

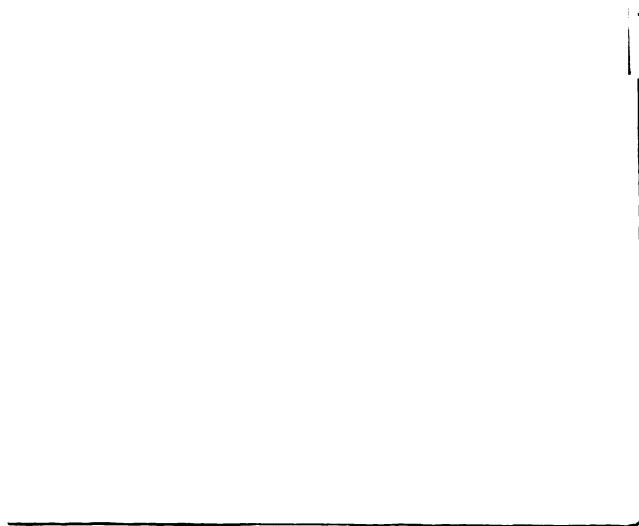
A STUDY OF THE ECONOMIC VALUE
OF SIPHON SETTINGS FOR LOW-HEAD
HYDRO-ELECTRIC POWER PLANTS

THESIS FOR DEGREE OF C. E.

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A STUDY OF
THE ECONOMIC VALUE OF SIPHON SETTINGS FOR
LOW - HEAD HYDRO - ELECTRIC
POWER PLANTS

A Thesis Submitted to the Faculty of
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THESIS

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INTRODUCTION

The developments in the design of hydro-electric power plants and the advances made in the design of the necessary machinery have been very rapid during the last fifteen years. Many plants operating today while not obsolete in the sense that they cannot compete in production with newer plants are nevertheless far from modern when compared with the latest developments. New ideas are developed with each new plant designed and while it is not the duty of the engineer to keep plants in style with the latest fashion, it is his duty to keep pace with the modern developments so that the plants which he designs may be as efficient and productive as it is possible for them to be. The large investment necessary for a hydro-electric plant demands that the maximum production possible be obtained. The steady downward trend of costs of current in large steam generating stations makes it necessary that hydro-electric costs also be reduced to the absolute minimum. The time was not so long ago that hydro power represented the only really cheap power available. Those cities or industries blessed with this power in the necessary quantities were able to reduce costs of producing manufactured goods and so obtained an advantage over their neighbors. This present age has brought us low cost steam power but more valuable still, electric power from central generating stations which means low cost power

to the small as well as the large consumer. Under these new conditions the designer of hydro-electric power plants must take advantage of every modern means to increase efficiency and reduce the investment in the plants which he designs. .

There are no two hydro plants that are exactly alike and each development presents its own special problems. The high-head hydro-electric plant uses a small quantity of water under high pressure. This presents problems to the designer which must be met and solved. The low-head hydro-electric plant must utilize large quantities of water and this condition presents its problems equally subject to serious study in order that the loss of head may be reduced to a minimum and that the acceleration and deceleration of so large a mass of water may be accomplished during load changes without serious injury to the plant or equipment.

The terms low-head and high-head are relative. Plants with heads as high as eighty (80) to one hundred (100) feet may be and are considered as low-head developments. It is easy to see how the operator of a plant with a head of eight hundred (800) feet might consider a plant with a head of eighty (80) feet as a low-head plant. However, to the operator of a plant with a head of eight (8) feet the plant with the head of eighty (80) feet really appears to be a high-head plant. In order that this subject may be properly limited to those

plants where the siphon setting is applicable, the term "Low-Head hydro-electric power plant" as used in this thesis shall be taken to mean only those plants operating with a head of twenty (20) feet or less. While this type of plant is not the kind that challenges the imagination of the public mind it nevertheless is a very prevalent type of installation in this country and Canada. These plants may be found along many of our streams and they are usually designed to take what water is available as it comes as no storage is available as a rule. H. E. M. Kensit writing in the Electrical Times, London, on the subject of "Water Power in Great Britain", states that in Canada there are about thirty (30) central station plants operating with a head of ten (10) feet or less. This does not include that multitude of plants developed by private industries to provide power in their own factories. So Canada with its abundant water-power resources also sees value in the low-head hydro-electric plant. In this country the number of this type of plants is even larger and the extent to which they are developed is no doubt due to the early use of hydro power by the people who settled and developed the great central territory of our country. The higher heads have been more rapidly developed since the generation of electricity by water power has made possible their utilization. In a report of the water power resources of Illinois published in 1913 over 50 power sites were

listed in the state. Most of these were operating small mills or factories at that time and only three (3) of the plants listed had heads over fifteen (15) feet. Many of these plants have since been converted to modern hydro-electric plants.

The term "Siphon setting" as used in the title to this thesis refers to that design of the turbine pit or wheel pit which permits the water surrounding the turbine to be raised above the level of the normal head water by a siphon or vacuum action to provide the required submergence of the turbine. It differs from the open flume setting which is the type of design which preceded it, mainly by reason of the fact that the walls and ceiling of the pit are air tight and at the intake or entrance, the upstream wall extends below the surface of the head water to form a lip. This lip prevents air being drawn into the turbine pit while the unit is operating. A more detailed description will be given later when describing actual installations in operation. While this simple principle is old its general application to powerhouse design is rather recent.

No study can be made of any one feature of power house design without also considering the part which the improvements in machinery and equipment have played in its development. So long as power was required in small units and used direct in factories

there was no demand for large capacity high speed turbines. When necessity demanded it the turbine designer produced the high specific speed turbine which is now built in such large capacities that for low-head hydro-electric power plants the siphon setting becomes an absolute economic necessity. A brief review of the history of the development of water power is necessary for this study of the economic value of siphon settings for low-head hydro-electric power plants.

Beside the Nile, the Euphrates and the Yellow Rivers thousands of years ago primitive Hydraulic Engineers planned and constructed their simple forms of current wheels. These consisted simply of a wheel with paddles attached to the rim and so set that the paddles, dipping below the water surface were moved by the current and the wheel kept in motion. They utilized this energy which they took from the stream to raise water for irrigation and so transformed the otherwise barren land adjacent to the streams into gardens of plenty. In some remote sections of China there can still be seen in operation irrigation works which are almost as primitive but which are nevertheless working and supply their owners with all the power they need. As civilization developed man found ways of developing power from the more swiftly moving water at rapids and falls, at first with breast wheels and later with the overshot water wheels. The energy thus obtained was

applied to the grinding of grain as well as pumping and as long as man was able to provide the power necessary for his immediate needs and relieve him of the hard manual labor incident to grinding and pumping for irrigation he was satisfied and little progress was made for thousands of years. By the time of the American Revolution these water wheels were developed to a state that made them of considerable value wherever a dam could be built or where nature had provided the necessary fall. They were generally used for the grinding of feed and flour and such other manufacturing as had at that time been developed to a state where power could be applied to the process. The mills were built on the banks of the streams and the power was taken directly from the waterwheel shaft either by belts or crude gears. The development of these water power sites in New England was the beginning of the industrial development of this part of our country. As the central part of our country was settled, power sites along the streams were developed for grinding feed and flour that were later destined to be redeveloped as hydro-electric generating plants to provide more universal use of this waterpower. The plants at these dams are today in still another stage of redevelopment as modern hydro-electric plants which are interconnected in large systems supplying power to many far removed from the banks of the stream.

The old type breast and overshot water wheels

served for many centuries as the principle means of power development but in 1843 the hydraulic turbine was introduced into this country by Ellwood Morris of Pennsylvania. This turbine was later developed and brought to popular attention largely through the inventions of Uriah A. Boyden. The great advantages claimed for the water turbine over the old style water wheel were (1) it occupied a smaller space, (2) it operated at a higher speed, (3) it would work submerged, (4) it could be built in much greater capacity, (5) it could be used in cold climates as it was more readily protected from ice. All of the above features had become increasingly important with the more widespread application of power to manufacturing processes. Here again the turbine was a product born of man's necessity.

About 1849 James B. Francis, Hydraulic Engineer, connected with the hydraulic plants at Lowell, Massachusetts, designed an inward flow turbine which had many improvements and a higher efficiency than the turbines then in use. This type of water turbine, much improved today and now manufactured by many water wheel manufacturers still bears the name of the Francis type runner. These water turbines rapidly replaced the older less efficient overshot and breast wheels and they are to be found in practically all sections of the country today.

