

THE EFFICIENT CONDITIONS
OF A
HYDRY-ELECTRIC POWER UNIT

Thesis for the Degree of B. S.

Harold J. Rich

1927

THESIS

Water-power, thermal plants

copy

And again my Hyacinth leaves

THE EFFICIENT CONDITIONS
OF A
HYDRO-ELECTRIC POWER UNIT.

A THESIS

SUBMITTED TO THE FACULTY OF
THE MICHIGAN STATE COLLEGE OF
AGRICULTURE AND APPLIED SCIENCE.

By
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THESIS

2011

Machine design is based on a correct mathematical theory. In the construction of any machine, however, theoretical lines cannot be followed in all details, and, even if this were possible, the truth of the theory must be demonstrated by actual trial under such conditions as the machine is required to run, for there are usually many factors involved which cannot be theoretically considered and yet effect the results. Much depends upon the character of the workmanship, class of materials used, and on all the details of construction, installation and operation as well as design. All of these matters can not be included in the theoretical, and it therefore becomes necessary to determine the actual results by a trial of the machine under working conditions.

The ease with which such determinations are made is usually a criterion of the rapidity with which improvements in the design and construction of a particular machine take place. Where the determinations require a large expenditure of time and money, the resulting delays and expense usually so limit such determinations that good results are attained but slowly.

The value of testing water wheels was recognized by Smeaton who tested various water wheels about the middle of the Eighteenth Century. The invention of the turbine also brought methods of testing, which have been potent factors in the improvement of turbines. While the methods of testing has improved since that time, they have not yet reached that point which assures the high grade of design and workmanship in their manufacture as in other machinery

where testing is more generally and easily practiced.

The principle causes of this backward condition are the difficulties and expense of making an accurate test in place, and the unsatisfactory results of testing a turbine in a testing flume where the head and capacity are so limited as to confine satisfactory tests to heads seventeen feet or less and to wheels of a capacity of about 250 cubic feet per second or less. Apparently slight variations in turbine construction produces radical changes in its performance, and the high results of a wheel do not assure equal results in a wheel of the same make and size, even though they be of the same pattern, This is especially true when the contingencies of competition and impossibility an improbability of the wheel being tested offer a premium on careless construction and cheap work.

It is unfortunate for progress that the records and conditions of failures are not kept and published. The records of failures are of the most benefit to the engineer from an educational standpoint, but they injure the reputation of the manufacturer. Only the best results after years of trials are preserved. So that these results are in no way indicative of the performance of the wheel in use, but they do promote development of the type of wheel in general.

Water turbines may be tested for various purposes among which may be named:

- (1) To establish the general principles of the operation of such wheels.

- (2) To ascertain the most favorable condition for the operation of a particular type of wheel.
- (3) To ascertain the results of operating a particular wheel or size , or type of wheel, under particular conditions.
- (4) To investigate the various losses in the turbine in order that such losses may be reduced as low as possible.

The wheel which is the subject of this paper is to be tested for the second purpose mentioned; that is, to find the most favorable operating conditions within the limits of the supply.

There are three methods of testing wheels, namely:

- (1) Prony brake method.
- (2) Chemical method.
- (3) Indirect method.

By far the most commonly used of these three methods is the Prony Brake method, which gives the generated power or brake horse power direct and accurately. It is almost positive in its results for either high or low speed wheels, impulse or reaction wheels.

The second or Chemical method applies only to the reaction turbine and is a means of measuring the efficiency of the wheel by studying the flow of the water used on each side of the wheel.

The third method, which is the indirect method, and the one which was used in this case is really the best for testing wheels in place. The generated energy is the electric power produced by the generator as it is attached to the wheel. In this method,

the wheel is operating under its normal conditions and produces its required power.

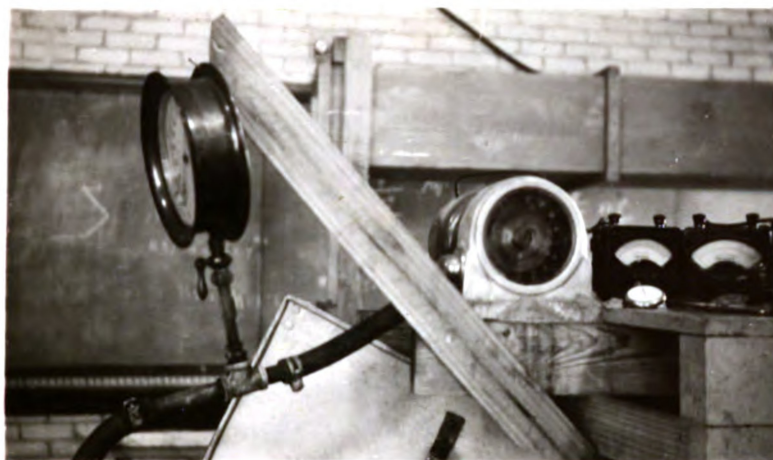
Some of the disadvantages of this method however, consist of the difficulty of measuring the water discharged and the determination of the electrical losses together with the increased friction losses, all of which are possible, but inconvenient and expensive to obtain.

In this test, an attempt was made to determine the electrical and bearing losses in the generator by running the unit as a motor at the same speed as found in the test and with the same field current excited separately, but it was found impossible to reproduce the speeds because of the size of the machine. Any direct reading tachometer required so much power to run that the speed was decreased considerably. If time were taken to count the revolutions, the current would fluctuate, giving imperfect results.

The unit tested in this paper, is a 4 inch "Doble" wheel with fixed buckets and a one-quarter inch "Doble" needle nozzle as in plate 1. Attached to the wheel is a 0.075 Kilowatt generator rated at 1800 v.p.m., 110 volt, 0.68 amperes.

As shown in the accompanying photographs the unit was connected to the mains of the college water supply by means of a three-quarter inch pipe and hose with a pressure gage between the connecting valve and the needle nozzle.

The end of the case was fitted with a glass plate to enable



visibility of the wheel while in motion. It was necessary to drill a hole through this plate opposite the end of a shaft to facilitate the use of a revolution counter in obtaining the speed of the wheel.

The water discharged through the base and was caught in a tank on scales by means of which the water discharged in a given interval of time could be weighed to give the velocity and quantity of water in jet.

The generator is equipped for both direct and alternating current of which direct current was used. Since the generator is shunt wound the current used in the field of the machine could be measured as a start toward the losses of the machine. The armature was connected to a bank of lamps with an ammeter in series and voltmeter across the brushes.

Since the action of the wheel is affected by the speed of the jet and the speed of the wheel, it was decided to vary the pressure head, the size of jet and the load on the machine. To accomplish this, three pressure heads were used, the greatest of which was the largest that could be attained with the needle nozzle fully open and lowest at 104 feet.

At each head the nozzle was opened to amounts varied by one-half turn of the needle valve from two full turns to four turns, and the head adjusted by means of the connecting valve at the mains. With a set head and a given nozzle opening, the loads were varied from very small load to the maximum of the bank which was 130 watts

and beyond rating.

Here let it be explained what is meant by load. Load is the power consumed by the lamp bank. The power consumed in the machine is not known. It is true that the machine losses increase as the load decreases. Decrease in load caused and increase in speed which caused an increase in voltage. An increase in voltage increases the field current. Electrical losses such as hysteresis, heat, core, and eddy currents vary as the speed and field current or flux density, bearing and brush friction and windage increase as the speed. Therefore at speeds which produced less than 120 volts, the field loss alone varied anywhere from small quantity to approximately equal to the line load, at voltages above 120 the field losses exceeded the line load to say nothing of the other losses.

