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A Study of Surface Condenser Practice

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A STUDY OF SURFACE CONDENSER PRACTICE

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

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ENTITLED A STUDY OF SURFACE CONDENSER PRACTICE

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

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A Study of Surface Condenser Practice.

Introduction.

The extensive use of surface condensers in the best of high vacuum installations in power plants and on board of ships, makes it very necessary for the designer to have complete data at hand upon which he can base his calculations. In looking over the field one very soon realizes that but little such data exists, except possibly among manufacturers. The machinery built and sold from stock is rarely furnished under definite guarantee of certain performance and is always supplied with a large factor of safety.

With these facts in mind the present thesis was attempted. In a surface condenser there exist four absolute variables, namely: circulating water, condensate, vacuum and capacity. The term condensate is used to mean condensed steam and will be so used in this entire thesis. Another class of variables are those due to construction: cooling surface, steam inlet and outlet, circulating water inlet and outlet, and number of passes of circulating water or effective tube length. These main variables are governed by certain conditions some of which are uncontrolable. Arranged in outline form these facts may be presented as follows:

Absolute Variables.

1. Circulating Water.

   Temperature.

   Weight (Velocity of flow).

2. Condensate.

   Initial pressure and quality.

   Weight and temperature.

3. Vacuum.

4. Capacity.

Constructive Variables.

1. Cooling Surface.

   Area.

   Form.

2. Steam Inlet and Outlet.

3. Circulating Water Inlet and Outlet.

4. Number of passes of Circulating Water.

To make a study of real value, it is necessary that all of these features should be tried out thoroughly. This would contemplate a complete series of tests on all approved designs, now manufactured, under all the above conditions. While studying, wherever possible, the constructive features should be changed so as to find out just what influence these factors have on the general performance of the condenser. From the conclusions made from a careful study of the data thus obtained, new designs should be constructed and then tested to prove the correctness of these conclusions.

Object of Tests.

It will be obvious at once that an investigation as outlined above would be a study that would require years of close application by a number of experts and one not practicable for an under-graduate thesis. Realizing this, it was proposed in this investigation to make a series of tests on the available apparatus in the Mechanical Laboratory, keeping such factors constant as could be controled and study their relation to certain other variables.

Apparatus.

The apparatus consisted of a Worthington condenser having separate circulating and vacuum pumps and 360 sq. ft. of cooling surface.

Method.

As there was no apparatus of sufficient size in the Laboratory to furnish an amount of exhaust steam equal to the capacity of the condenser, steam was taken from the Laboratory steam main and throttled down so that a constant flow was maintained. The effect of varying the circulating water upon the vacuum hot-well temperature and capacity was attempted. Owing to delays and breaking of tubes the time available was so short that it was not possible to study the effect upon capacity.

Other Work.

As stated before, the work done in this field has been very meager. Prof. R. L. Weighton of the Institution of Naval Architects reports in their transactions for the year of 1906, an extensive series of tests on an old type of condenser and a new design, the result of study and experiment. These tests were carried on at Armstrong College, Newcastle-on-Tyne. The work and results are by far the best of anything published.

A quadruple expansion marine engine was used to supply the steam. To one of the pistons was attached a walking beam and to this a vacuum pump of the vertical, single-acting, bucket type. The load on the engine was measured by a water brake. The condensers, both of the old and new type were designed so as to have a very close connection to the engine. In order to study the effect of air pump capacity, a separate, three cylinder, motor-driven air pump of the Edwards type was subsequently installed. It was found that a certain capacity existed which gave the maximum vacuum and any increase did not produce an effect of an appreciable amount.

These tests were carried out in very minute detail with every regard for getting accurate results. The data thus taken from the test of what is called an old type of condenser and two new designs is very complete. The most noteworthy change in the new design is the compartment drainage of the condensate. The condenser is divided into three parts by nearly horizontal baffles and the steam and air pass crosswise over

the tubes thru the compartments. The circulating water enters at the bottom and leaves at the top. The steam enters centrally at the top and side. By draining the condensate off from the upper compartments, it comes off several degrees hotter than if it passed thru the bottom chamber and came in contact with the coldest tubes. By compartment drainage the efficiency of the cooling surface is increased and the last and coldest compartment is left to cool the air for the air pump. This type of condenser is called Contra-flo by Prof. Weighton because the steam is made to flow in a plane at right angles to the flow of the circulating water.

In conducting these trials a constant flow of steam was maintained for a series of about five tests and the circulating water varied to the maximum amount. The circulating water was taken from the city mains. As the tests extended thru a year and a half, the conditions of practice were met with. The vacuum maintained was measured by both gages and a mercury column.

In analyzing the results, Prof. Weighton says, "There are several possible criteria of efficiency in a condenser according to the point of view. In this connection the factors directly involved are the following:- Steam condensed (condensate) per square foot of surface; water required per pound of steam (condensate); vacuum attained; hot-well temperature; power expended in producing the vacuum (i. e., on circulating and air pumps); and size, weight, and first cost of condenser.

The writer takes it that that condenser will be the most efficient which, with given water inlet, temperature, air leakage, and air pump capacity, maintains a given vacuum with the smallest condensing surface per pound of steam condensed (condensate), the smallest relative power expended in driving the circulating and air pumps, the highest hot-well temperature, and the smallest weight and first cost in relation to the steam condensed. Another way of putting it would be, that that condenser is the most efficient which, all other things equal as enumerated above, maintains the highest vacuum."

The results of the tests are clearly shown in the curves drawn from the results which are included here, pages 21, 22, 23, and 24. For the old type of condenser there is a separate curve for each quantity of circulating water per pound of condensate. This is claimed to be due to the falling off of the surface efficiency of the tubes.

By surface efficiency is meant the ratio of heat transmitted from the condensate to the circulating water. When this is maximum the highest vacuum will be maintained with the minimum amount of circulating water, cooling surface and cubical capacity. By increasing the efficiency, the weight is decreased and a saving in first cost effected.

A table is given below which shows the relation between the new and old types of condensers, from Prof. Weighton's tests.

Condenser.	#2	#3	Old Type.
Surface, sq. ft.	100	62	170
Capacity, cu. ft.	9.6	6.0	18.0
Steam condensed (Condensate) per sq. ft. per hour, lbs.	20	33	10
Vacuum, inches	28	28	28
Condensing Water per lb. of Steam (Condensate) (inlet = 50°), lbs.	24	32	43
Surface per I. H. P. (allowing 12 lbs. of Steam per I. H. P. per hour) sq. ft.	0.60	0.36	1.20
Relative Capacity per I. H. P. (#3 being = 1)	1.63	1.00	3.60

The best Thermal efficiency of a condenser is realized when the temperature of the hot-well is the highest possible with the maximum amount of condensate. By the compartment drainage it was possible to obtain a temperature 10° to 15° higher than in the old type of condenser. This is due to the temperature in the upper sections of the condenser being higher than in the lowest section and as the bulk of the condensing is done in the first two compartments, only a small amount of very cold condensate is given off to reduce the temperature of the whole.

How far it is economical to carry a vacuum depends upon the power expended in the auxiliaries to produce it. The amount and head against which the circulating water has to be pumped is the large factor in this determination, as the most economical speed for the air pump remains about constant. Any condenser that maintains the highest vacuum with an equal amount of circulating water or that maintains the same vacuum with a less amount of circulating water is the most economical. Since the same vacuum can be maintained with a less amount of circulating water the power expended for pumping is necessarily less and a saving is thereby effected. The most economical vacuum will be the one where an increase of circulating water has a very small effect in vacuum or where the curve between vacuum and circulating water becomes flat or nearly so.

The surface section ratio is the relation of the surface of the effective tube length to the cross sectional area

of the bore of the tube. The results showed that the larger this ratio was, the larger the vacuum obtained. This would naturally be expected because the water core would be smaller and more surface exposed for absorbing heat. By the use of triangular cores the exposed surface was made even greater but this gave results the same as though the size of the tubes had been changed so as to give the same surface section ratio.

The best conclusions deduced by Prof. Weighton are included here.

"(1.) It is conducive to efficiency in a surface condenser that the water resulting from condensation (condensate) should be intercepted and removed from the condenser as soon as possible after it is formed.

"(2.) It is conducive to efficiency that the condenser capacity should be a minimum consistent with the accommodation of the necessary surface, and that the design should be such as to secure a pervading and uniform flow of vapour throughout the condenser section, thus utilizing the whole of the condensing surface provided, as well as obviating stagnant recesses in which air might be retained.

"(3.) It is conducive to efficiency that the condensing water should travel at a fairly high speed thru the tubes, and that it should enter at the bottom and leave at the top of the condenser.

"(4.) With suitable condenser design and proportions, the temperature of the condensing water at the discharge point may be equal to, or slightly higher than, the

temperature due to the vacuum. This holds true for vacuua up to slightly over 29 in.

"(5.) With suitable condenser design and proportions, the temperature of the hot-well may be from 3° to 5° higher than the temperature due to the vacuum. This holds true for vacuua up to slightly over 29 in.

"(6.) With suitable condenser arrangements, and a reasonably air tight system, there is nothing gained in efficiency by the use of air pumps exceeding in capacity 0.7 of a cubic foot per pound of steam condensed (condensate), up to a limit of close upon 29 in. vacuum. For vacuua exceeding this limit, or for cases in which air leakage is considerable, the air pump capacity must be increased or else the vacuum efficiency will fall.

