ECONOMY CHARACTERISTICS OF V.P.I.
TURBO-GENERATOR UNITS

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

MASTER OF SCIENCE

in

Mechanical Engineering

BY

CALVIN C. GREENE

and

GEORGE W. SWITZER

Approved:

Head of the Department
of Heat and Power

Dean of Engineering

Chairman, Committee on
Graduate Programs and
Degrees

Virginia Polytechnic Institute

1937

PREFACE

The Heating and Power Plant of the Virginia Polytechnic Institute has two types of steam turbo-generating units, either of which is capable of supplying low-pressure steam for heating and at the same time generating electrical power as demanded by the Institute and the City of Blacksburg. The two turbines of dissimilar types, were chosen with a view toward meeting seasonal variations in both load demands with best economy. However, the selection of one or the other of the units for use at a given time has heretofore been based on the judgment of the plant personnel with very little concrete data as a guide. Since the power generating unit takes approximately one-third to a half of the steam generated in the boiler room, the authors believed that here was a vulnerable point to effect economies in operation.

The authors wish to express their sincere appreciation for the cooperation and suggestions given by the following:

Prof. W. T. Ellis, Head of the Dept. of Heat and Power, Virginia Polytechnic Institute.

Mr. E. H. Wheat, Engineer, Virginia Polytechnic Institute, Heating and Power Plant.

Mr. B. G. Brooe, Foreman, Virginia Polytechnic Institute, Heating and Power Plant.

TABLE OF CONTENTS

INDEX TO FIGURES AND CHARTS

INTRODUCTION

In the operation of combined heating and power plants, there are two serious threats to economy as measured by fuel consumption for the service rendered. These are loss of exhaust steam to the atmosphere and, less serious, exhaust of steam to a condenser. The greater part of the heat supplied to the steam in the form of latent heat by the boilers is lost in either case. Use of exhaust steam for heating makes available a maximum amount of heat to useful purpose and consequently shows decided economical advantages over systems wherein the heating and power supplies are separate. Still further economies are possible by operating units having the best possible economy characteristics at the particular load range in question at any time.

As often happens when the electrical and exhaust steam requirements vary considerably, two dissimilar types of units must be installed to maintain satisfactory economy over the complete range of load demand on the plant. When the capacities of two such units are equal or overlap in some portion of the demand range, it is evident that there should be some load condition at which either of the units could be operated with equal economy; below which condition, one unit would show the better economy, and above which, the other unit would be more suitable.

The Virginia Polytechnic Institute Heating and Power Plant has one back-pressure turbine and one condensing, bleeder-type turbine. Either of these units is capable of carrying the present electrical load. When, due to electrical load limitations, the low-pressure steam available is insufficient, the reducing valves installed enable either of the units to satisfactorily supply this low-pressure steam demand. However, at high electrical and low low-pressure demands, the back-pressure unit will discharge part of its exhaust steam to the atmosphere, while the condensing unit will discharge the excess supply, over and above the low-pressure demand, into the condenser. In the condenser, the circulating water removes the latent heat of the steam. The problem, then, is one of obtaining a quantitative comparison of the two machines throughout the range of seasonal variation of both electrical and low-pressure loads.

The authors believe that the investigation will lead to fairly accurate results which, if used as a guide in operation, will aid considerably in preventing possible future fuel waste from the operation of the wrong unit for any particular set of conditions.

THE INVESTIGATION

Object

The object of the investigation was to obtain data in order to determine the relative economies of the units. It was desired to determine the characteristics over the entire range of both electrical and low-pressure demands on the plant. It seemed likely that daily plant records and tests on the machines, coordinated wherever possible, would give sufficient data to accomplish this object.

General Consideration of the Factors Involved

Steam flow to the main unit is, of course, of primary importance in comparing machines giving the same output in electrical power and useful low-pressure steam. When the heating steam demand is low, however, the Westinghouse condensing bleeder turbine supplies this demand after extracting some heat for power in the first stages, then expands the excess to the vacuum in the condenser. This extracts more of the heat per pound of throttle flow in the form of power. The Allis-Chalmers back-pressure turbine, under the same conditions, wastes the excess amount of its exhaust to the atmosphere. With this waste, the greater portion of the heat supplied, by the boiler, to each pound of wasted steam is lost. By expanding a portion of its throttle flow to a vacuum, the net throttle flow to maintain speed under any given electrical load is less for the Westinghouse unit. However, at high heating steam demands, the fact that the Westinghouse unit bleeds the low-pressure steam against the same pressure as the exhaust of the back-pressure unit, low-pressure demand being equal, the available heat drop per unit mass of the bled steam is theoretically the same. The steam is bled to the low-pressure header after passing through two velocity stages in one impulse stage while in the Allis-Chalmers turbine, a reaction-bladed machine, the total throttle flow must exhaust against the pressure in the low-pressure header. In the higher ranges of low-pressure demand with moderate or low electrical load, the bleeder valve on the Westinghouse will be fully open although part of the steam is allowed to go through to the condenser to cool the reaction stages. This is arranged through an opening in the diaphragm between the impulse and the reaction blades. High low-pressure demand with lower electrical loads may exceed the maximum bleeding capacity of the Westinghouse unit and still be within the capabilities of the back-pressure unit. This is because of the decrease in water rate through condensing part of the throttle flow on the bleeder unit. Another factor to be considered is that at high electrical and high heating steam loads, it is necessary to close, either manually or automatically, the bleeder valve and run at a greater degree condensing in order to maintain the proper frequency on the bleeder turbine. High electrical loads on the back-pressure machine have just the opposite effect, making more low-pressure steam available to the heating mains. In the event that either machine is unable, because of frequency and electrical load governing, to supply sufficient low-pressure steam to maintain the desired header pressure, a reducing valve opens from the high-pressure header and admits the deficiency to the low-pressure header. This must, of course, be charged against the turbine whenever it is a part of the characteristic of the relation of the machine to the demands.

There is still another possibility. Both of the turbines may be operated in parallel, allowing the back-pressure machine to take enough steam to supply the low-pressure demand and letting the bleeder machine operate non-bleeding, or full condensing, and take the remainder of the electrical load. An automatic back-pressure governing valve is installed in the supply line to the Allis-Chalmers unit for this purpose. This valve can be manually set to allow automatic operation; a constant flow; or, its restriction may be cut out completely.

With the present auxiliary installations, it is necessary to operate the steam turbine-driven feedwater pump and forced draft fan whenever the heating load is at all considerable. This is because the electric motor-driven units, as installed at present, do not have sufficient capacity to serve more than two of the four boilers in the plant at high ratings. These auxiliary steam turbines exhaust into the low-pressure header and, since their flow is not metered, some account of the steam they supply to the heating line is necessary.

The low-pressure demand is composed of: 1. Heating or radiator demand. 2. Domestic Hot Water Heaters. 3. The Feedwater Heater. The heating and domestic water heater steam consumption are measured by meters, read daily, but the feedwater heater steam flow is not measured. However, as will be shown, close estimation of the flow is possible.

Since meter readings on the pertinent quantities concerned in this study have in the past been taken once a day and would probably be more reliable and practicable on this basis in the future, it was deemed advisable to make all analyses on the basis of readings once in a 24-hour day.

Separate Analyses of the Units and the Demand

Westinghouse Condensing Bleeder Turbine

Eight-hour tests were run on this machine under the conditions of full condensing, full bleeding, and partial bleeding. Willans lines for the former two were drawn. It will be noticed in Figure 1, the full bleeding line, that the curve is broken beyond a load of 400 Kilowatt net output. This is to indicate that the line was indeterminate beyond this load as no higher load could be carried and still maintain correct frequency without decreasing the bleeder opening. Figures 1 and 2 are on the net output basis, that is, the line is offset 25 Kilowatts, showing higher mass flow per kilowatt-hour than do the curves as taken from the tests. This is to account for the power taken by the condenser circulating water pump and the condensate pump motors and to place the output of the Westinghouse Turbine on the same basis as that of the Allis-Chalmers. On both full bleeding and full-condensing tests, the condensate was piped to the automatic dump bucket-type weigh meter. The flow meter and weigh meter checked within 1½ % on the full, condensing test and on the full bleeding test, showed that the amount of steam passed through the reaction blades to cool them was 14.4 % of the throttle flow. This is the ultimate instantaneous bleeding condition.