As each load was applied, the pressure head was adjusted and recorded; the water was collected in the tank in quantities of 200 to 300 pounds and the required time of discharge recorded; the revolutions of the wheel were counted for three consecutive minutes from which the average was obtained; and the load was determined in watts from the ammeter and voltmeter.

It was decided to decrease the load to keep the speed increasing rather than decreasing, and a short interval of time left to enable it to become stable before beginning to count revolutions.

Of prime importance in obtaining the velocity of jet was the determination of the diameter and for such small diameters, extreme accuracy had to be maintained. To do this accurately, it was conceived to pass the jet between two pieces of sheet iron which could be closed together at the vena contracta until each just touched the jet as shown by a small hand lens. The distance between edges was measured to one-one hundredth of an inch by means of the hand lens.

The effective diameter of the wheel was measured from center to the point of impact of the jet and found to be three and three quarter inches.

The angle of returns or bucket angle of the wheel was not supplied, but was obtained by using the average angle as observed and measured for all buckets and was found to be 160° or 20° clearance.

As stated before, three heads of 104, 115.5 and 129.5 feet were used, all of which were above and below the head recommended by the manufacturer. This made fifteen sets of data with an average of seven conditions in each or a total of 100 conditions.

In computing this material the first step was to plot curves, as shown in plates II, III, and IV, of load and speed. Each nozzle opening and each head had its own curve. Smooth curves were drawn through this data as it was believed the smooth curve gave more accurate conditions.

From these curves were then taken loads corresponding to speeds ranging by fifty revolution per minute within the range of recorded speeds, to make up the tables I to XV. The different values of these tables were then plotted and the conditions producing the greatest efficiency curve were taken as the most efficient operating conditions.

The efficiency of a machine is the ratio of energy delivered by the machine to that which was supplied to it and it may have various significations. In the impulse wheel there are three of these significations.

In an impulse wheel the theoretical power of the water in the forebay or per stock in horse-power is:-

$$E = \frac{wh}{550}$$

(1) The power just inside the outlet of the pipe is:-

$$E_1 = \frac{w(h+h')}{550}$$

(2) The power of the jet is:-

$$E' = \frac{\pi C^2}{2g \times 550}$$

(3) and the theoretical power delivered to the bucket is:-

$$(4) \quad P = \frac{w(c-v)(1-\cos\alpha)v}{g \times 550}$$

If C represents the actual power delivered by the wheel then

(5) $N = \frac{C}{E}$ = efficiency of entire installation including pipe, nozzle, jet, wheel, etc..

(6) $N = \frac{C}{E_1}$ = efficiency of water wheel including nozzle and buckets.

(7) $N' = \frac{C}{E'}$ - efficiency of the runner, and jet.

(8) $N'' = \frac{E}{P}$ - hydraulic efficiency of the bucket.

In the testing of water wheels, the efficiency (6), $\frac{e}{E}$, is the ratio ordinarily determined since it involves the losses in the nozzle, jet, and buckets as well as the residual energy in the water discharged by the buckets, all of which are properly chargeable to the operation of the wheel. In this case since the head is measured at the nozzle and the velocity of approach to the nozzle is negligible efficiency (5) $\frac{e}{E}$ and efficiency (6), $\frac{e}{E}$, are equal.

Nomenclature used.

a. Area of jet at vena contracta.

∞ Angle of return of jet = 180°

C. Velocity of jet.

D. Effective diameter of wheel = 3.75"

E. Power of water in pipe = $\frac{wh}{550}$

E'. Power of jet = $\frac{wc}{2g \times 550}$

e. Generated power

P. Theoretical hydraulic power = $\frac{W(C-V)(1-\cos \infty)V}{g \times 550}$

N. Overall efficiency = $\frac{e}{E}$

N'. Efficiency = $\frac{e}{E'}$

N''. Theoretical hydraulic efficiency = $\frac{e}{P}$

V. Peripheral velocity of wheel

W. Weight of water used per second

h. Effective head of water at nozzle.

By an examination of tables 1 to XV and plates VI to XI it was observed that the most efficient condition or that which gave the highest efficiency, in relation to Head of water in forebay, for the range of loads was a head of 129.5 feet or 56 pounds per square inch, a nozzle opening of two and one-half turns and a speed of 2400 to 2450 revolutions per minute. The same conditions produced the maximum efficiency with respect to the power of the jet. But the efficiency with relation to the theoretical hydraulic power at the buckets required a smaller nozzle opening by one-half turn and an increase of wheel speed to about 2500 revolutions per minute.

It was attempted to determine the ratio of efficiency to the specific speed of the wheel but the variation in electrical losses in the generator destroyed all relations as well as those between efficiency and nozzle openings.

An observation of plates VI to XI will show that in all conditions of setting except one, that which gave maximum theoretical power efficiency, there is almost a constant difference in efficiencies between that with relation to jet energy and that with relation to theoretical hydraulic power at the buckets or between N' and N'' , and the difference is quite small in all cases. In the one case with a head of 129.5 feet, a nozzle opening of two turns (half open) and a speed of 2500 revolutions per minute the difference between N' and N'' is practically equal to that between N' and N' .

In concluding let it be said that, though the results seem

rather interesting and near those which might be expected, it might have been more interesting and perhaps more accurate if the wheel were equipped with a Prony Brake rather than the electric generator. It would be just as convenient, if it were possible to determine the actual electrical and mechanical losses in the electric generator for each condition. Let it be further state that, It is hoped that this meagre attempt will instill in the mind of those who follow an idea and an ambition to continue and improve the method of construction and testing hydraulic turbines and to publish all results.

TABLE 1

Valve open 2 turns

	R.P.M.	Load	e	P	N	N'	N''
Head 104.5'	2200	48.8	0.0654	0.1465	32.4	43.3	44.55
E - 0.2015	2250	49.0	0.0656	0.1462	32.6	43.5	44.9
E' - 0.1510	2300	48.0	0.064	0.1460	31.9	42.5	44.0
W - 1.062	2350	46.0	0.0613	0.1458	30.6	40.8	42.3
C - 71'/sec.	2400	42.1	0.0564	0.1455	27.5	37.3	38.8
a - 0.000240	2450	36.0	0.0482	0.1445	23.9	31.9	33.4
	2500	25.4	0.0340	0.1430	16.9	22.5	23.8

TABLE 11

Valve open 2 1/2 turns.

	R.P.M.	Load	e	P	N	N'	N''
Head 104.5'	2200	52.8	0.0707	0.1608	32.1	42.6	44.0
E - 0.220	2250	52.4	0.0701	0.1602	31.8	42.3	43.7
E' - 0.166	2300	51.0	0.0684	0.1600	31.0	41.2	42.7
W - 1.162	2350	48.5	0.0650	0.1598	29.5	39.2	40.7
C - 71'/sec.	2400	45.0	0.0603	0.1590	27.4	36.2	37.9
a - 0.000264	2450	40.0	0.0535	0.1582	24.3	32.2	33.8
	2500	40.8	0.0460	0.1570	20.9	27.7	29.2

TABLE 111

Valve open 3 turns

	R.P.M.	Load	e	P	N	N'	N''
Head 104.5'	2200	55.5	0.0744	0.1840	31.2	39.2	40.4
E - 0.238	2250	55.0	0.0737	0.1842	31.0	38.9	40.0
E' - 0.1895	2300	53.4	0.0715	0.1840	30.0	37.7	38.9
W - 1.26	2350	50.6	0.0678	0.1835	28.5	35.8	37.0
C - 73.1 ft.	2400	47.0	0.0650	0.1830	26.5	33.2	34.4
a 0.000276	2450	42.0	0.0562	0.1825	25.6	29.6	30.8
	2500	36.0	0.0482	0.1820	20.33	25.5	26.5

TABLE 1V

Valve open 3 1/2 turns.