Description of Apparatus.

The apparatus consisted of a surface condenser made by Henry P. Worthington containing 127 brass tubes 5/8" external diameter and 0.55" internal diameter in the upper section and 132 tubes in the lower section, all 8'-7" long. The circulating water passed thru the lower section and then back thru the upper section. This is clearly shown in the photograph on page # 18 which also shows the wier used for measuring the amount of flow. The circulating water was pumped from the Bone-yard Creek thru a suction pipe about 100 ft. long with

8 or 10 ft. of raise. The temperature of the water was measured before entering the pump. A thermometer just in front of the flange connection, partly seen in the photo, measured the outlet temperature. The circulating and air pumps were two 6" x 9" x 10" Blake simplex pumps. The condensate and air were pumped by the air pump and the condensate was measured by a tank and scales. One end of this tank can be seen in the photo on page # 17 . The temperature of the condensate was measured by the thermometer in the discharge pipe as shown in this same photo.

Steam was taken from the Laboratory supply main and throttled by the gate valve shown at A in the photo on page # 17. The quality of the steam was measured by a throttling calorimeter. A thermometer in the top of the tee shown at B in the photo on page # 17 was found to give such erratic readings that nothing could be deduced from them.

The vacuum was measured by mercury columns having separators in between the connections so as to keep water from getting on top of the mercury and producing an error in the readings. The vacuua was taken at four points, the two ends, the bottom and the tee shown at B in the photo on page # 17 By this means the action inside of the condenser was quite well known at all times.

The circulating water was measured by a wier with a suitable channel for eliminating velocity of approach. The head above the crest of the wier was measured by a hook gage

reading to one hundredths of an inch.

Tests were run with a constant flow of steam and varying the amount of circulating water. Readings were taken every ten minutes and tests were from an hour to an hour and forty minutes long. Care was taken to maintain all the conditions as constant as possible during a test.

Work Done.

Only a few tests were run on this thesis as trouble was experienced from the first by tubes splitting and at other times it was impossible to get steam without interfering with other work.

Method of Testing.

The auxiliaries were started and set to maintain the desired velocity in the tubes in the upper section of the tubes as shown in the drawing on page # 16. The steam was then turned on and the flow regulated to the constant amount desired. The flow of circulating water was measured by the wier and hook gage. The condensate was measured by a large tank and scales. The pressure and quality of the steam was taken before throttling and the condenser was assumed, on account of the close connection, to absorb all the heat in the steam except that in the condensate.

Data.

Readings were taken every ten minutes as follows:

1. Vacuum.

   Top, Bottom and both Ends.

2. Steam.

   Pressure and Quality by throttling calorimeter.

3. Condensate.

   Weight and Temperature.

4. Cooling Water.

   Temperature entering and leaving.

   Amount by Hook Gage on Wier.

This data was corrected and averaged and is tabulated in condensed form for each test on page # 20.

The results are shown graphically by the curves drawn. It will be seen that for the constant flow of condensate the most economical vacuum was realized when maintained at 25.5" and about 38# of circulating water per lb. of condensate. The condenser efficiency is taken as the relation between the total heat in the condensate over the total heat in the steam. The average vacuum was taken as that existing between the two ends and the bottom as shown by averaging those readings.

Further Study.

Method.

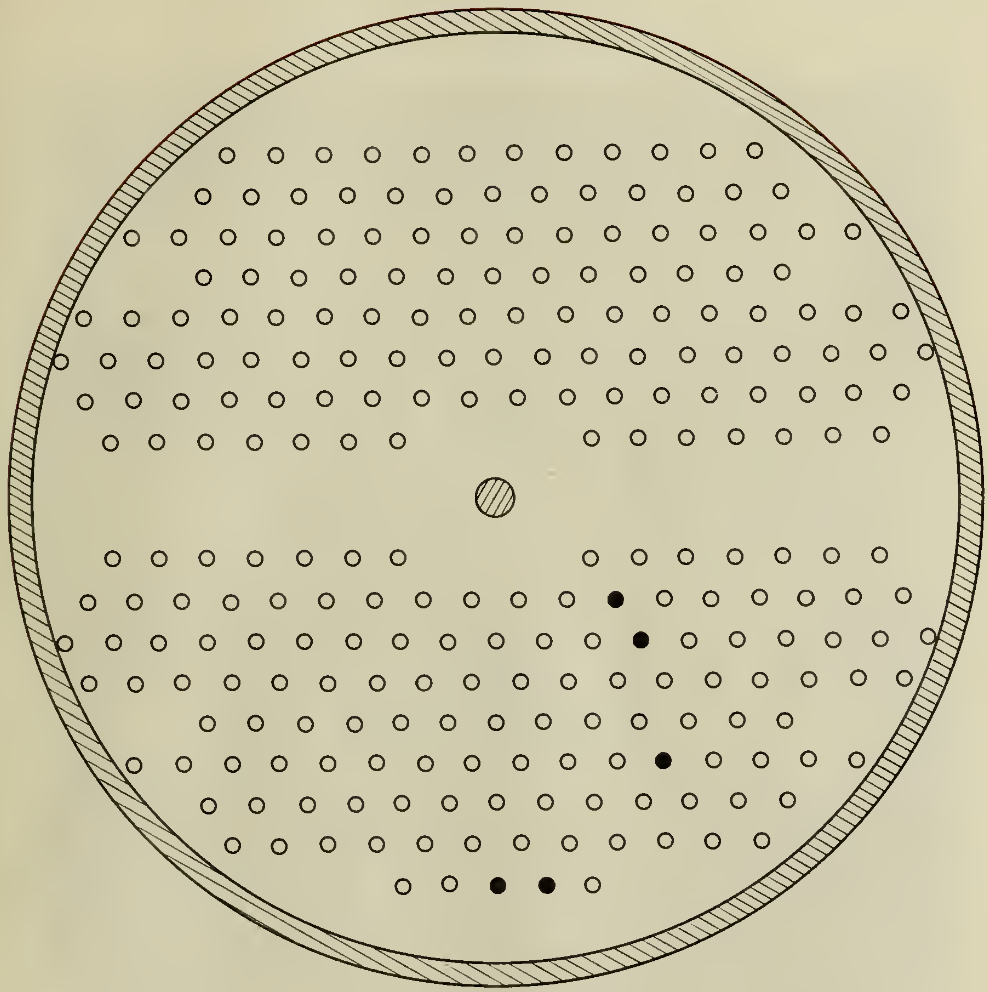
The work accomplished is in reality not much more than a good preliminary test. Had time permitted, study would have been continued under much better conditions. A large number of tests were contemplated to show the relations of some of the constructive variables as well as the absolute.

Apparatus.

The method of steam supply was to be changed. It was intended to install two pressure reducing valves of the best type made by the Foster Engineering Co. The first one was to be set so as to maintain the supply pressure at 100 pounds. The quality of this steam was to be determined as before by calorimeter. The second pressure reducing valve was to reduce the pressure from 100 to 2 or 5 pounds. At this known constant pressure sizes of orifices were to be calculated and then installed for giving various constant rates of steam flow. Two stop valves were to be placed in the connecting line in order to make sure of being able to shut off the supply and prevent it from leaking into the condenser and keeping it hot. No make-shifts were to be accepted. Before starting in on the work the assurance of having the apparatus for our exclusive use was to be secured. The auxiliaries were to have been gone over and put in the best possible condition. Once in good condition it was to be kept so, so as to get uniform

action. All apparatus was to be calibrated and extra thermometers procured for all positions. The new heads for changing from a two pass to a three pass condenser were to be procured from the manufacturers. The steam entrance was to be changed to the ends and the best position determined. By taking out or plugging up tubes, the section was to be changed and thus attempt to prove that by keeping the condensate from trickling over the tubes the efficiency is increased. Results were to be kept worked up and all conditions kept familiar, so that what was taking place was known all the time.