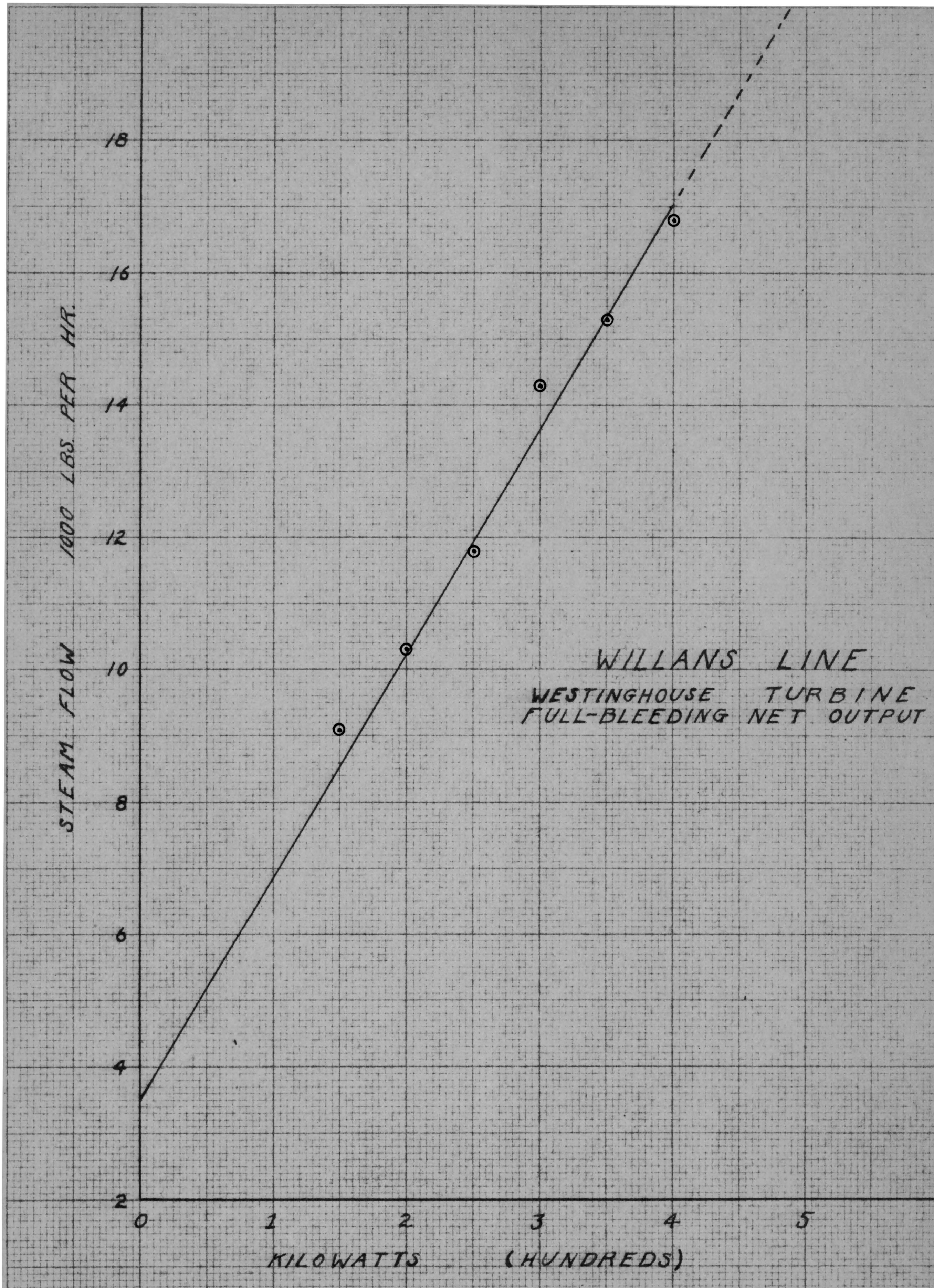

WILLANS LINE
WESTINGHOUSE TURBINE
FULL-BLEEDING NET OUTPUT
STEAM FLOW 1000 LBS. PER HR.
KILOWATTS (HUNDREDS)
18
16
14
12
10
8
6
4
2
0
1
2
3
4
5

FIG. I

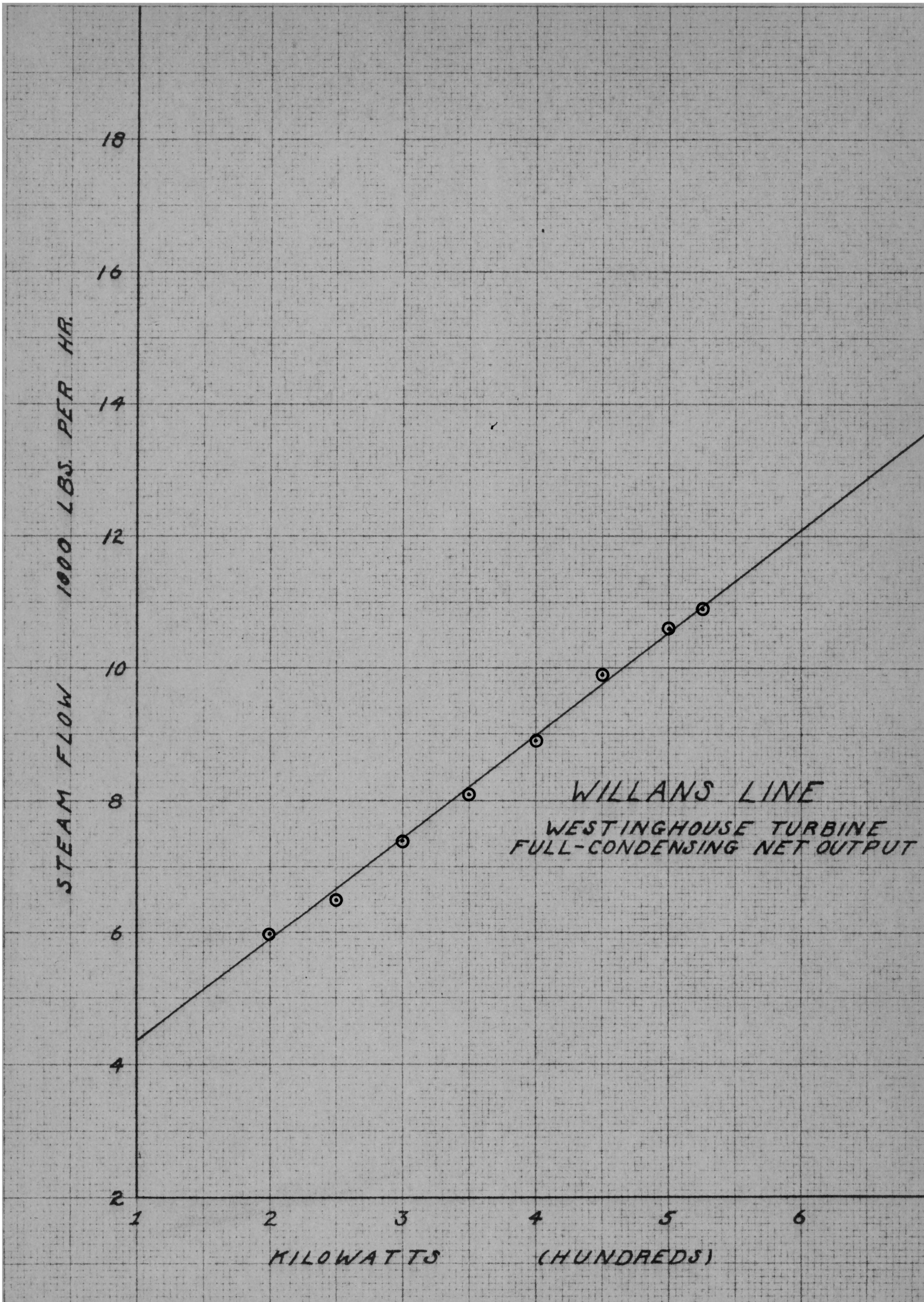

STEAM FLOW 1000 LBS. PER HR.
18
16
14
12
10
8
6
4
2
1
2
3
4
5
6
KILOWATTS (HUNDREDS)
WILLANS LINE
WESTINGHOUSE TURBINE
FULL-CONDENSING NET OUTPUT