On the smaller stream the power was usually developed by a single individual or company but on the

1

larger streams more power was available than could profitably be used in one factory and in such cases companies were formed to make the development and the power was allotted to the several owners in proportion to the amount of money they had put into the company for the building of the dam and canals. This era of development lasted from about 1843 until near the end of the last century. This period was marked by a wide spread application of waterpower to industry and many of our present large industrial institutions had their beginnings in this period when the factory with available water power had a considerable advantage over its competitor. These industries as a rule used small turbines as turbines are rated today and the development of the low heads which were available on most streams presented no very serious problem. When more power was required than could be developed with one turbine as many turbines as were required were installed and their combined output utilized by gearing them to a common shaft. There were many examples of this type of development along the Rock River in northern Illinois and the heads available at these dams were usually very low.

In 1879 Edison invented the electric lamp and the following year installed the first generating station for producing electric power with steam. In 1882 there was installed at Appleton, Wisconsin the first hydro-electric power plant. This plant contained one of the

early Edison bi-polar generators of 250 lamp capacity. The single turbine was geared to a horizontal shaft and a belt from this shaft turned the generator. This plant was crude indeed when compared with the modern plants of today, but the idea developed in this original plant was used in many small electric generating plants for years until the increased use of electricity and development of the steam turbine provided the urge for further development in the hydro-electric plant. The result is the large capacity high-speed hydraulic turbine which today replaces several small turbines and so combines in a single compact unit what before was an inefficient collection of gears, bearings, shafting and in many cases long expensive belts.

The modern type of hydro-electric plant with its concrete foundations and substantial superstructure of brick or concrete is so different from the early type of hydro-electric plant of 40 or 50 years ago as hardly to be recognized as a decendent. In place of the turbine operating in an open flume usually floored over with planks soaked with grease from frequent applications of oil and gear dope the modern turbine is entirely enclosed in an air tight chamber and operates without vibration or noise and where oil or grease is required it is applied with such efficiency that there is no surplus remaining to soak the floor or detract from the cleanliness of the place. In place of the numerous

gears, shafting and bearing boxes requiring constant attention and maintenance a single rugged shaft extends vertically through a substantial water lubricated bearing. In place of the large pulley and long belt or endless rope drive a few strong bolts connect the turbine shaft and the generator shaft together and the two pieces of machinery operate as a single unit.

The low-head hydro plants which a few years ago were turning factory or mill wheels and which later were converted into electric generating stations by belting generators to the turbine shafts are now being economically converted into modern hydro-electric plants with the generators directly connected to the turbines. The machinery developed for this purpose requires the application of the principle of the siphon setting for low heads but these plants have already proved their worth in many cases by several years of successful operation. Considerable progress has already been made in this redevelopment of the old power sites but there are many more waiting to be modernized.

In addition to those sites which were previously developed as sources of power for factories and which are now being changed to modern hydro-electric plants there are many sites which are not utilized. These sites are equally valuable and many of them may now be economically developed. Some of these sites are being utilized but as these plants must of necessity be

run-of-river plants they can be most economically utilized as a part of interconnected systems where steam reserves are already available to supply the demand in seasons of deficient flow. Steam power and hydro power have now joined hands in interconnected systems to supply power for home and industry in a way which was impossible a few years ago.

Modern Low-head Hydro-electric

Power Plants with Siphon Settings.

The energy of falling water is converted into electricity, a more useful and more readily controlled form of energy, by means of hydro-electric power plants. Following the installation of the first hydro-electric plant at Appleton, Wisconsin in 1882, many of the power sites which were furnishing power to grist mills and small industries were changed to electric generating plants by belting the generators to the horizontal shafts of the hydraulic plant. Prior to 1890 synchronous speeds were not a problem in water turbine design as most installations were provided with either belt or gear drive between the prime mover and the generator. Turbines were built with either vertical or horizontal shafts depending on the application but for the very low-head plants vertical turbines with bevel mortis gears and horizontal shafts were generally used. These early plants consisted of an open box or flume in which the turbine was set. The upstream side was open and was protected with rack

bars to keep out drift wood and ice. Beneath the turbine was a similar area opening down stream. The draft tubes used with these early turbines consisted of short conical sections which discharged vertically into the draft pit. These early draft tubes were not very efficient as they were short and the discharge velocity was high. Another source of loss in the extremely low-head plants was the air which was drawn into the turbine by the vortexes or small whirlpools. In order to prevent the formation of these vortexes and reduce the loss in power from this source it was considered necessary to install the turbine so that the top of the gates were from one to one and a quarter times the turbine diameter below the surface of the water. This rule of submergence, given in Professor Mead's text on Water Power, was a limiting factor in the size of the turbines for low-head plants and in order to reduce the cost of the generator and improve its efficiency, several turbines geared to a horizontal shaft through bevel mortis gears were usually employed to drive the generator. A typical installation of this kind built in 1908 is still in operation at Oregon, Illinois on the Rock River. In this plant there are three Leffel Samson turbines and two New American turbines driving a horizontal shaft through bevel mortis gears. The turbines operate at $66 \frac{2}{3}$ r.p.m. and the shaft revolves at 200 r.p.m.

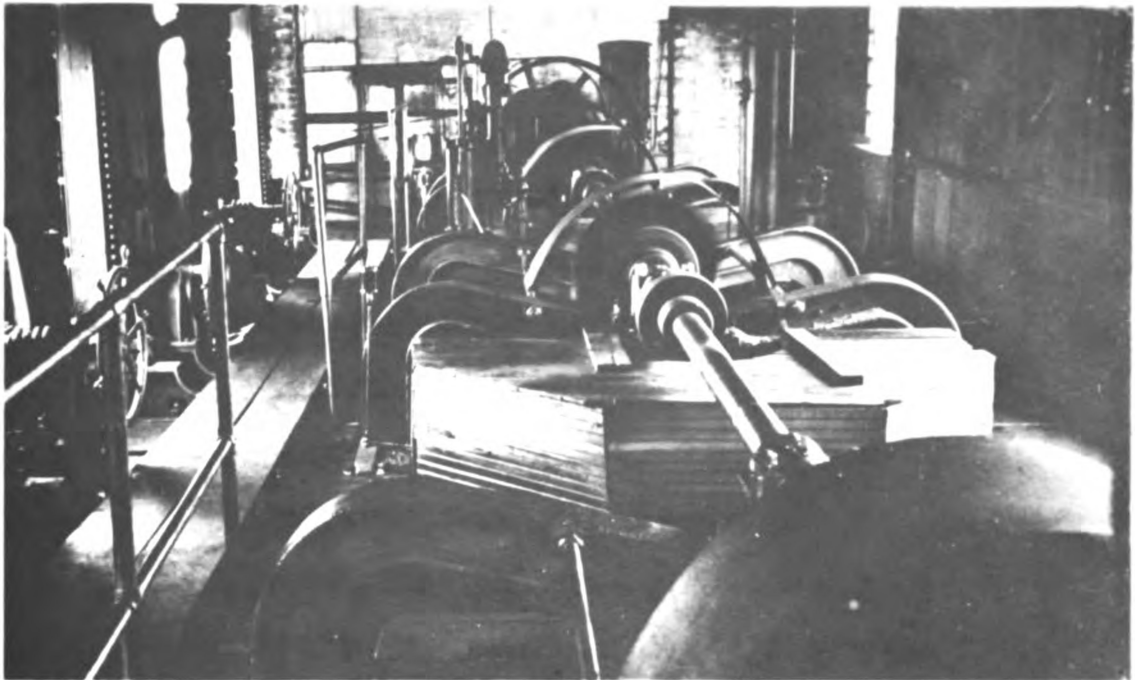
Another typical plant of this kind designed

by Professor Mead and built in 1904 is still in operation at Sterling, Illinois. Plate No. 1 shows an interior and an exterior view of this plant. The number of turbines employed to drive one generator varied and depended usually on the water available. The type of drive also varied, some generators being driven by gears, some were belted and others were direct connected to the horizontal shaft.