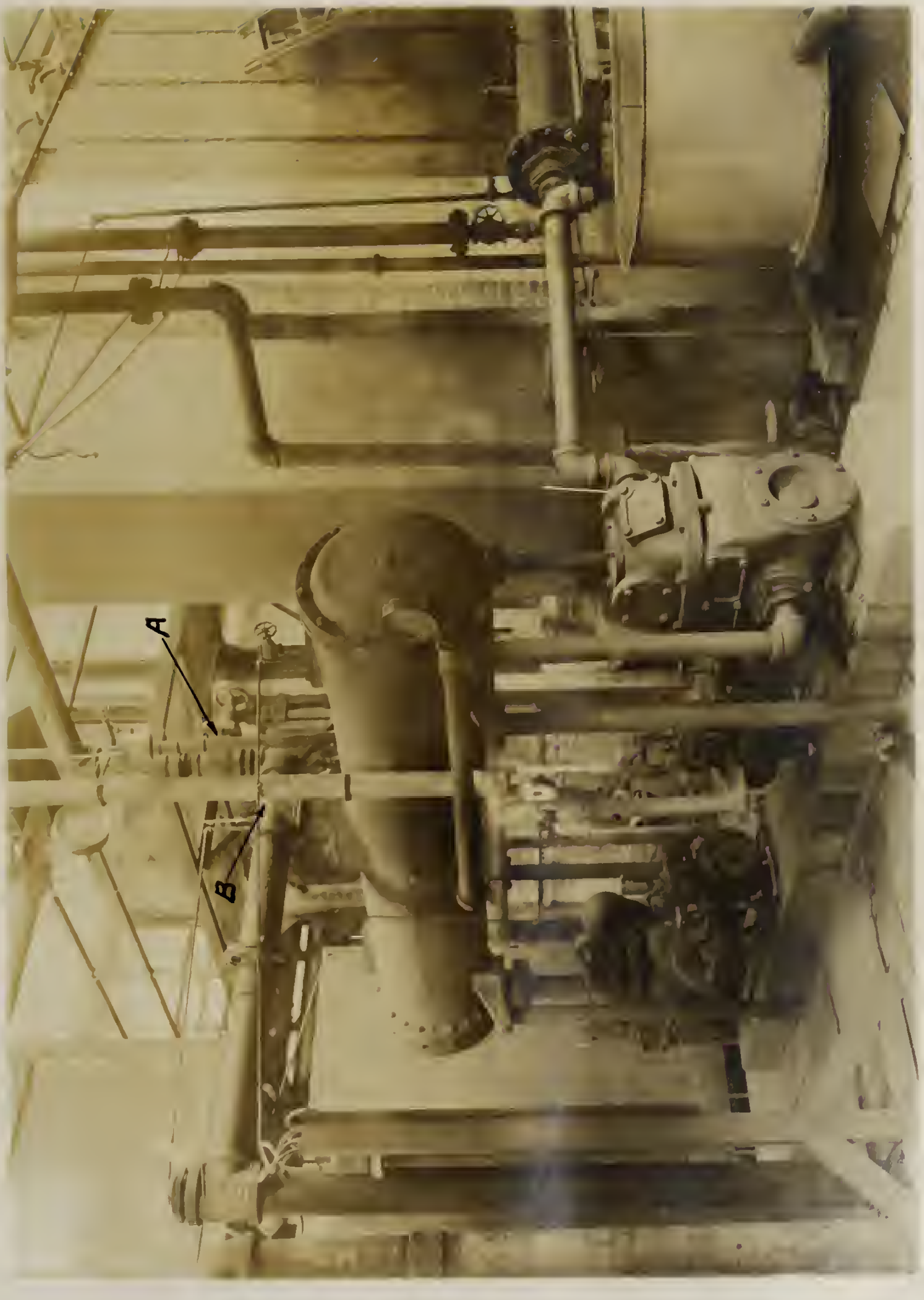
On account of accidents to the apparatus and the inability to work independently of other tests in the Laboratory it was impossible to complete the work as above outlined. The results given herein therefore are those obtained in the preliminary study, only.

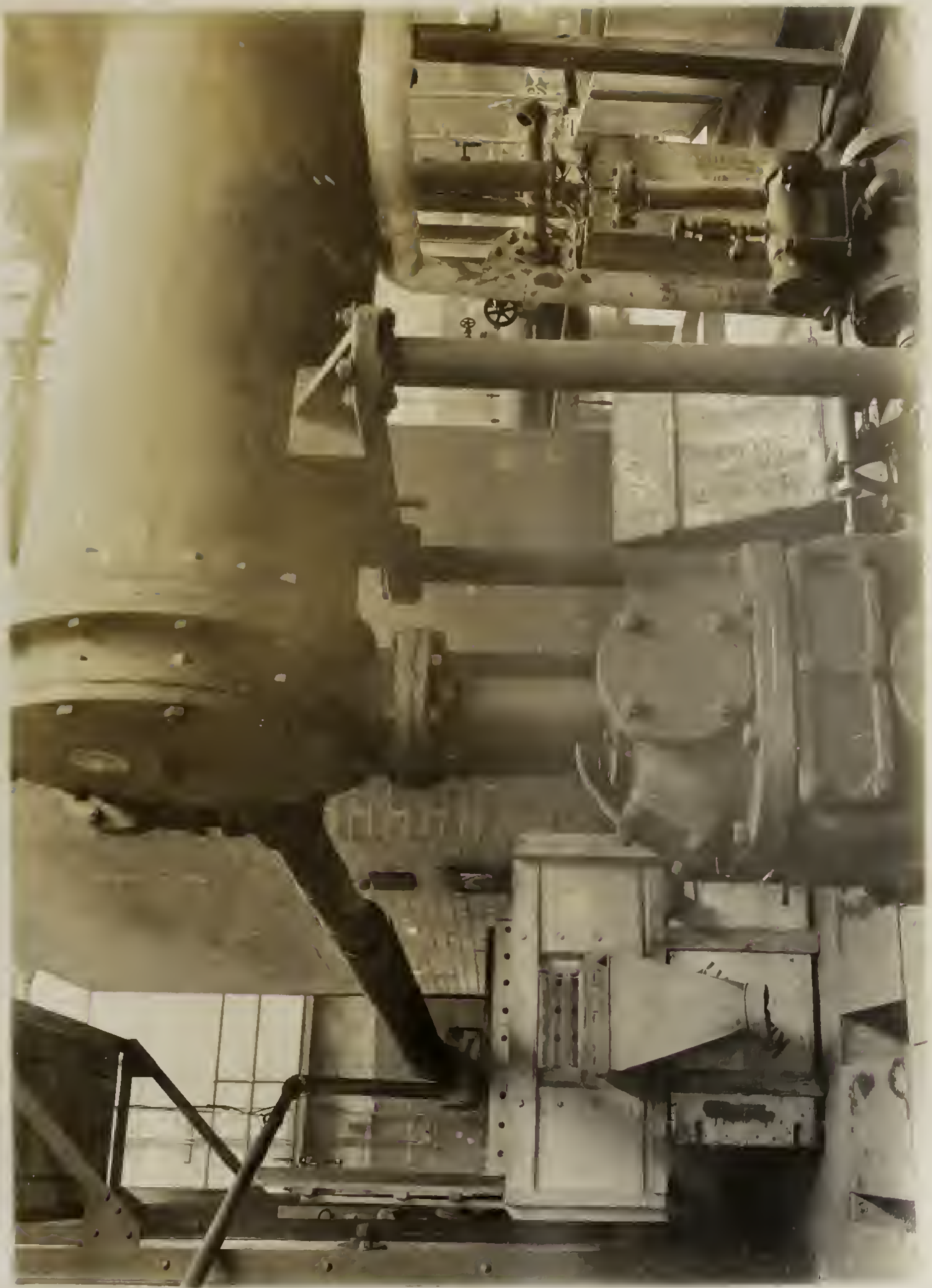


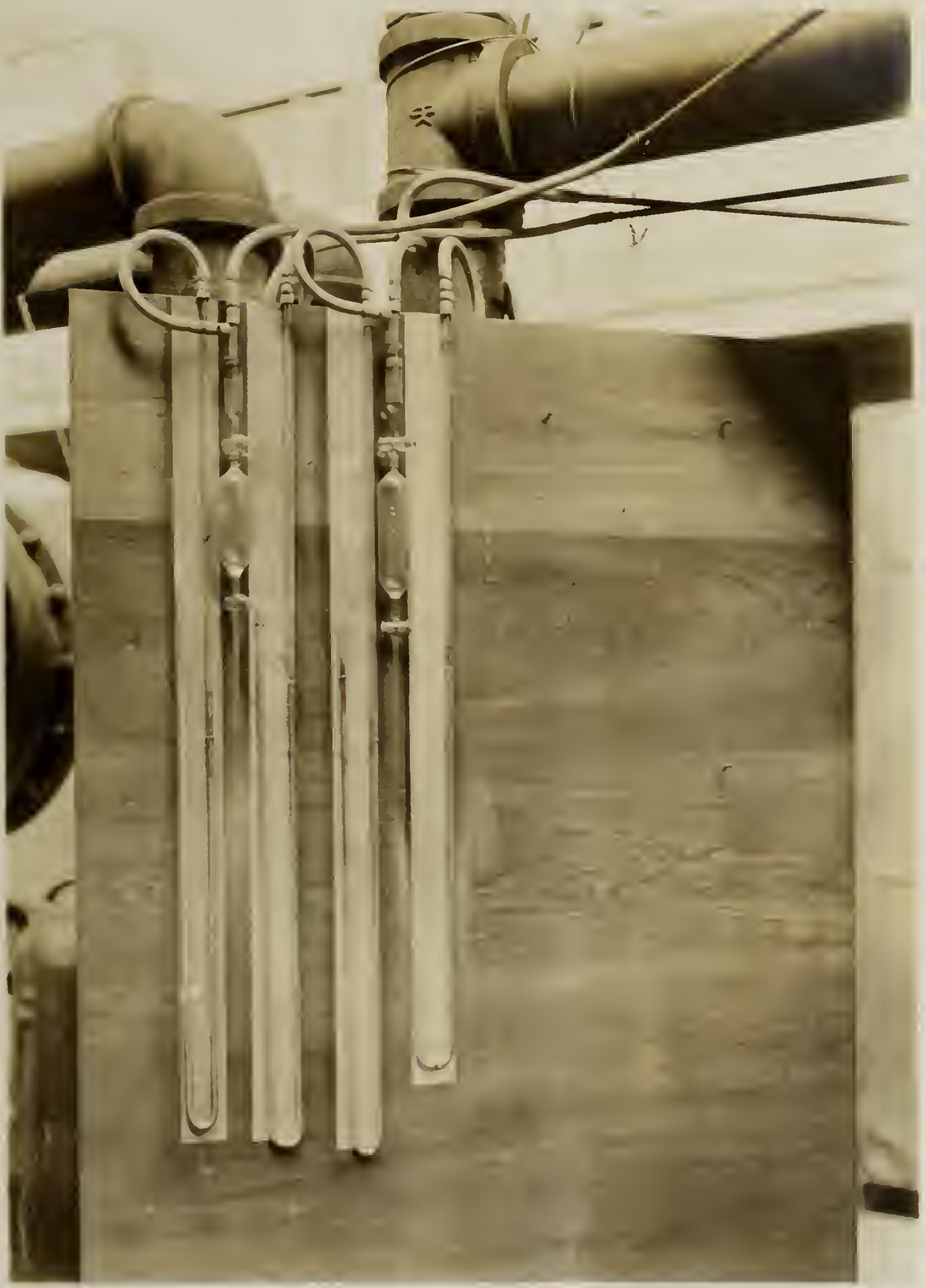
CROSS SECTION OF CONDENSER.

