is a plot of the overall heat transfer coefficient (U_o) showing the effect of conductivity (k) for 7/8 in., OD, 18 BWG tubes of the following metals: Arsenical Copper (k = 102), Muntz (k = 78), Admiralty (k = 64), Aluminum Brass (k = 58), Aluminum Bronze (k = 48), and Copper Nickel (k = 17). Calculated values, as in the case of the diameter and wall thickness series, are included to allow comparison with the experimental values. The calculated values show a continued rise in overall heat transfer coefficients with conductivity while the experimental values of Admiralty and Aluminum Brass prove this trend does not hold in practice.

From theoretical considerations the water film coefficients of the various tubes at a given velocity are approximately equal, this would hold for any end effect correction as it would be applicable to all tubes within a group. As the tube wall resistances are not of sufficient magnitude to exercise the variation in the overall coefficients as shown, the only other contributing factor could be the steam film resistance. Relative steam film coefficients were calculated using equation (4) and the end effect correction of 1.32 on the water film coefficient. These values are listed in Table XVI. They by nature of their derivation follow the trend of the experimental values except in the case of Copper-Nickel in which the wall resistance becomes an important factor.

An explanation of different steam film resistances might lie in the different surface conditions of the individual tubes as influenced by the type of metal.

Calculated Overall Coefficients for Copper-Nickel

Using the end effect correction factors established for the Admiralty tubes and the steam film coefficient calculated for the 7/8 in., OD, 18 BWG Copper-Nickel tube, modified for diameter, the overall coefficients for the 5/8 in. and 1/2 in., OD, 18 BWG Copper-Nickel tubes were calculated. These calculated values and their deviations from the experimental values appear in Table XVII. Graphical displays are presented in Figs. 20 and 21. Deviations are well within experimental errors of the original data.

CONCLUSIONS

Based on the data contained in this report, overall heat transfer coefficients may be calculated in the following manner.

1. Calculate the water film by means of the Dittus-Boelter equation times a correction factor.
2. Obtain correction factor from Table XV or from Fig. 19.
3. Calculate tube wall resistance from Fourier's equation using accepted values of conductivity.
4. Obtain steam film by multiplying the values found in Table XVI by the correction factor $hs/hs' = (Do'/Do)^{1/4}$ where the primed values are for the 7/8 inch OD, 18 BWG tube used as a basis.
5. Compute the overall coefficient in the usual manner from the two films and the tube wall resistance.

This work is limited to 100° F. steam, 80° F. inlet water, 18 BWG tubing and the metals studied. The correction factors used in (2) are specific for the apparatus and tube length used.

Table XV. Relative Correction Factors on 18 BWG Admiralty Tubes,

O.D. (inches)	x h_w	h_s
1	1.37	3380
7/8	1.32	3500
3/4	1.28	3610
5/8	1.23	3820
1/2	1.09	4030
3/8	0.94	4330

The steam film coefficients (h_s) are based on the 7/8 in. OD Tube.

Table XVI. Relative Steam Film Coefficients of 7/8 in. OD,
18 BWG Tubes of Different Conductivities,

Tube Metal	k	h_s
Arsenical-Copper	102	3100
Muntz	78	2900
Admiralty	64	3500
Aluminum-Brass	58	3050
Aluminum-Bronze	48	2800
Copper-Nickel	17	2850

