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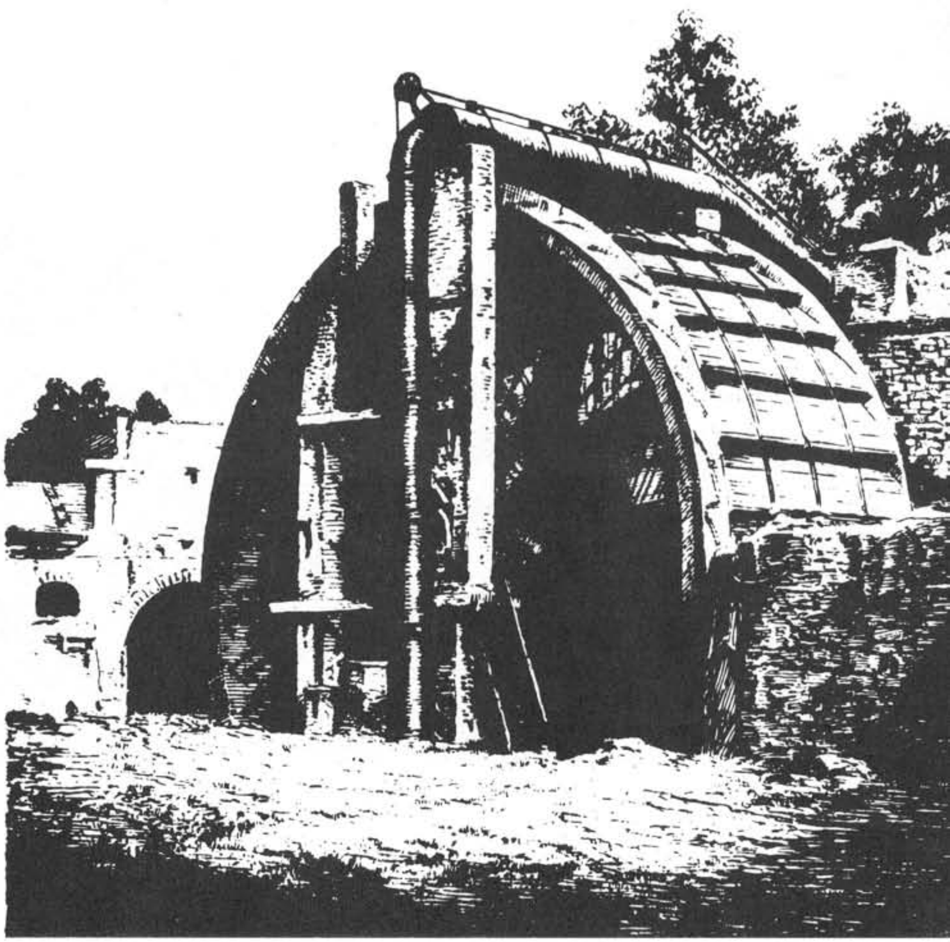
THE BURDEN WATER-WHEEL

F. R. I. Sweeny



REPRINTED FROM THE 1915 TRANSACTIONS OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS, WITH ADDITIONAL ILLUSTRATIONS, AND AN INTRODUCTION BY ROBERT M. VOGEL.

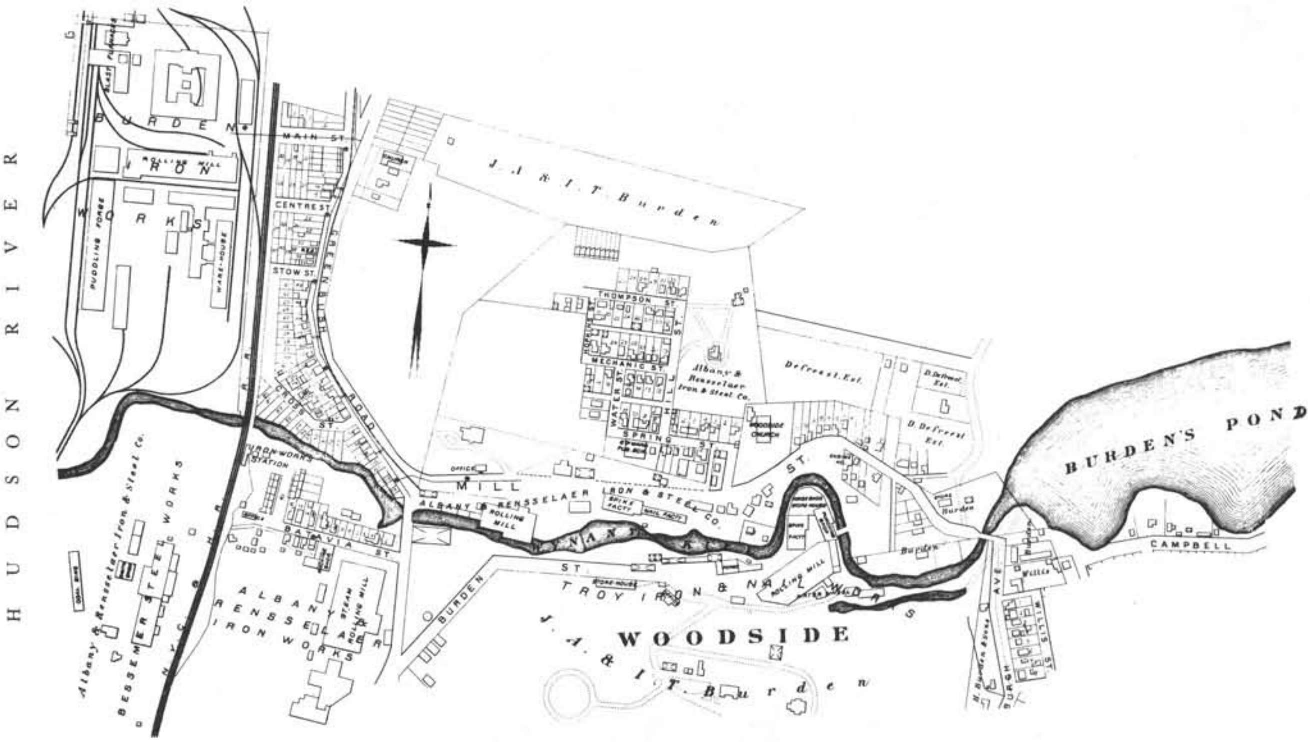
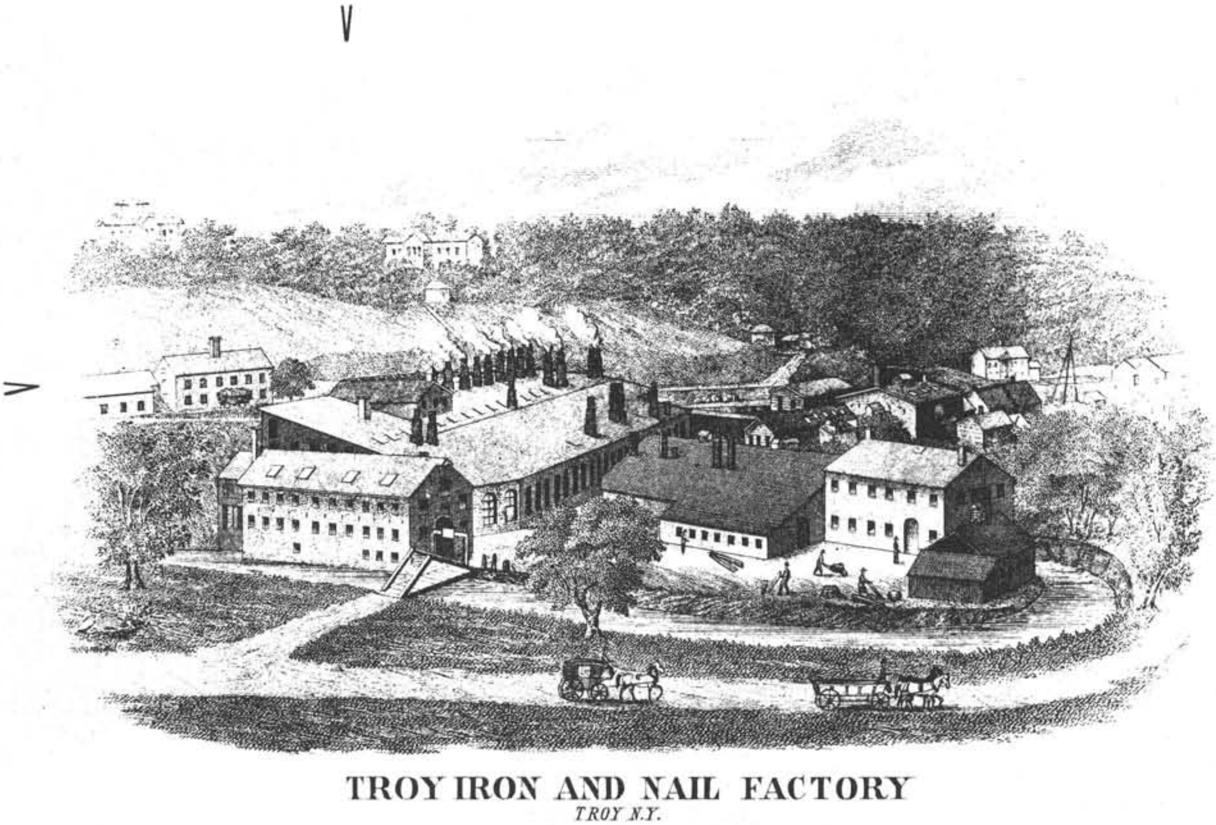
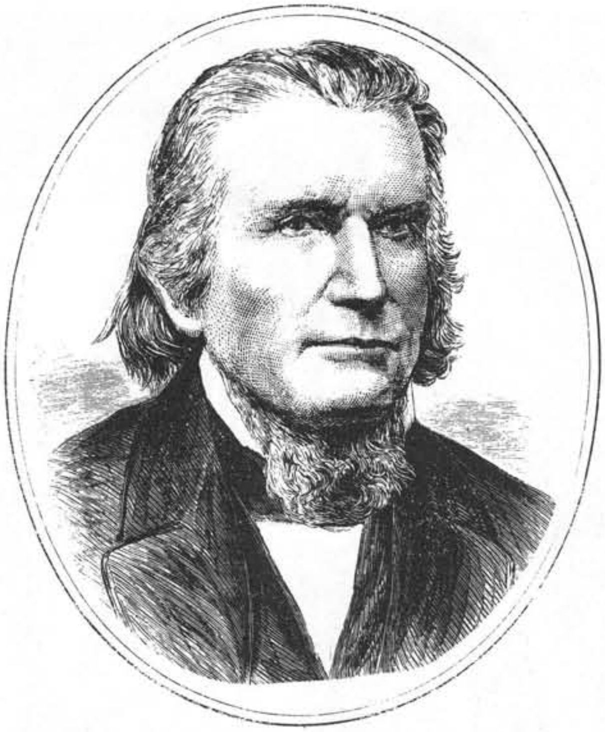