Scale:— 3" = 1'.

Outside Diameter of Condenser Shell — 20¼".
Inside Diameter of Condenser Shell — 19¼".
Nº of Tubes: Upper Section – 127; Lower Section – 132.
Outside Diameter of Tubes:- .625" ; Inside Diameter — .550"
● Plugged Tubes.


A
B





TRIAL		Barometer. Inches of Mercury	VACUUM (Inches of Mercury)						TEMPERATURE.			CONDENSING WATER.		Condensed Steam. Lbs per Hr.	Lbs of Water per Lb of Steam.	Lbs of Steam per Sq. Ft Surface	Condensing Efficiency. η.
			As Recorded.				Average.	V_a reduced to 30" barometer.	Hot-well.	Condensing Water.		Maximum speed in Tube in ft/sec.	Quantity. Lbs per hr.				
Date.	Nº		Top.	Btm.	Left.	Right.				Inlet	Outlet.						
		B	V_t	V_b	V_l	V_r	V_a	V	T_H	T_i	T_o		Q	$W.$			$\frac{\lambda - q_{H.W}}{\lambda}$
April 9	2	29.38	20.03	22.15	21.94	22.22	22.10	22.60	129.55	68.40	128.8	0.780	36,720	2141	17.14	5.90	0.913
May 4	2A.	29.18	18.60	18.80	19.12	19.08	19.00	19.55	149.65	66.91	167.68	0.805	37,850	2137	17.74	5.88	0.897
April 6	1	28.94	21.60	23.78	23.58	24.56	23.97	24.85	111.15	60.61	111.40	1.115	52,500	1853	28.30	5.10	0.932
April 16	A.	29.20	22.21	22.95	23.40	23.55	23.30	23.97	113.78	62.50	124.80	1.113	53,200	2008	26.50	5.72	0.928
May 4	1A	29.16	22.28	23.52	22.97	23.00	23.16	23.83	83.05	65.20	118.45	1.160	54,600	2156	25.35	5.92	0.955
May 3	3A	29.06	22.63	24.53	24.83	24.93	24.76	25.54	99.40	55.60	98.71	1.690	79,500	2250	35.30	6.20	0.933
April 9	3	29.35	22.69	24.55	25.17	25.24	24.99	25.53	91.81	69.00	89.46	1.770	83.350	2220	37.55	6.11	0.949
April 9	4	29.35	22.79	24.76	25.44	26.38	25.53	26.10	81.64	50.25	68.20	2.760	129,900	2085	62.30	5.74	0.955
April 24	6	29.35	24.46	25.35	26.21	26.35	25.94	26.52	85.06	59.40	77.90	3.260	153,400	2016	76.30	5.55	0.953
April 10	5	29.51	23.87	26.28	26.91	26.95	26.71	27.15	68.40	48.46	65.80	3.450	162,400	2145	75.70	5.90	0.968

