THE RATING OF AN UNDERSHOT WATER WHEEL AT GRAYLING MICHIGAN

Thesis for the Degree of B. S.
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John L. Meyer
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The Rating of an Undershot Water Wheel

at Grayling Michigan

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by

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Located along the north branch of the Ausable River, four miles due East of Grayling is the Grayling State Fish Hatchery. Thousands of fish are produced here annually and planted in the surrounding rivers, streams and brooks making a "fisherman's paradise" of Northern Michigan.

A great share of the work that has been done in and around the hatchery is through the Civilians Conservation Corps. The ground surrounding the buildings is beautifully landscaped with rustic bridges and foot-paths so placed and so constructed that in the sense of the word the groungs can be considered as a park. The hatchery itself is a very attractive structure and on the second floor provisions have been made to take care of two or three tourists or visitors.

During the late fall, all through the winter, and the early spring the troughs in the hatchery are filled with small fish that will be planted the following spring. In order to safeguard themselves against any shortage of water supply, provisions must be made for pumping and storage. Such is the case in all hatcheries; aech individual hatchery having its own problem of supply. Some hatcheries have an artesian supply, some a direct gravity supply from a stream or river, some a gasoline or electric pump, and many other ways to numerous to mention.

At the Grayling Hatchery use was made of an undershot water wheel, utilizing the power produced by a small head at that point. Although the average efficiency of an undershot water wheel is between .25 and .33 the power produced is sufficient for its specifis purpose.

During the summer of 1939, Proffessor Cade of Michigan State college was asked to redesign the wheel and make any changes and sug-

gestions that he deemed necessary. This was Prof. Cade's first experience in the design of this type of wheel and to know more about the actual working, tests were made and the results tabulated to form this thesis.

First let us investigate a few of the underlying fundimental principals that must be known before any significant conclusions can be drawn.

* Water-power can be best defined as the pressure of water used as a prime mover of machinery. The value of water-power depends largely on the nature of the source of supply, whether it is steady or not. Small streams, impounding resevoirs, or ponds are provided to insure a steady flow; but on large rivers there is in general, only a weir or dam across the river to direct the water into the various intakes.

The most usual, and generally the most eligable, method of applying water to the driving of machinery is by means of a vertical wheel put in motion either by the water acting on blades and floats, by impulse derived from it's velocity aquired in falling, or by the weight of water being applied to one side of the wheel. The first method of applying the water is the one which will be investigated.

This first method of application is generally applied in low falls, say under six feet, to what is called and undershot wheel, that is, a wheel where the effective head is below the centre of the wheel. To make application more efficient, that portion of the periphery measured from the point of impact of the water to a point directly below the centre should be surrounded by a casing, generally of stone, but sometimes of cast-iron, called the arc. This casing must be closely fitted to the extremeties of the floats to prevent any considerable

* New Standard Encyclopedia, Vol. 10

escape of water as shown in fig. 1.

The wheel may be made of either timber or of cast-iron, or partly of both, consisting of axle, a; arms, b; floats, c; and generalyya sole plate, d; being a lining around the circumference at the lower edge of the floats, having openings for the escape of air; and a shrouding or cisoular plate, e; at each side of the wheel and of the same depth as the floats. When there is very little beyond the mere flow of the current the paddles are allowed to simply dip in the water like the paddles of a steam boat, in which case no sole or shrouding is required. This latter case is usually applied towhat are called current

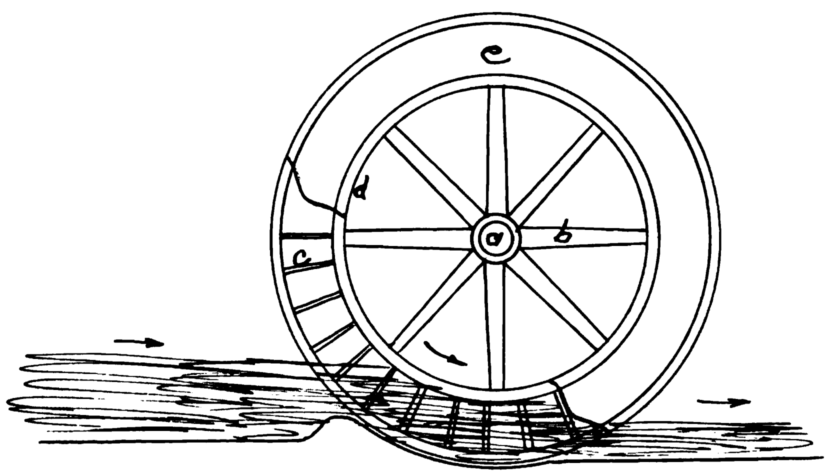


Fig. 1

wheels and will not be considered.

Knowing a bit more about the general construction and operation of an undershot water wheel it is possible to go further into the discussion of the Grayling Wheel.

Aside from being a wheel that can be easily used under the existing conditions of current and head, that is simple in construction, and comparitively low in cost, one might say that this type of wheel is obsolete. There are only a few of these wheels in operation through-

out the country and then for small jobs that require little horse powere

When the wheel was revamped and a new design for the pumphouse drawn up, two different types of wheel were suggested, one of 30% and one of 50% efficiency as shown on the blue print. As the wheel of 30% came the closest to the original design and would be the easiest to fix over, this design was adopted. Probably the best thing that could have been done would have been to completely change the design, but in so doing difficulties again arise. People who have an engineer designing for them feel that the engineer has no personal interest in the job he is undertaking and the person in question will not therefore cooperate to the fullest extent. When an engineer designs something and draws up certain specifications for machinery to be installed it is because he thinks his choice of machinery will work best under these specific conditions. The engineer may be wrong but after all his logic is as good or perhaps better than yours because he is probably more learned in that line.

In this case the wheel was designed for twp horse powerewhen the wheel would turn 30 R.P.M. and a gear ratio worked up so that the final speed woild be 860 R.P.M. For best results it was essential that a low speed pump be used, one probably between 800 and 900 R.P.M. But a pump of 1000 R.P.M. was instaled and so far has proven very unsatisfactory.