FIG. 2

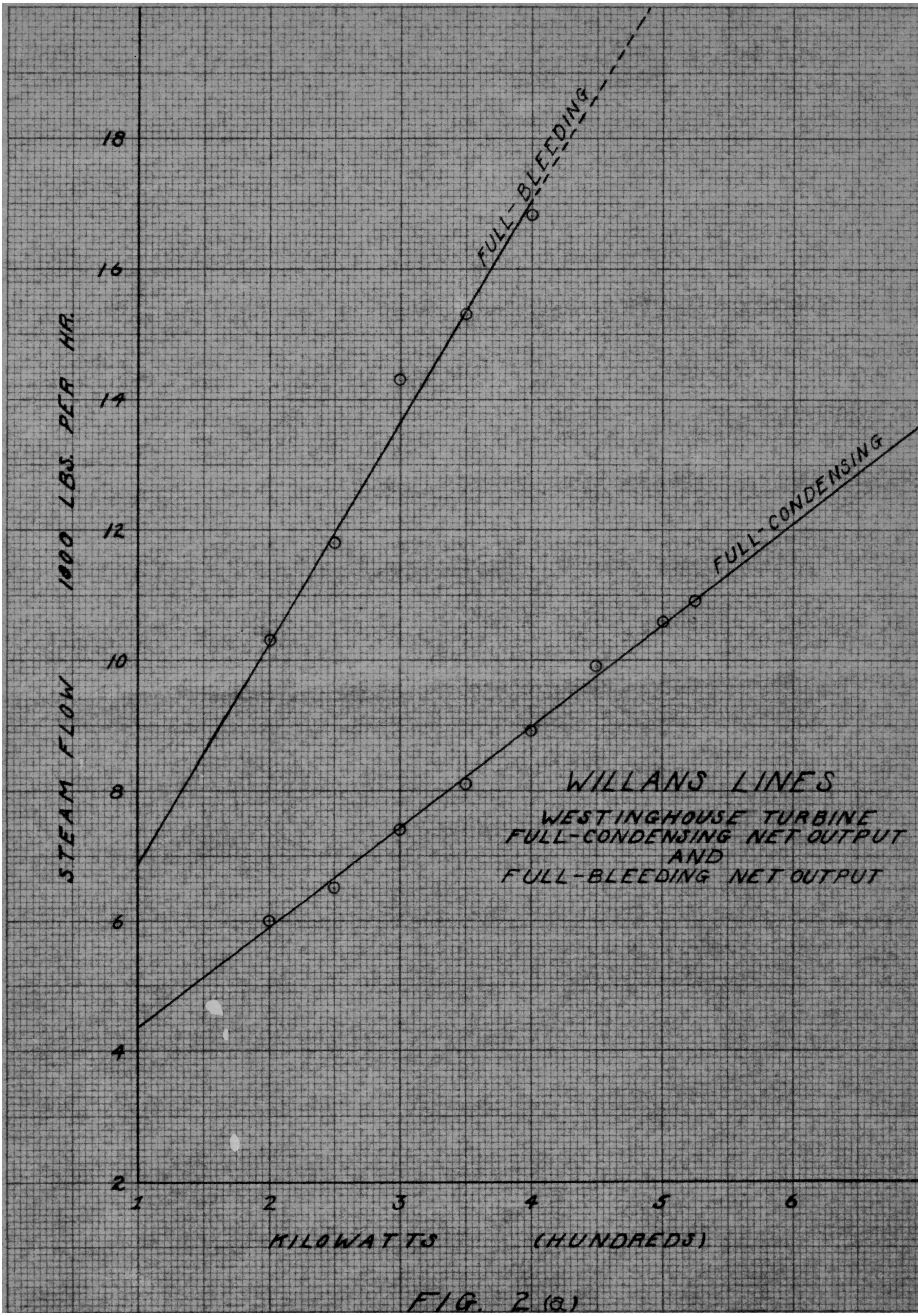

FULL-BLEEDING
FULL-CONDENSING
WILLANS LINES
WESTINGHOUSE TURBINE
FULL-CONDENSING NET OUTPUT
AND
FULL-BLEEDING NET OUTPUT
STEAM FLOW 1000 LBS. PER HR.
KILOWATTS (HUNDREDS)
2
4
6
8
10
12
14
16
18
1
2
3
4
5
6

FIG. 2 (a)

Table 1 of the Appendix gives a formula for calculating the percent of the throttle flow which is bled. This formula uses, as constants, the water rate observed, or to be permitted in predicting performances; the full condensing water rate at the electrical load in question; and the full bleeding water rate at the same electrical load. Eight-hour partial bleeding tests at relatively high electrical loads showed that the formula gives accurate results, even when the full bleeding water rate is taken from the extrapolated portion of Figure 1.

The Westinghouse curves in Figures 6, 7, 8, and 9 were calculated by solving the equation in Table 2 by trial. In computing the B. T. U. charge shown on these charts, steam flow to the throttle was charged at 1255 B. T. U. per pound and returns credited at 98 B. T. U. per pound, both from the condenser and from the heating returns. These values correspond to average recorded conditions of temperature and pressure of the steam and water. The charge is really the net heat which the boiler must supply to accommodate both the heating and the power demands. The heat abstraction of the turbine is considerably less than this value, but it is obvious that in a comparison of this kind, it would be useless to consider the turbines in any other light than their abilities to meet the load conditions. It was not necessary to alter the instantaneous quantities found by test on this machine as daily records gave very good checks on the data.

Allis-Chalmers Back-Pressure Turbine

The flow meter on this unit was not installed until February, 1937, so that daily recorded data on this unit is comparatively meager. However, with what plant data was available and the eight-hour tests performed, operating characteristics were determined. For Figures 6, 7, 8, and 9, the turbine was charged at 1255 B. T. U. per pound and credited with returns at 98 B. T. U. per pound, similar to the charge against the Westinghouse Unit, except that in the case of the back-pressure unit, credit was only given for that portion of the steam which went to the low-pressure system as the excess is wasted to the atmosphere and produces no return of heat to the boiler.