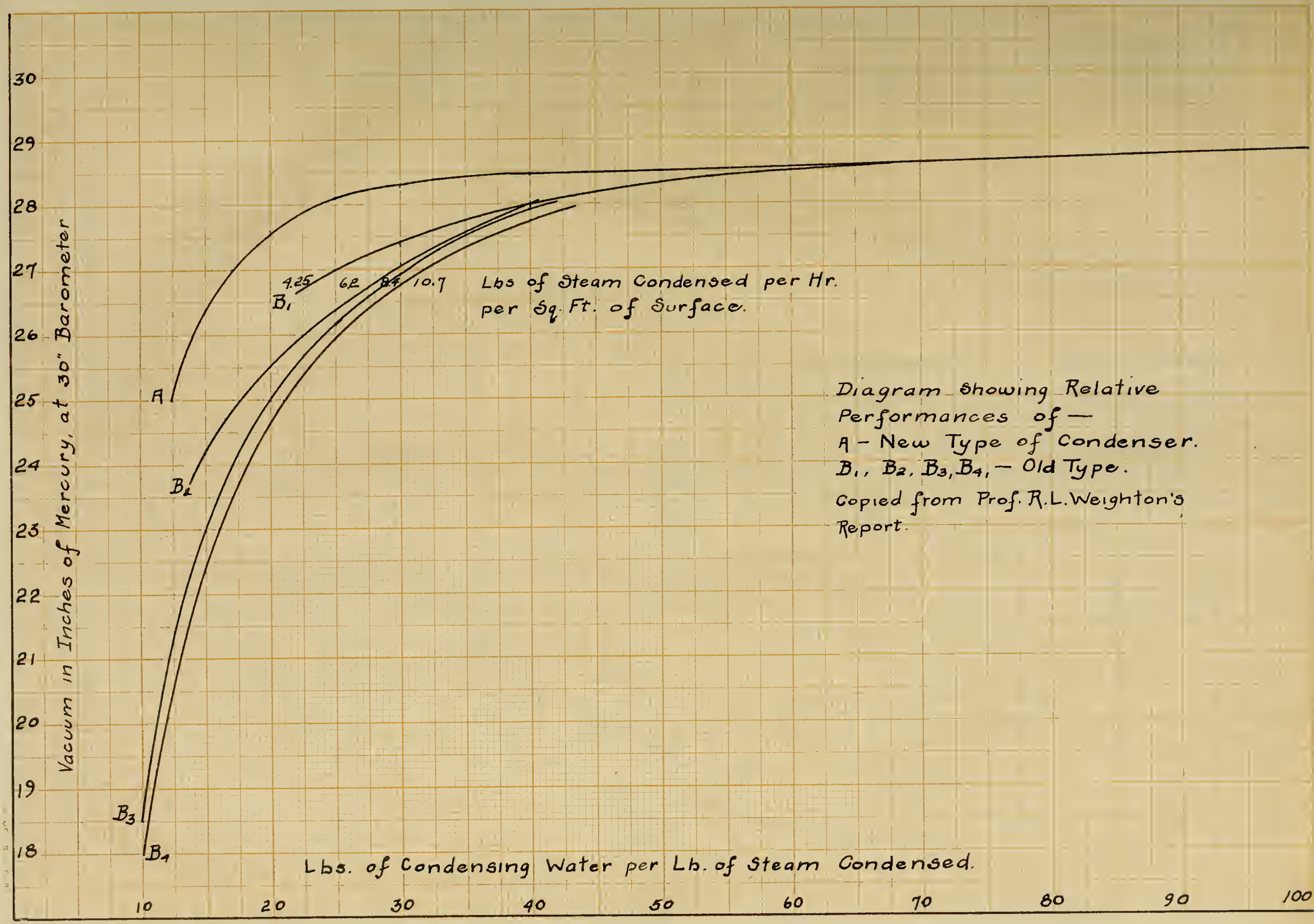
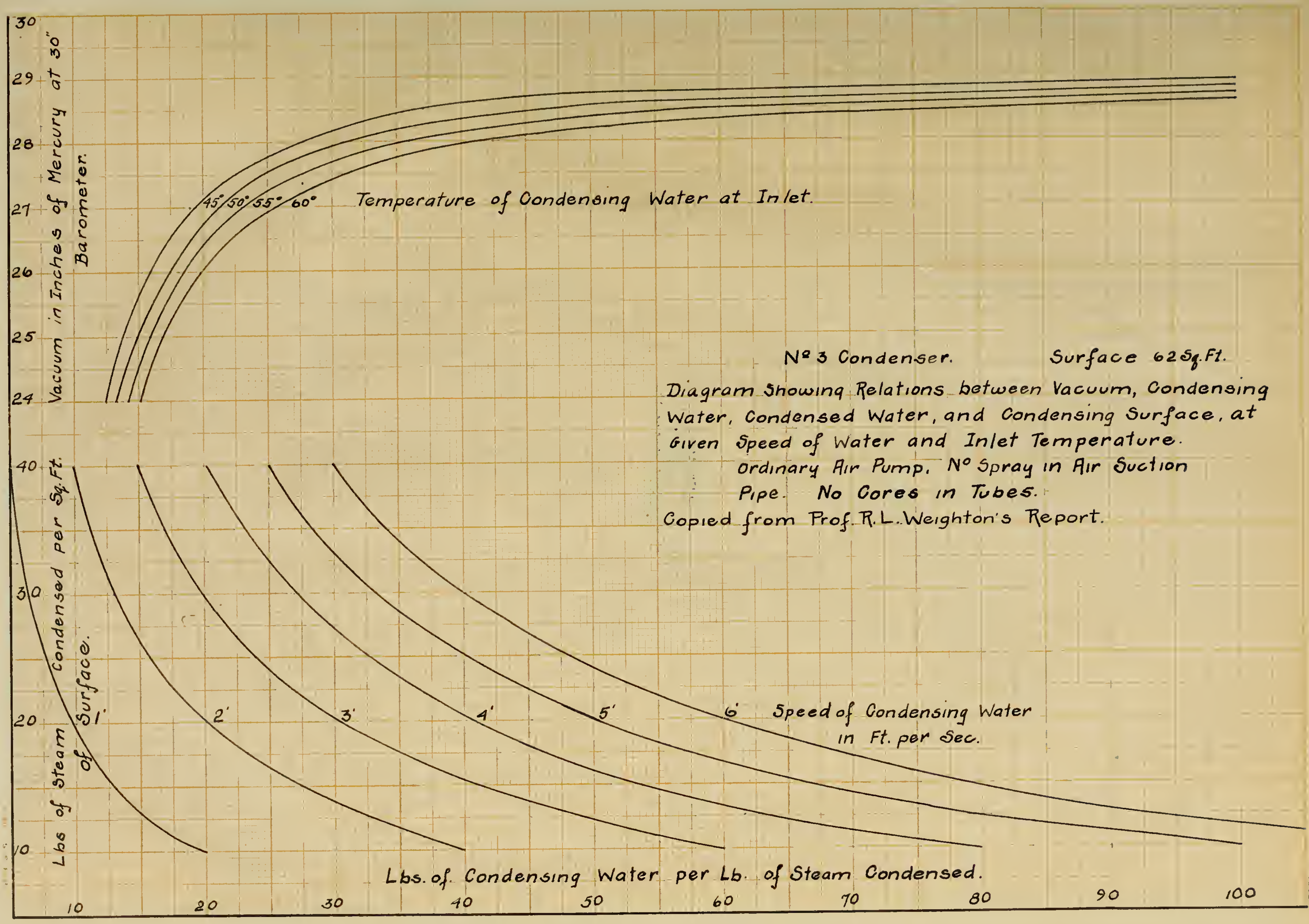
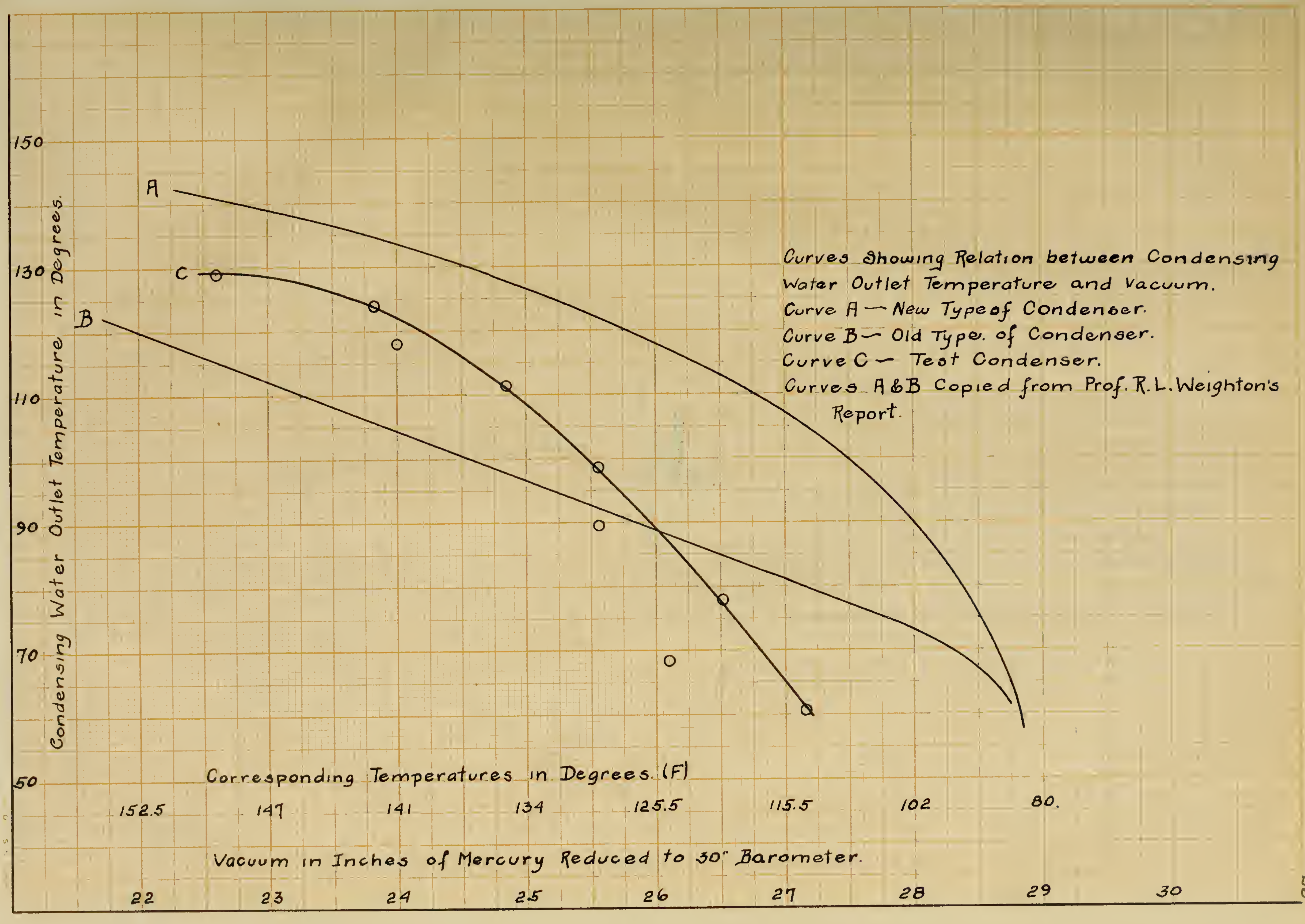


Diagram showing Relative Performances of —
A – New Type of Condenser.
B1, B2, B3, B4, – Old Type.
Copied from Prof. R.L. Weighton's Report.
Vacuum in Inches of Mercury, at 30" Barometer
Lbs. of Condensing Water per Lb. of Steam Condensed.
Lbs of Steam Condensed per Hr. per Sq. Ft. of Surface.
4.25
6.2
8.4
10.7
A
B1
B2
B3
B4
30
29
28
27
26
25
24
23
22
21
20
19
18
10
20
30
40
50
60
70
80
90
100


Nº 3 Condenser.
Surface 62 Sq. Ft.
Diagram Showing Relations between Vacuum, Condensing Water, Condensed Water, and Condensing Surface, at Given Speed of Water and Inlet Temperature.
Ordinary Air Pump. Nº Spray in Air Suction Pipe. No Cores in Tubes.
Copied from Prof. R.L. Weighton's Report.
Vacuum in Inches of Mercury at 30" Barometer.
30
29
28
27
26
25
24
45° 50° 55° 60°
Temperature of Condensing Water at Inlet.
Lbs of Steam Condensed per Sq. Ft. of Surface.
40
30
20
10
1'
2'
3'
4'
5'
6'
Speed of Condensing Water in Ft. per Sec.
Lbs. of Condensing Water per Lb. of Steam Condensed.
10
20
30
40
50
60
70
80
90
100


Curves Showing Relation between Condensing Water Outlet Temperature and Vacuum.
Curve A — New Type of Condenser.
Curve B — Old Type of Condenser.
Curve C — Test Condenser.
Curves A&B Copied from Prof. R.L. Weighton's Report.
A
B
C
Condensing Water Outlet Temperature in Degrees.
150
130
110
90
70
50
Corresponding Temperatures in Degrees (F)
152.5
147
141
134
125.5
115.5
102
80.
Vacuum in Inches of Mercury Reduced to 30" Barometer.
22
23
24
25
26
27
28
29
30