END EFFECT CORRECTION ON WATER-FILM COEFFICIENT
vs.
INSIDE DIAMETER

18 BWG, ADMIRALTY TUBES

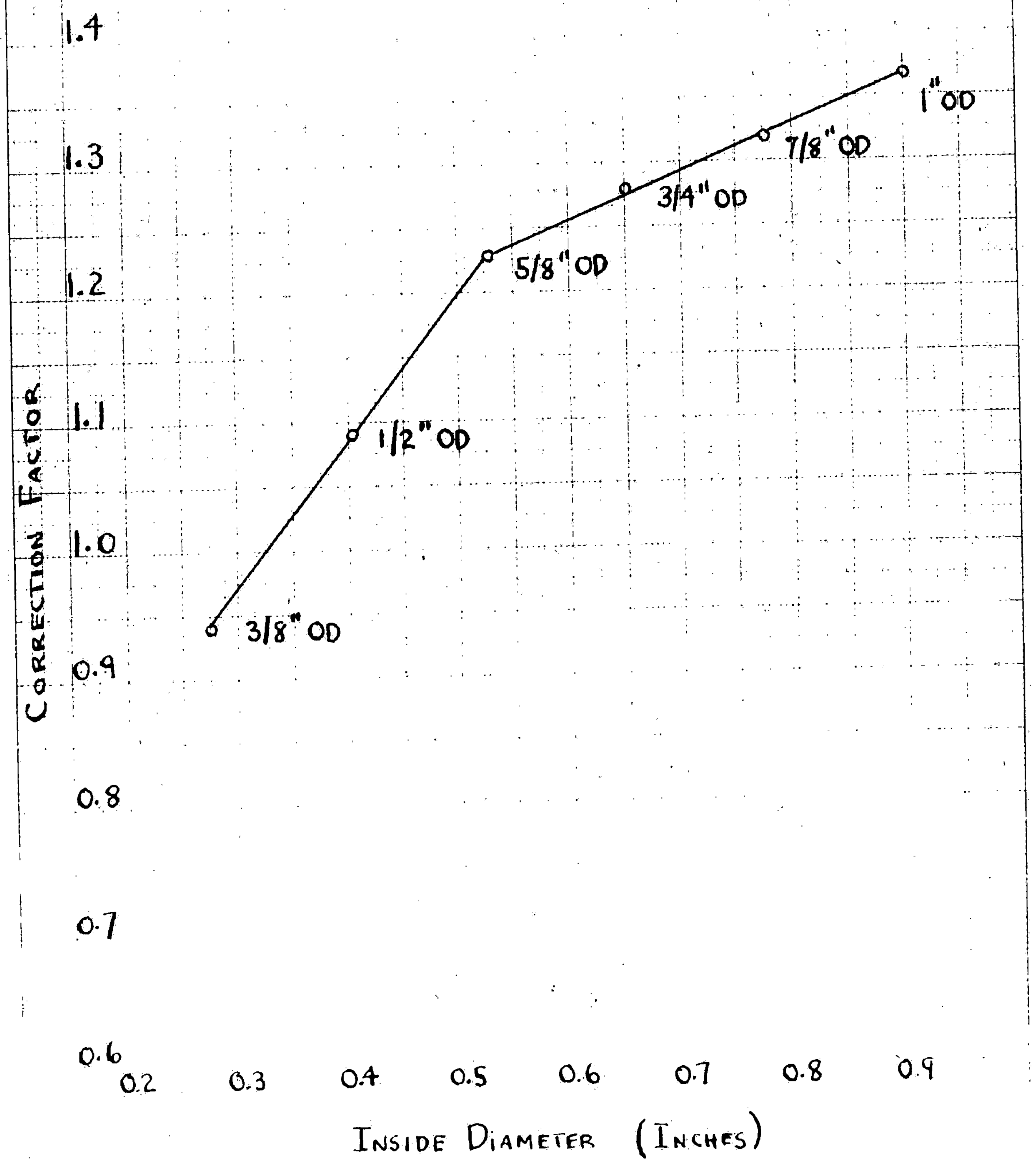


FIG. 19

Table XVII. Calculated Values of Overall Coefficients

Based on Relative Corrections.

Tube Size: 5/8 in., OD, 18 BWG, 70-30 Copper-Nickel

V	h_w	h_w(Corr.)	h_s	U_o(Calc.)	U_o(Exp.)	% Dev.
2.73	721	888	3110	516	506	1.98
4.03	988	1215	3110	642	627	2.4
7.0	1535	1885	3110	825	825	0.0
10.1	2060	2535	3110	950	973	2.42
13.0	2550	3090	3110	1033	1013	1.97
15.0	2835	3482	3110	1082	1045(ave.)	3.52