Figure 1. Site plan of Burden's Upper or Water Works (the by-then archaic style *Troy Iron & Nail Works* is used). The later Lower or Steam Works (1862) is at the left. *Woodside* was the Burden estate. *G. M. Hopkins,* City Atlas of Troy, N. Y. *Philadelphia, 1881.*

Figure 2. View of the Upper Works, c1858, looking southwest across the Wynants Kill. The Water Wheel was housed in the gabled section of the rolling mill (at arrows). *William Barton,* Map of the City of Troy and Green Island, N. Y. *Troy, 1869 (map printed 1858).*



TROY IRON AND NAIL FACTORY
TROY N.Y.

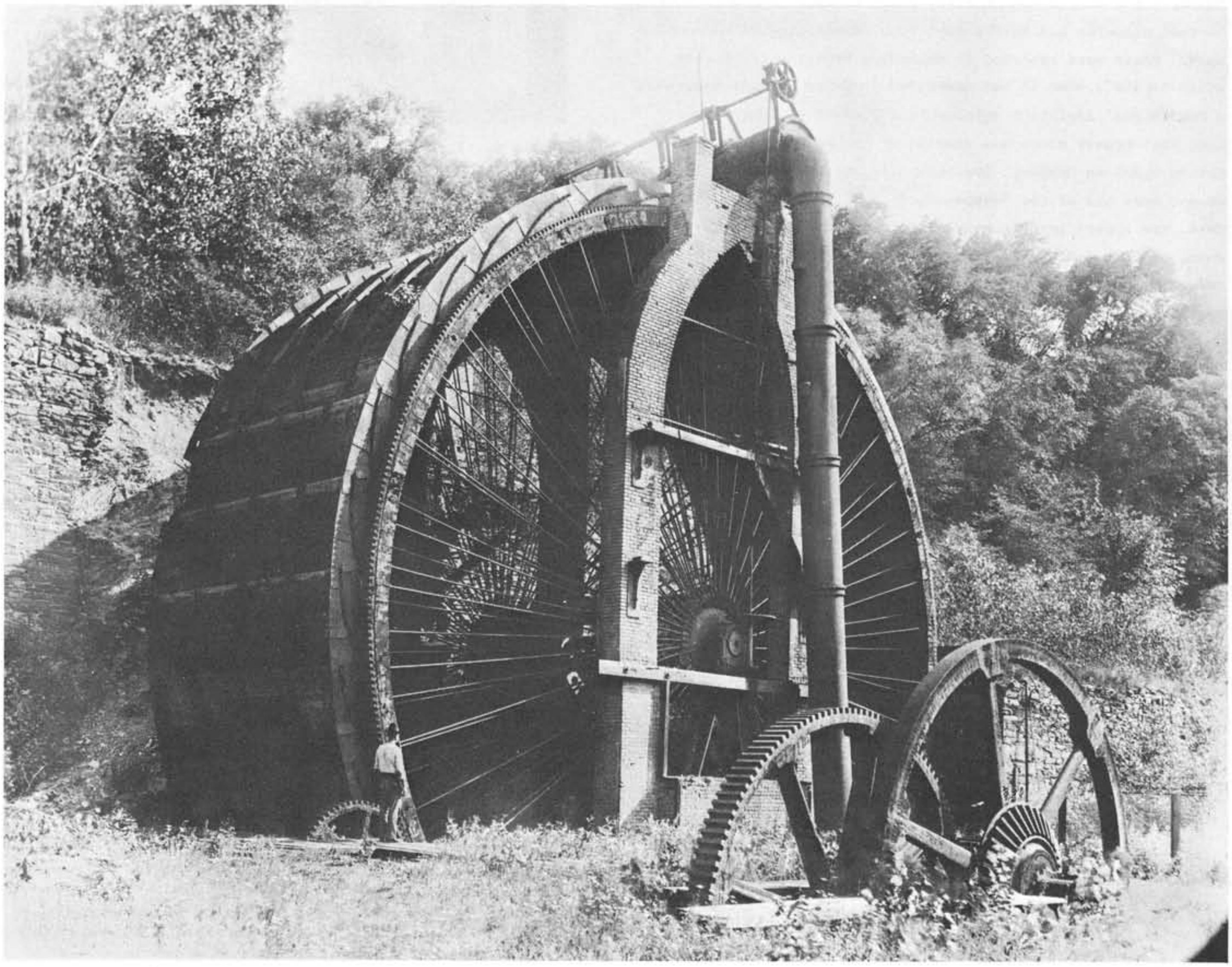


INTRODUCTION

The great overshot water wheel designed and built in 1851 by Henry Burden, Troy ironmaster, to power the machinery of his horseshoe factory, was the most singular and spectacular industrial feature of an area that throughout the 19th century abounded with the products of technological innovation. The eminent hydraulic engineer Edward Dean Adams years later called it The Niagara of Water Wheels. Despite the fact that Burden was one of the greatest original thinkers of his time, literally "inventing" the machine-made horseshoe by developing a series of machines and processes for its mass production, it cannot be said -- nor did he claim -- that his water wheel in any sense broke new ground. It simply was his answer to the need for a prime mover to furnish a large, dependable quantity of power. Its significance lay in its scale and masterful detailing.