Althouh the wheel was designed for 30 R.P.M. only 24 R.P.M. is actually produced making the final ratio still lowere than what it originally was. Then during the winter another element enters in, one that was probably not even considered, that of ice and slush. When the river is filled with slush it accumulates on the wheel and slows the

speed of the wheel as low as 18 R.P.M. In order that the pump operate at all the lowest speed of the wheel can be no lower than 20 R.P.M. Probably the best remedy for this condition would be to buy a new pump, one that operates at a low speed.

Another violation of the design is that of the screen through which the water passes before it comes in contact with the wheel. The drawing specifies a screen 1" by $\frac{1}{4}$" bars 1" c-c, but the one actually installed is much finer than this. Using such a fine screen lowers the velocity of the water, this principal being a function of the friction of the water on the screen. A screen just fine enough to catch the large objects floating in the water would have been sufficient.

From just first observations, before any tests were taken at all it was quite obvious that there was entirely too much tail water. Pictures were taken to show the spray and water carried up by the wheel as it rose up out of the water. To see if any difference could be noted by lowering the tail water, flash boards were removed and an increase of 2 R.P.M. noted. This improvement in R.P.M. is not enough to compensate for a complete change of the fish beds below the wheel as a drop of the tail water failed to supply enough water to the lower beds.

The quantity of water flowing in the river was measured by two methods, the float method and the current meter method, each serving as a check on the other. Probably the current meter method is the closest to being correct as a varying current and numerous eddy currents would introduce error into the float method.

Considering first the current meter method, intervals of two feet across an 18' portion of the river were determined; at each interval a

FLOW MEASUREMENT ON THE AUSABLE RIVER

Dist. from Initial Point	Depth	Depth of Reading	R.P.M.	Time in Seconds	Velocity: At Point	Velocity: Mean in Vertical	Velocity: Mean in Section	Area	Mean Depth	Width	Discharge cu.ft./sec.
0	1.6	.5	49	60	1.59	1.59	.795	.80	.80	1	.636
2	2.3	.8	40	"	1.37	1.37	1.480	1.95	1.95	1	2.885
		.2	40	"	1.37						
4	3.4	.8	40	"	1.37	1.35	1.357	2.85	2.85	1	3.870
		.2	38	"	1.32						
6	3.8	.8	35	"	1.25	1.27	1.310	3.60	3.60	1	4.720
		.2	37	"	1.30						
8	3.5	.8	38	"	1.32	1.29	1.280	3.65	3.65	1	4.670
		.2	36	"	1.26						
10	3.3	.8	32	"	1.17	1.09	1.190	3.40	3.40	1	4.050
		.2	25	"	1.01						
12	3.2	.8	34	"	1.23	1.18	1.135	3.25	3.25	1	3.695
		.2	30	"	1.13						
14	2.9	.8	24	"	.98	1.01	2.093	3.05	3.05	1	6.390
		.2	26	"	1.03						
16	1.5	.5	4	"	.44	.44	.722	2.20	2.20	1	1.590
18	1.2	.5	4	"	.44	.44	.440	1.35	1.35	1	.595
											33.091

$Q = 33.091 \times 2 = 66.182$ cu. ft./sec.

depth reading taken, and R.P.M. readings of the current meter at .8 and .2 of the depth when possible. From the graph of the current meter showing the relation between R.P.M. and the velocity, the rate of speed of the current at each point was calculated and by multiplying the cross-section of the stream the quantity of water in the stream was found. Q = 66.182 cu. ft./ sec.

The use of the float method as a second trial and as a check on the current meter method was used in preference to the weir method because of the uneven banks and the size of the river. Again the velocity of the stream is determined an multiplyed by the cross section of the stream to find the quantity of water.

If correct data could be taken the results would of course be absolutely correct but by making the measurements as carefully as possible the results will be approximately correct and sufficient for practical purposes.

Selecting a portion of the stream that was uniform in depth and width and free from sharp curves, intervals of 6" were taken across the river and the depths of these points recorded. Adding together all the depths taken and dividing their sum by the number of 6" intervals taken an average depth is determined. Multiply this result by the width of stream and we have the cross section at that point.

Owing to the friction of water on the bed of the stream, the velocity is greatest at the surface and near the center of the stream. It has been determined by careful experiment that the average velocity is about 80% of that at the centeral surface.

Bearing this in mind the average velocity may be estimated by throwing a body into the stream having nearly the same specific gravity

Float Method

Depth in feet at 6" intervals.

1	.84	11	3.35	21	3.66	31	1.79
2	1.24	12	3.45	22	3.39	32	1.63
3	1.46	13	3.46	23	2.91	33	2.09
4	1.68	14	3.48	24	3.00	34	1.55
5	1.92	15	3.43	25	2.86	35	1.20
6	2.25	16	3.52	26	2.84	36	1.13
7	2.39	17	3.50	27	2.85		
8	2.50	18	3.60	28	2.65		
9	2.85	19	3.49	29	2.47		
10	2.96	20	3.65	30	2.15		

1.) Total = 93.21 ft.

2.) Mean = 93.21 ÷ 36 = 2.58 ft.

3.) Cross Sectional Area = 18 x 2.58 = 46.44 sq.ft.

Rate of flow by the float.

Trial	Actual Time (Min.)	Average Time (Min.)	Time in Sec.
1	.99	1.24	74.4
2	.94	1.17	70.2
3	1.00	1.25	75.0
4	1.03	1.29	77.4
5	.97	1.21	72.6

1.) Mean = 369.6 ÷ 5 = 73.9 seconds

2.) V = 100 ÷ 73.9 = 1.35 ft./sec.

3.) Q = 46.44 x 1.35 = 62.8 cu.ft./sec.

or weight as water. In this case a bottle partially filled with water worked very well amply serving our purpose. Keeping the float as near the middle of the stream as possible the rate of flow was determined for a distance of 100' and the distance and time converted into feet per second. Taking 80% of this value as the average rate and multiplying by the cross sectional area we have the cubic feet of water flowing in the stream per second. Calculations for the float method will be found on the following page.

Comparing the quanties by the two methods we have,

Current Meter Method - Q = 66.182 cu. ft./sec.

Float Method - Q = 62.8 cu.ft./sec.