Tube Size: 1/2 in., OD, 18 BWG, 70-30 Copper-Nickel

V	h_w	h_w(Corr.)	h_s	U_o(Calc.)	U_o(Exp.)	% Dev.
7.0	1620	1765	3280	785	806	2.6
11.1	2350	2560	3280	948	952	0.42
14.0	2780	3030	3280	1020	1031(ave.)	1.06
16.1	3150	3440	3280	1073	1085	1.2
21.0	3850	4200	3280	1140	1168	2.4

OVERALL HEAT TRANSFER COEFFICIENT
vs.
PROCESS WATER VELOCITY
5/8 in. OD, 18 BWG, 70-30 COPPER-NICKEL TUBE

Steam Temperature: 100°F
Inlet Water Temperature: 80°F

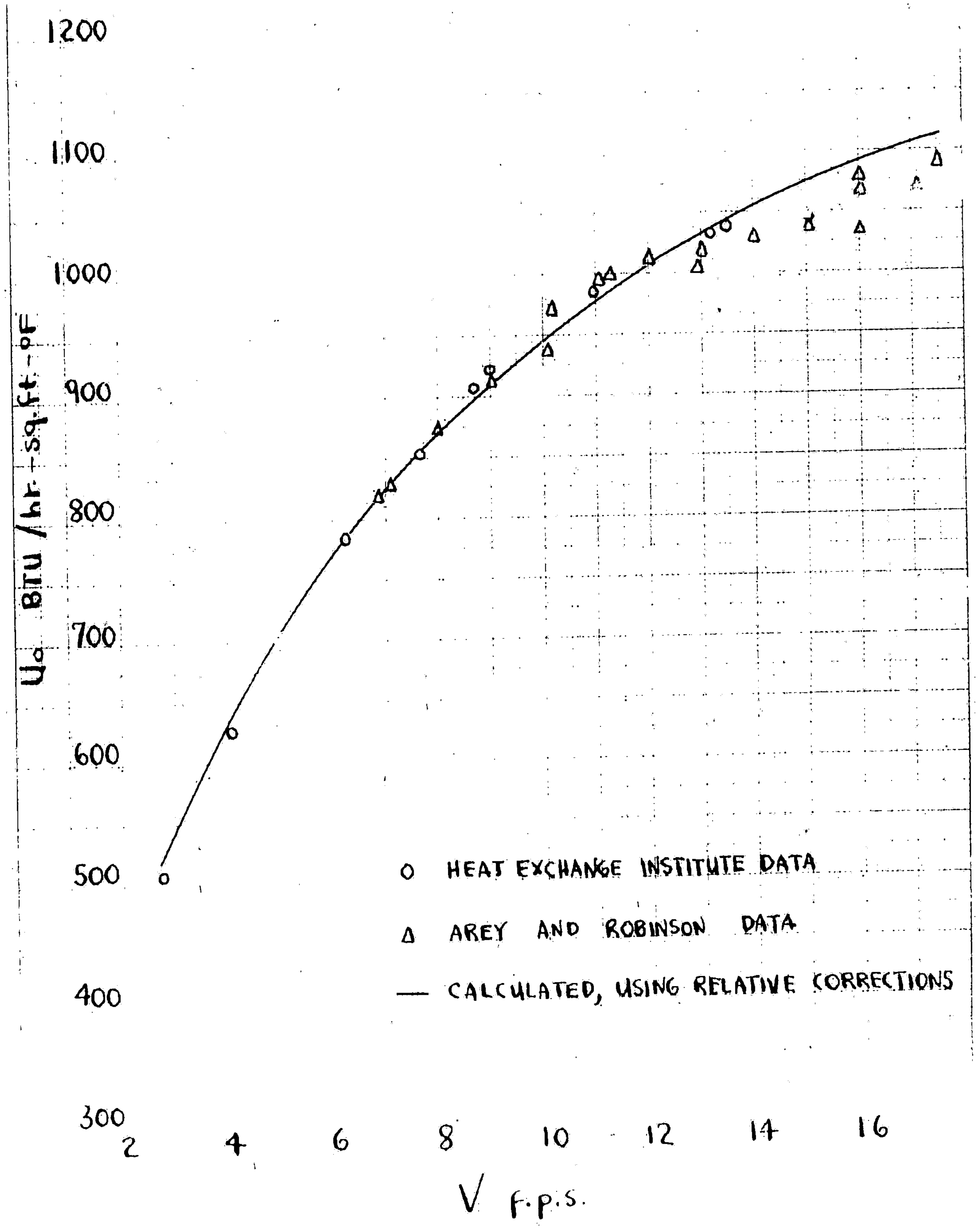


FIG. 20

OVERALL HEAT TRANSFER COEFFICIENT
vs.
PROCESS WATER VELOCITY
1/2 in. OD, 18 BWG, 70-30 COPPER-NICKEL TUBE

Steam Temperature: 100°F
Inlet Water Temperature: 80°F

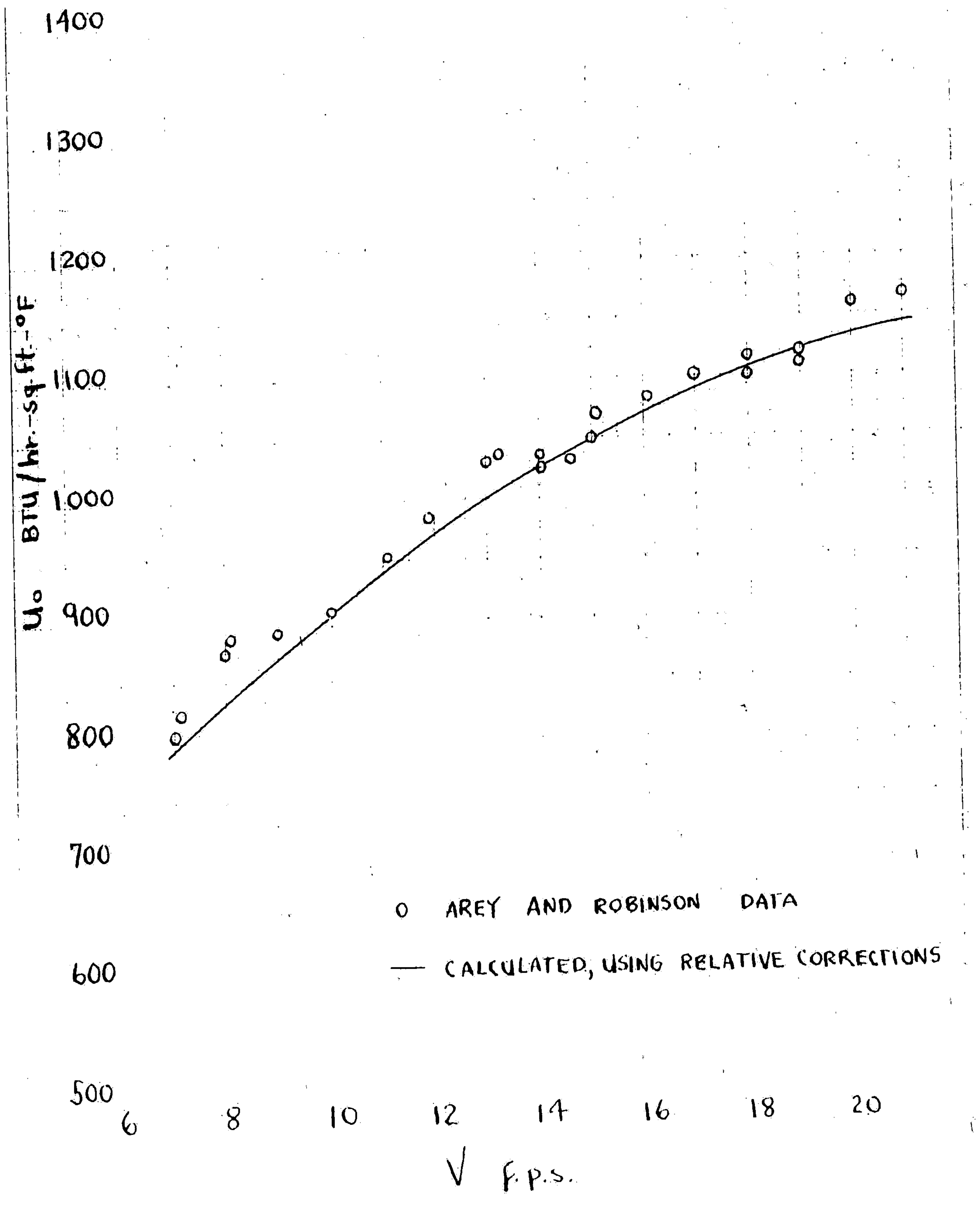


FIG. 21

SAMPLE CALCULATION OF RELATIVE VALUES

Steam-film Coefficient (h_s) - 3/8 in., OD, 18 BWG Admiralty Tube.

For this, use equation $h_s/h_s' = (D_o'/D_o)^{1/4}$ and the steam-film coefficient (h_s' - 3500) established for the 7/8 in., OD, 18 BWG Admiralty Tube.

$D_o' = 0.875$ in.

$D_o = 0.375$ in.

$h_s = 3500(0.875/0.375)^{1/4} = 4330$