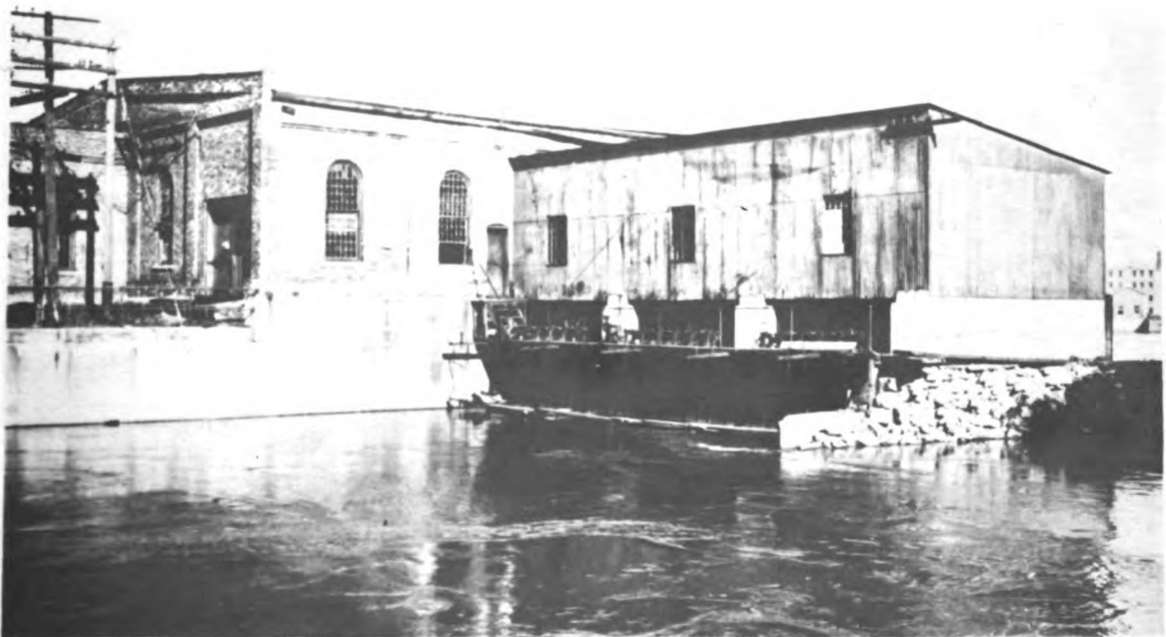
Improvements in turbine design and methods of manufacture made possible some developments along entirely different lines and in the period from 1900 to 1910 a great many multiple runner units were built where the head was sufficiently high. These usually consisted of either a double, triple, or quadruple runner unit on one shaft and built so that the thrust on the runners was balanced. The shafts were usually set horizontal and this type of plant, illustrated on plate No. 2, utilized larger capacity generators operating at higher speeds which not only reduced the cost of the direct-connected generator but also increased its efficiency. With this type of installation the length of the plant was reduced as two or four units were placed in a flume not much wider than would have been required by a single runner of the same diameter but the distance from the intake to the downstream side of the power house was greatly increased. This type of runner could be used only with such heads as would provide submergence of the turbines

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Plate No. 1



Interior view of plant with bevel mortis gear drive
at Sterling, Illinois.



Exterior view of the plant at Sterling Illinois.

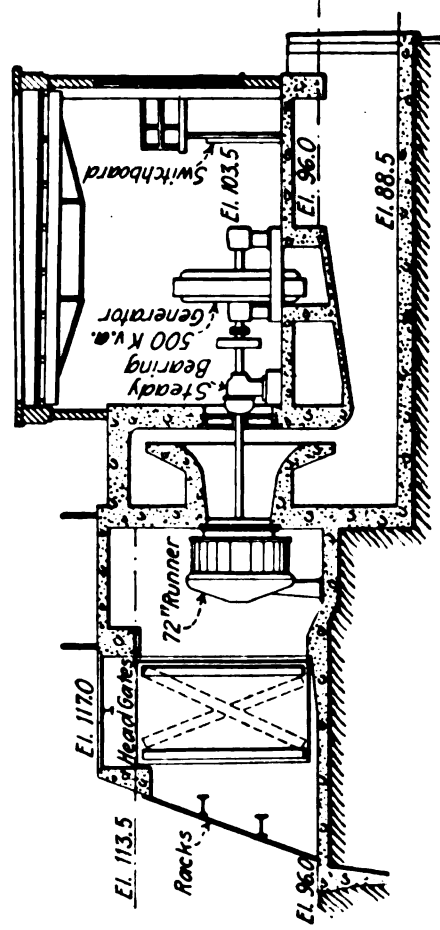
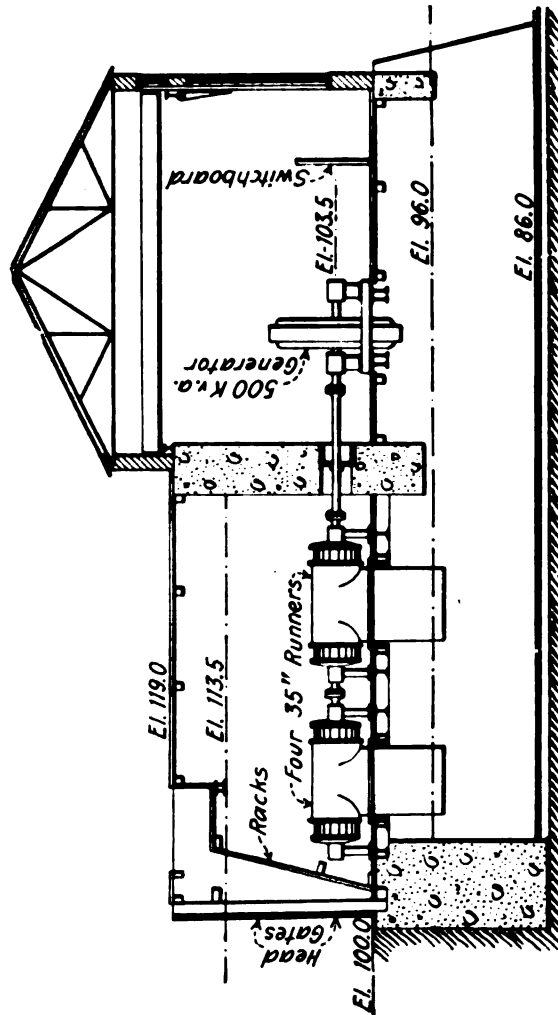


FIG. 1. COMPARISON OF THE OLD-TYPE LOW HEAD PLANT WITH THE NEW.

On the left is shown a section through old hydro-electric plant of the Cheboygan Electric Light & Power Company, Cheboygan, Mich. On the right is a section through new hydro-electric plant of the Cheboygan Electric Light & Power Company, showing compactness as compared with the old installation. The over-all distance from bulk-head to upstream bearing was reduced by half.

Comparison of old and new plants at Cheboygan, Michigan.

with the shaft high enough to permit the generator being placed well above tail water. At the Kilbourne plant of the Wisconsin Power and Light Company on the Wisconsin River the top of the runners were so close to the water surface that a steel cover or umbrella was provided over the top of the runners to prevent the drawing of air into the turbines. One of the disadvantages of this type of plant was the placing of the generator so low that the generating room was below high tail water during the flood season. This type of plant could not be built where the heads were extremely low and at these sites the vertical unit plants with bevel mortis gears continued to be built.

During this period from 1900 to 1910 a number of installations were also made with multiple runners on vertical shafts. This accomplished the desired result of high speed on the generator shaft and placed the generator well above the high tail water elevation. The distance from intake to the down stream wall of the power house was reduced and the longer spillway was retained but a very complicated concrete structure was required for the draft tubes. Among the earlier plants with this type of installation was the plant at Beznau, Switzerland built in 1901. The turbines were rated at 1000 h.p. and operated at 67 r.p.m. The effective head was 14.5 feet. A similar plant was built in this country for the Concord Electric Company at Concord, New Hampshire

in 1905. The head was 16 feet and the turbine capacity was 900 h.p. at 100 r.p.m. A sketch showing this plant is shown on plate No. 3. Many units of this type were built in this country following the Concord units and one installation was made with a twin runner for a head as low as 7 feet at Carpentersville, Illinois. This unit was replaced with a single runner turbine in a siphon setting in 1927.