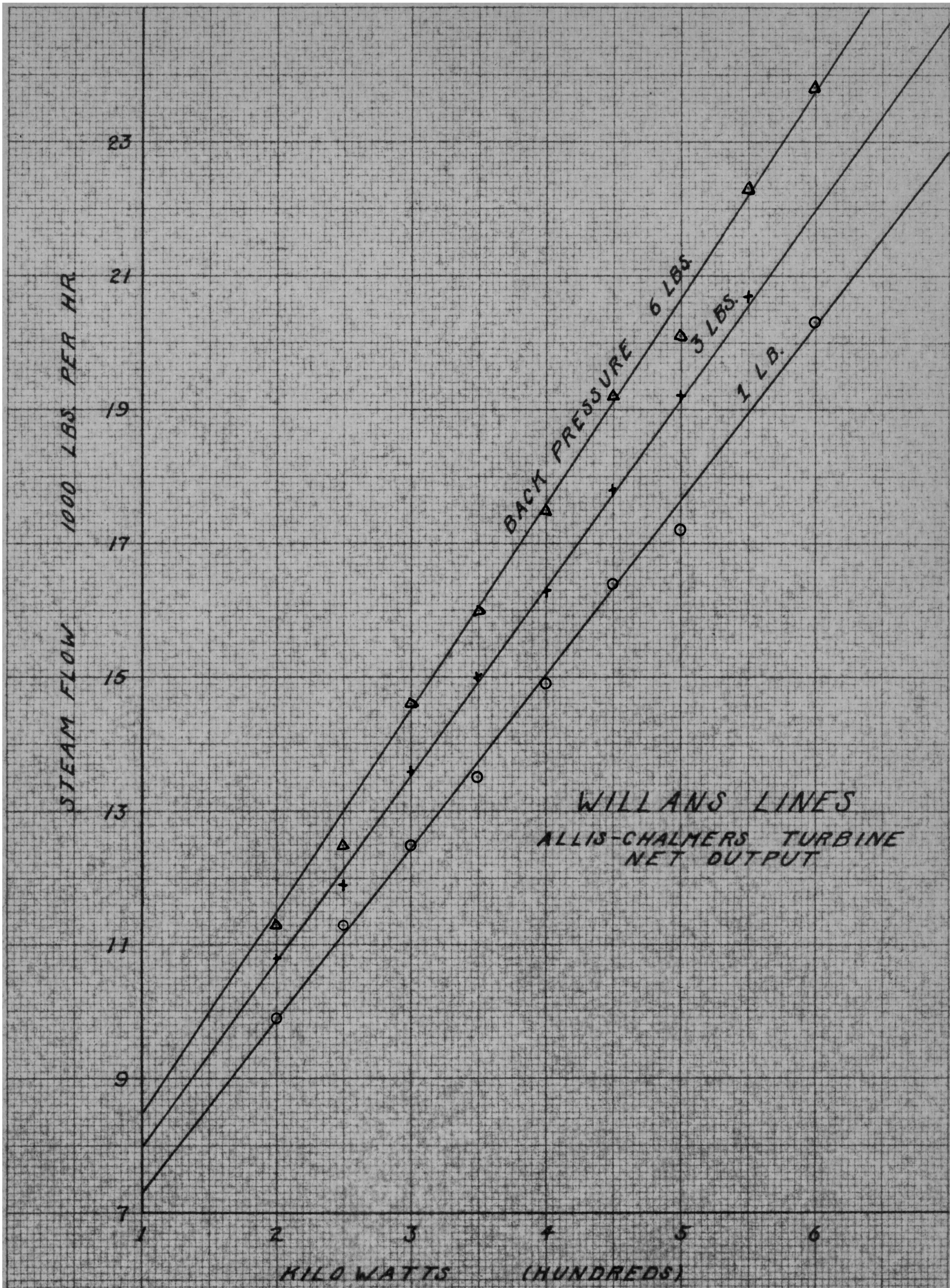
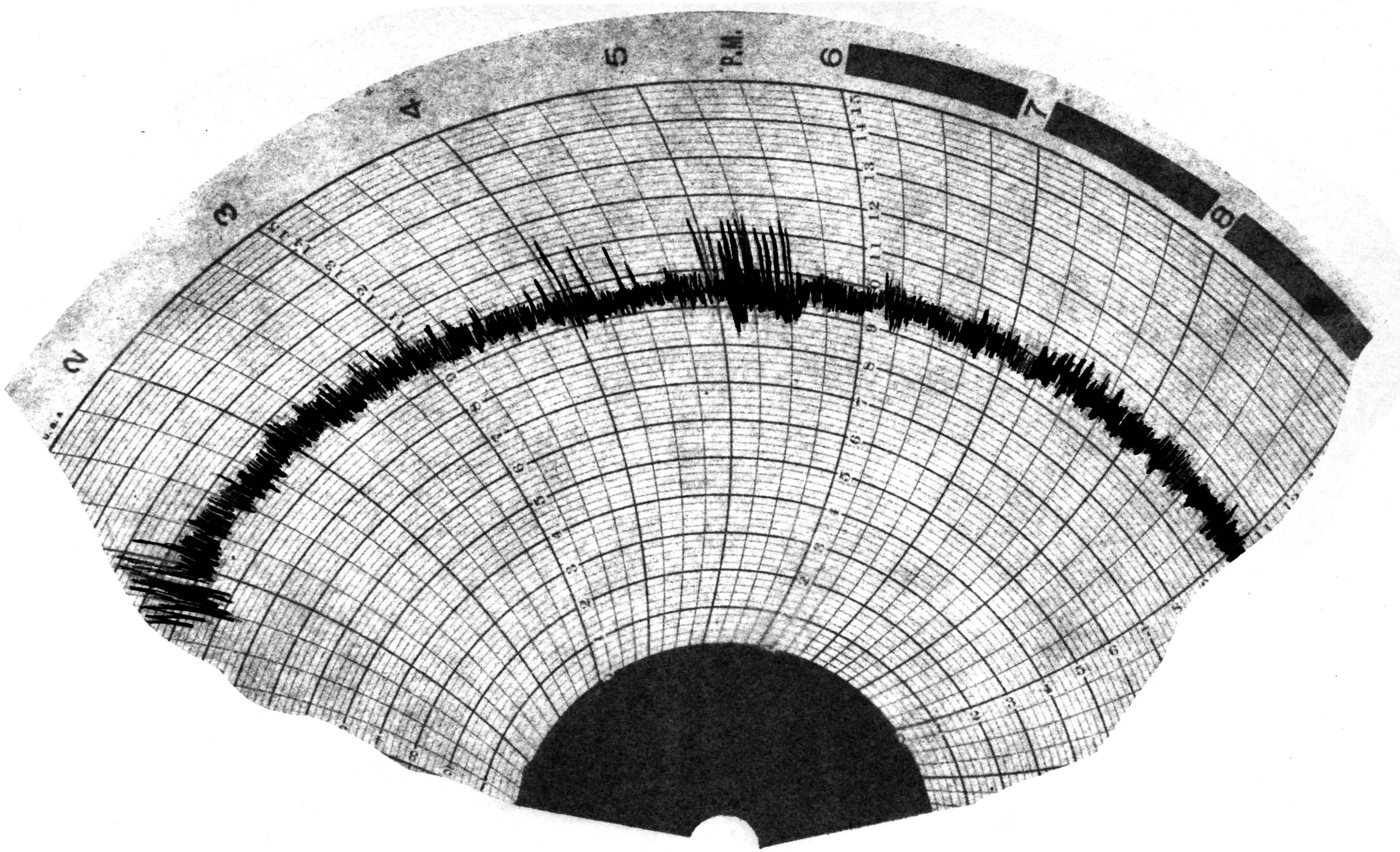

STEAM FLOW 1000 LBS. PER HR.
23
21
19
17
15
13
11
9
7
1
2
3
4
5
6
KILOWATTS (HUNDREDS)
BACK PRESSURE 6 LBS.
3 LBS.
1 LB.
WILLANS LINES
ALLIS-CHALMERS TURBINE
NET OUTPUT

FIG. 3

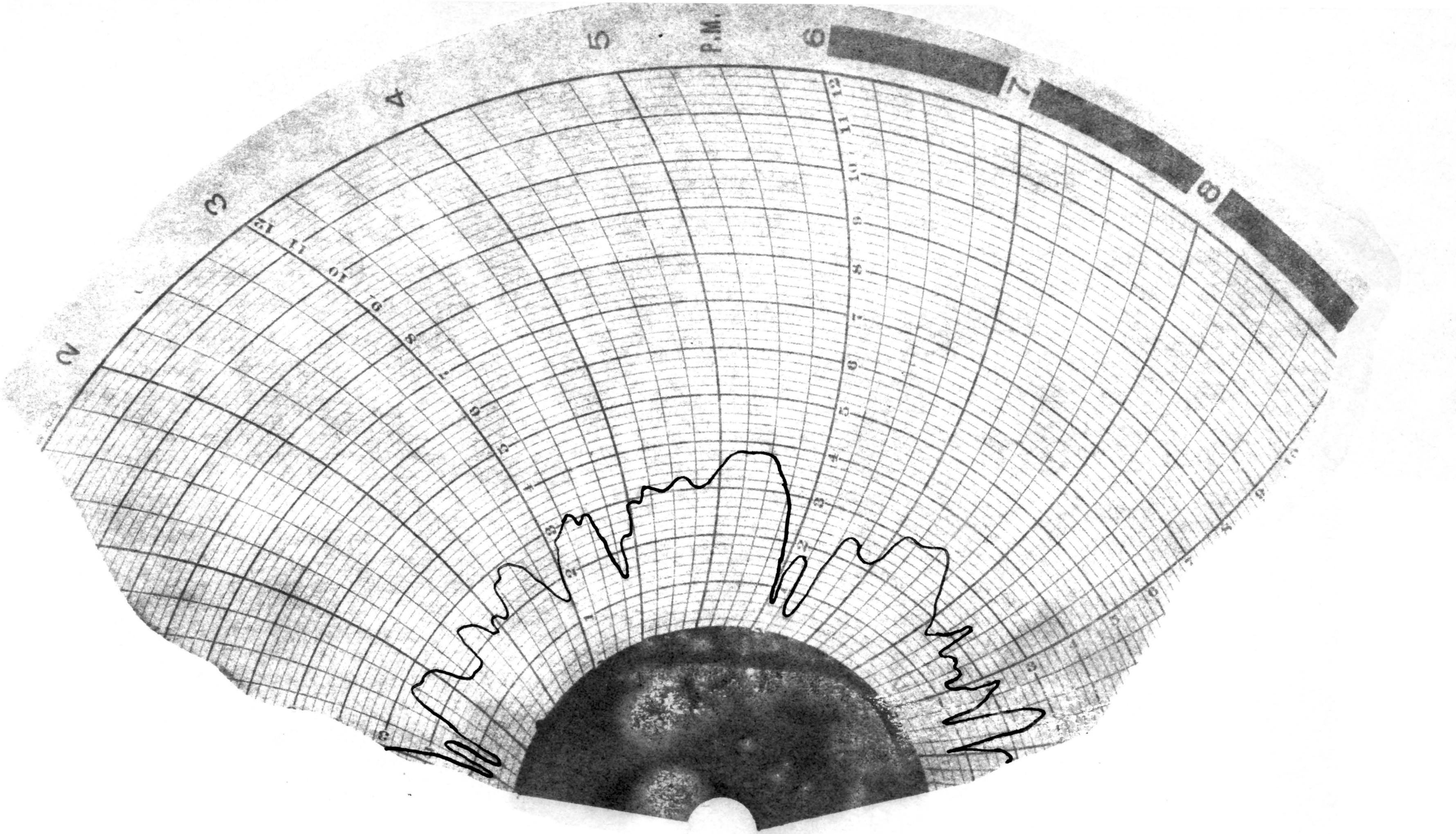
A Combination of the Two Units Operated in Parallel