Steam-film Coefficient (h_s) - 7/8 in., OD, 18 BWG Copper-Nickel Tube.

For this, use equation (4) and the water-film coefficient correction of 1.32 as established for the 7/8 in., OD 18 BWG Admiralty tube. Water-Film coefficients used in the following examples were calculated from equation (2). No calculations are shown as standard procedure was followed.

$U_o(\text{Exp.}) = 878$

$h_w = 1590$

$K = 17$

$D_o = 0.875$ in.

$D_a = 0.826$ in.

$D_i = 0.777$ in.

L 0.049 in. = 0.00408 ft.

$$1/h_s = 1/878 - \frac{0.00408 \times 0.875}{17 \times 0.826} - \frac{0.875}{0.777 \times 1.32 \times 1590}$$

$$= 0.001140 - 0.000254 - 0.000535$$

$$= 0.000351$$

$$h_s = 2850$$

End Effect Correction (corr. factor) - 3/8 in., OD, 18 BWG Admiralty Tube.

For this, again use equation (4) and the steam-film coefficient ($h_s = 4330$) from previous calculations.

U_o(Exp.) = 455

h_w = 760

K = 64

D_o = 0.375 in.

Da = 0.326 in.

Di = 0.277 in.

L = 0.049 in. = 0.00408 ft.

$$\text{corr. factor} = \frac{0.375/(0.277 \times 760)}{\frac{1}{455} - \frac{1}{4330} - \frac{0.00408 \times 0.375}{64 \times 0.326}}$$