Figure 3. Henry Burden 1791-1871. American Artisan, *1 February 1871.*

Figure 4. The Burden Wheel as it stood from about 1899 to 1914, the wheelhouse removed. *Courtesy Rensselaer Polytechnic Institute Library.*



That Burden built a water wheel rather than a turbine is perfectly logical. The hydraulic turbine had reached a state of commercial practicality only a few years previously, and in the US, only a few turbines were in use: principally Uriah Boyden's famed units at Lowell. Moreover, the turbine, to achieve any sort of reasonable efficiency, required in its design a degree of theoretical sophistication that probably was beyond Burden's largely practical training.

Burden, a Scot, undoubtedly was fully conversant with the contemporary state of the water wheel art in the US and abroad. In 1838, when the Wheel was first built (although invariably it is reported to have been "rebuilt" in 1851, it has always been my belief that it was totally reconstructed then), there were in use in this country numerous large, powerful breast wheels, most in the great cotton mills of New England. These were principally of wood, with a certain amount of iron reinforcement, in a few cases having iron buckets. They reached diameters of thirty feet with maximum face widths of about twelve feet.

In Europe, the water wheel had reached a high degree of refinement in the hands of such engineers as William Fairbairn (whose illustrious career began with the construction of iron wheels) and Thomas Hewes. In 1827 Hewes designed and Fairbairn built, for a Scotch cotton mill, a set of four iron wheels of 50-foot diameter and twelve-foot face, developing 96 horsepower each. These were reported in *Mechanics Magazine*. Sometime prior to 1847, when it was described in David Scott's *Engineers' & Machinists' Assistant* (Glasgow), a 70-foot by twelve-foot iron high-breast wheel was erected at the mill of Shaw's Water Cotton Spinning Company, Greenock. As was Burden's, these iron wheels were all of the "suspension" or "bicycle-wheel" pattern, the spokes being purely radial, of relatively thin iron rods, the rim and buckets supported solely by tension. As the drive was always taken from a segmental gear at the rim, there was little torsional stress between rim and axle.

A number of notable large water wheels followed Burden's, some perhaps inspired by it, but never one to exceed it either in capacity or overall massiveness. Its most heralded successor, and the only water wheel in the world to achieve anything like the notoriety of the Burden Wheel, was the famed *Lady Isabella*, erected in 1854 by the Great Laxey Mining Company on the Isle of Man. Known more popularly as the Great Laxey Wheel, it operated until 1929 and is now privately preserved. It is 72 feet in diameter by six feet wide, and developed about 200 horsepower, pumping water from a lead mine through an elaborate series of reciprocating rods driven by a crank on the wheel's shaft. It is of composite construction: mostly iron but with timber arms (alternating with iron stay rods) transmitting the torsion to the hubs. The *Lady Isabella*, despite its isolated location, has always been something more of an attraction than Burden's Wheel ever was, principally because it was intended to be. It is architecturally elaborate, brightly colored, prominently placed in the landscape, and was never housed in. The Burden Wheel, all business, was fully visible only during the period of its decline, following closure of the Upper Works and removal of the building in which it worked.

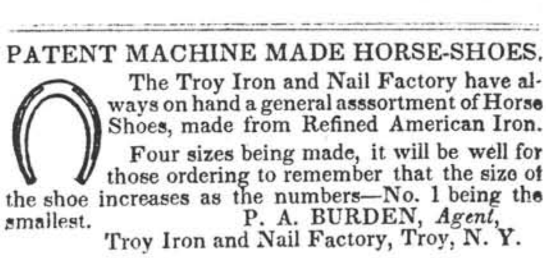


Figure 5. American Railroad Journal, *1849*.

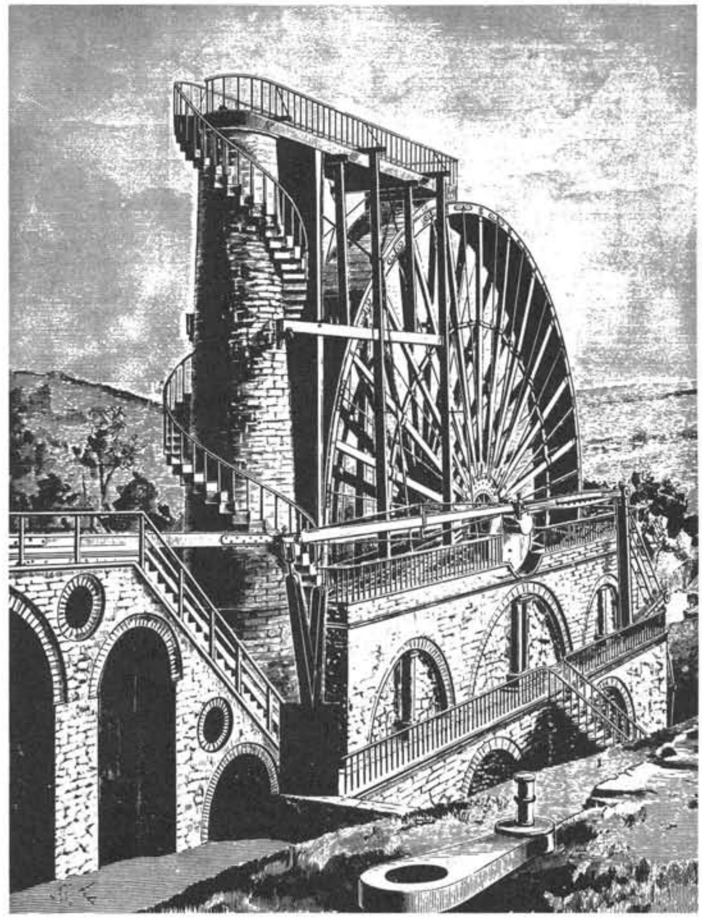


Figure 6. The *Lady Isabella* or *Great Laxey Wheel*, Isle of Man. Cassier's Magazine, *Volume 6, 1894*.

Much was written about the Burden Wheel, in both the technical and the popular press. It was endlessly investigated. During its active life it was the basis for many of the theses that were a graduation requirement at nearby Rensselaer Polytechnic Institute. In his *Review of Burden's Suspension Water Wheel*, G. F. Kirby (Class of 1857) analyzed the wheel as both a prime mover and a structure, concluding,

> . . . that the wheel, taken as a structure is a firm one in most respects, and that it stands among the first in rank, as a motor, of its kind -- if not actually <u>the first</u>.[1]

The Wheel's final examination was that of F. R. I. Sweeny, carried outwhile he was a student at RPI (Class of 1915, civil engineering), during its declining years. It was not only the last critical look at the old giant, but by far the most thorough, both analytically and graphically. Sweeny, who must have

1. Manuscript copy of Kirby's thesis is in the RPI Library; Xerox copy in the Library of the National Museum of History and Technology.

been profoundly intrigued by the Wheel, was, unknown to himself, conducting an unusually interesting *industrial archeological field project!* His findings, reproduced herewith in their published form, should be regarded as a model study by us, his humble followers.

If Sweeny had done nothing else, he once and for all settled the question of the Wheel's capacity, a figure widely given and wildly ranging; up to 1200 horsepower. Sweeny tells us that the *maximum* capacity was 482 horsepower, while the *usual* output was 282, at the very respectable efficiency of 84%.