In testing the combination, mechanical difficulties with the back-pressure governing valve on the Allis-Chalmers turbine prevented fully automatic operation. The valve was set manually to give this unit sufficient steam to approximately supply the low-pressure steam demand. The remainder of the electrical load, including all the variation, was taken by the Westinghouse Unit, as is shown by Figures 4 and 5, typical heating and water heater steam flow charts, this is probably the best way to operate the combination. Charges were made as on the separate units all flow being returned and credited at 98 B. T. U. per pound. Only one test of the combination was made as it is possible to predict its characteristics from those of the separate units.



CHARACTERISTIC HEATING STEAM DEMAND CHART

FIG. 4



CHARACTERISTIC WATER HEATING STEAM DEMAND CHART

FIG 5

Auxiliaries and Feedwater Heater

Although steam flow to the individual auxiliary units has not been metered or recorded, it was possible, by difference in total auxiliary steam with the steam-driven auxiliaries and with the electrically-driven units in operation, to calculate approximately the quantity of steam which these steam units exhaust into the low-pressure header. Monthly averages were used and this difference, attributed to the steam auxiliary units, was found to be approximately seven percent of the boiler output [1] for the feedwater heater steam consumption, a calculation [2] on the basis of heat gained by the feedwater, whose mass and temperature is regularly recorded showed that the feedwater heaters take, in pounds of low-pressure steam, an amount equal to approximately 6 % of the boiler output. Since these two factors so nearly balanced one another, they were eliminated from further consideration of plant quantities.

---

1. N. E. Funk and F. C. Ralston;
   Boiler Plant Economics;
   The American Society of Mechanical Engineers
   Publication No. 1912; 1923

---

2. Robert B. Creel and Richard L. Young;
   A Steam Load Study of the V. P. I. Power Plant; (Page 57)
   Thesis, Virginia Polytechnic Institute, 1936

DISCUSSION OF RESULTS

Westinghouse Condensing Bleeder Turbine

As will be seen in Figures 6, 7, and 8, the amount of steam which could be bled from the Westinghouse turbine operated 24 hours at a constant load is greater than the amount shown by the point on the curves at which make-up begins. This is due to the fact that for part of an average day, the electrical load is too high or too low to permit bleeding at the same rate as instantaneously at an electrical load equal to the day's weighted average. The maximum amount bled in a day was found from the plant records and taken as the point of make-up beginning. Make-up to the low-pressure system is charged against the machine just as though it had gone to the throttle. This is believed to be the only fair way to compare units beyond the bleeding range of one of them.

Allis-Chalmers Back-Pressure Turbine

The water rates as recorded on the daily plant records during February and March, 1937, were somewhat worse than those predicted by the manufacturers. This machine is referred to as a 1000 kilowatt unit, and was designed for operation at 230 pounds throttle pressure. Operated as it is, at 167 pounds gage throttle pressure, its load capacity is probably near 800 kilowatts but its performance with regard to economy of electrical generation is relatively poor. It will be seen that in Figures 7, 8, and 9 the Allis-Chalmers curves have a positive slope. This is due to the fact that the increase in back-pressure corresponding to the higher values of low-pressure steam demand causes the charge in water rate to increase faster than do the credits on the returns.

Combination in Parallel

The curves for the combination are derived from the instantaneous curves for the Westinghouse turbine and the Allis-Chalmers turbine operated together. The Allis-Chalmers machine was operated at constant steam flow for a given daily low-pressure steam demand. Its electrical output was, therefore, a constant quantity. The Westinghouse machine was used as a full-condensing turbine, carrying the fluctuations of the electrical load. This means that the figures for the Allis-Chalmers machine should be very nearly correct, over the whole play, while the Westinghouse data may be in slight error. The error is due to difference between the instantaneous water rate for a given electrical load and the daily water rate for the same average load. The daily rate, of course, takes into account operation for a considerable time at low electrical loads. The no-load steam flow to the Westinghouse unit is seldom over 15 % of the total flow to the combination so that the curves are not subject to much error.

General Discussion of Results

Results are all expressed in terms of daily figures for the following reasons:

1. The quantities being considered are currently taken on plant records on readings once a day. This makes the results simpler of use by the plant personnel.
2. Results expressed on the hourly basis might indicate a change of units desirable during the day, whereas such procedure in operation is not feasible.
3. Direct use of past plant records was made possible.

Elimination of calculations was deemed desirable in order to simplify the use of the results by the plant personnel. These results are based on the present installed equipment and operating conditions. Change in auxiliary equipment to give electrically-driven units equal in capacity to the present steam turbine-driven units would have some small effect on the results in that the calculation or metering of the low-pressure steam to the feedwater heater would become necessary. Change in the operating conditions would probably seriously affect these results and additional data would have to be collected. The curves on Figure 9 are predicted results as no average daily electrical load of 450 kilowatts has thus far been recorded though the eight-hour tests were of this magnitude. The B. T. U. per kilowatt-hour rate as shown is the boiler room duty and fuel savings may be computed, using these figures in connection with boiler efficiencies on bituminous coal as the semi-anthracite coal-fired boiler carries a base load and economies in the fuel consumption are in the form of bituminous coal savings. It has been assumed that in times of make-up, the Westinghouse unit is bled as heavily as the electrical load will permit. This does not require an undue amount of attention on the part of the operator.

In the daily plant records, there was no noticeable distinction between the turbines for any given outside temperature. This, then, should not be used as a basis of comparison for the two units.