Engineers were continually working toward the goal of increased size, increased speed, and increased economy through simplification of the power house design. To the late Gardner S. Williams, however, belongs the credit for pioneer work with direct connected single runner units. In 1906 he designed and installed the first plant of this type for the Edison Sault Electric Company at Sault Ste. Marie, Michigan. This plant is illustrated on Plate No. 4. The head on this plant was 14 to 18 feet and the turbines operated at 100 r.p.m. They were 71 inch Samson runners of 785 h.p. each. The following year Mr. Williams designed a similar plant using the same sized units at the Superior plant of the Eastern Michigan Edison Electric Company near Ypsilanti, Michigan. In 1910 he designed and built a plant for the city of Sturgis, Michigan in which direct-connected Allis Chalmers' units were installed. This plant had a head of 25 feet. All of the above installations by Mr. Williams are also notable for the fact that he employed

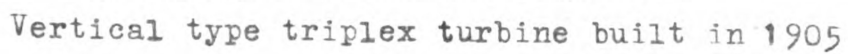
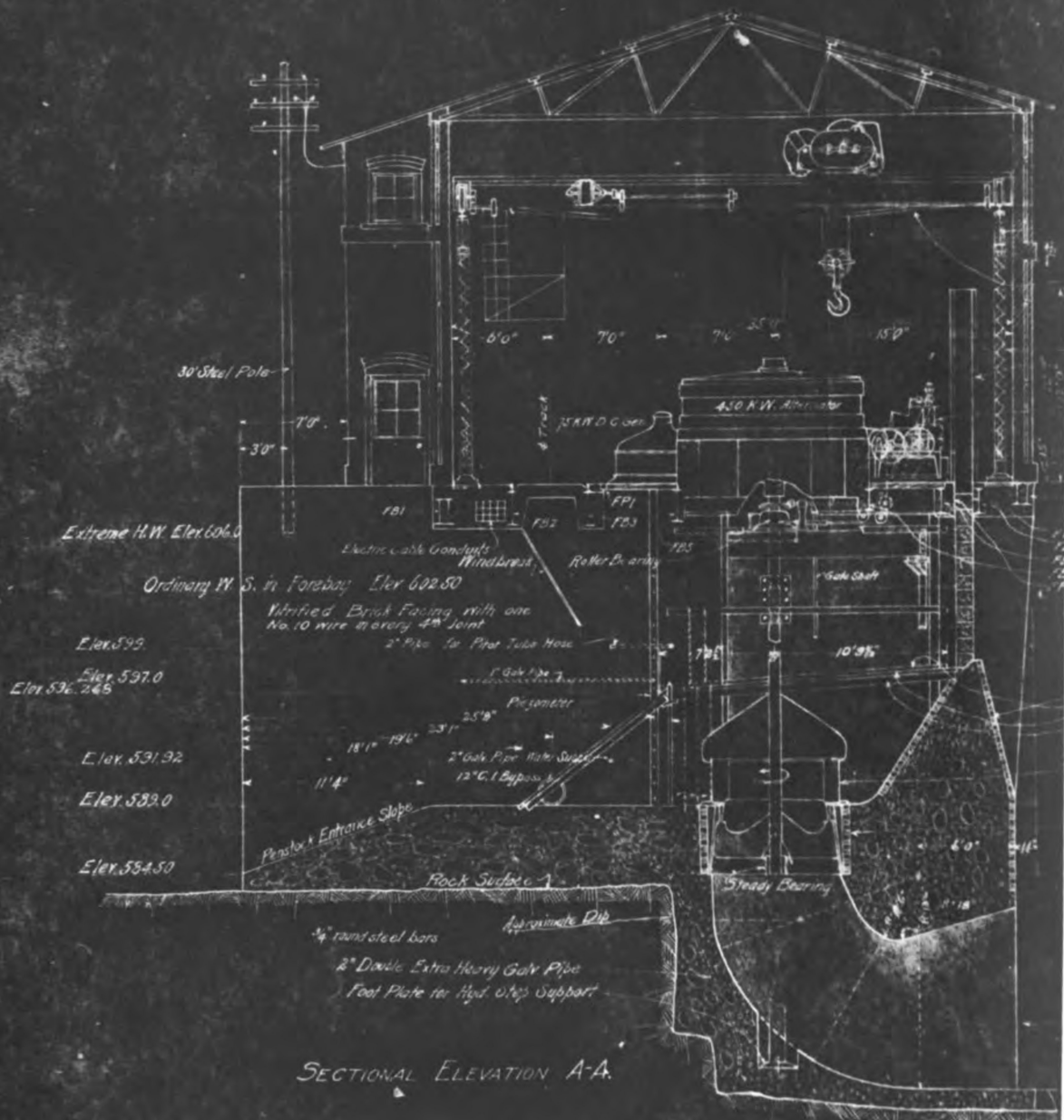


Plate No. 4



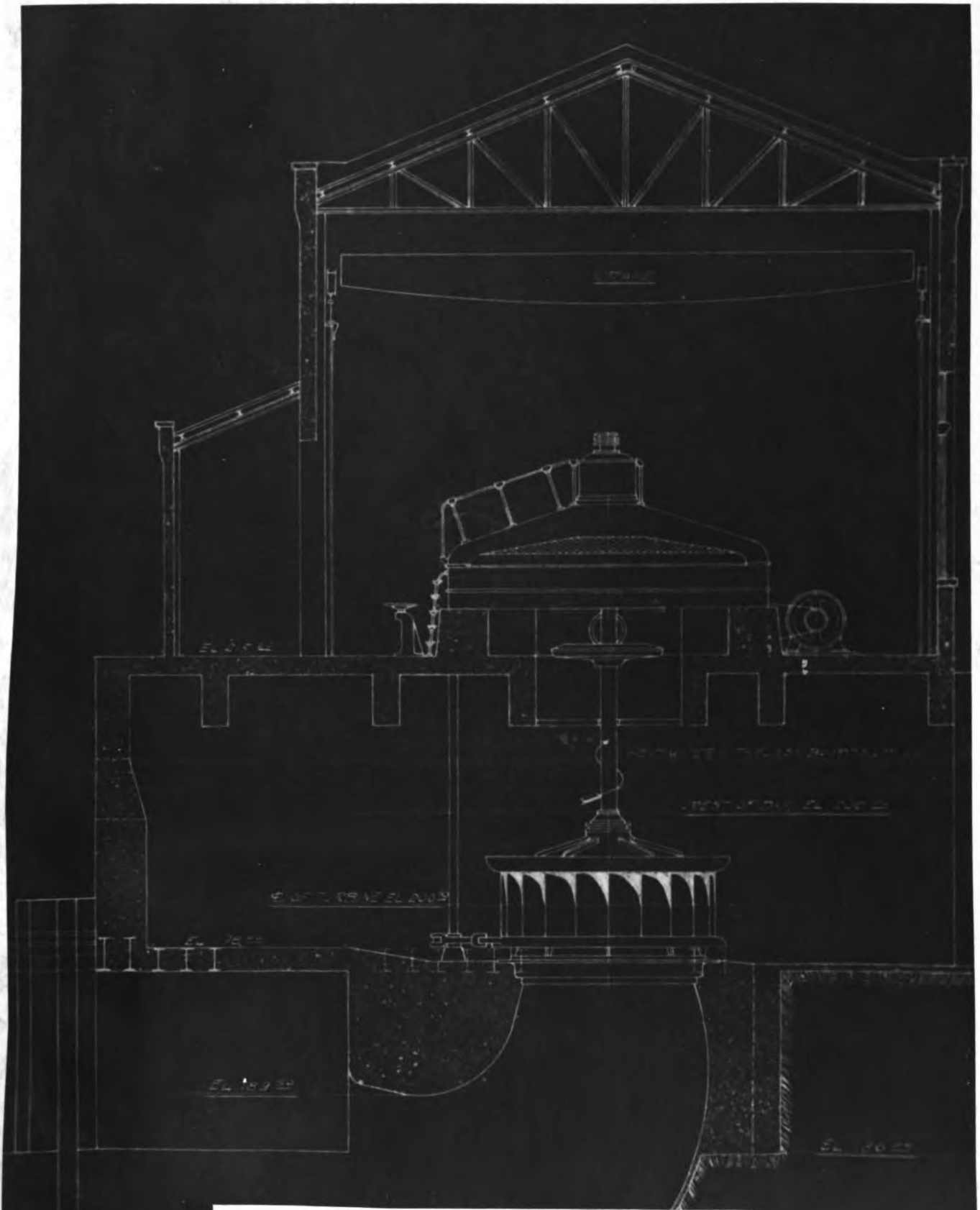
Cross-section of the plant of the Edison Sault
Electric Company at Sault Ste. Marie, Michigan
First direct connected single runner plant in
the United States.

a concrete scroll case type of wheel pit which departed from the conventional open flume type of setting in general use. He also employed concrete elbow type draft tubes which were new in draft tube design at that time.