	R.P.M.	Load	e	P	N	N'	N''
Head 104'	2200	57.2	0.0766	0.2005	30.5	37.1	38.2
E - 0.2515	2250	57.2	0.0766	0.2005	30.5	37.1	38.2
E' - 0.2065	2300	56.2	0.0753	0.2002	30.0	36.4	37.6
W - 1.35	2350	54.0	0.0724	0.2000	28.8	35.0	36.2
C - 74.3'	2400	50.8	0.0680	0.2000	27.1	32.9	34.0
a 0.000288	2450	46.2	0.0620	0.1995	24.55	30.0	31.1
	2500	40.0	0.0536	0.1990	21.30	26.9	26.9

TABLE V

Valve open 4 turns.

	R.P.M.	Load	ϵ	P	N	N'	N''
Head - 104'	2200	62.7	0.0840	0.2020	32.4	40.3	41.6
E - 0.2595	2250	62.8	0.0841	0.2020	32.4	40.3	41.6
E' -0.2085	2300	61.9	0.0828	0.2015	31.9	39.7	41.2
W - 1.37	2350	59.9	0.0802	0.2015	30.9	38.5	39.9
C -73.4' /sec	2400	56.8	0.0760	0.2010	29.3	36.5	37.8
a 0.00030	2450	52.8	0.0707	0.2000	27.2	33.9	35.4
	2500	47.2	0.0632	0.1995	24.4	30.3	31.2

TABLE VI

Valve open 2 turns

	R.P.M.	Load	ϵ	P	N	N'	N''
Head 115.5'	2200	58.4	0.0782	0.1670	33.5	45.3	46.8
E - 0.233	2250	59.0	0.0790	0.1670	33.9	45.8	47.3
E' -0.1725	2300	58.8	0.0788	0.1670	33.8	45.7	47.2
W - 1.11	2350	57.7	0.0773	0.1670	33.2	44.8	46.3
C - 74.2' /sec	2400	55.4	0.0742	0.1665	31.8	43.0	44.6
a - 0.000240	2450	51.5	0.0690	0.1660	29.6	40.0	41.6
	2500	45.2	0.0605	0.1655	26.0	35.0	36.6

TABLE VII

Valve open 2 1/2 turns.

	R.P.M.	Load	e	P	N	N'	N''
Head 115.5'	2200	60.0	0.0804	0.2030	31.4	38.2	59.6
E - 0.256	2250	60.7	0.0813	0.2030	31.7	38.7	40.0
E' - 0.210	2300	61.0	0.0817	0.2025	31.4	38.9	40.2
W - 1.22	2350	60.6	0.0812	0.2035	31.9	38.6	59.8
C - 78.28/sec	2400	59.2	0.0793	0.2040	31.0	37.7	38.8
a - 0.000250	2450	56.7	0.0760	0.2040	29.7	36.2	37.3
	2500	52.0	0.0696	0.2040	27.2	33.2	34.2

TABLE VIII

Valve open 3 turns.

	R.P.M.	Load	e	P	N	N'	N''
Head 115.5'	2300	66.8	0.0895	0.2485	31.5	32.8	36.0
E - 0.2840	2350	68.4	0.0915	0.2490	32.2	35.5	36.7
E' - 0.2575	2400	68.6	0.0920	0.2490	32.4	35.8	36.9
W - 1.35	2450	67.0	0.0897	0.2500	31.6	34.8	35.8
C - 82.28 / sec	2500	63.1	0.0845	0.2500	29.8	32.8	33.8
a - 0.000264	2550	56.0	0.0750	0.2500	26.4	29.1	30.0
	2600	43.2	0.0579	0.2495	20.5	22.5	23.2

TABLE 1K

Valve 3 1/2 turns open.

	R.P.M.	Load	e	P	N	N'	N''
Head 115.5'	2300	73.2	0.0982	0.250	52.7	37.9	39.3
E - 0.3000	2350	73.1	0.0980	0.250	52.6	37.8	39.2
E' - 0.2590	2400	72.0	0.0965	0.250	52.1	37.3	38.6
W - 1.43	2450	69.6	0.0954	0.250	51.1	36.1	37.3
C - 80' / sec	2500	65.2	0.0873	0.250	29.1	33.7	34.9
a - 0.00028	2550	61.3	0.0820	0.250	27.3	31.7	32.8
	2600	55.0	0.0755	0.250	24.5	28.4	29.4

TABLE 1K

Valve open 4 turns

	R.P.M.	Load	e	P	N	N'	N''
Head 115.5'	2300	69.2	0.0936	0.2225	30.2	40.4	41.6
E - 0.307	2350	71.4	0.0955	0.2225	31.1	41.6	42.9
E' - 0.2295	2400	72.2	0.0967	0.2220	31.5	42.1	43.5
W - 1.46	2450	71.2	0.0955	0.2215	31.0	41.5	43.0
C - 74.6 ft.	2500	68.4	0.0916	0.2205	29.8	39.9	41.4
a 0.000314	2550	63.3	0.0844	0.2195	27.6	36.9	38.5
	2600	55.0	0.0735	0.2180	23.9	32.0	33.7

TABLE XI

Valve open 2 turns.

	R.P.M.	Load	●	P	N	N'	N''
Head - 129.5'	2400	70.1	0.0940	0.1645	25.1	41.0	57.1
E - 0.280	2450	70.6	0.0947	0.1635	25.22	41.3	57.9
E' - 0.171	2500	70.8	0.0948	0.1625	25.3	41.4	58.3
W - 1.18 [#]	2550	70.2	0.0940	0.1615	25.1	41.0	58.1
C - 71.6 ft.	2600	68.1	0.0914	0.1600	24.4	39.8	57.1
a - 0.000265	2650	64.5	0.0865	0.1580	23.1	37.7	54.6
	2700	59.0	0.0790	0.1565	21.1	34.5	50.5

TABLE XII

Valve open 2 1/2 turns.

	R.P.M.	Load	●	P	N	N'	N''
Head - 129.5	2400	79.4	0.1061	0.207	34.4	49.6	51.4
E - 0.309	2450	79.1	0.1060	0.207	34.4	49.5	51.2
E' - 0.214	2500	78.5	0.1052	0.206	34.1	49.2	51.0
W - 1.31 [#]	2550	77.5	0.1038	0.206	33.6	48.4	50.4
C - 76.1 ft	2600	75.8	0.1015	0.205	32.8	47.5	49.5
a - 0.000276	2650	73.2	0.0980	0.203	31.7	45.8	48.3
	2700	69.7	0.0934	0.202	30.2	43.6	46.1

TABLE XIII

Valve open 3 turns.

	R.P.M.	Load	e	P	N	N'	N''
Head 129.5'	2400	78.9	0.1055	0.2175	31.9	47.2	48.5
E - 0.3311	2450	80.7	0.1080	0.2175	32.6	48.3	49.7
E' -0.224	2500	81.8	0.1095	0.2170	33.1	48.9	50.5
W - 1.405	2550	82.1	0.1100	0.2160	33.2	49.2	51.0
C - 75.3 ft.	2600	81.4	0.1090	0.2150	33.0	48.7	50.7
a 0.000288	2650	79.8	0.1070	0.2130	32.4	47.8	50.3
	2700	77.7	0.1040	0.2115	31.4	46.5	49.2

TABLE XIV

Valve open 3 1/2 turns.