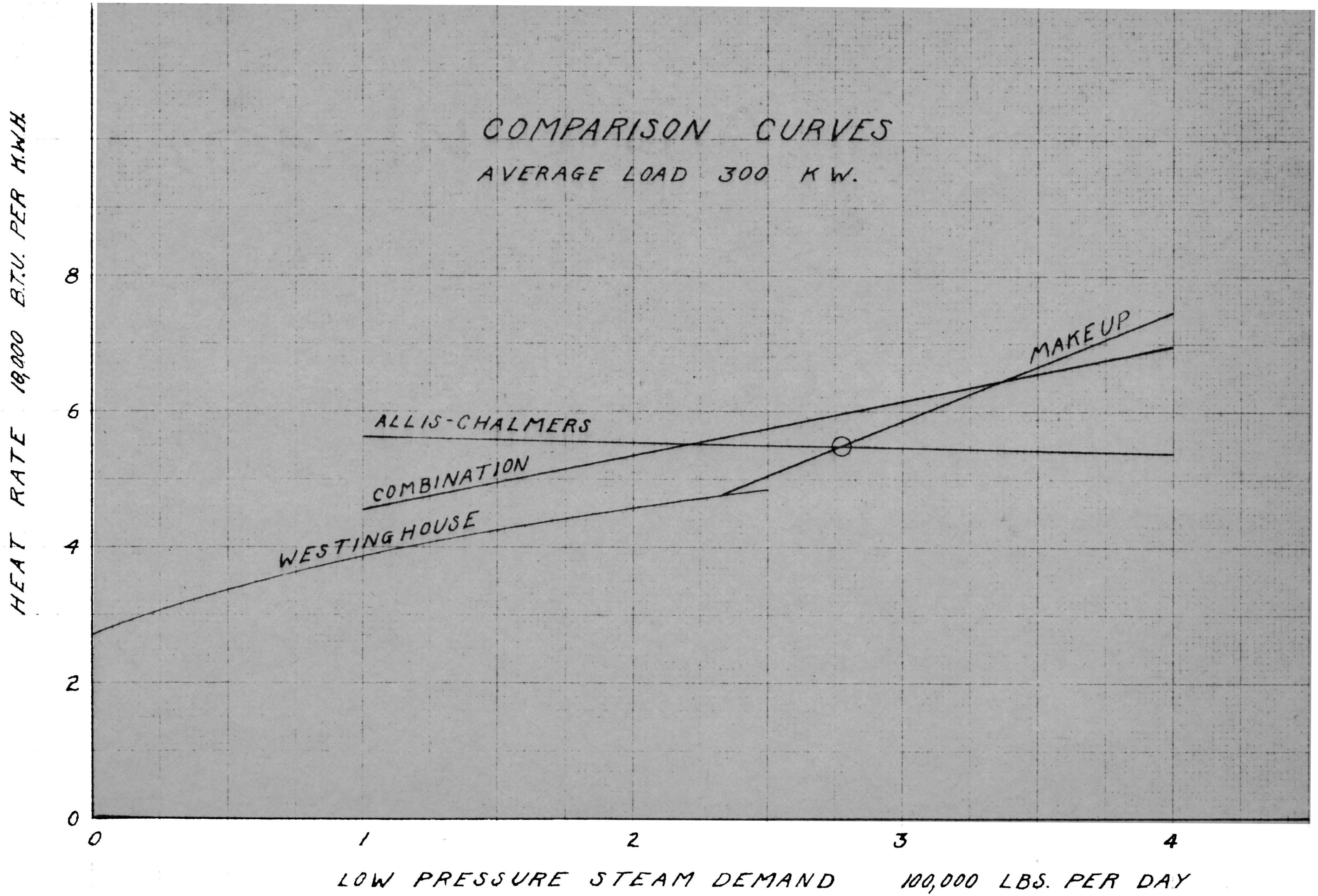

COMPARISON CURVES
AVERAGE LOAD 300 KW.
HEAT RATE 10,000 B.T.U. PER K.W.H.
8
6
4
2
0
0
1
2
3
4
LOW PRESSURE STEAM DEMAND 100,000 LBS. PER DAY
ALLIS-CHALMERS
COMBINATION
WESTINGHOUSE
MAKEUP

FIG. 6

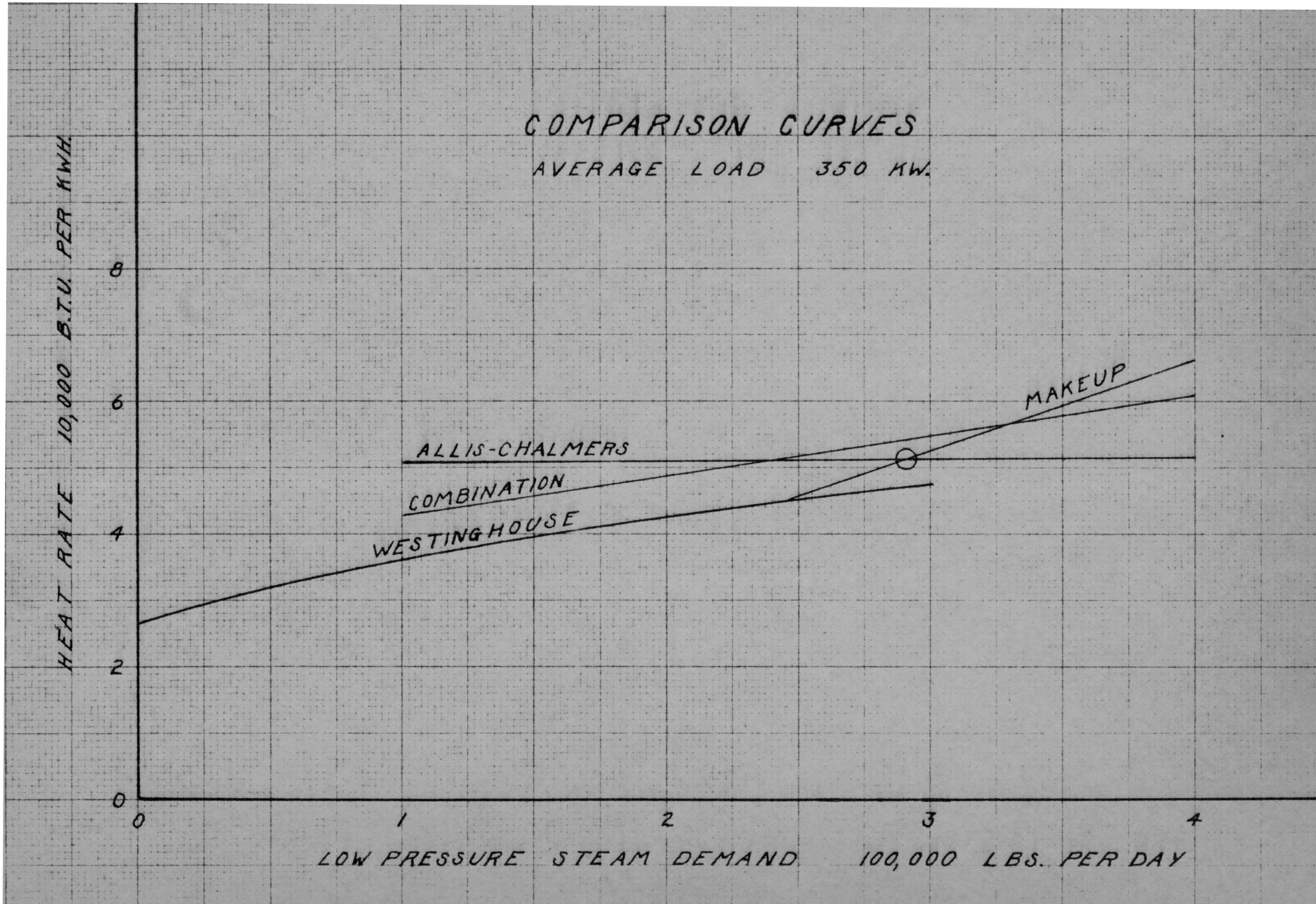

COMPARISON CURVES
AVERAGE LOAD 350 KW.
HEAT RATE 10,000 B.T.U. PER KWH.
LOW PRESSURE STEAM DEMAND 100,000 LBS. PER DAY
ALLIS-CHALMERS
COMBINATION
WESTINGHOUSE
MAKEUP
0
2
4
6
8
0
1
2
3
4