A difference of 3.3 cu.ft./sec. is noted and as the bottom of the stream was exceedingly muddy a small difference in the depth readings would occur. For all practical purposes these two values are a close enough check and can be considered adequate.

From the drawings made by Prof. Cade the difference between the head water and the tail water is 1.40 ft. As a check I also measured the head water and the tail water and found a head of 1.38 feet. Following is a sample of the level notes.

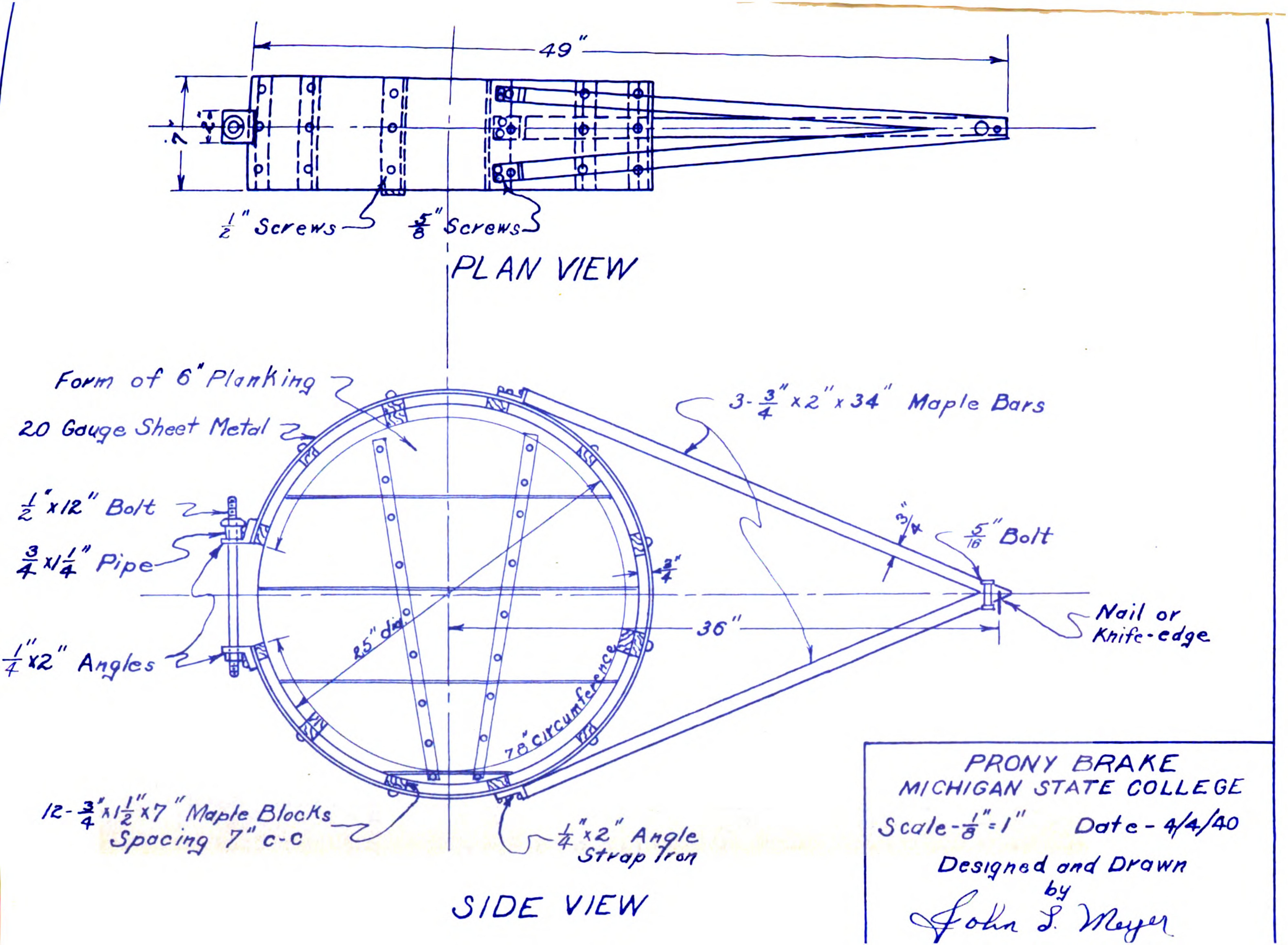
Sta.	+S	HI	-S	Elev.	Remarks
1				100	Sidewalk NE Corner of Hatchery
TP.	2.24	102.24			
			4.63	97.61	Head Water
			6.01	96.23	Tail Water
				1.38	Head