EPILOG

The Trojans of the 20th century were not unconscious of the historical treasure in their midst, and during the years of the Wheel's terminal agonies there were periodic movements to restore it to its former glory. *The Locomotive* for July 1931 reported that a group of electrical engineers, interested in its restoration, believed that despite the fact that "souvenir hunters have removed so many of the parts that once went to make up its mighty whole that there remains only a bare hint of its original majestic outline," there was enough left to make rebuilding practical. We may assume that then, as now, the insurmountable hurdle to an otherwise worthy preservation scheme was lack of money, and like earlier ones, it failed.

For nearly another decade the ruins lay. Shortly before World War II, the owners of the site, Poor & Company, gave the land to the adjoining Immaculate Conception Monastary, at which time they dynamited the remains for scrap.

National Museum of History & Technology,
Washington, D. C. R. M. V.

Note: The Sweeny Paper is reprinted with the kind permission of the American Society of Civil Engineers, from Volume 79 of their TRANSACTIONS *(1915), pages 708-726. The original arrangement and figure numbering have been altered to conform with that of this publication. Figures 7-13 are Sweeny's, reproduced in their original order, but his figure 3, essentially identical to figure 6 herein, has not been used.*

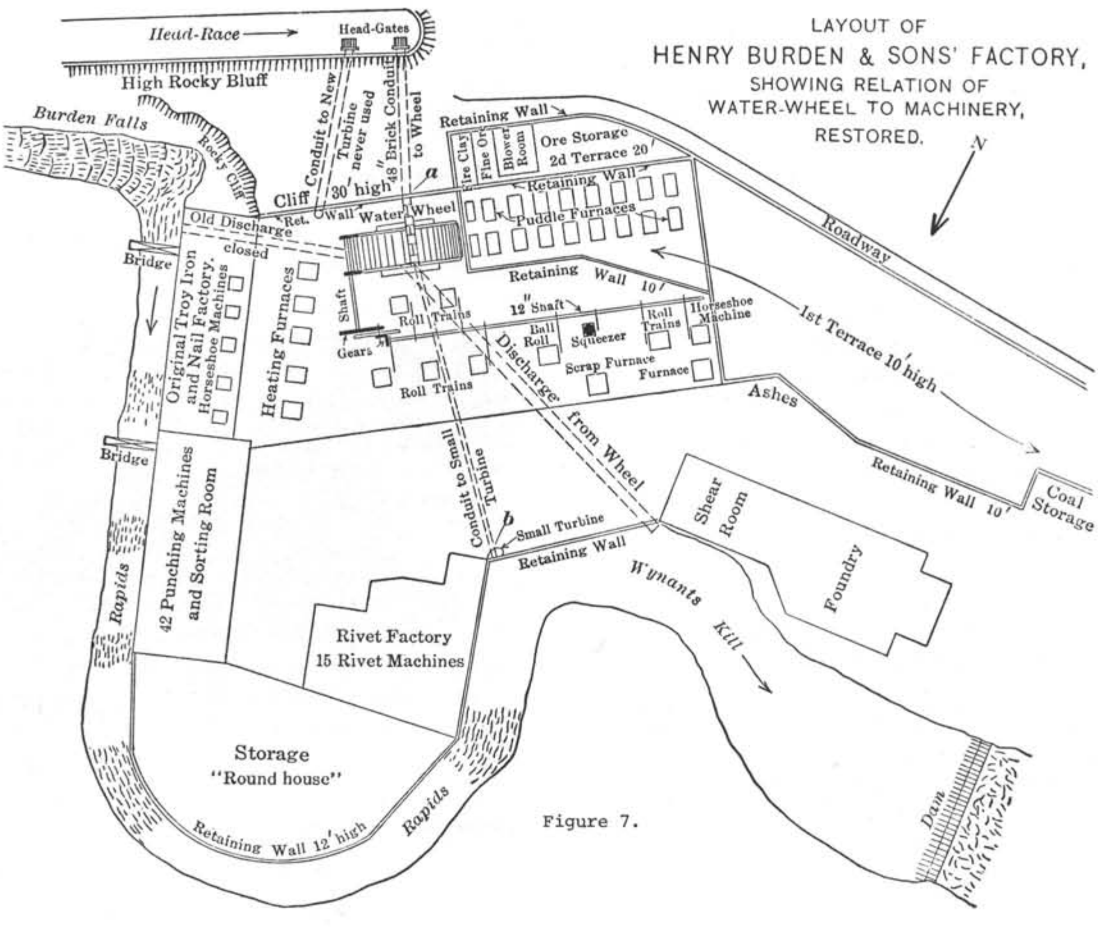


Figure 7.

Paper No. 1343

THE BURDEN WATER-WHEEL

By F. R. I. Sweeny, Esq.

Synopsis.

The south supporting pier of the old Burden water-wheel at Troy, N. Y., gave way on August 22d, 1914, and since that time there has been a general and rapid decay. In view of the fact that this wheel was the greatest in America, of a type now virtually obsolete, it seems proper at this time that its history, construction, and operation should be reviewed and placed on record in the publications of this Society. The writer was fortunate in having obtained complete measurements of the dimensions of the wheel and its setting prior to its failure, and these are given in the accompanying illustrations.

A paper* by the late Joseph P. Frizell, M. Am. Soc. C. E., entitled "The Old-Time Water-Wheels of America", unfortunately, did not mention this wheel. In the discussion of that paper, however, the desire was expressed that it be pictured, "and its efficiency, present condition and relative usefulness made known". Partly in response to this and to the feeling previously expressed, this paper is presented.

Historical.

Water-wheels, in the past, have been used for a variety of purposes, but it is doubtful if there ever existed a case having such a historic setting as the old Burden water-wheel. It is intimately associated with those great inventions of its designer and was born of the same genius, so that it is difficult to separate it from its setting. Thus, in order to understand the conditions leading up to its origin, it is necessary to revert to a brief historical outline prior to its inception.

Henry Burden, the designer of the wheel, was born in Dunblane, Scotland, in 1791, and after receiving an engineering education in Edinburgh, came to the United States in 1819, settling in Albany, N. Y., where he engaged in the manufacture of agricultural implements. In 1822 he moved to Troy, and took over the superintendency of the Troy Iron and Nail Factory, at that time a comparatively insignificant establishment. He began at once on his career as an inventor and manufacturer, changing the whole process of the manufacture of wrought iron and its products, and transforming the Troy Iron and Nail Factory into the largest works of the kind. It will suffice to state that it was here that he invented, built, and, for years, operated machines for the manufacture of ship and railroad spikes, nails, and horseshoes, as well as his concentric squeezer for reducing puddle balls. Thus, it will be noted that he was very progressive, constantly aiming to operate the plant more efficiently. The factory became very profitable, and because of his various inventions, Mr. Burden gradually acquired full interest, and in 1840 became proprietor. The firm was known thereafter as Henry Burden and Sons. It appears that in the early history of these works five small water-wheels were used, but, about 1838, due to the tremendous increase in the volume of business, it became necessary to secure more power with which to operate the new machines.

The foregoing were the conditions incident to the construction of the large wheel which is the subject of this paper.

Description.

The works were on the banks of the Wynants Kill, a small stream entering the Hudson River a few hundred yards below, as shown by Fig. 7. Quite close to the plant are the Burden Falls having a height of about 50 ft. and followed by a succession of rapids. The flow of this little stream was quite variable, and at some periods in the summer almost ceased entirely, being too low to furnish sufficient power. About 10 miles above this point the stream has its source in four lakes, and at the plant the total drainage area is approximately 36 sq. miles. It is evident, therefore, that to accomplish the results sought it would be necessary to regulate the stream in some manner and also to build a wheel of sufficient size to utilize practically the total available head of about 70 ft. In attacking this problem Mr. Burden exhibited the same resourcefulness as in all his other undertakings. To accomplish the proper regulation of the stream, a lake was formed in the vicinity of the others by building a dam across a narrow part of the valley and placing therein regulating gates. It was found that this provided sufficient storage to regulate the stream and sufficient power at all times. In solving the second part of the problem, he recognized the fact that one large unit would be more efficient than five small ones, and thereupon commenced the construction of the wheel, popularly known later as "The Niagara of Water-Wheels".