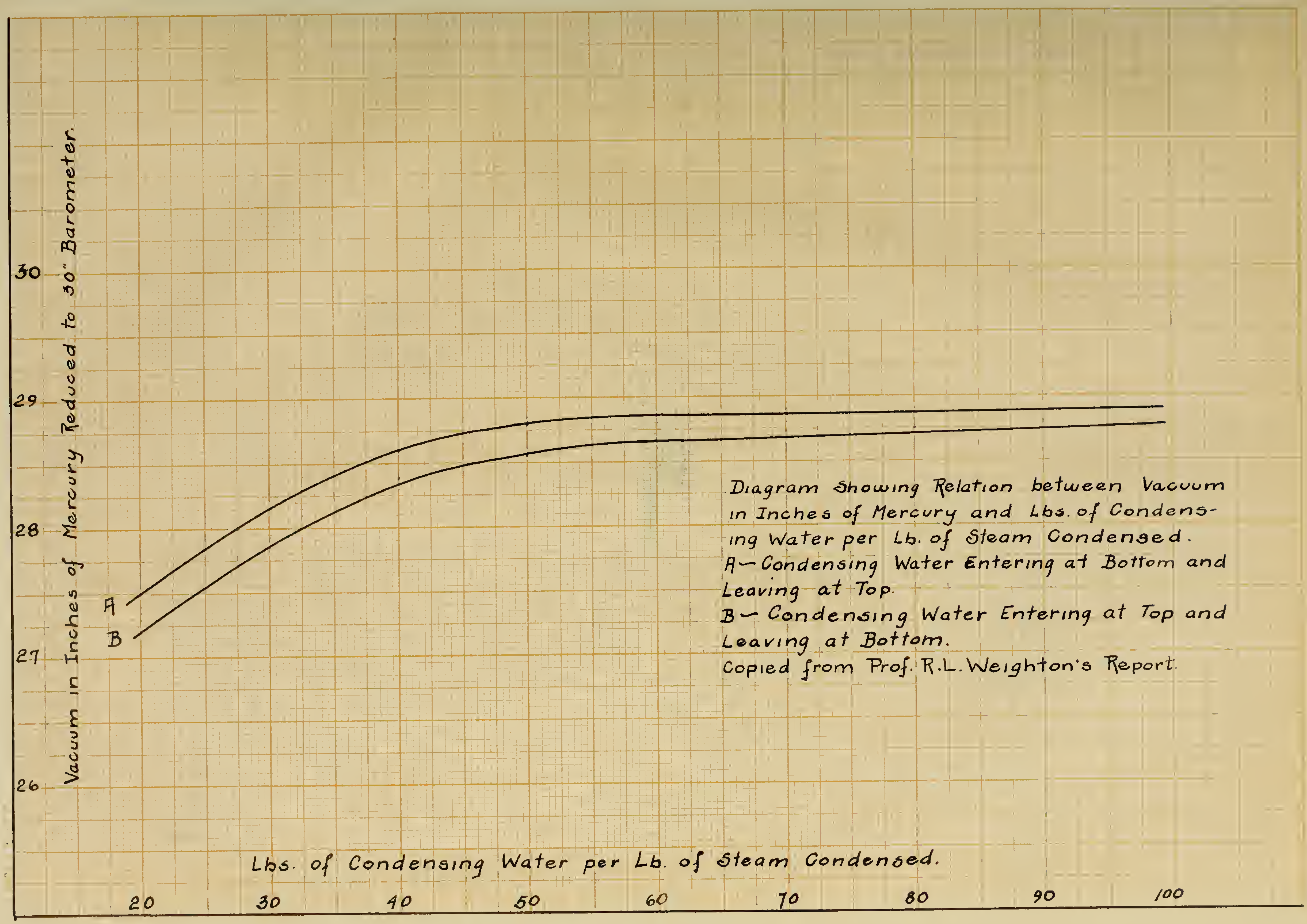
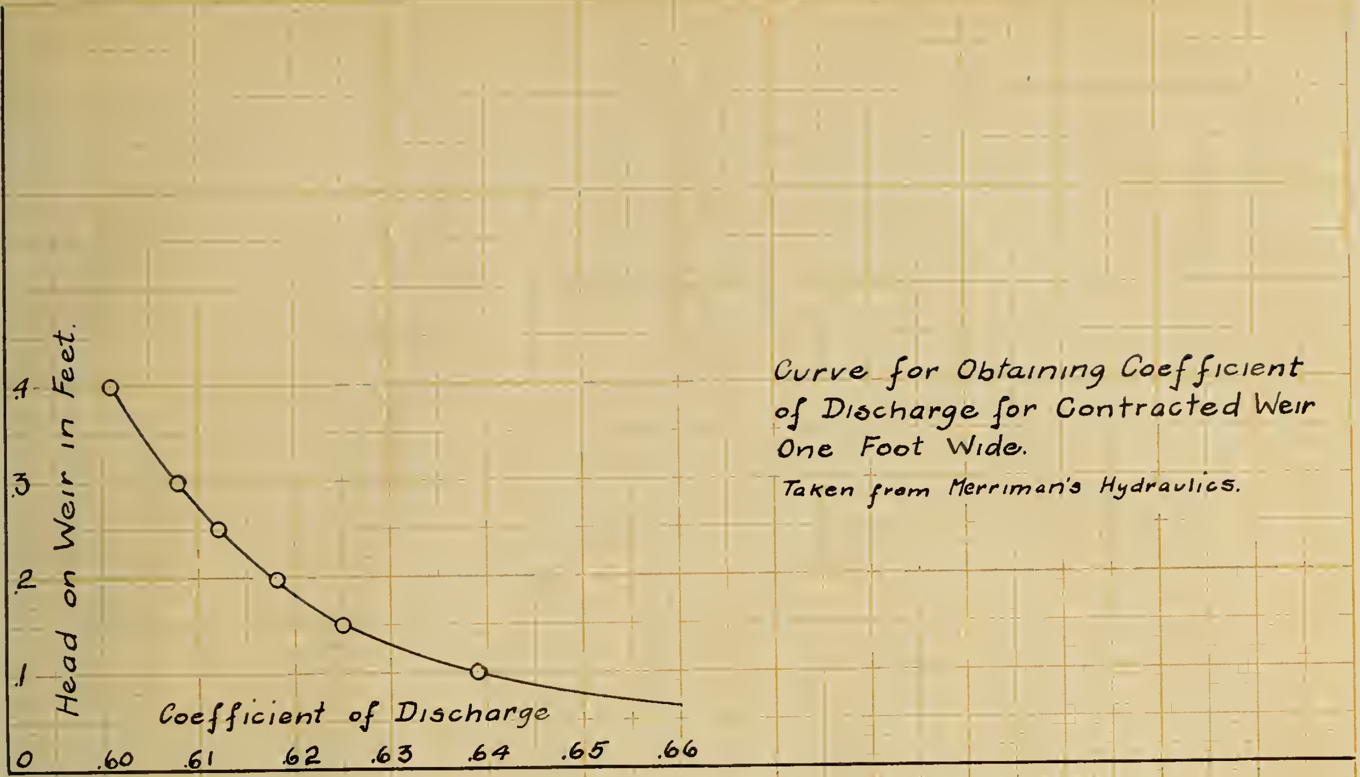
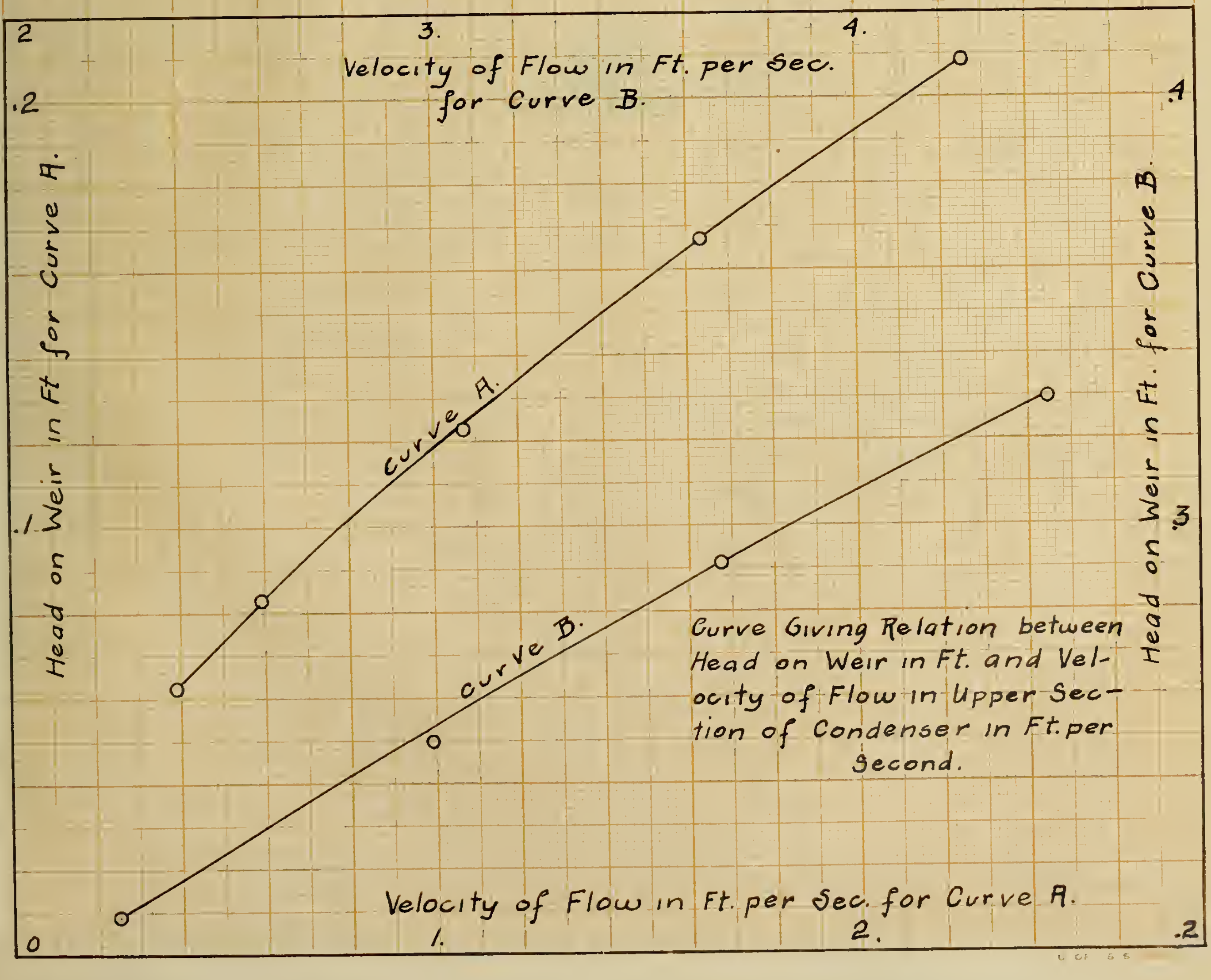
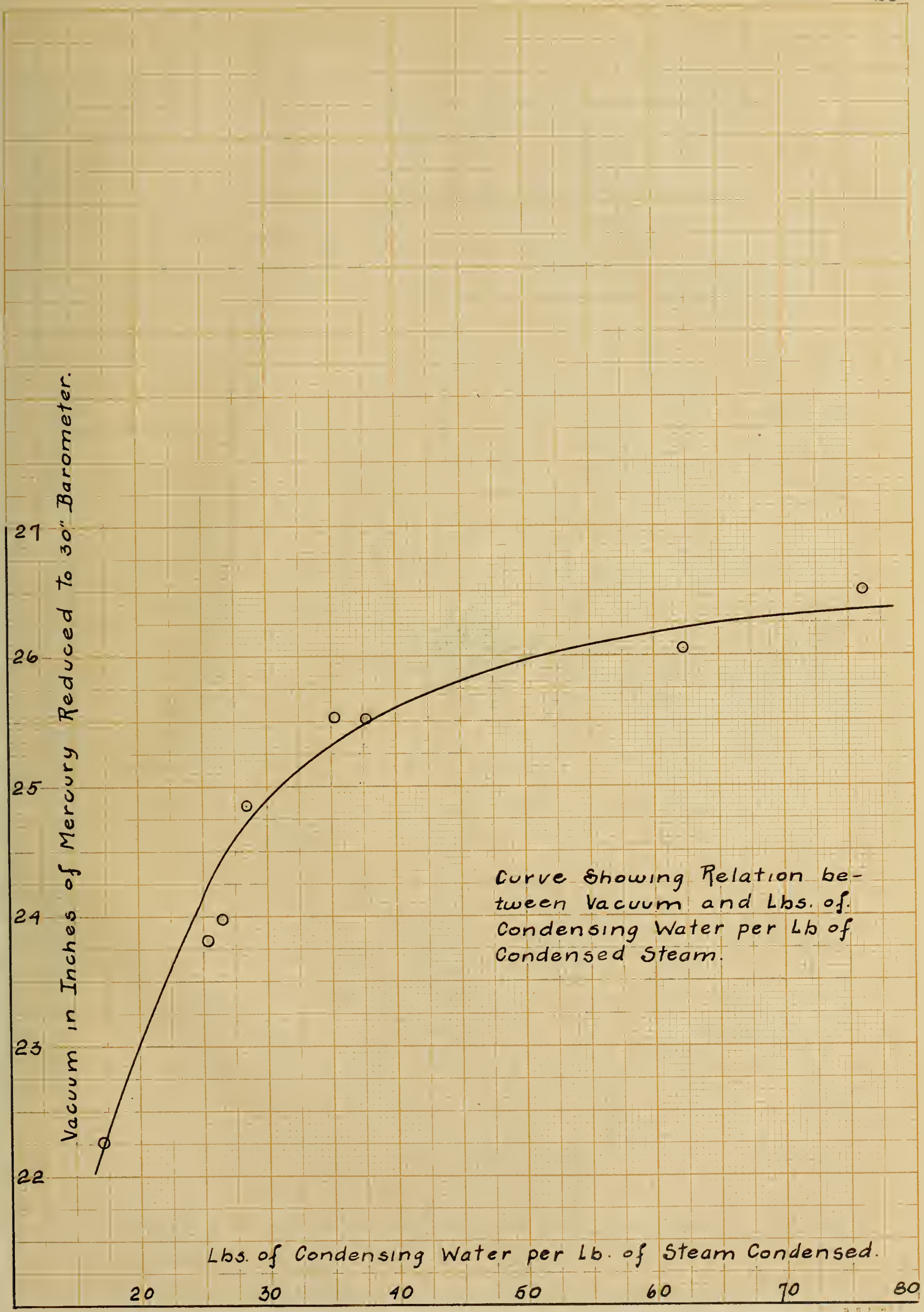
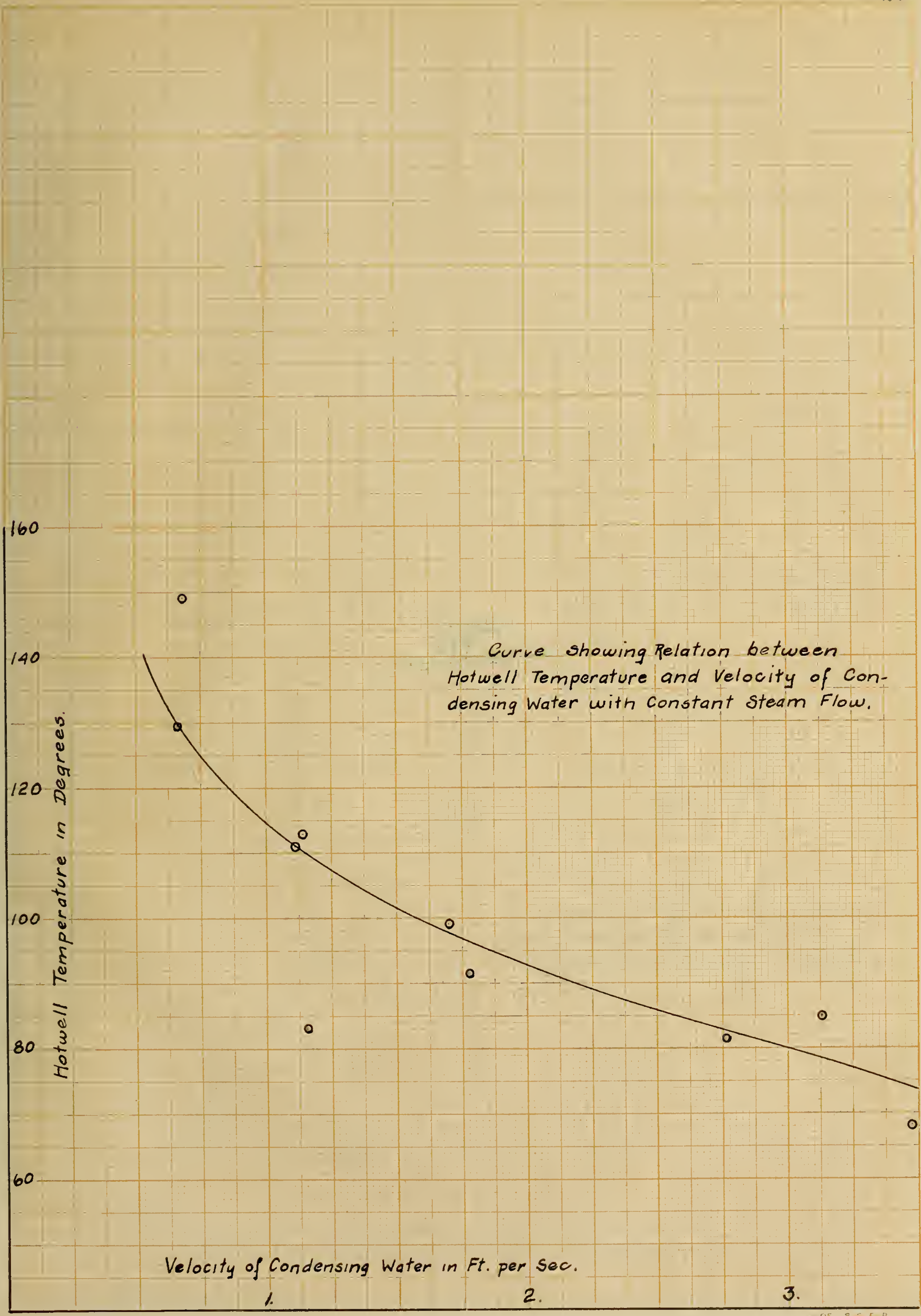