With these pioneer plants by Mr. Williams in successful operation there began about 1910 a new era in low-head power plant design. In 1911 a 5 unit plant was installed at Defiance, Ohio with 1450 h.p. single runner turbines operating under a head of 22 feet. While this was an upward step in turbine capacity for low heads the big step was taken in 1912 when the 10,000 h.p. turbines were installed on the Mississippi River at Keokuk, Iowa where a head of 37 feet was created by a masonry dam across the river valley. While plants with heads below 15 feet do not command the attention of the public as do plants like Niagara and Keokuk, there were equally interesting developments with these low-head plants during this period just prior to the world war. In 1912 there was installed for the Centralia Pulp and Paper Company at Grand Rapids, Wisconsin a 4 unit plant on the Wisconsin River. This plant has a head of 13 feet and the units have a capacity of 590 h.p. and operate at 90 r.p.m. The same year the Allis Chalmers Manufacturing Company built three 600 h.p. turbines to operate at 60 r.p.m. with a head of 9 feet for a plant at Watertown, New York. The following year these units were duplicated for a 5

unit plant on the Rock River at Sterling, Illinois for the Rock River Light and Power Company. These units developed 560 h.p. under an 8.5 foot head and also operated at 60 r.p.m. This plant is shown on Plate No. 5 and it is interesting to note that the foundations for this plant were built in 1904 when the bevel mortis gear type of plants were considered the best and logical development for this low head. Six wheel pits were built and the plans were for six units driving one generator through bevel mortis gears and a horizontal shaft. When built in 1913 and 1914 the plant contained the 5 direct connected units described above and one wheel pit was left without a unit until 1930 when a direct connected, adjustable blade turbine was installed in a siphon setting. This plant was planned during an era of multiple unit installations and because of delays in financing was not built until the era when single runner direct connected units were installed. Plate No. 6 shows construction in progress at this plant in 1913. The forms for the elbow draft tubes can be seen laying on what later became the generator floor.

By 1915 the single runner vertical shaft turbine had become thoroughly established and had for all practical purposes superceeded the geared arrangement, the multiple runner horizontal shaft and the multiple runner vertical shaft turbines. For installations such as had previously required multiple runners or several



Cross-section of the plant of the
Rock River Light and Power Company
at Sterling, Illinois.

Plate No. 6



Plant of the Rock River Light and Power
Company Sterling, Illinois
Construction view showing draft tube forms.

runners geared to a horizontal shaft there was now available single runner turbines which would operate at speeds sufficiently high so that 60 cycle alternating current generators could be built for direct connection. These units were of sufficient capacity in h.p. so that the generators were reasonably economical and efficient. A generator operating at less than 60 r.p.m. was considered impractical and if the generator size was small the cost per K.W. made the unit uneconomical.

Referring to the drawing showing the units at Sterling, Illinois, it will be noted that these units were installed in open flumes with less than the usual submergence and operated at 60 r.p.m. Their capacity was relatively large being 560 h.p. While they are not large turbines when compared to present day standards they are large units for this head as measured by the standards of 1913. It will be noted that these turbines in order to avoid losses due to lack of proper submergence were placed with the lower seal ring below even the lowest tail water which was determined by the crest of a dam one-half mile down stream. Even this lowering of the turbine setting has failed to entirely remove this source of loss and because of this low setting the cost of maintenance has been higher than it would otherwise have been and the original investment was increased by the cost of permanent steel stoplogs that had to be provided. These units represented about the largest practical installation that could be made for this low

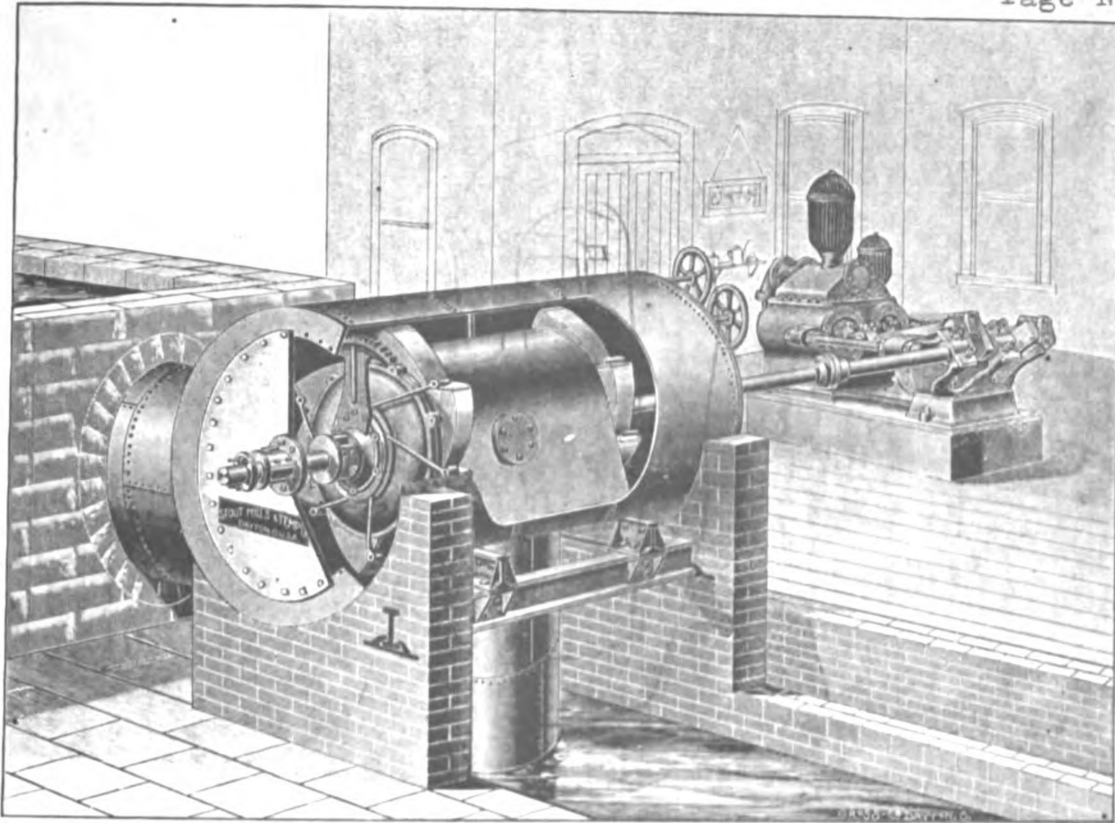
head with the equipment available in this country at that time and they were a very decided improvement over the installations at a dam one-half mile down stream where owners of water power sites had established plants along races on either side of the river. Many of these old plants are still in operation and they represent almost every possible style and type of design offered by the manufacturers of small turbines to users of water power at low dams previous to 1910. The modern type of installations with siphon settings are an equally marked improvement over the installations of 1910 to 1915.

It is not definitely known just when the first application of the principle of the siphon setting was made but from the records that are available the use of this principle is almost as old as the turbine itself. As stated above the question of synchronous speeds did not come in for consideration until about 1890. Previous to this time most of the installations were for direct connection to factory and mill machinery and the manufacturers of this equipment usually made up the units completely assembled ready for setting by a millwright or local mechanic, little or no engineering entering into the construction of many of these plants. As they were usually required for some small local factory they were often quite small and their capacity in h.p. would compare with the electric motor sizes which are purchased today for the same purposes. Some

of these completely assembled units were housed in plate steel cases or flumes from which the air could readily be exhausted and it is quite evident that the tops of some of these steel cases were set above the head-water level where the heads were low and the air exhausted to raise the water to the top of the case. Photostats of four pages of an old catalogue of Stout Mills and Temple are shown on Plates No. 7 and No. 8. The date of this catalogue is not known but from a penciled date below the out labeled "Design No. 19" it is evident that a similar installation was made in 1887. From the design and the descriptive matter it will be seen that this principle was understood and applied in this country at even this early date. In a letter written in 1921 to Mr. A. Streiff of the Fargo Engineering Company, Mr. J. H. Felthausen of the Engineering Department of the S. Morgan Smith Company makes the following statement:

"There were other installations on the vacuum flume principle, during the period between 1870 and 1890 by several of the turbine manufacturers in this country but either for reasons of their not being thoroughly worked out and the possibilities of the principle being determined more closely, or from lack of confidence in the subject generally there seems to be no records of such installations kept by the different builders, from which an intelligent description could be worked out from one step to the other."