It is stated that Mr. Burden commenced the construction of this wheel in 1838, and it appears in the records that, after experiencing considerable difficulty in its operation, it was rebuilt in 1851. The records show that at one time one of the journals broke off from the rosette, due to excessive heating of the bearing. This was corrected to a certain extent in the rebuilt wheel by making the journal hollow and by providing for the circulation of water over the bearings. To what extent it was rebuilt is not known, but it would seem that the same general dimensions were retained, though there was considerable alteration in the details. However, the wheel as it stands to-day is the same as the one rebuilt in 1851, save for a few changes in the penstock, which was constructed of wooden staves instead of the riveted iron pipe now standing. It is stated that, outside of the ordinary

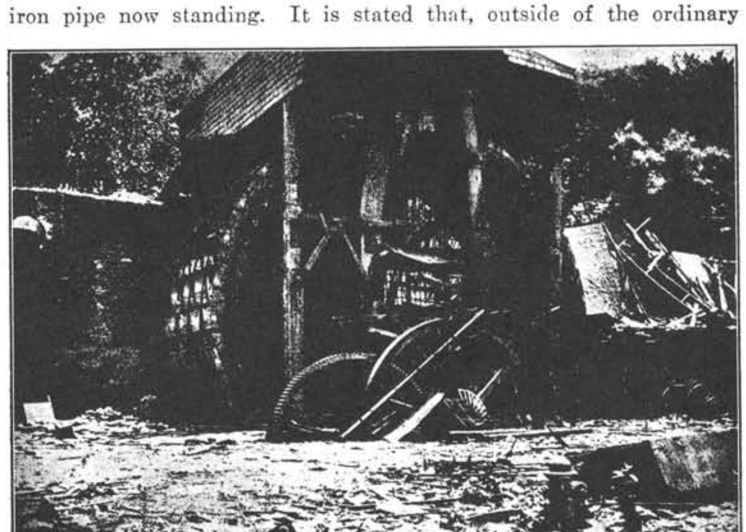


Fig. 8.—Burden Water-Wheel After Dismantling of Works, Showing Portion of Roof.

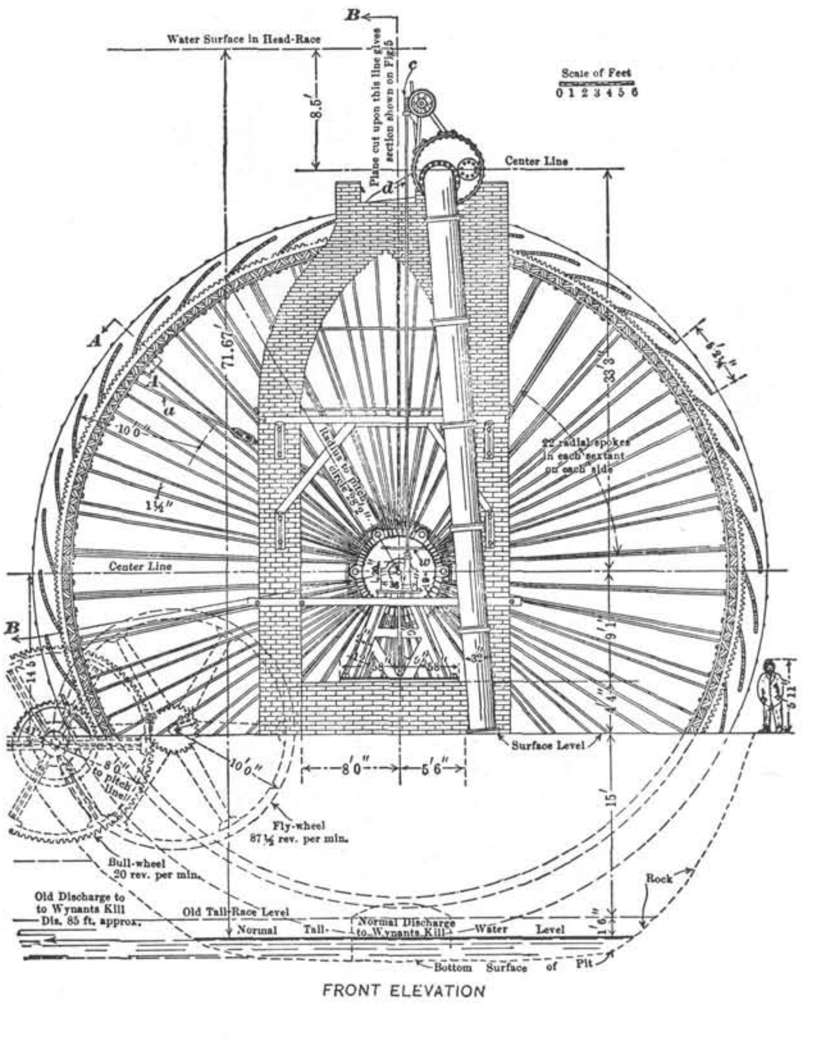
* *Transactions*, Am. Soc. C. E., April, 1893, Vol. XXVIII, p. 237.

repairs incident to the operation of the wheel, the only part that was renewed was the segment gearing, which was replaced about 1882.

The dam was a few hundred yards above the falls, and the water flowed in a canal along the hillside, ending at a point about 100 ft. from the center of the wheel, as shown by Fig. 7. From this point it was carried in a brick conduit, 4 ft. in diameter, to the edge of the cliff, and there this conduit was joined to the riveted steel penstock, also shown by Fig. 7. In the canal at the head of the conduit there were head-gates.

The wheel is of the overshot type, and in general consists of a central hub to which are fastened radially 264 iron rods, $1\frac{1}{2}$ in. in diameter. These are fastened to 10 by 10-in. Georgia pine timbers forming the soling on which the floats or buckets are built. On each side of the wheel on the soling is fastened the segment gearing which gears with two pinions keyed to the same shaft, as shown at the ground level in Figs. 9 and 10. The wheel stands in a pit, about 20 ft. deep at the lowest point, cut out of solid Hudson River shale. The sides of the pit, along the faces of the wheel, are lined with brick to the ground level. At the center, under the bearings, the wall is carried up about 4 ft. on the north side and 9 ft. on the south. On each of the piers there is a cast-iron base-plate on which rests a cast-iron pedestal, shown in Figs. 9, 10 and 11. The reason for the shorter pedestal on the south side is apparently due to the fact that the rock on that side is against the face of the cliff. Before the wheel was constructed, the cliff extended out for a considerable distance, but this was all removed in order to obtain the proper setting for the wheel.

On the pedestals rest the main bearings which support the wheel. The hub is made up of two rosettes fastened together by hollow bars, as shown in Fig 11. Each of these rosettes is 7 ft. in diameter, and is cast integral with the journal, which is 20 in. in diameter. A section through the hub on the center line of the journal (Fig. 11) shows it to be of T-form, with the stem of the T larger where it joins the journal, and curved in outline. The top of the T is 12 in. across and radially through it are drilled three rows of holes, the outer row having eight and the other two rows seven holes to the sextant into which the hub is divided. The center holes are drilled into the body of the casting and tapped to receive the rods; the outer and inner rows are bored through the shoulders of the T and the rods are held by nuts. At each of the six points, *a* (Fig. 11), holes were drilled, parallel to the axis of the journal, and through them were placed 2 ft. 6-in. by $4\frac{1}{2}$-in. wrought-iron pins, on each of which a shoulder was turned. Over each pin fits a hollow stiffening bar, 10 in. in diameter at the ends and 12 in. at the middle. These are fastened to the pins rigidly by gib and cotter, *c*. At the center of each stiffening bar is turned a shoulder, *d*, and over each is slipped the stiffening ring, *b*, and driven to a fit. Thus the whole central portion of the wheel or hub is rigidly assembled. In the actual construction of the wheel, all this was first assembled, then the first rods vertically under the hub were placed, and suspended from these was a 10 by 10-in. Georgia pine timber, 22 ft. long, which formed a part of the floor or soling on which was constructed the buckets, gears, etc. The rods, alternately on one side and then the other, were placed, and the correspond-



FRONT ELEVATION

FIG. 9.