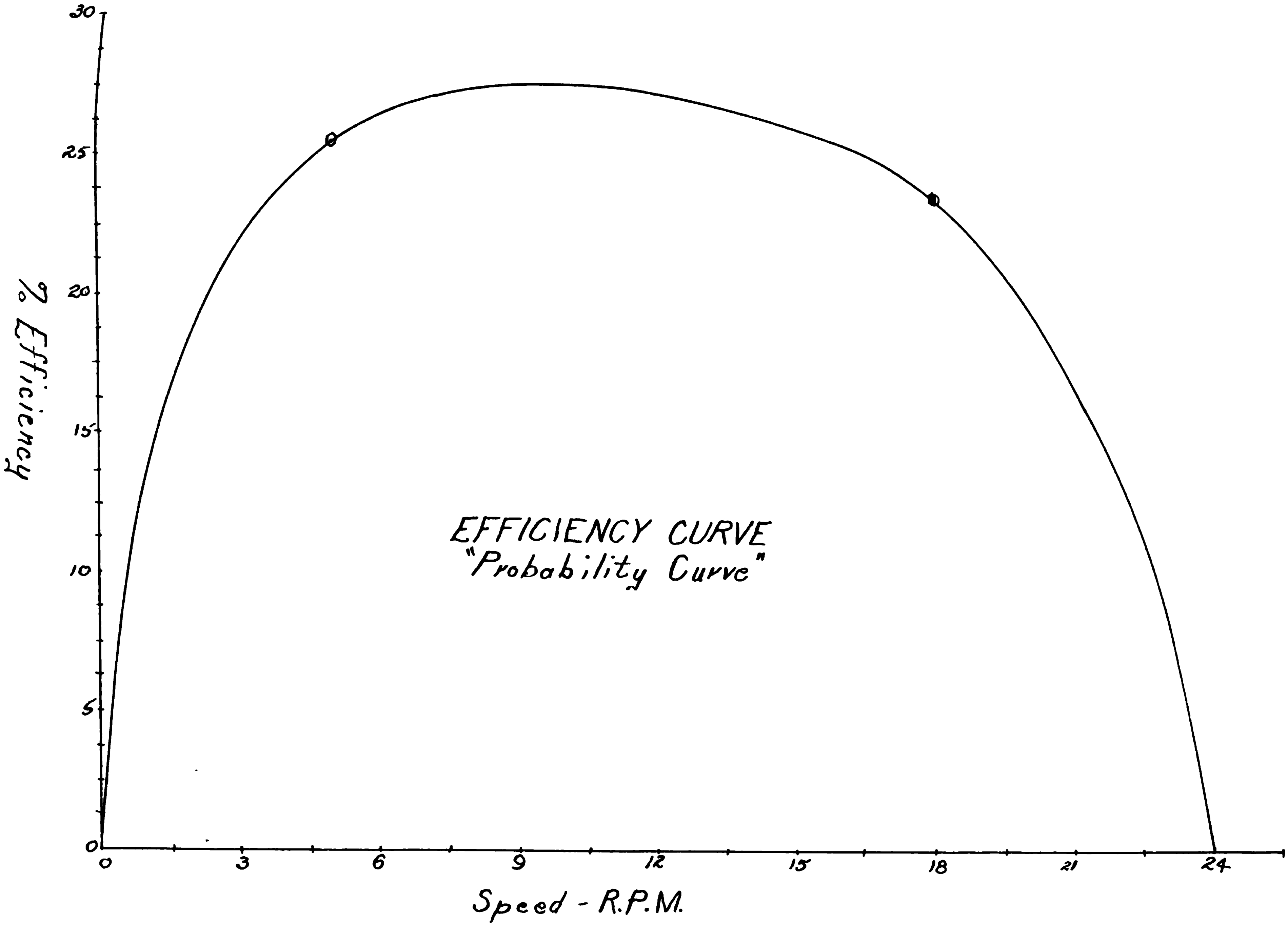
To measure the horse power of the wheel it was first necessary to build a prony brake, strong enough to take care of approximately 2 horse,power. On the following page is a drawing of the design of the brake. This design was picked entirely at random as no tests had ever been made on the wheel and nothing definite as to the actual horse power could be obtained. Assuming a value of 2 horse power exactly for the wheel, and a lever arm, a; of 3 feet, the force, P; that theoretically should be applied to the scale at nomal speed, N; would be

$$HP = \frac{2\pi PaN}{33,000} \qquad \therefore P = \frac{33,000HP}{2\pi aN}$$

$$P = \frac{66,000}{6.28 \times 3 \times 24} = 146 \text{ \#}$$

But before any definite order or proceedure was carried out in running the tests, the brake was applied to the wheel to determine the maximum horse power it realy would produce. This being accomplished intervals could be taken and arranged in such a manner that an even distribution of speed values could be plotted on the graph. A reading w was first taken at 18 R.P.M. measuring 149 lbs. and another at 5 R.P.M. measuring 549 lbs. Then when the tail water was lowered, the brake was again applied to the wheel, attempting to find the increase in power resulting from less water being carried up on the wheel. The last measurement taken with the tail water lower resulted in the failure of the prony brake. The failure occurred at the angles holding the lever arms to the brake band. One eighth inch metal had been provided for that purpose but after the failure the design was changed to one quarter inch angles. Although the brake did fail making it impossible to collect more data, the two readings taken show that the wheel is operating at less than the 30% efficiency it was designed for.


49"
7"
2"
1/2" Screws
5/8" Screws
PLAN VIEW
Form of 6" Planking
20 Gauge Sheet Metal
1/2" x 12" Bolt
3/4 x 1 1/4" Pipe
1/4" x 2" Angles
25" dia.
78" circumference
3/4"
3-3/4" x 2" x 34" Maple Bars
3/4"
5/16" Bolt
36"
Nail or
Knife-edge
12-3/4" x 1 1/2" x 7" Maple Blocks
Spacing 7" c-c
1/4" x 2" Angle
Strap Iron
SIDE VIEW
PRONY BRAKE
MICHIGAN STATE COLLEGE
Scale-1/8"=1"
Date-4/4/40
Designed and Drawn
by
John L. Meyer


EFFICIENCY CURVE
"Probability Curve"
% Efficiency
Speed - R.P.M.
0
5
10
15
20
25
30
0
3
6
9
12
15
18
21
24

The horse power rating of the wheel at the two readings are at 18 R.P.M., P= 149 #

$$HP = \frac{2\pi PaN}{33,000} = \frac{6.28 \times 149 \times 3 \times 18}{33,000} = 1.512$$

and at 5 R.P.M., P = 549 #

$$HP = \frac{6.28 \times 549 \times 3 \times 5}{33,000} = 1.713$$

Since the wheel was designed for 2 horse power, the efficiency rating of the wheel at that value would be 30% and the actual efficiency as determined by the tests would be

(1.) $\frac{1.512}{6.67}$ = 22.7 % efficient at 18 R.P.M.

(2.) $\frac{1.713}{6.67}$ = 25.7 % efficient at 5 R.P.M.

6.67 being the theoretical horse power at 100 % efficiency. Although these values may look rather low, a study of all undershot water wheels will show that about the best efficiency that can be had from a wheel is between .25 and .33. I f more readings could have been taken at different speeds and the efficiencies calculated at that time, a graph of the wheel could be drawn similar to the one in fig. 2. In the plotting of the graph maximum speed and no speed are considered as having an efficiency of zero and at some point between a maximum value determined.

While looking through some references for material on undershot water wheels, I ran across an artical on the Poncelet Undershot Water Wheel. After reading over the material it seemed as if this type of wheel could be used very nicely at Grayling but after a few calculations it is plain that this wheel is not applicable for this purpose as will be shown later.