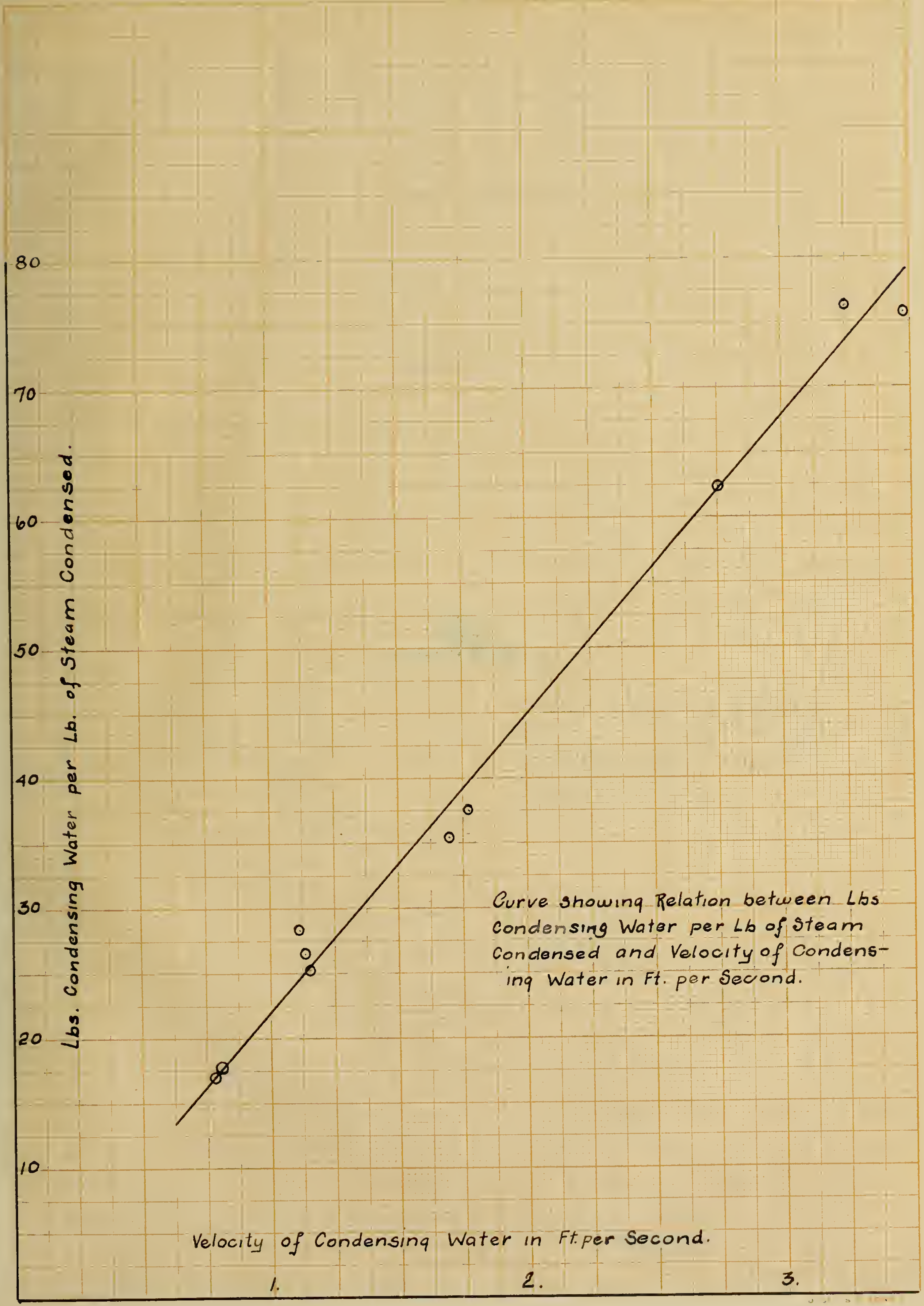
Diagram Showing Relation between Vacuum in Inches of Mercury and Lbs. of Condensing Water per Lb. of Steam Condensed.
A — Condensing Water Entering at Bottom and Leaving at Top.
B — Condensing Water Entering at Top and Leaving at Bottom.
Copied from Prof. R.L. Weighton's Report.
Vacuum in Inches of Mercury Reduced to 30" Barometer.
Lbs. of Condensing Water per Lb. of Steam Condensed.
A
B
30
29
28
27
26
20
30
40
50
60
70
80
90
100