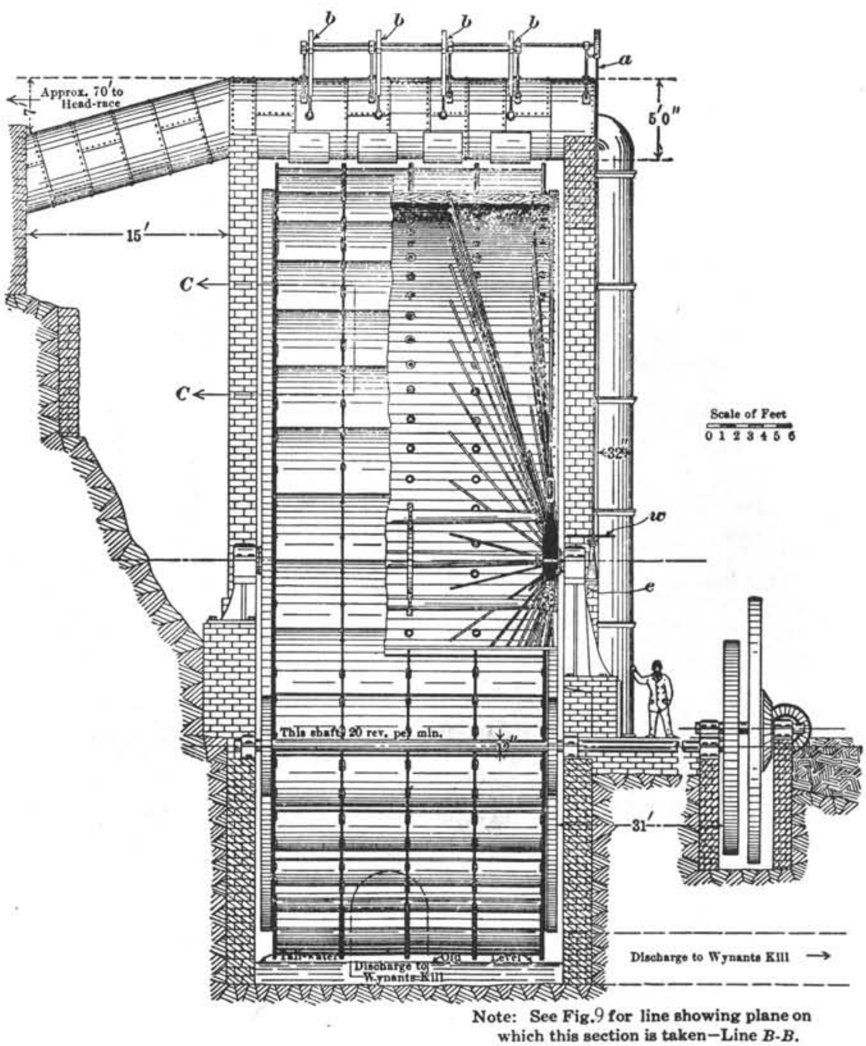
ing timbers were attached. This operation was repeated until one-half the soling was in place, which formed an inverted arch. Through each of these timbers were run wrought-iron rods which served to bind the whole together and hold them in line in a radial plane. These are shown at *a* (Fig.11). After the lower half was thus placed, a center was built for the upper half, as would be done for a full centered arch, on which the remaining portion of the soling was placed.

It will be noticed that the center row of holes in the rosettes requires that a turnbuckle be placed on each rod running to them, otherwise there would be no way to regulate their tension. The rods passing through the outer and inner rows of holes, which are bored through the shoulders of the **T**, permit of adjustment with nuts, as shown at *e* (Fig.11). In order to stay the wheel against any axial motion, the three rows of rods on each side are disposed as shown in Figs.10 and 11, which is the same as in a bicycle wheel.

Figs. 9 – 11 show the method of constructing the buckets and segment gearing. The shrouding, *b*, is of cast iron, $\frac{3}{8}$ in. thick and 29 in. deep, 2 in. of it being set into the soling for the purpose of caulking the buckets. This was cast in sections and fastened together with rivets as shown at *c*. Through the shrouding passes 1-in. bolts which go through the soling and are secured by nuts and washers, as shown at *d*. There are 36 buckets, the timbers of which are of Georgia pine, 2 in. thick. Each of the timbers passes through a slot in the shrouding, and in order to caulk effectively against leakage the ends were kerfed and small wooden wedges were driven which forced the wood against the shrouding. On the inside of the shrouding and against the soling a quarter round strip was fastened, and oakum was packed behind this to prevent leakage. In after years it was found necessary to place the small angle, *e*, between the shrouding and the segment gear and to caulk between this and the shrouding, for at times the water squirted out into the shop.

In order to support the buckets at intermediate points, three cast-iron spacers, *f*, were used. These are merely frames which permit of free access from one part of the bucket to another, and yet effectively support the timbers. The same method of attachment to the soling is used as in the case of the shrouding. The spacers are cast in sections and fastened together at *g* (Fig.11). The planks of the buckets are doweled to each other, as at *g* (Fig.11), in order to prevent springing under pressure, which would render the oakum caulking ineffective. Another function of this doweling was to stay the buckets and shrouding from transverse motion.

The main gear is made up in segments 6 ft. long and of the dimensions shown at *h* (Fig. 11). Each of these segments is fastened to the soling by five bolts which pass clear through it and also through a $\frac{3}{4}$ by $5\frac{3}{4}$-in. bar inside the wheel. There is one of these gears on each side of the wheel, as shown by Fig.11, and they gear with two pinions, 7 ft. in diameter and 9-in. face. These pinions are keyed to a shaft which is 12 in. in diameter and is supported on bearings on each side of the pit. The shaft extends out into the room about 31 ft. from the face of the wheel, and terminates in a large gear 16 ft. in diameter. This in turn meshes with a 44-in. pinion which is keyed to a shaft carrying a fly-wheel 20 ft. in diameter. On the same shaft



Note: See Fig.9 for line showing plane on which this section is taken—Line *B-B*.

FIG. 10.

SIDE ELEVATION AND PART SECTION.

and adjacent to the fly-wheel is keyed a miter gear which meshes with another keyed to the line shaft. This line shaft ran the length of the shop, a little above ground level, and was 12 in. in diameter.

It is seen from the drawings that, the power being taken off at the periphery of the wheel, instead of at the axis, the only torque produced at the axis was due to journal friction. It is estimated that the wheel weighs about 250 tons in a soaked condition or 125 tons on each bearing. This weight was sufficient to require some means of taking care of the frictional torque produced, and accordingly the two rods, *a* (Fig. 4), were placed and provided with turnbuckles.

A very novel feature is the method of bringing the water to the buckets. The canal ends at a point about 100 ft. from the center of the wheel, and there the water is taken into a brick conduit through a head-gate. This conduit is made of three rings of brick, each ring being cemented and hooped around with wrought-iron bands. This stands to-day in apparently perfect condition. At the edge of the cliff this brick conduit is joined to a riveted iron penstock which rises and is carried over the top of the wheel, resting on brick arches close to each side. All this has fallen in, due to the failure of the foundation walls on August 22d, 1914. Up to that time the wheel was in almost as good condition as when it stopped in 1896. On the top of the iron penstock there are five iron brackets supporting a shaft which terminates in a worm wheel and has keyed to it four pinions in intermediate positions, as shown at *b* (Fig. 5). In the side of the penstock there are four rectangular orifices, equally spaced over the breadth of the wheel. Inside of each there is a sliding gate which is fastened to a stem passing up through a stuffing-box and connected to a rack. This rack gears with the pinion on the shaft referred to, and is held in gear with it by an idler which runs on a small shaft supported by the brackets. At *c* (Fig. 9) a worm engages the worm wheel and is keyed to the shaft, *d*, which runs down to the hand-wheel, *w*. This is supported by the bracket, *e* (Fig. 10), which is attached to the pedestal of the main bearing. In the operation of the wheel, a man was constantly kept at this hand-wheel and, at a signal from the shop, would admit more or less water and thereby maintain the speed constant at 2½ rev. per min.