Manufacturers continued to build these turbines with vacuum flumes but there is no indication that they were very popular. The S. Morgan Smith Company built a



Design No. 20. NANSEMOND WATER CO., SUFFOLK, VA.

Plate No. 8

Pages from catalogue of Stout Mills and Temple
showing early siphon settings.

Description of the Cut on the Opposite Page. Horizontal Wheels under Low Falls.

The cut on the opposite page shows, in a general way, the system of horizontal wheels under low falls usually recommended by us. Although the location will control the plan in many cases, an arrangement similar to that on the opposite page will be found advantageous. If the wheels are located so that the top of the runner is level with the head-water line and the center of the shaft about two feet below it, no additional gate will be required for a primer and the water will run through the gates of the water wheel as soon as they are open. In such locations the pipe connecting the top of the case with the draft-tube is always necessary or the water will not rise to the top of the case. The low gates marked in the preceding article need only be used in the mills where the head is liable to be drawn down and would then only be used in starting in dry times.

In a large number of locations where the power is conveyed by a belt-pulley or gear on the water wheel shaft, it is best to protect the lower half of the pulley by a water-tight box so that high water cannot reach the belt until it has risen to the center of the shaft.

Under low heads we recommend a pair of wheels mounted as shown on the opposite page, or as shown in cut No. 1, because two small wheels will make more revolutions than one large wheel of the combined power of the two. Also the variations in the fall are proportionally greater, owing to floods and storms, than they are on high falls. When two wheels are fastened to the same shaft but have independent gate-gearing, so that one or both may be used at any stage of gate, it is easy to adapt the water wheels to the amount of power required, or to the variations in the amount of water or of head.

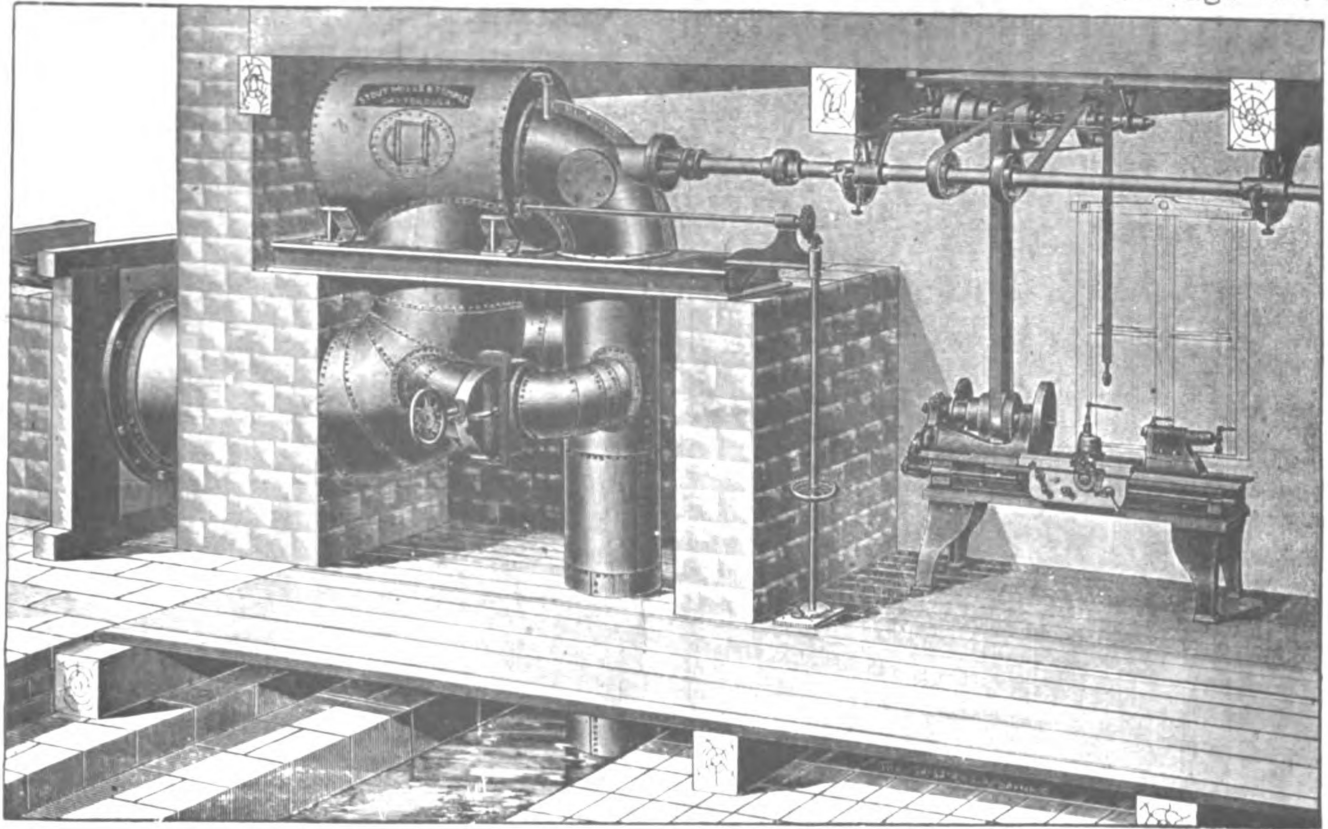
A cheaper arrangement is to make the flume of wood and to cover the water wheels with an inverted pan of boiler plate. This makes a very satisfactory and reliable arrangement and is less expensive than the form shown in the cut.

Nansemond Company's Pump House.

The cut on the opposite page shows our method of driving pumps without gears. Here two fifty-four inch wheels of the American pattern, but of reduced capacity, are coupled direct to a pump furnished by the Holly Manufacturing Company, of Lockport, N. Y. This pump is provided with cylinders of large diameter and short stroke. In this way the speed of the water wheels is so reduced and the speed of the pumps is so increased that they can be coupled together without intermediate gearing. So that the back water may not reach the pump-floor even during floods, the center of the shaft is raised as much as possible by the methods described in the previous article.

For work requiring a slow speed and small number of revolutions the American Turbine is superior to any.

For the ordinary domestic service of this place only one of these wheels is used, and the gates of the other are closed while the wheel revolves idly on the shaft. For fire service the pressure and power are increased by opening the gates of the other.



Design No. 19. Patent applied for.

Plate No. 7

Pages from catalogue of Stout Mills and Temple
showing early siphon settings.

Mounting the New American Turbine Above the Line of Head Water.

The cut on the opposite page shows our method of mounting water wheels above the line of head water. It consists in placing the water wheel at the summit of a siphon, through which the water is carried to and from it. That a water wheel would run in a siphon after it is once started is clear from the principles of aerostatic pressure. The only practical difficulty is to get the air out of the water wheel and case, and to get the siphon filled with water, so as to start the wheel. We accomplish that by the following means:

It will be noticed in the cut that there is a small pipe which connects the flume and supply pipe with the draft tube, and that this pipe is provided with a valve. To start the wheel, we open this valve and allow the water to run through the draft tube. This current carries the air out of the draft-tube just as in the ordinary horizontal wheel the water running through the wheel carries the air out of the draft-tube. The water then rises in the tube to fill the place occupied by the air, as it rises in the suction pipe of a pump.

Now, the draft-tube and water wheel case constitute an air-tight chamber, which is only open at the extremities of the draft tube and feeder. Therefore the same cause which will suck the water up in the draft tube will also suck it up in the feeder. If it rises five feet in the draft tube, it will rise five feet in the feeder, and run through the gates of the water wheel, and carry the remaining air out, as in the ordinary horizontal wheel. When the water has risen in the case so as to cut off the escape of the air through the wheel, the air then tends to collect in the top of the case as it collects in the air chamber of a pump. To provide an escape for this air, we connect the top of the case and the draft pipe by a small pipe shown in the cut, through which the remainder of the air escapes, until the case is full of water.