FIG. 7

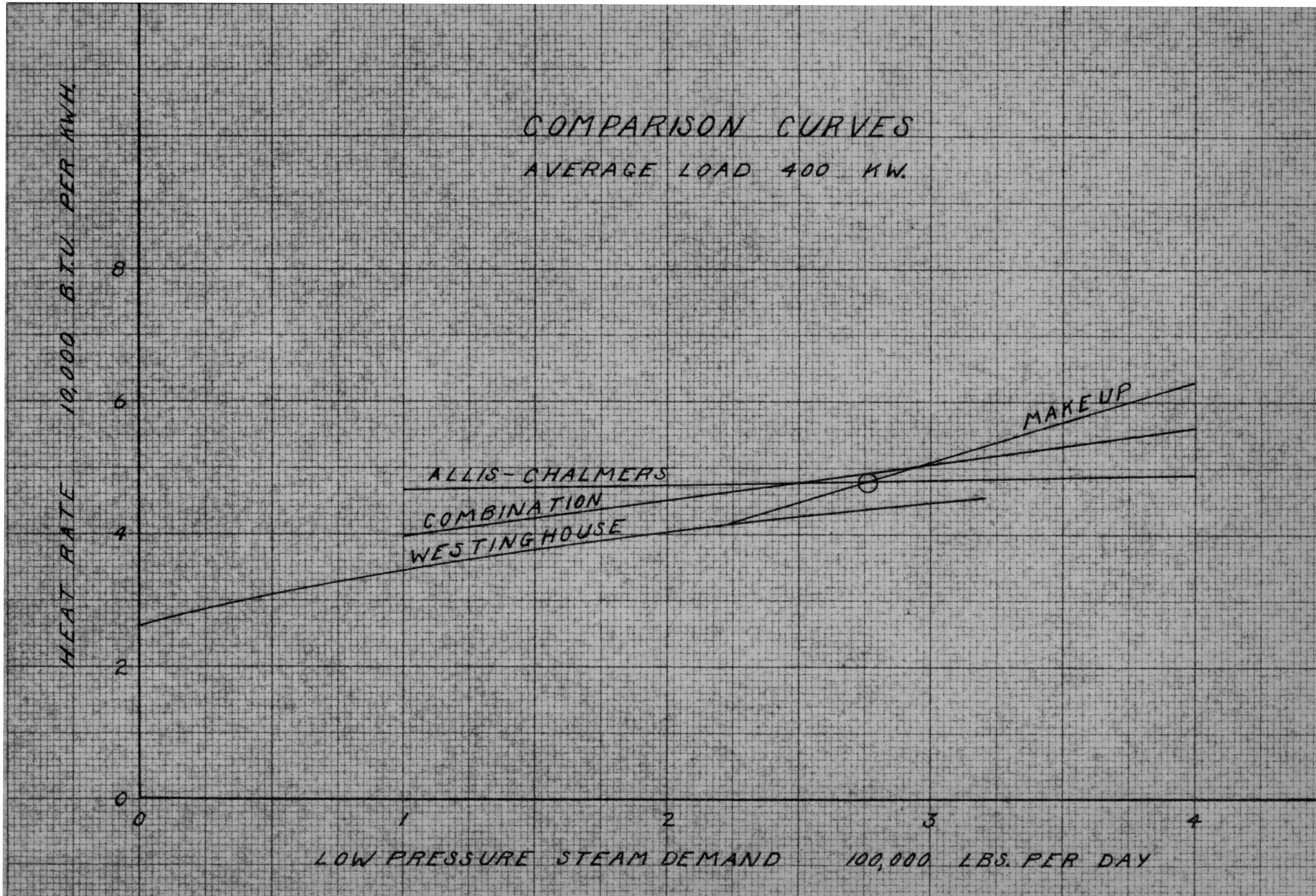

COMPARISON CURVES
AVERAGE LOAD 400 KW.
HEAT RATE 10,000 B.T.U. PER KWH.
8
6
4
2
0
MAKEUP
ALLIS-CHALMERS
COMBINATION
WESTINGHOUSE
0
1
2
3
4
LOW PRESSURE STEAM DEMAND 100,000 LBS. PER DAY

FIG. 8

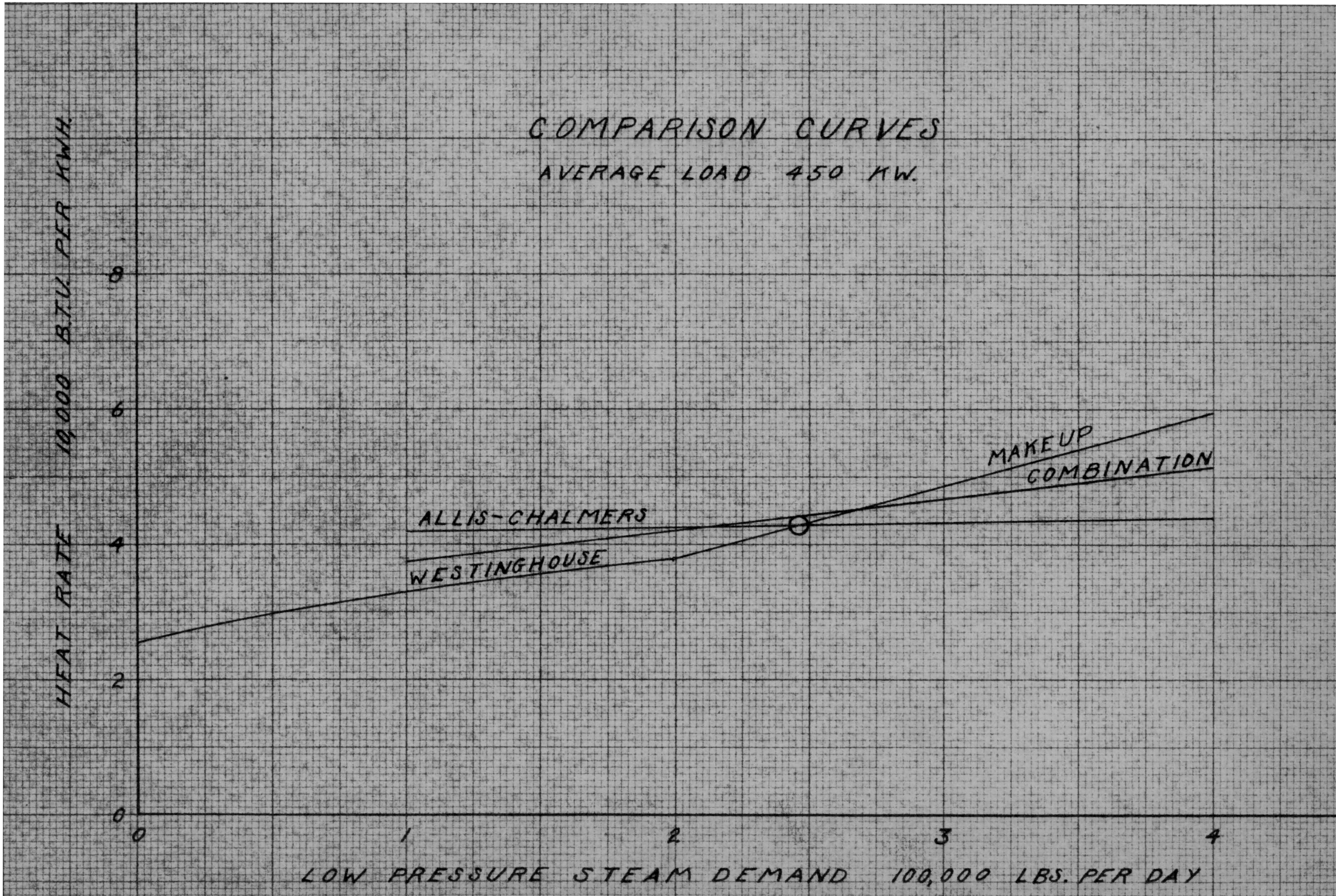

COMPARISON CURVES
AVERAGE LOAD 450 KW.
HEAT RATE 10,000 B.T.U. PER KWH.
0
2
4
6
8
MAKEUP
COMBINATION
ALLIS-CHALMERS
WESTINGHOUSE
0
1
2
3
4
LOW PRESSURE STEAM DEMAND 100,000 LBS. PER DAY