With the Poncelet Wheel the water acts very nearly the same way as with the turbine, although slightly less efficient than the best turbines, in normal conditions of working, is superior to most of them when working with a reduced supply of water. Fig. 3 shows its general construction. The water penned back between the side walls of the wheel jet flows to the wheel under a movable sluice, at a velocity nearly equal to the velocity due to the entire fall. The water flows down a slope of 1 in 10 being either a straight or curved race entering the wheel with as little shock as possible. After gliding up on the curved floats, the water comes to rest, falls backwards, and at the point of discharge, aquires a backward velocity reletive to the wheel nearly equal to the forward velocity of the wheel. Therefore the wheel is left

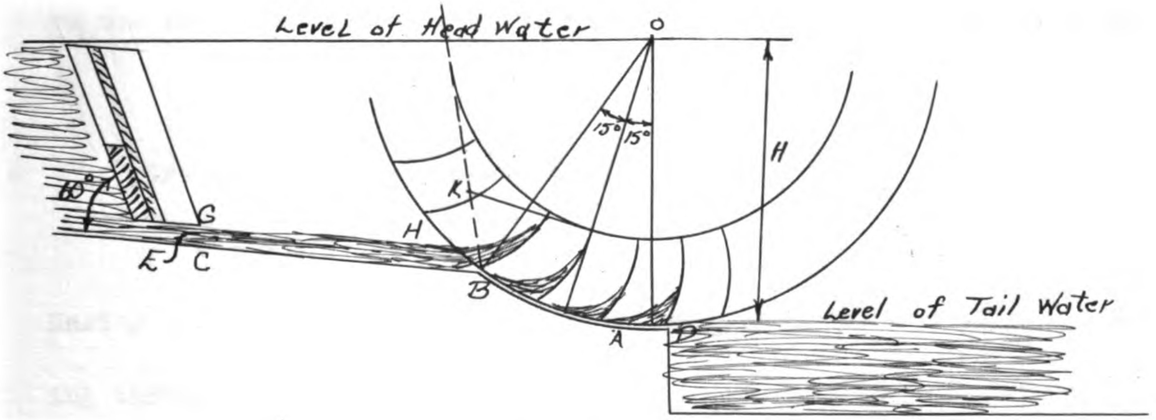


Fig. 3

with almost the whole of the original kinetic energy of the water.

Taking the efficiency at 60 % and putting H for available fall, HP for horse power, and Q for water supply per second.

$$HP = .068QH$$

The diameter of the wheel may be taken arbitrarily but should not

be less then twice the fall and more often it is taken at four times the fall. The radial depth of the buckets should be at least half the fall and the curvature of the paddles about half the radius as that of the wheel.

Let H be the fall measured from the surface of the head water to a point F where the mean layer of water enters the wheel; the velocity of the water entering the wheel then being $v = \sqrt{2gH}$, the best circumferential velocity of the wheel being either $V = .55v$ or $V = .60v$. The speed of the wheel in revolutions per second is $N = V/D$. The thickness of the sheet of water entering the wheel has been determined by experiment as between 8 and 10 inches. With a surplus supply of water the thickness of the water should not exceed 15 inches. Let "e" be the thickness of water entering the wheel and "b" its width. Then

$$bev = Q \qquad \text{or} \qquad b = Q/ev$$

Grashof takes $e = 1/6\ H$ then

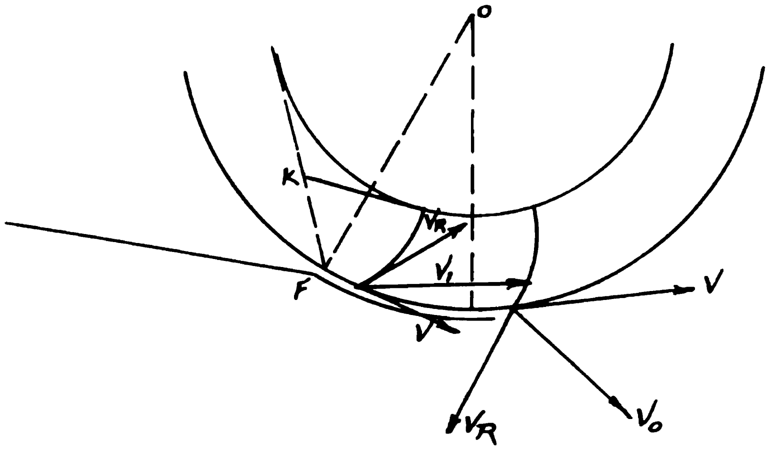
$$b = 6\ Q/H\sqrt{2gH}$$

Making allowances for contraction of the stream the area of the opening through the sluice may be 1.25 be to 1.3 be. The inside width of the wheel should be 4 inches greater than "b".

Of all the possible constructions for the floats of the Poncelet Wheel the following is probably the simplest.

Let OA be the vertical radius of the wheel. Set off OB, OD making angles of 15 degrees with OA then BD may be the length of the close breasting fitted to the wheel. Draw the bottom of the head race BC at a slope of 1 to 10. Parallel to this, at a distance of ½e and "e", draw

EF and GH. Then EF is the mean layer and GH the surface layer entering the wheel. Join OF and make OFK equal to 23 degrees making FK = 0.5 to 0.7 H. Then K is the centre from which the bucket curve is struck and KF is the radius. To prevent the rising of water over the top of the



v = Initial velocity

v = Final velocity

v = Parallel to vane

V = Vel. of wheel

Fig. 4

floats, shrouds must be sufficiently deep, probably between $\frac{1}{2}$ H to 2/3H. Usually buckets are placed one foot apart on the circumference of the wheel, the exact number of buckets being rather unimportant.

From the above theory let us try a few substitutions of the data obtained from the existing hydraulic conditions at the Grayling State Fish Hatchery.

$H = 1.38$ ft. $\quad Q = 66.128$ cu.ft./sec.