	R.P.M.	Load	e	P	N	N'	N''
Head 129.5'	2400	84.4	0.1130	0.266	32.8	41.7	42.5
E 0.345	2450	84.6	0.1135	0.266	32.9	41.8	42.6
E' 0.274	2500	83.6	0.1120	0.266	32.4	41.4	42.1
W 1.465	2550	81.7	0.1095	0.266	31.8	40.1	41.2
C 81.5 ft.	2600	79.3	0.1062	0.266	30.8	39.2	40.0
a 0.000288	2650	76.2	0.1020	0.265	29.6	37.6	38.4
	2700	72.7	0.0975	0.264	28.3	35.6	36.8

TABLE XV

Valve open 4 turns.

	R.P.M.	Load	e	P	N	N'	N''
Head 129.5'	2400	81.8	0.1095	0.275	30.6	38.5	39.9
E 0.358	2450	83.8	0.1120	0.275	31.3	39.4	40.7
E' 0.284	2500	84.9	0.1135	0.275	31.7	39.9	41.2
W 1.52	2550	85.0	0.1139	0.275	31.8	40.1	41.4
C 81.5	2600	83.9	0.1121	0.275	31.4	39.5	40.8
a 0.00050	2650	82.0	0.1100	0.275	30.7	38.7	40.0
	2700	79.13	0.1060	0.274	29.6	37.3	38.7

Doble Needle
Nozzle

Doble Wheel
160°

20°

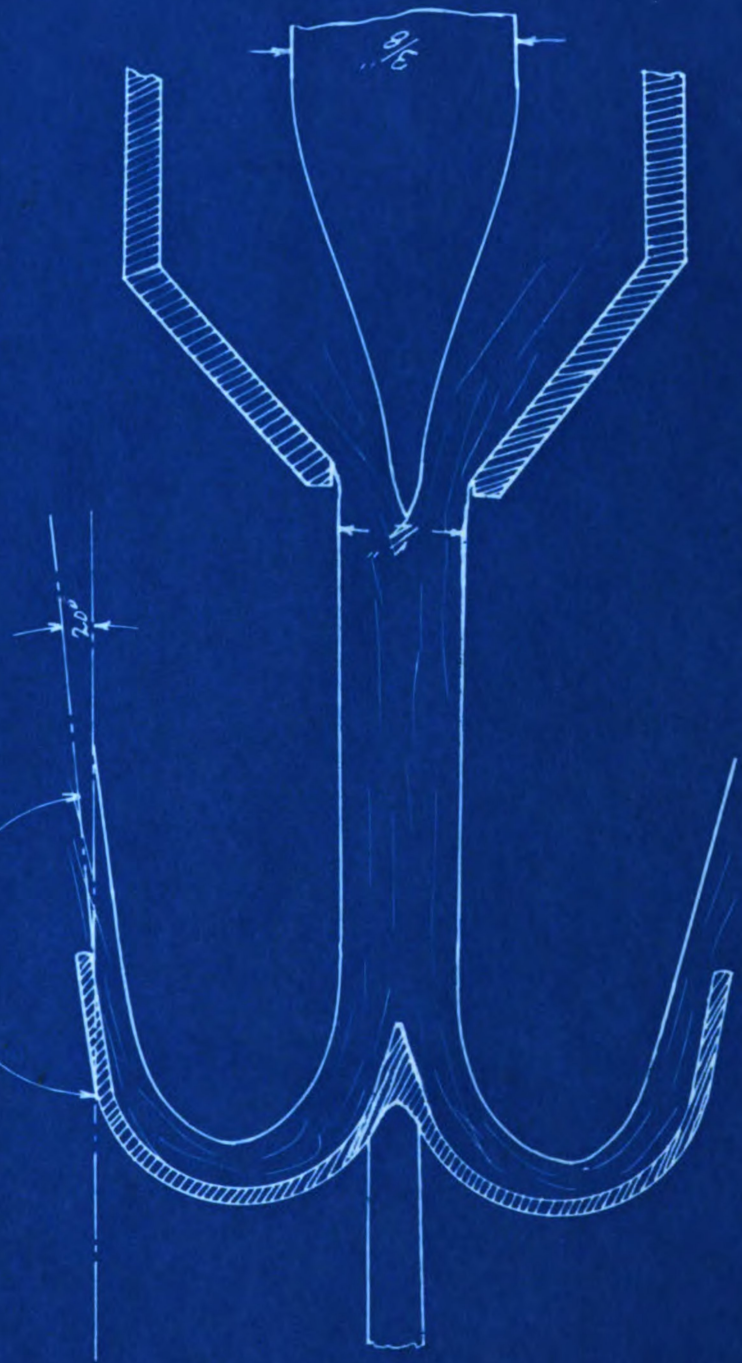
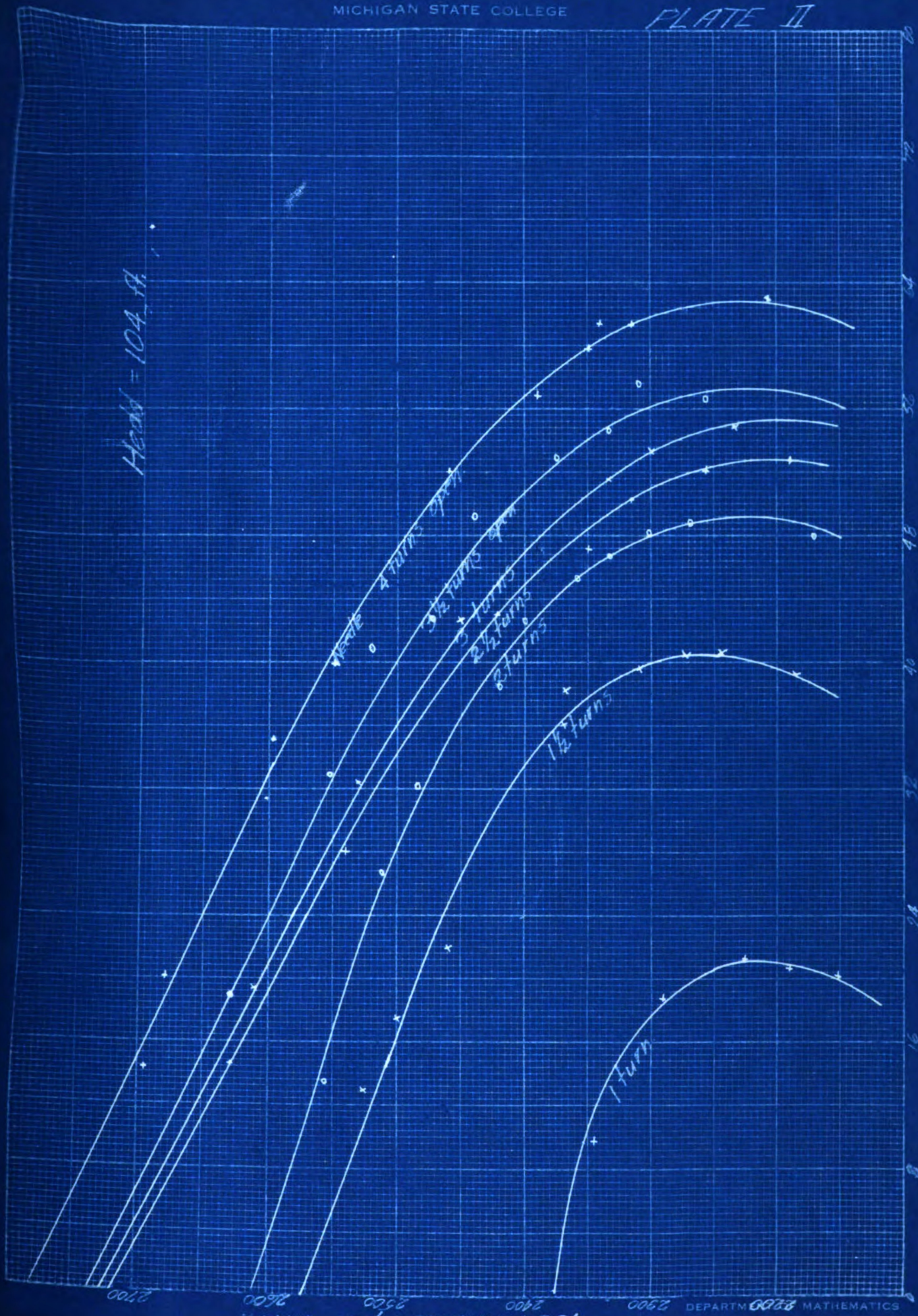