The discharge from the wheel was taken through a tunnel cut in the solid rock to the creek, a distance of about 200 ft. This represents the normal tail-race; but, in the early history of the wheel, a suit was brought by the owners of the property on the other side of the creek and adjoining the falls, demanding that the water be returned to the stream at the foot of the falls. Due to the numerous small rapids between this point and the point of normal discharge, this meant that the bottom of the wheel would be submerged for 2 or 3 ft., which would cut down the power very materially. This matter was adjusted subsequently, and the old discharge was opened again. The two discharge tunnels are shown on Fig. 7; the short one to the foot of the falls was closed after the adjustment of the difficulty. The vertical cast-iron pipe bolted to the end of the penstock and running down beside the pedestal was used as a penstock to a small turbine at *b* (Fig. 7). The conditions that brought about this addition are not known.

The drawings only show the restored wheel. A part of the roofing

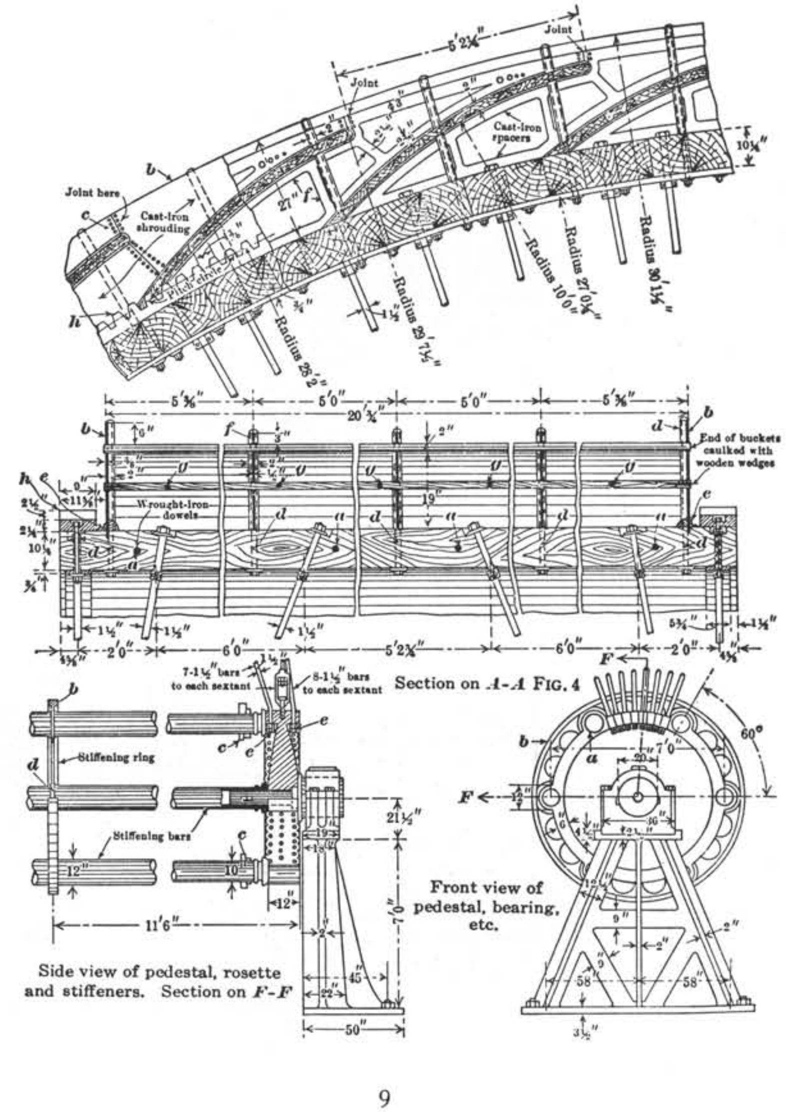


FIG. 11.

is shown on Fig. 8. The point of connection with the main factory roof is clearly shown. The wheel stood in the main room of the works (Fig. 7), and being under the same roof was afforded protection from severe weather. The rear wall of the works was built up on the edge of the cliff immediately adjacent to the wheel, and for a height of 10 ft., and the roof started from this. In this wall, and opposite the wheel, a door was placed, and from this a gangway was constructed up alongside the penstock and over the top of the brick arches which supported it. The wheel, just after it was built, became quite famous, and was constantly inspected by a large number of visitors. The gangway leading to the top was opened to them by the proprietor, and quite a good idea of the magnitude of the wheel could be obtained by looking down into the shop from this height.

In severe winter weather, after a shut down, considerable trouble was caused by ice, which formed on the top and had to be chopped away before the wheel could be operated. Of course this never occurred during normal operation, as it was prevented by the heat from the furnaces. The bearings were lubricated with suet, and the caps, being hollow, were packed with this lubricant. However, the bearings became heated occasionally, and, to remedy this, water was circulated over them. The wheel was very rigid for a machine of this size, yet there was some vibration, and this eventually loosened some of the rods and occasionally broke one. The proper tension had to be maintained at all times, in order to secure the necessary rigidity and also make the gears mesh properly. It was also the constant aim of the attendants to maintain the wheel in a uniformly soaked condition because any drying out would tend toward an unbalanced operation. This also would affect the proper meshing of the gears.

Fig. 7 gives a good idea of the general layout of the plant. In operation the following machines were driven by the wheel: one rotary concentric squeezer and muck-bar train, six 9-in. trains for rolling horseshoe and rivet iron, six horseshoe machines, fifteen rivet machines, forty-two punching machines, machine shop, roll lathes, shears, and other machines required in a rolling mill.

The wheel was in continuous operation for a period of 45 years, often running day and night for long periods; but, due to the growth of the business and the necessity for more power, the works were abandoned in 1896 and the machinery was moved to the steam mill which is a short distance away on the banks of the Hudson.

The wheel is rapidly falling into decay, and before long its destruction will be complete. The supporting piers have failed, and the wheel has settled into the pit. The brick arches also have fallen, and the iron penstock is resting on the top of the wheel, broken away from its connection with the brick conduit and vertical cast-iron pipe. As one stands and looks on this, he is forcibly reminded of the irresistible advancement in engineering lines, there is such a contrast between this huge motor and the compact, high-power units of to-day.

Power and Efficiency.

Thus far nothing has been said of the power and efficiency of this wheel, but, as this is of interest, the writer has worked up, from known conditions of operation, the curves shown. A brief explanation of the method of deriving these curves is given.

To determine the power and efficiency of an overshot wheel, for different conditions, by the methods given by Weisbach, would be very troublesome, and so the writer has resorted to a graphical solution. It will be assumed at the outset that each bucket is completely filled at the top of the wheel, and then the intermediate conditions can be readily determined.

It is clear that if the bucket is initially completely filled, it will start spilling at once and continue to do so until it is completely discharged. To determine the power developed under these conditions, an integral expression of the form,

$$\text{Horse power} = \int \frac{W\ dH}{33\ 000}.$$

must be evaluated. In this expression there are two variables, and, from a well-known principle of the calculus, if for all values of H we can determine the corresponding values of W, it can be evaluated. It is evident that, for every position of the bucket, the water contained therein is a definite quantity which fulfills the foregoing conditions. By making a drawing of one of the buckets to a large scale, and considering it in ten consecutive positions from the top around to the lowest point, would mean that by drawing lines tangent to the lip of the bucket every 10°, the area within each and the outline of the bucket is a measure of the quantity of water contained. The center of gravity of each section thus determined, was plotted, and the head above tail-water measured. The integral was changed to the form,

$$\text{Horse power} = \int \frac{C\ A}{33\ 000}\ dH,$$

in which C is a constant and A is the cross-sectional area of the water in the bucket. In Fig. 13, the term $\frac{C\ A}{33\ 000}$ was plotted as abscissas against H as ordinates.