Solving for the velocity

$$v = \sqrt{2gH} = \sqrt{2 \times 32.2 \times 1.38} = 9.42 \text{ ft./sec.}$$

and

$$V = .6v = 5.65 \text{ ft./sec. (circumferential velocity)}$$

But by the float method the velocity was found in the normal stream current as 1.35 ft./sec. This velocity calculated above does not, however, apply to the normal stream current but at the point where the

water enters the wheel, which, in this case, could very well exist. Assuming b = 11 ft. solve for "e", the thickness of the sheet of water.

$$e = Q/bv = 66.128/11x9.42 = .602x12 = 7.2 "$$

This value is close enough to 10" as the size of the wheel will be comparitively small. Making the speed the same as now exists the diameter of the wheel will be

$$V = N D \qquad or \qquad D = V/ N$$

$$D = 5.65/3.14x\tfrac{1}{2} = 3.6 \text{ ft.}$$

It is this factor that makes this type of wheel impossible to use. A wheel of such small diameter would not be large enough to produce the horse power that needs to be produced to carry out the work most efficiently. If the head were made greater the size of the wheel would be increased but an addition of only one foot could be arranged under the present conditions; this increase in head making very little difference in the size of the wheel.

FREDRICK UNDERSHOT WATER WHEEL

About ten miles farther north on route U.S. 27 is another undershot wheel, a rather antiquited affair but nevertheless a wheel that has been to a specific use. The wheel is located on the same river as i is the Grayling wheel at a point where the current runs very swift. A small earth dam has been constructed across the river storing the water to such a heigth that a head of about 3 feet is produced.

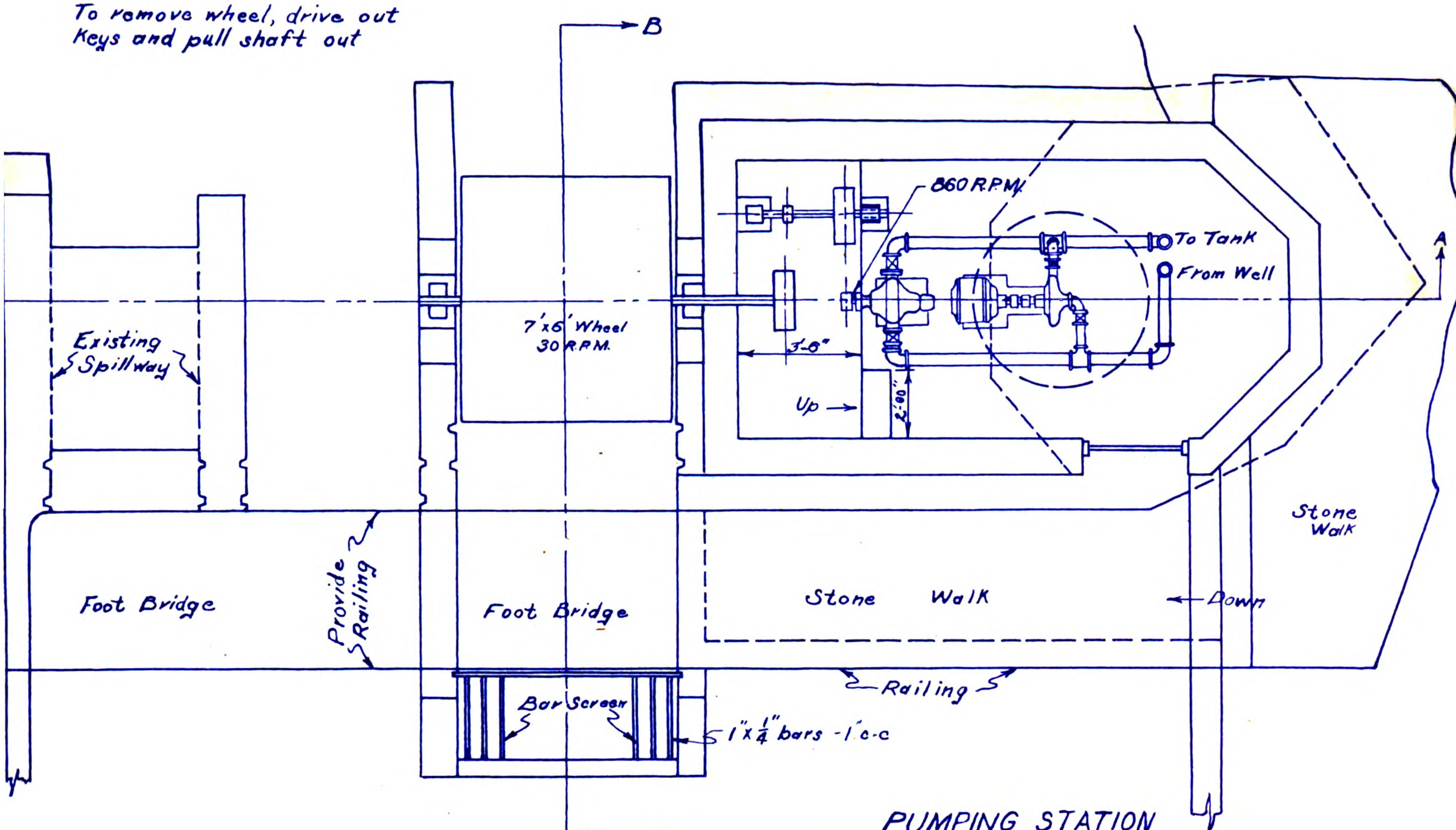
The wheel has been built of numerous individual parts gathered form every imaginable source appearing to be strictly a home made affair. The paddles consist of 20 gauge sheet metal fastened to metal spokes by pieces of strap iron. A gear connected to the end of the wheel shaft drives a generator within a small power house by means of a chain drive. The wheelmeasures 5 feet in diameter by 8 feet in width having a speed of 9 R.P.M.

The generator provides a home about 100 feet distant from the wheel with electricity. Although the wheel turns at a comparitively low speed, a gear ratio within the power house steps the speed up to 1000 R.P.M. The whole generating system is small but sufficient for supplying electricity to this on e home.