All the gauges shown and described in Design No. 21 are attached to this arrangement in the same way as illustrated there. But in this arrangement there is also an additional draft-tube gauge C attached to the case, to show whether all the air has passed into the draft tube, and whether the case is full of water.

duplex unit of this type in 1904 for the Empire Sulphite Pulp Company of Carthage, New York which had a capacity of 120 h.p. and operated at 87 r.p.m. This was a horizontal unit and was belted to the generator. The idea seems next to have gone abroad and while engineers like Mr. Gardner S. Williams were working on the vertical single unit direct connected type of plant, the European engineers who still favored the horizontal shaft principle were increasing the size of these units by an application of the principle of the siphon setting. In an article published in the magazine "Die Turbine" Vol. IX page 80, December 5, 1912 Mr. H. Keller describes several plants in Europe utilizing this principle. The first described was a plant with three quadruplex units of 650 h.p. each at 15.4 feet head installed in 1908 at Unterbrück, Germany. In 1909 two units were installed at St. Mortier, France producing 945 h.p. each under a head of 23 feet. In 1910 a smaller quadruplex unit operating under a 10.5 feet head was installed at Kennelbach in Austria which produced 250 h.p. A similar unit was installed at Barcelona, Spain in 1911. No doubt there were many other units of this type placed in service before the war broke out in 1914. All of the above plants consisted of multiple turbines on a horizontal shaft similar to the arrangement shown on Plate No. 2. In order that the size might be as large as possible under the low heads available the turbine pit was sealed

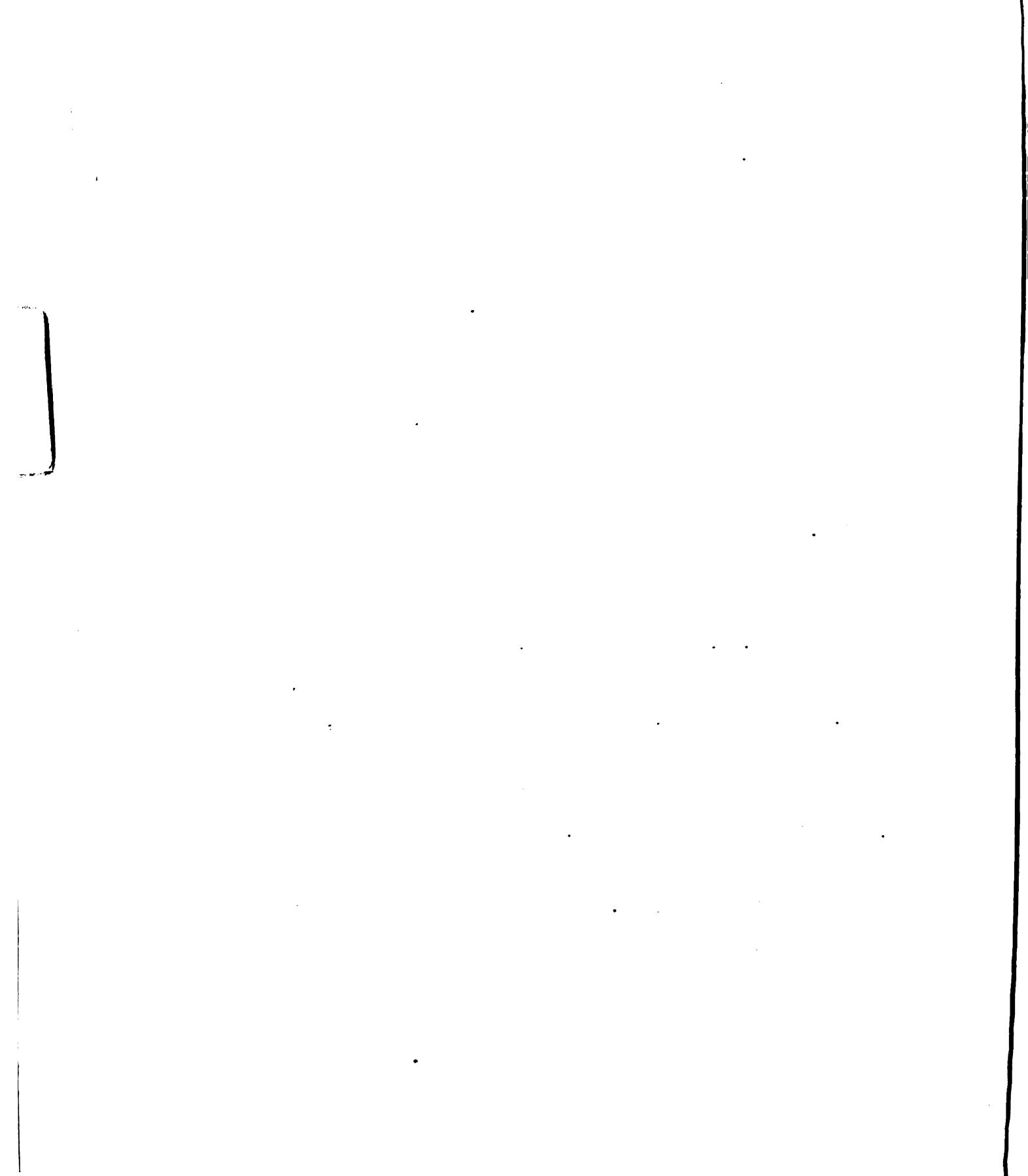


by extending the upstream wall of the power house to a point below the surface of the head water and in this way an air tight chamber was formed into which the water might be raised by exhausting the air from above the turbine either by means of an ejector or by connecting the turbine pit to the throat of the draft tube. The Escher Wyss Company of Zurich were evidently the pioneers in developing these units in Europe but tests of units in siphon settings were made later in the testing flume of the J. M. Voith Company in Heidenheim, Germany and these tests show that there may be a drop of about one percent in turbine efficiency where siphon settings are used. With present day refinements in power house design it is doubtful if tests today would show this same drop in turbine efficiency by the use of this principle.

In this country the vertical shaft direct-connected unit became so popular that it practically replaced the multiple unit horizontal shaft type of development long before the war. The horizontal shaft units that have been installed since that time have usually been installed in wheelpits built for horizontal units where it is desired to keep the costs of redevelopment down by utilizing the old wheel pit. Plate No. 2 shows a case of this kind where a quadruplex unit at Cheboygan, Michigan was replaced with a single runner horizontal unit 72 inches in diameter driving the original 500 K.V.A. generator. This plant was designed in

1917 by Gardner S. Williams who had pioneered the vertical single runner direct connected unit principle as mentioned above. The replacing of the quadruplex unit with a larger diameter single runner turbine where the head was only 17 feet reduced the clearance above the runner so much that it was necessary to employ the siphon principle and seal the turbine pit. This was one of the first applications of this principle to modern installations in this country and very definitely demonstrated the economic value of this principle. An unusual feature of this design was the placing also of a part of the draft tube chamber above the head water elevation.