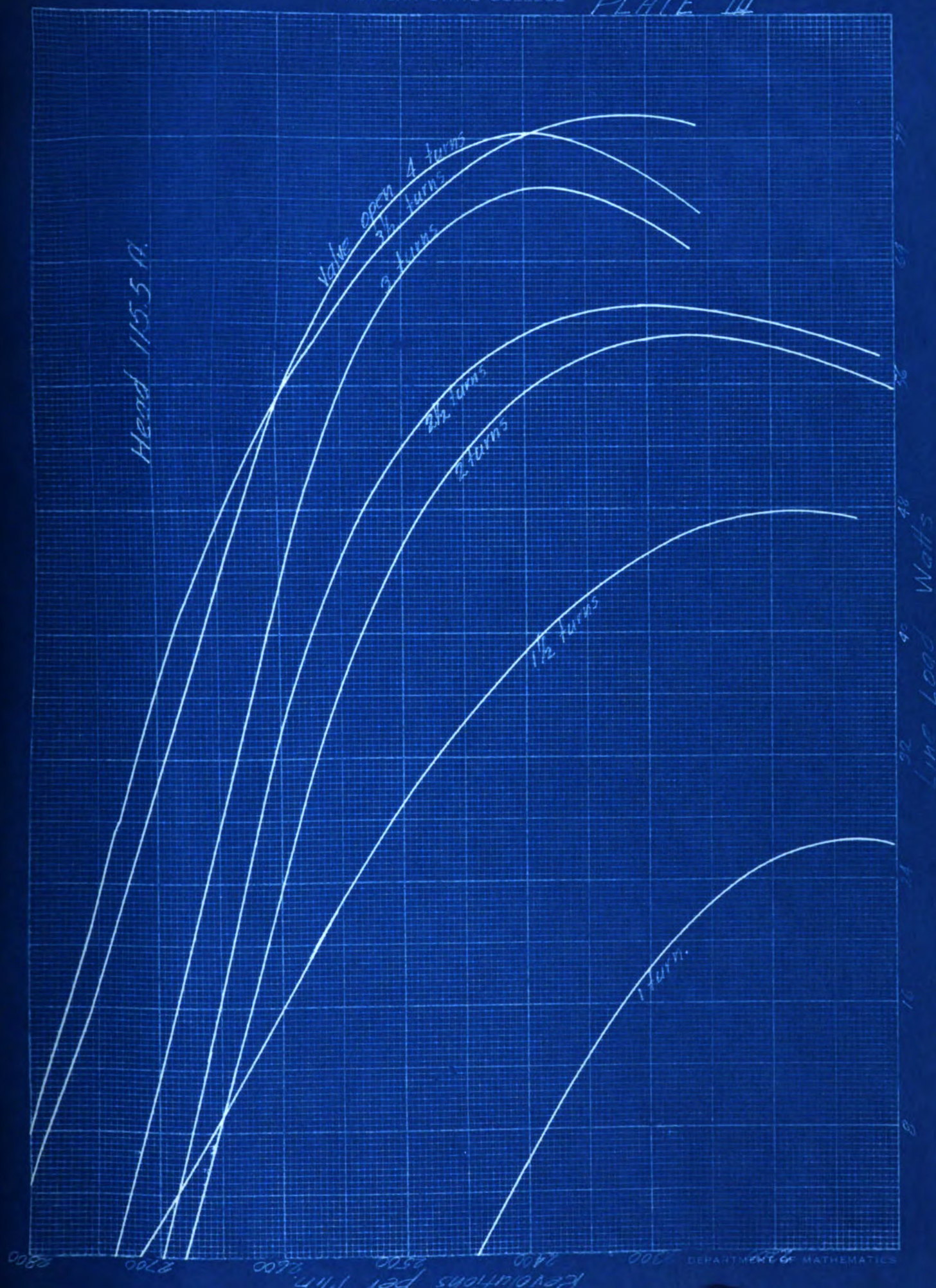
PLATE I

Head = 104 ft.

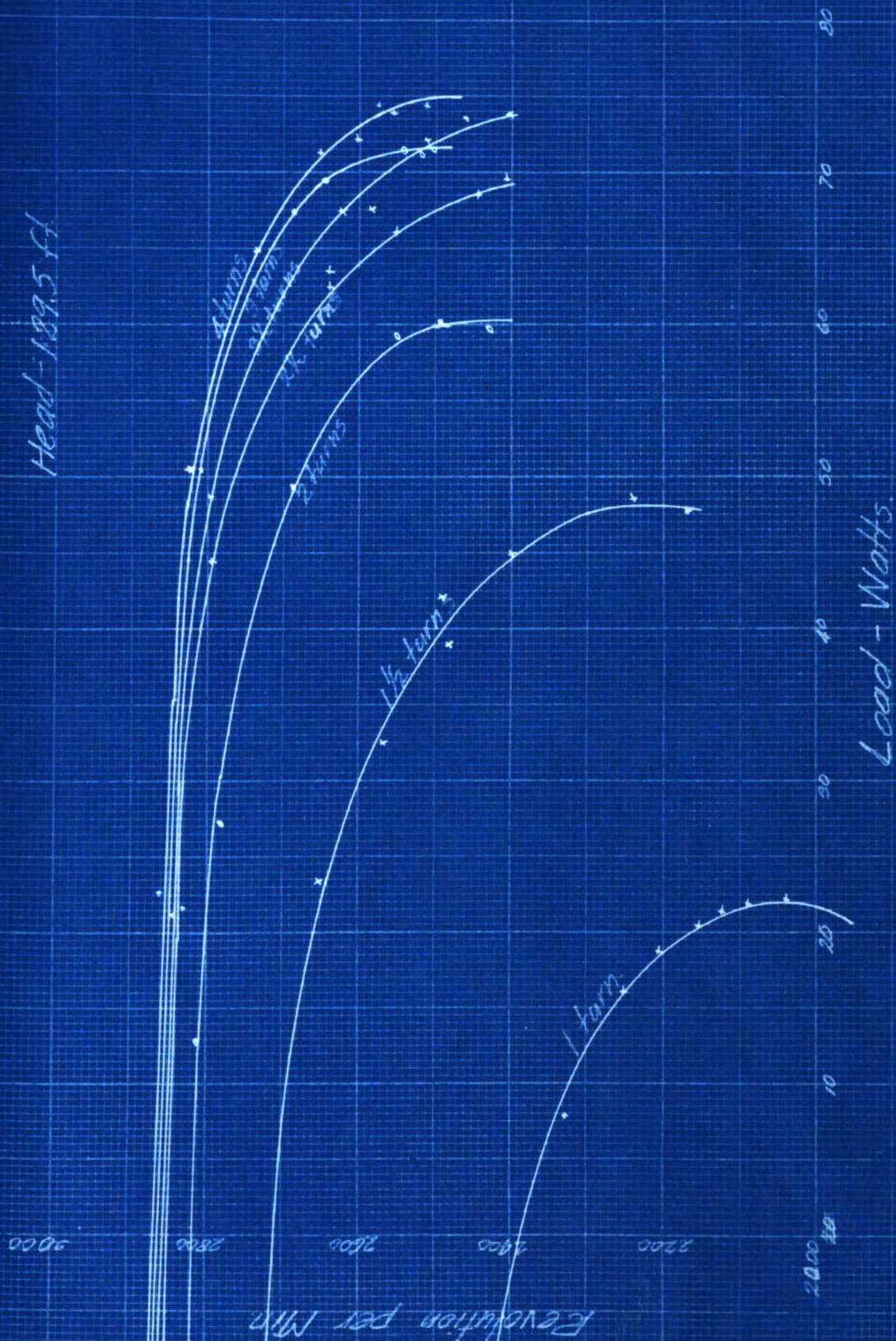
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1 1/2 turns
2 turns
2 1/2 turns
3 turns
3 1/2 turns
4 turns open