Perhaps the most outstanding principal in construction that could be improved on is the periphery of the wheel. The whole set up shows an absense of design and, probably, had some definite design been concidered the wheel would be a great deal more efficient. But as mentioned before, the space between the lower tips of the

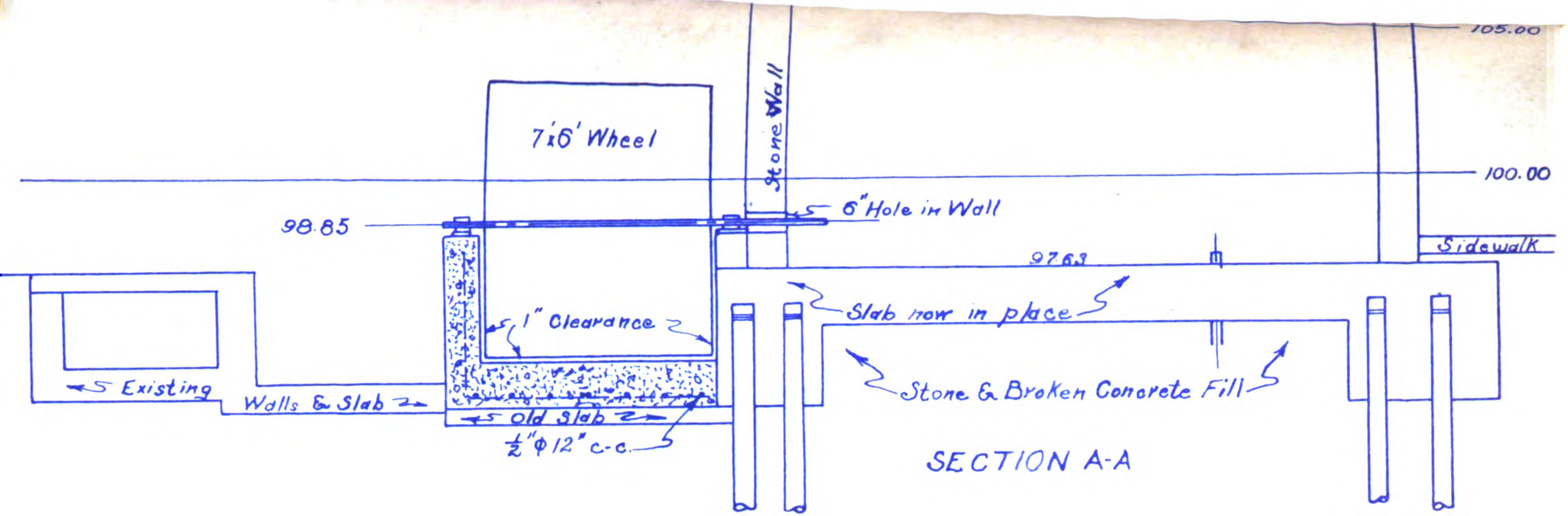
blades as they pass over the periphery is so great that a big loss in power results by part of the water passing through without giving up any of its energy. The bottom of the periphery looked exceedingly rough and should measures be taken to build up the bottom, more volocity would be produced, both by a lowering of the friction and by more water coming in direct contact with the wheel. This one particular fault seemed to be the most noticeable but should anyone care to study it further a host more of faults could be found. Mention was just made of this wheel as it was close to the Grayling wheel and was of interest at the particular time.

In this paper I have attempted to rate this wheel at Grayling in order to facilitate in the revamping that is being contemplated for this summer. A graph of the efficiency of the wheel at different speeds could not be plotted because of the failure of the brake, but two readings were taken and the results true enough to know a bit more than was previously known about the wheel. The design of the wheel and pumphouse were very well done and should the exact material that was specified in the drawings used the wheel would be still more efficient.



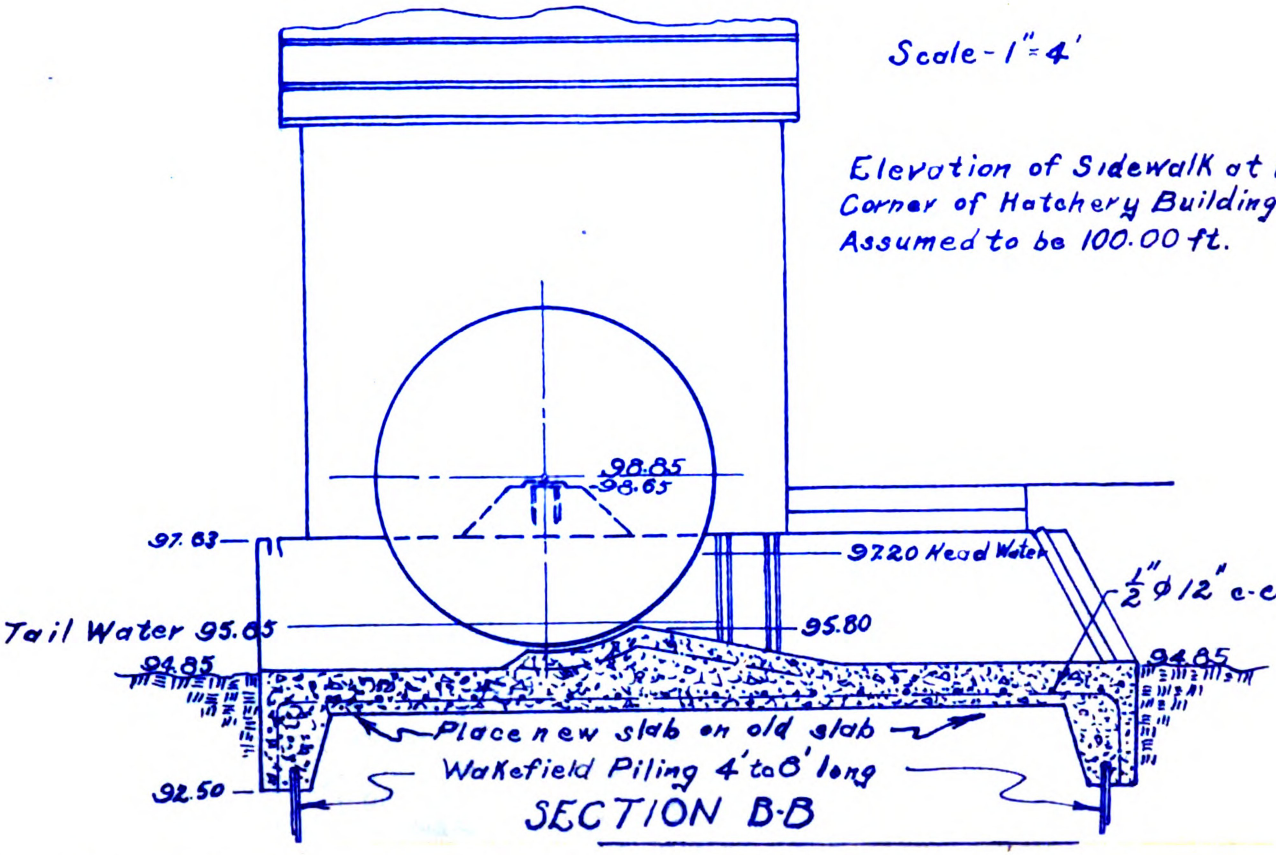
PLAN VIEW
Scale - 1" = 4'