FIG. 9

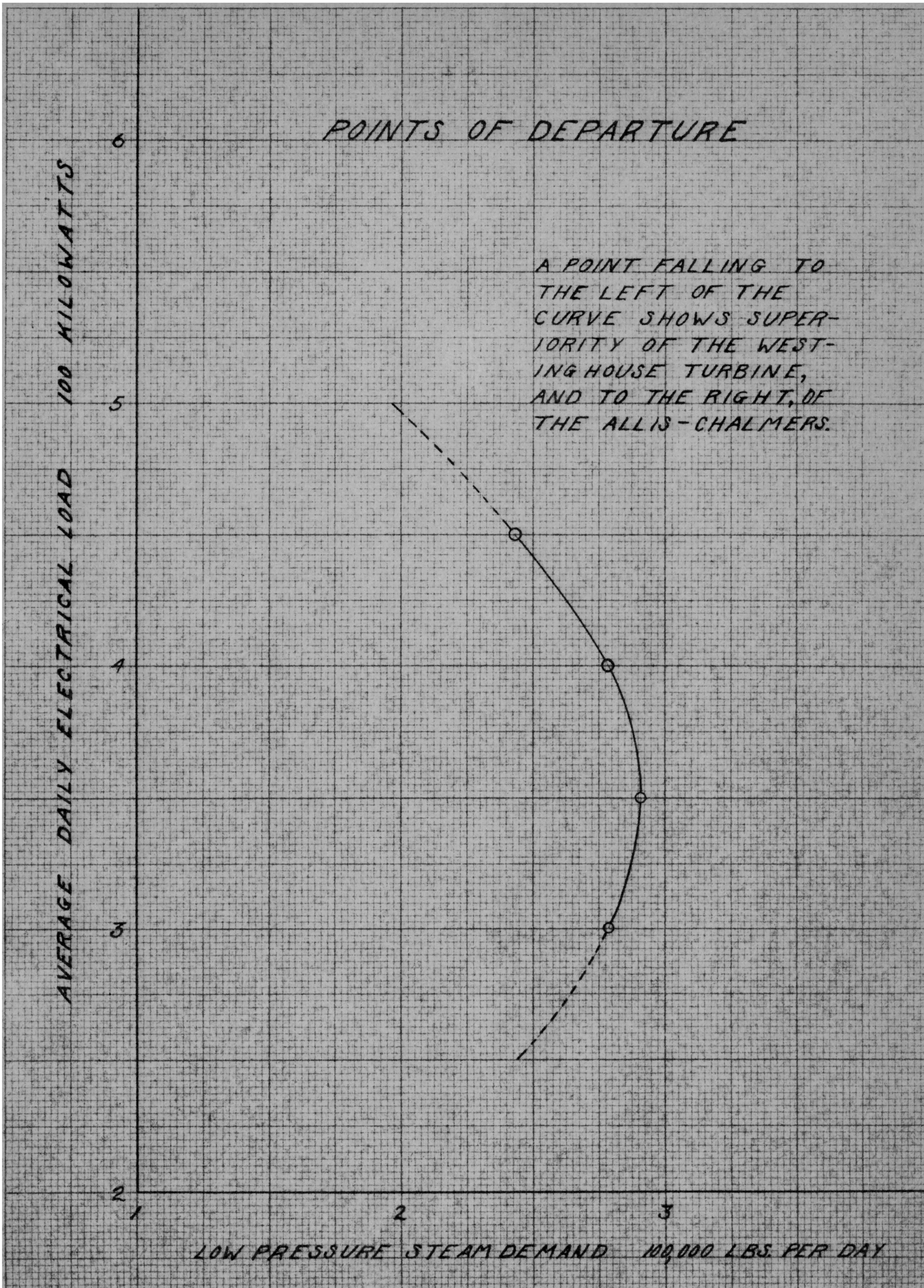

POINTS OF DEPARTURE
A POINT FALLING TO THE LEFT OF THE CURVE SHOWS SUPERIORITY OF THE WESTINGHOUSE TURBINE, AND TO THE RIGHT, OF THE ALLIS-CHALMERS.
AVERAGE DAILY ELECTRICAL LOAD 100 KILOWATTS
6
5
4
3
2
1
2
3
LOW PRESSURE STEAM DEMAND 100,000 LBS. PER DAY

FIG. 10

CONCLUSIONS

1. The Westinghouse Condenser Bleeder Turbine is the more flexible unit and maintains its full economic superiority somewhat beyond the point of its maximum bleeding ability at any daily electrical load thus far recorded.
2. If the meters are kept in good condition, the atmospheric temperature variation should be ignored as a criterion for determining the most suitable unit to operate. The total low-pressure demand of the heating lines and domestic water heaters is a more reliable guide.
3. The Allis-Chalmers Unit has a decided advantage when the low-pressure load is high. Since the highest figures of throttle flow shown are in excess of the present low-pressure demands, it seems desirable to balance up the operating period of the two units over the year by increasing the low-pressure load on the plant. This would effect further economies in the operating expense. The ultimate question of economics; considering piping, installation costs, etc. is not a consideration of this particular research.
4. If the electrical load increases beyond the capacity of either single unit for a major portion of the day, while the low-pressure load remains substantially in its present limits, the question of operating the combination in parallel would become of importance. With present and

immediate future load expectations, the suggestion is here rejected as not being economical. There is the further objection that operation in parallel involves the danger of a short circuit on the electrical lines' burning out both machines. Protective equipment would involve a capital outlay.

APPENDIX

Table No. 1

Westinghouse Bleeding Formula

$$W_c(1-X) - W_bX = W_o$$

W_c = Full condensing water rate in lbs. per Kw.-hr.

W_b = Full bleeding water rate

W_o = Observed or overall water rate

X = Percent throttle flow bled

Table No. 2

Westinghouse Bleeding Formula for Comparison Curves

$$X = \frac{W_o - W_c}{W_b - W_c} = \frac{B}{W_o \times P}$$

X = Percent throttle flow bled

W_c = Condensing water rate in lbs. per K. W.-hr.

W_b = Bleeding water rate

W_o = Overall water rate (observed or assumed)

B = Steam bleed rate, lbs. in any time interval

P = Kilowatt-hours output in same time interval

Table No. 3

Westinghouse Partial Bleed Test

Jan. 23, 1937 Test from 4:30 P. M. to 11:30 P. M.

Average outside temperature = 42.5° F.

Throttle flow = 103,155 Electrical output = 3500 K. W.-hrs.

Average water rate = $\frac{103,155}{3500}$ = 29.75 lbs. per K. W.-hr.

Weigh meter reading of condensed steam	=	52,095 lbs.
Ejector steam condensate correction	=	1,340
Net steam condensed		50,755

Net steam bled = 103,155 - 50,755 = 52,400

Percent bled by test = $\frac{52,400}{103,155}$ = 50.7 %

By Formula: $X = \frac{29.47 - 20.2}{38.8 - 20.2} = 49.8\ \%$

Table No. 4

Allis-Chalmers Test

Mar. 5. 1937   Test from 2:00 P. M. to 10:00 P. M.

Average outside temperature = 50.1° F.

Throttle flow = 135,519 lbs.

Total electrical output = 3500 K. W.-hrs.

Average water rate = $\frac{135,519}{3500}$ = 38.72

Low-Pressure Demand = 94,050

Percent waste of exhaust steam to atmosphere =

$$\frac{135,519 - 94,050}{135,519} = 30.6\ \%$$

Table No. 5

Test on Combination

Mar. 11. 1937 Average outside temperature = 49.6° F.

Allis-Chalmers:

Throttle flow = 65,070

K. W.-hr. output = 800

Westinghouse:

Throttle flow = 63,980

K. W.-hr. output = 2,800

Combination Figures:

Throttle flow = 129,050 lbs.

K. W.-hr. output = 3,600

Ave. water rate = $\frac{129,050}{3600}$ = 35.9 lb. per K. W.-hr.

Make-up = 9000 lbs.

Test Data for Westinghouse Instantaneous

Net Output Willans Lines

Full Bleeding Electrical Load (Kilowatts)	Throttle Flow (lb. per hr.)	Back Pressure	Full Condensing Electrical Load (Kilowatts)	Throttle Flow (lbs.)	Vacuum (ins) (Hg.)
150	9,100	3 lb.	200	6,000	26.5
200	10,300	"	250	6,500	26.5
250	11,800	"	300	7,400	26.3
300	14,300	"	350	8,100	26.0
350	15,300	"	400	8,900	25.6
400	16,800	"	450	9,900	24.9
			500	10,600	24.5
			525	10,900	24.0

Test Data for Allis-Chalmers Willans Lines

Electrical Load (Kilowatts)	Steam Flow (lb. per hr.)	Back Pressure
150	8,400	1 lb.
200	9,900	"
250	11,300	"
300	12,500	"
350	13,500	"
400	14,900	"
450	16,400	"
500	17,200	"
550	19,200	"
600	20,300	"

Test Data for Allis-Chalmers Willans Lines

Electrical Load (Kilowatts)	Steam Flow (lb. per hr.)	Back Pressure
150	8,000	3 lb.
200	10,800	"
250	11.900	"
300	13,600	"
350	15,000	"
400	16,300	"
450	17,800	"
500	19,200	"
550	20,700	"

Data for Allis-Chalmers Willans Lines

Electrical Load (Kilowatts)	Steam Flow (lb. per hr.)	Back Pressure
200	11,300	6 lb.
250	12,500	"
300	14,600	"
350	16,000	"
400	17,500	"
450	19,200	"
500	20,100	"
550	22,300	"
600	23,800	"

BIBLIOGRAPHY

Boiler Plant Economics; N. E. Funk and F. C. Ralston; The American Society of Mechanical Engineers Publication No. 1912; 1923

A Steam Load Study of the V. P. I. Power Plant; R. B. Creel and R. L. Young; (Thesis); Virginia Polytechnic Institute; 1936

Exhaust Steam Engineering; C. S. Darling; Chapman and Hall, Ltd.; London; 1928