$$= \frac{0.00178}{0.002198 - 0.000231 - 0.0000735}$$

$$= \frac{0.00178}{0.001893}$$

$$\approx 0.94$$

NOMENCLATURE

A	Outside tube area, sq. ft.
c	Specific heat, BTU/lb.-OF.
D	Diameter, ft.
g	Accelaration of gravity, 4.18×10^8 ft./hr.^{2}
h	Film coefficient, BTU/hr.-sq. ft.-°F.
H	Flowmeter gauge reading, cm.
k	Thermal conductivity, BTU-ft./hr.-sq. ft.-°F.
L	Length, ft.
q	Heat transfer rate, BTU/hr.
t	Temperature, °F.
U	Overall heat transfer coefficient, BTU/hr.-sq. ft.-°F.
V	Circulating water velocity, ft./sec.
w	Circulating water flow rate, lb./hr.
Δt_m	Log mean temperature difference, °F.
λ	Latent heat of evaporation, BTU/lb.
μ	Absolute viscosity, lb./ft.-sec. or lb./ft.-hr.
ρ	Density, lb./cu. ft.

Subscripts

a	Average
i	Inside
o	Outside
s	Steam, or condensate film
w	Water film
1	Inlet
2	Outlet

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Lehigh University	1948-50

Professional Experience:

Electronics and Electronics Development Officer Naval Air Station, Guantanamo Bay, Cuba	1942- 43
Night Fighter Training Program	1944-47