PUMPING STATION
GRAYLING FISH HATCHERY
MICHIGAN STATE COLLEGE
Designed by C. M. Cade, Reg. C.E.
Redrawn
by
John L. Meyer



SECTION A-A

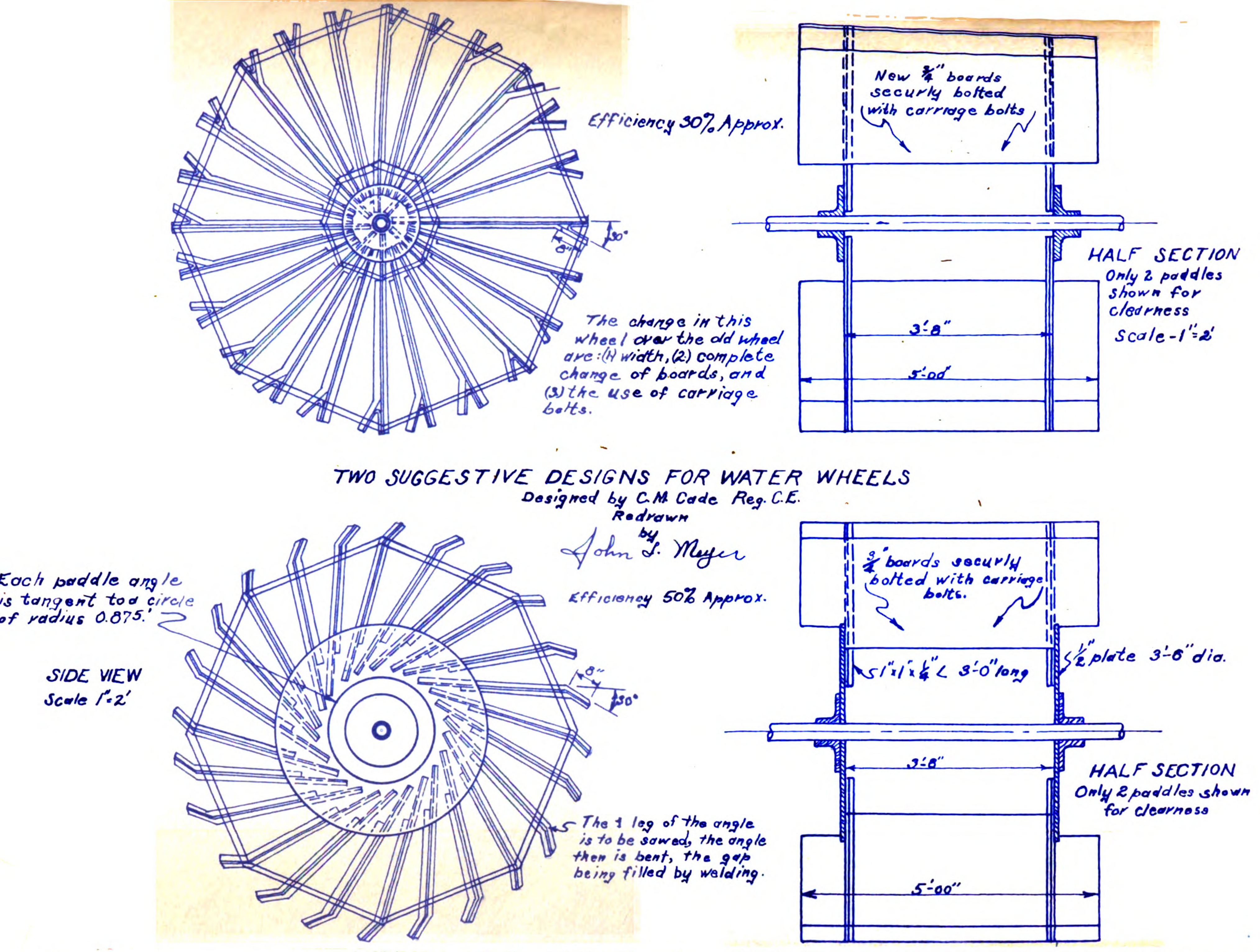
LAYOUT OF PUMPING STATION
GRAYLING FISH HATCHERY
MICHIGAN STATE COLLEGE
Designed by C.M. Cade Reg. C.E.
Redrawn
by
John L. Meyer



SECTION B-B

Scale - 1" = 4'

Elevation of Sidewalk at NE Corner of Hatchery Building Assumed to be 100.00 ft.



TWO SUGGESTIVE DESIGNS FOR WATER WHEELS
Designed by C.M. Cade Reg. C.E.
Redrawn by John S. Meyer
Efficiency 30% Approx.
New 3/4" boards securly bolted with carriage bolts
HALF SECTION
Only 2 paddles shown for clearness
Scale - 1" = 2'
3'-8"
5'-00"
30°
8"
The change in this wheel over the old wheel are: (1) width, (2) complete change of boards, and (3) the use of carriage bolts.
Each paddle angle is tangent to a circle of radius 0.875'
SIDE VIEW
Scale 1" = 2'
Efficiency 50% Approx.
3/4" boards securly bolted with carriage bolts.
1/2" plate 3'-6" dia.
1"x1"x1/4" L 3'-0" long
HALF SECTION
Only 2 paddles shown for clearness
The 1 leg of the angle is to be sawed, the angle then is bent, the gap being filled by welding.

Water Wheel in Motion Showing Tail Water

Side View of Wheel

Pump House Details

Pump House

Down Stream Showing Spillways

Fredrick Wheel