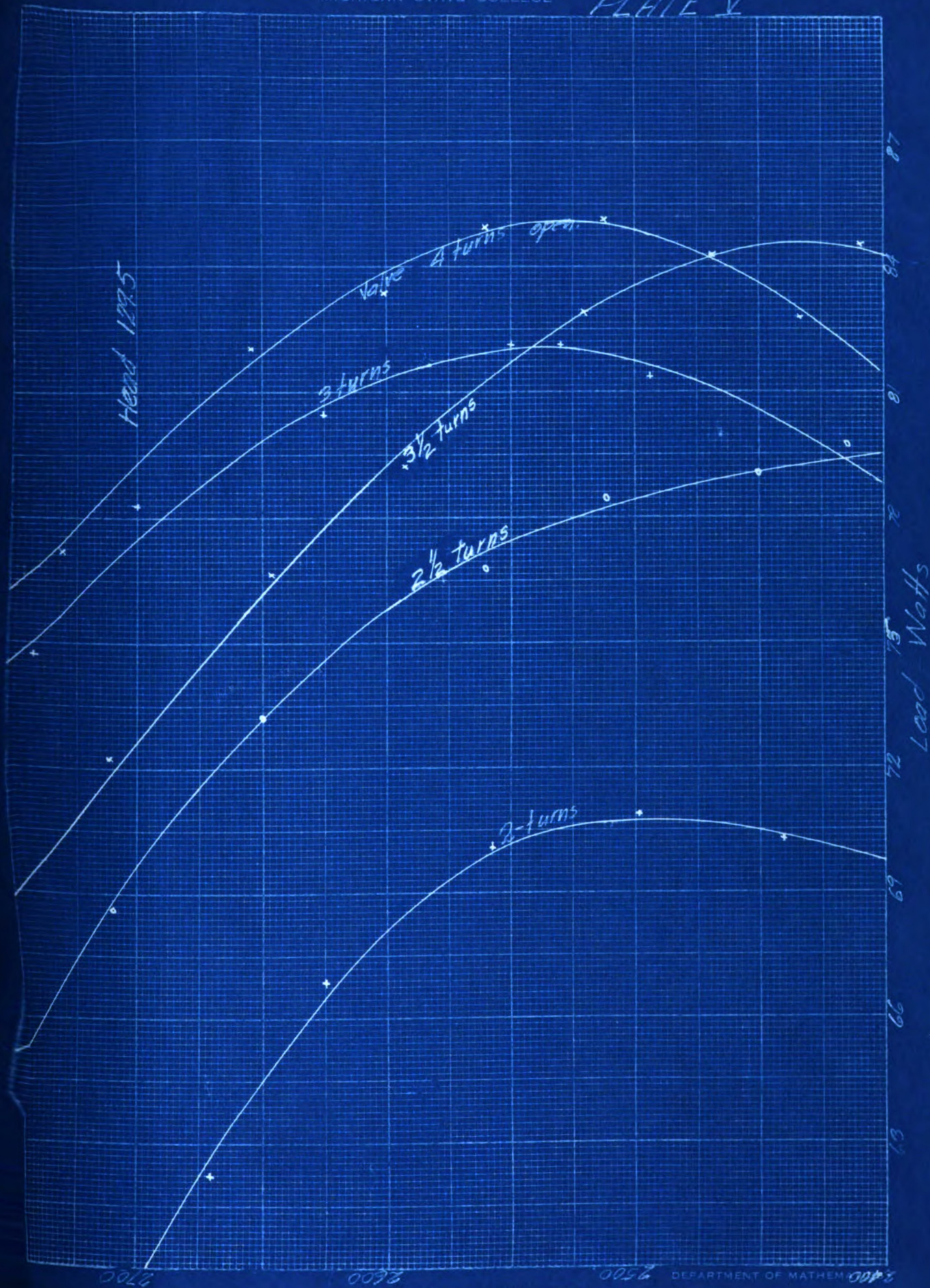
Line Load - Watts



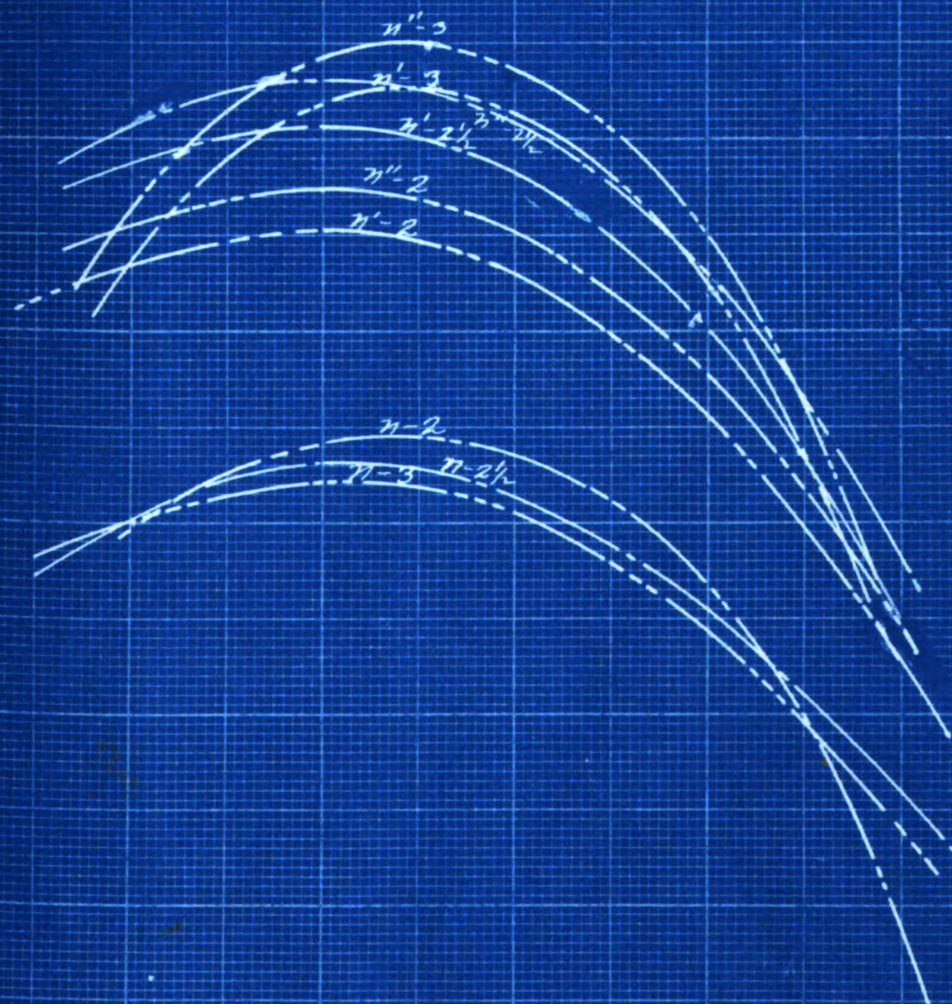


Head - 189.5 ft





Head - 104 Ft.