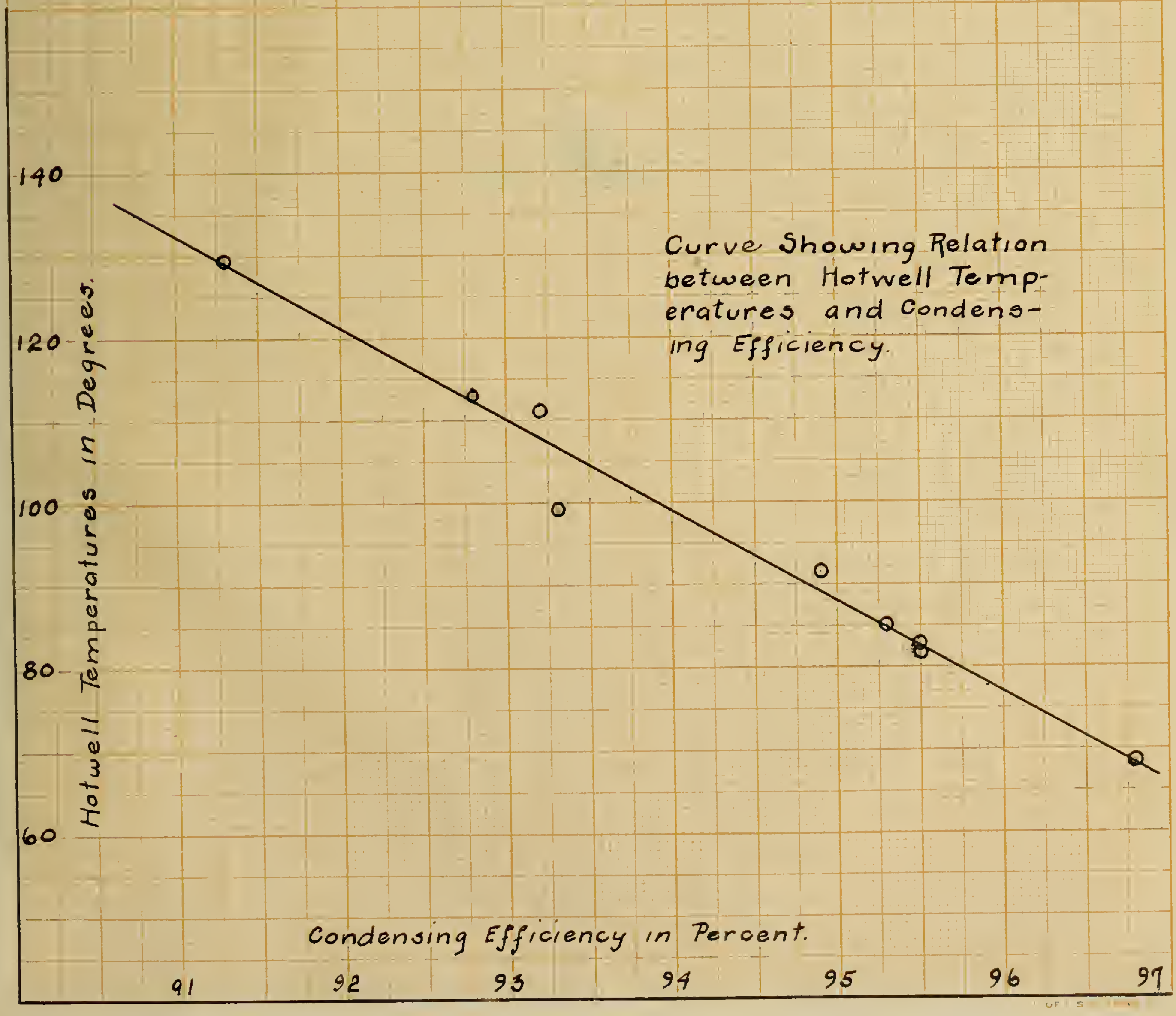

Curve for Obtaining Coefficient of Discharge for Contracted Weir One Foot Wide.
Taken from Merriman's Hydraulics.
Head on Weir in Feet.
Coefficient of Discharge
0
.1
.2
.3
.4
.60
.61
.62
.63
.64
.65
.66


Velocity of Flow in Ft. per Sec. for Curve B.
2
3.
4.
.2
.1
0
Head on Weir in Ft for Curve A.
Head on Weir in Ft. for Curve B.
.4
.3
.2
Curve A.
Curve B.
Curve Giving Relation between Head on Weir in Ft. and Velocity of Flow in Upper Section of Condenser in Ft. per Second.
Velocity of Flow in Ft. per Sec. for Curve A.
1.
2.


Vacuum in Inches of Mercury Reduced to 30" Barometer.
27
26
25
24
23
22
Curve Showing Relation between Vacuum and Lbs. of Condensing Water per Lb of Condensed Steam.
Lbs. of Condensing Water per Lb. of Steam Condensed.
20
30
40
50
60
70
80


Curve showing Relation between Hotwell Temperature and Velocity of Condensing Water with Constant Steam Flow.
Hotwell Temperature in Degrees.
160
140
120
100
80
60
Velocity of Condensing Water in Ft. per Sec.
1.
2.
3.


80
70
60
50
40
30
20
10
Lbs. Condensing Water per Lb. of Steam Condensed.
Curve showing Relation between Lbs Condensing Water per Lb of Steam Condensed and Velocity of Condensing Water in Ft. per Second.
Velocity of Condensing Water in Ft. per Second.
1.
2.
3.


Curve Showing Relation between Hotwell Temperatures and Condensing Efficiency.
Hotwell Temperatures in Degrees.
Condensing Efficiency in Percent.
140
120
100
80
60
91
92
93
94
95
96
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