This takes care of the water from the topmost bucket to the tail-race level and in order to include the effect due to the impulse of the entering jets from the four orifices the following expression was used:

$$\text{Effective head on top bucket} = (V \cos.\ O - u)\frac{u}{g},$$

in which V is the absolute velocity of the entering water, O is the angle the entering water makes with the tangent to the bucket, and u is the peripheral velocity of the center of gravity of the water in the bucket. V was determined by the Bernoulli equation, and found sensibly constant for different rates of discharge, because the area of the orifices is small compared with that of the conduit. By consulting the curve, Fig. 12, it will be seen that by dividing the greatest abscissa into ten equal parts by vertical lines, where these intersect the curve will give the height at which spilling commences for that quantity of water in the buckets. The circles on each of these lines represent the height of the center of gravity of the water in the highest bucket with this percentage of filling. Therefore, to the left of any one of these lines, the area included between it and the vertical axis and the lower curve will give the horse-power developed by the action of the water on the wheel, and that to the left of this line and the vertical axis and below the curve will give the lost energy due to spilling out of the buckets. Now, in order to take into consideration the energy due to the impulse at the top it will be observed that if each of these vertical lines be carried up a distance above the circles equal to the effective head on the bucket due to impulse, then the area to the left of this extra height and the vertical axis will give this power. In order to simplify the work a little, instead of doing this, a point equivalent to twice the effective head was found on the vertical axis and lines were drawn connecting the circles and this point, which gives the same area as before. It will be observed that we are now in a position to integrate for power under all conditions of initial filling, and at a constant speed of 2½ rev. per min. From this curve, the curve, Fig. 13, was constructed, and lines showing the conditions under which the wheel normally operated were drawn. This gives 278 h.p. at 84.25% efficiency. This, of course, means the hydraulic efficiency only, as a great quantity of power must necessarily have been lost in the gearing. It must be borne in mind that the possible maximum power was determined by the head on the orifices and their greatest area. This would be a little above the normal power because the gates were almost opened to their limit. The curves are instructive, however, in showing what the wheel could do with sufficient water, as well as showing its high efficiency.

The matter of centrifugal action was investigated, and it was found that the center of curvature of the surfaces of the water in the buckets was located on the vertical axis of the wheel, at a height of approximately 475 ft. above the center of the wheel. Its effect on the power of the wheel, therefore, was negligible.

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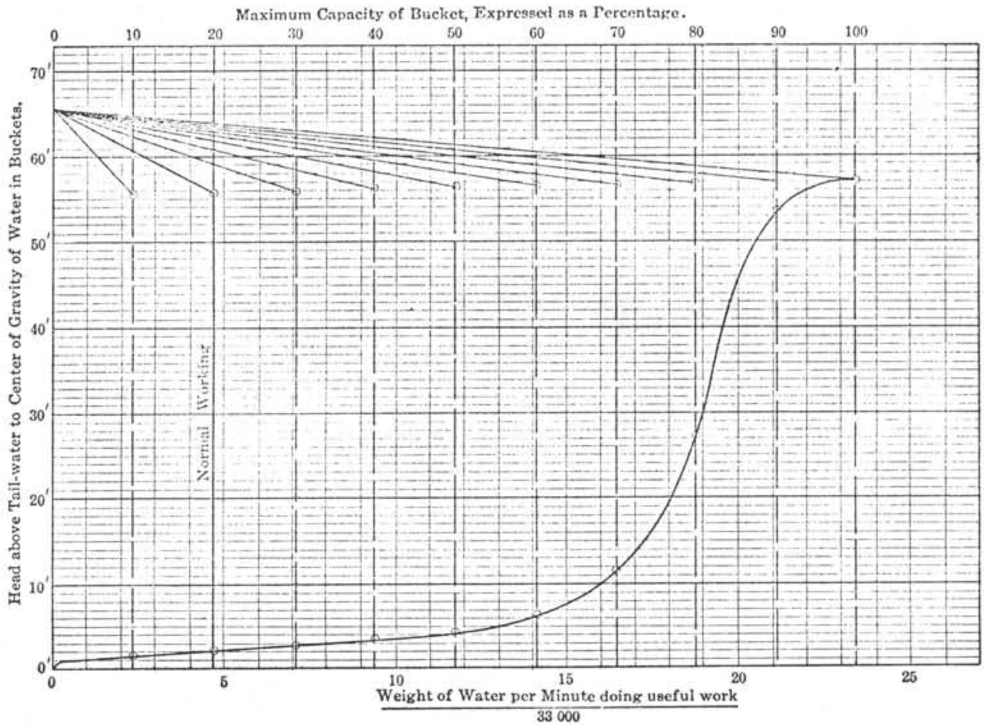

FIG. 12.

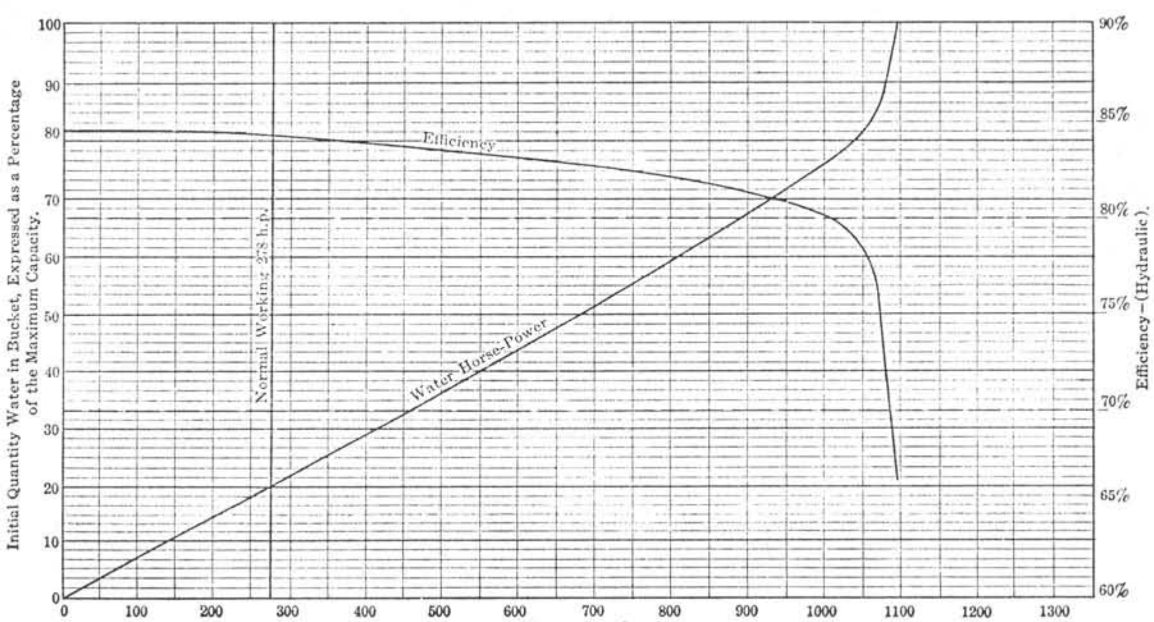

FIG. 13.

Figure 14. Burden's Great Wheel, as it lay in ruins during the period between collapse of the brick bearing pier in 1914 and final scrapping before World War II. *Photograph from the L. N. Edwards Collection, Division of Mechanical & Civil Engineering, National Museum of History & Technology.*

Figures 15 and 16. The site today. All that remains of The Niagara of Water Wheels is the stub end of the brick supply conduit as it emerges from the top of the bank, and the remnants of the inner brick pier. *R. M. Vogel photographs, 1971.*

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