Percent Efficiency

2300

2400

2500

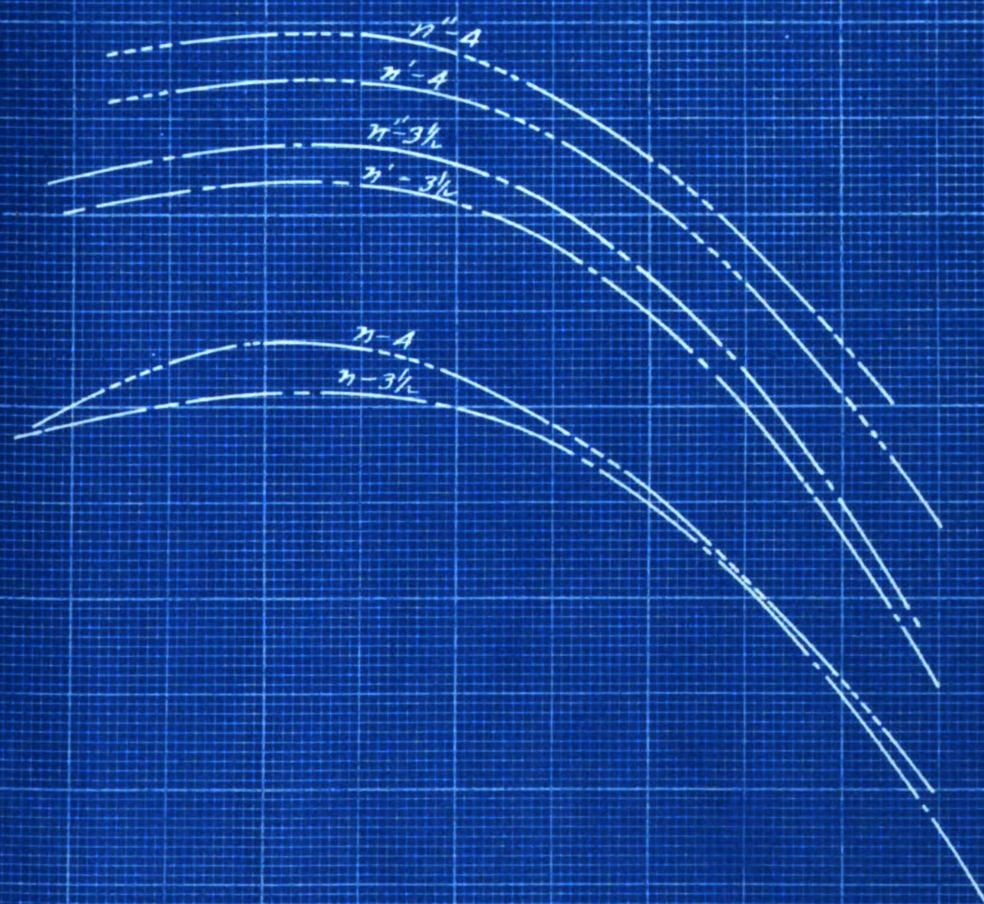
2600

2700

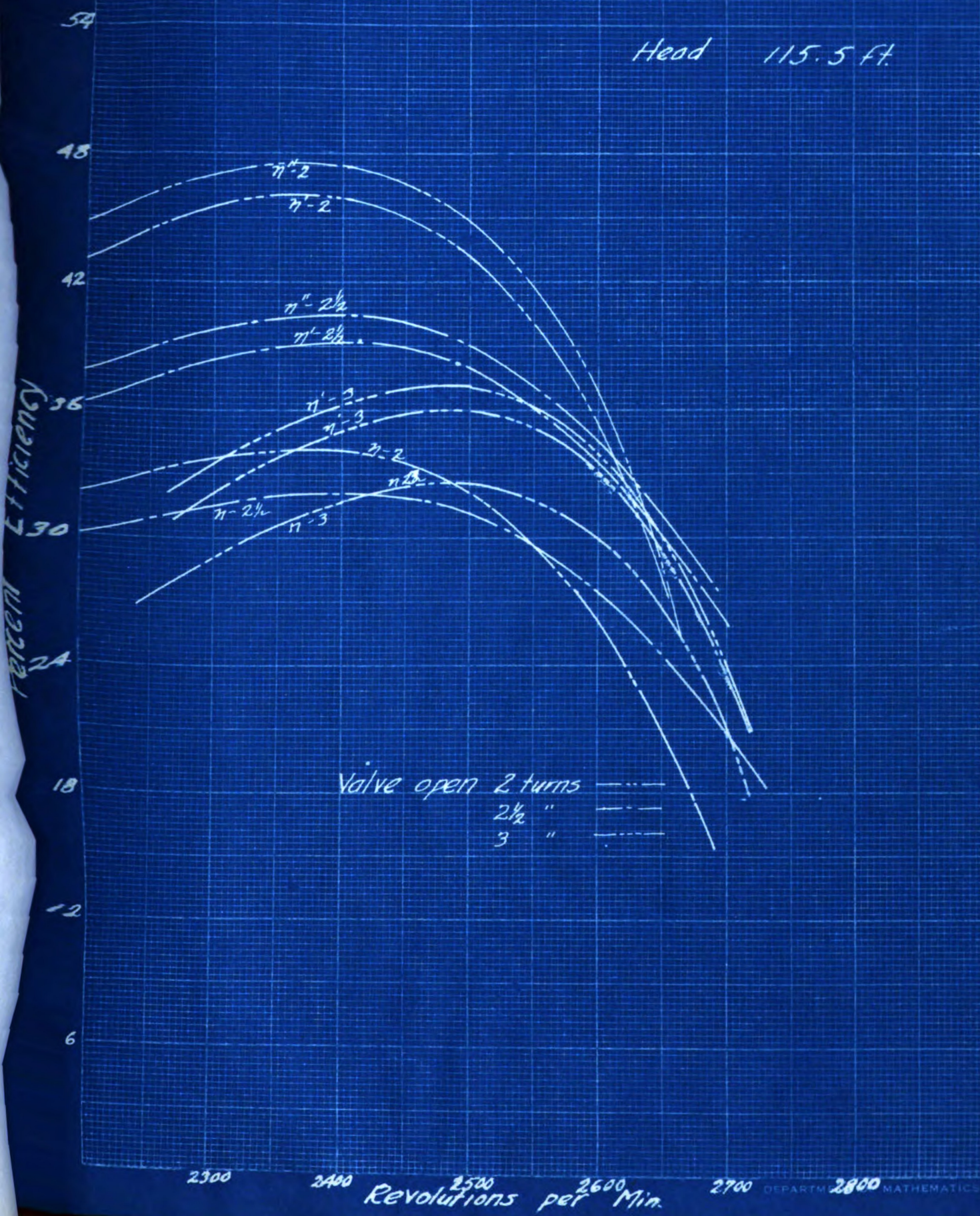
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Revolutions per Min

Head 104 ft.



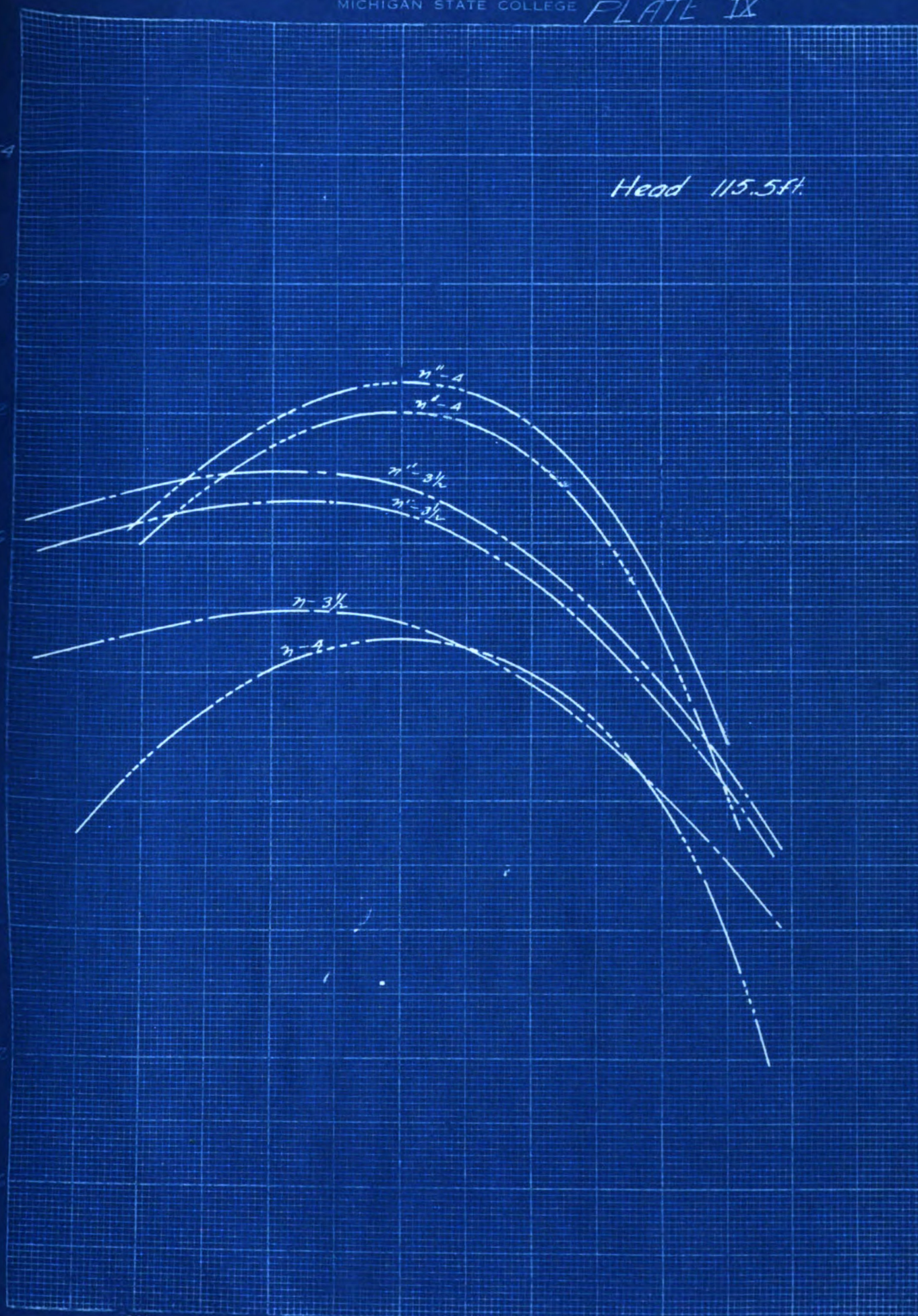
Revolutions per Min.

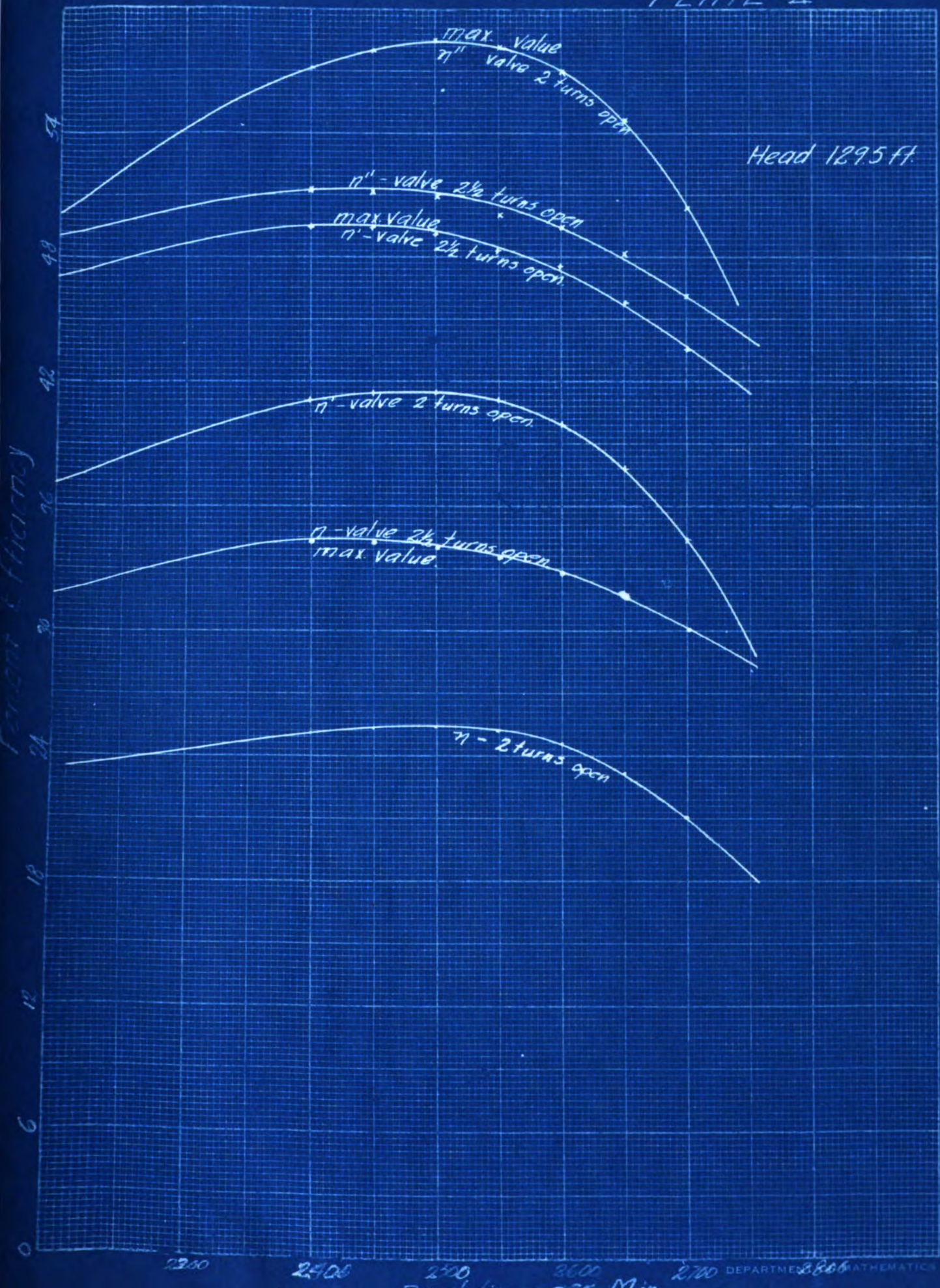


Head 115.5 ft.

Percent Efficiency

Revolutions per Min.





Head 129.5 ft.

Percent Efficiency

Valve open turns

..... 3
 ————— 3½
 - - - - - 4

Efficiencies

η — ●
 η' — x
 η'' — +

$\eta = 3$
 $\eta = 4$
 $\eta = 3\frac{1}{2}$

Revolutions per M.

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ROOM USE ONLY





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