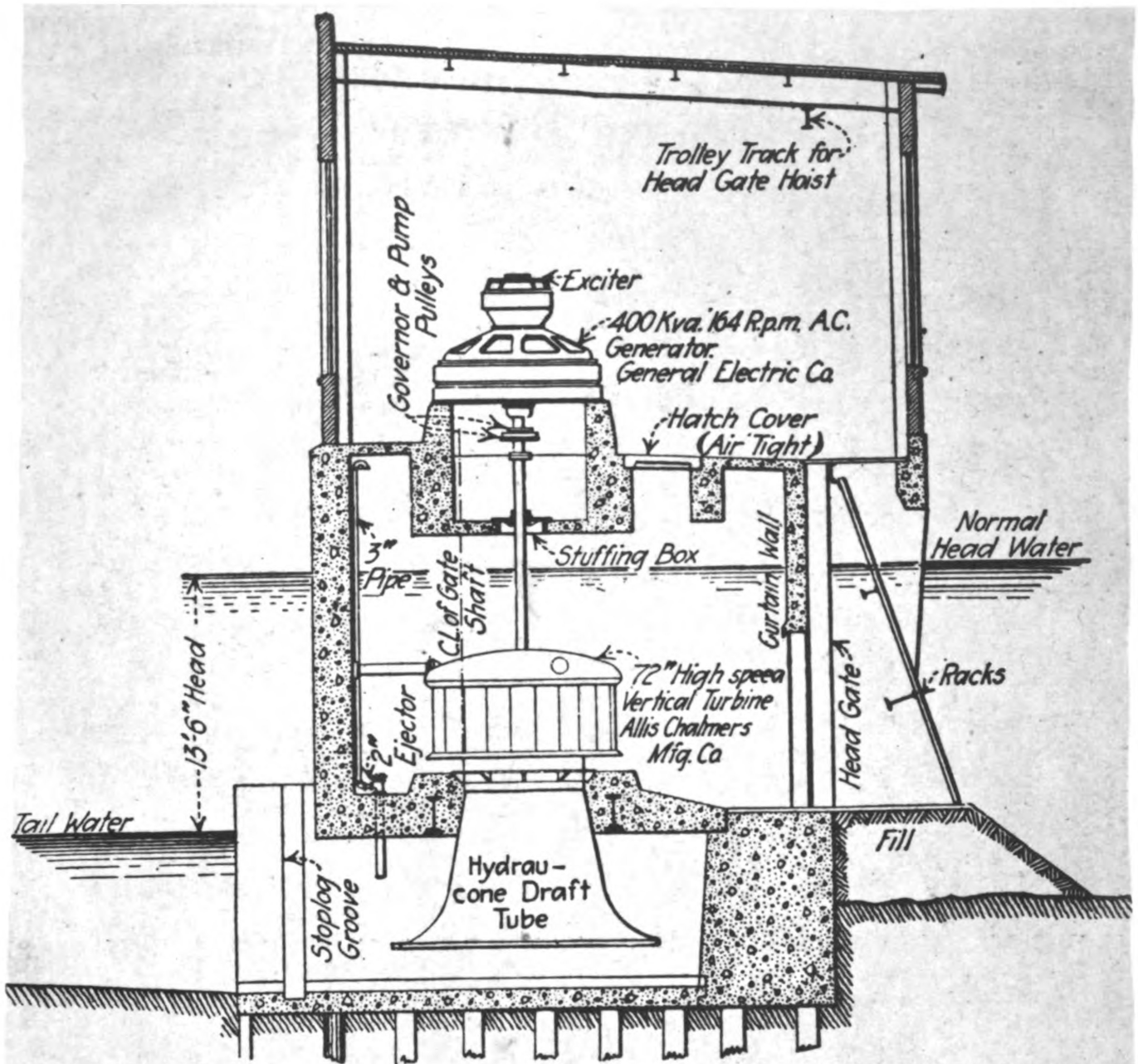
A similar redevelopment was made by the Fargo Engineering Company of Jackson, Michigan under the direction of Mr. A. Streiff in 1921. This plant was for the Indiana and Michigan Electric Company at Elkart, Indiana. In this plant, which has a head of 18 feet, Mr. Streiff followed the examples of the European designers and placed a quadruplex horizontal unit of 2400 h.p. capacity in a vacuum flume. While European example was followed in this design the size was much larger than previous installations. The flume was 22 feet wide and 71 feet long and the headwater was raised four and one-half ($4\frac{1}{2}$) feet by means of ejectors and this required the removal of over 7000 cubic feet of air to completely exhaust the air from the wheel pit.



The first application of the principle of the siphon setting to the modern vertical type unit in this country so far as the writer has been able to learn was at Plainwell, Michigan. This plant was also designed by Mr. Streiff of the Fargo Engineering Company and a Nagler high speed propeller type turbine was used. This plant replaced an older plant with timber flumes containing seven old type turbines geared to shaft and coupled to one 750 K.W. generator. A fire destroyed the old plant on May 20, 1919. The new plant shown on Plate No. 9 went into operation on January 28, 1920 and contained three direct connected units in siphon settings, each with a capacity of 400 K.V.A. Within the same space limitations a plant of practically 50 percent increased capacity had been installed. This increased capacity and high speed of 164 r.p.m. was possible due to the newly developed Nagler runner but runners of the size installed would not have had the required submergence in the conventional open flume. The siphon setting therefore made possible the use of the larger sized turbines in an installation, that would normally have been made with much smaller turbines because of the head available. This plant was described in the Electrical World for July 17, 1920 by Mr. Streiff and Plate No. 9 is from this paper.

The Plainwell plant was equipped with the hydraucone type of draft tubes but the turbine pit was the conventional open flume type of setting with only

Plate No. 9



SECTION OF PLAINWELL (MICH.) PLANT USING NEW TYPE OF HIGH-SPEED TURBINES.

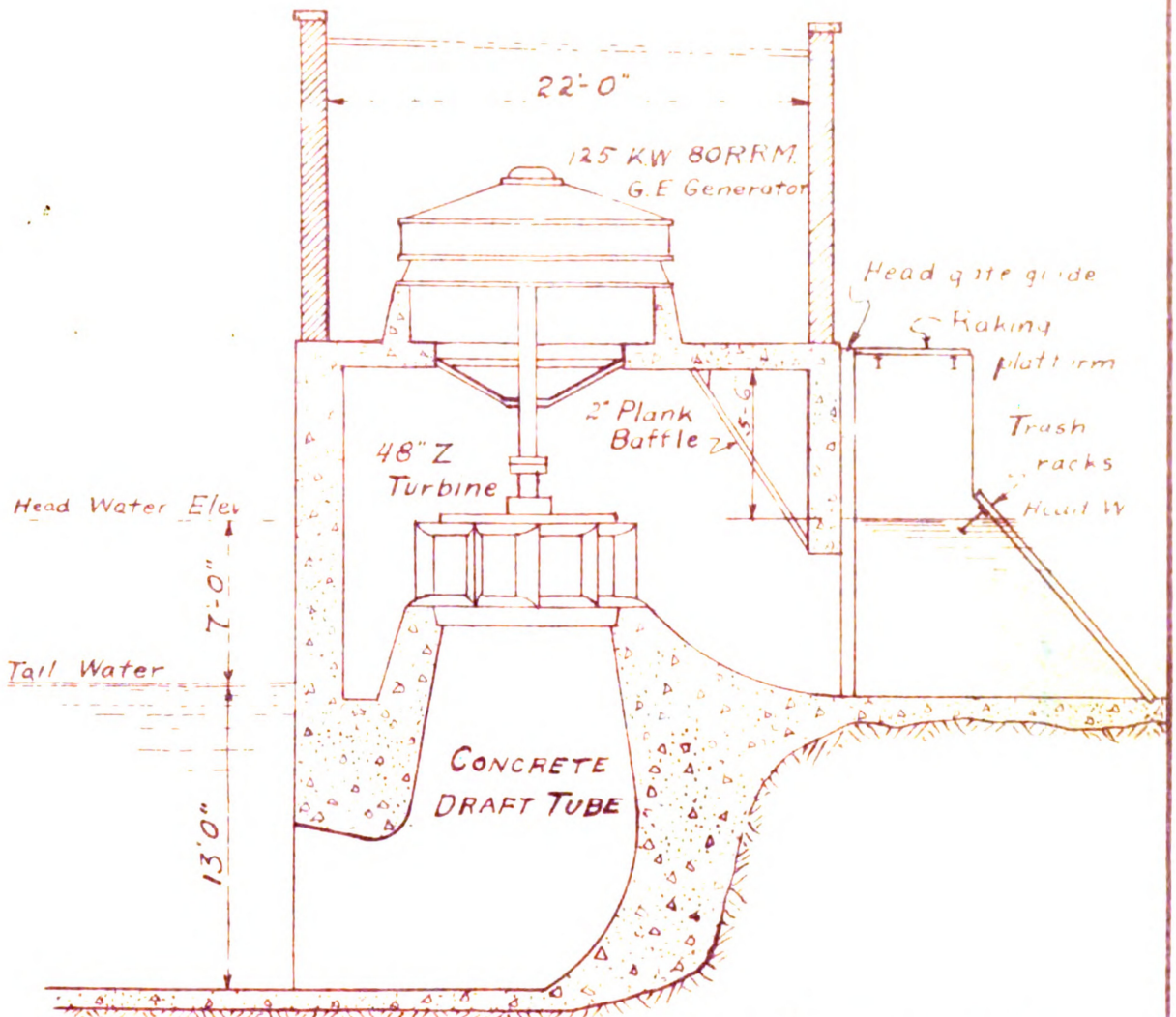
The so-called vacuum-turbine setting is used, being sealed off by the curtain wall. Air is removed by the 2-in. ejector.

the addition of air tight roof and an upstream wall extending below the surface of the headwater. A similar though smaller unit in a siphon setting was installed about this time at Oregon, Illinois for the Illinois Northern Utilities Company. This unit occupied an idle wheel pit that had been built for an additional unit to be geared to a horizontal shaft driving a horizontal generator. The five units adjacent to this siphon flume unit generate about 450 K.W. or about 90 K.W. per turbine under a head of 8 feet. The direct connected unit which is shown on Plate No. 10 generates 125 K.W. or nearly 40 % more and is installed in the same sized flume. By use of the higher speed Leffel "Z" turbine a speed of 80 r.p.m. was obtained. The adjacent units operated at $66\frac{2}{3}$ r.p.m.

While these two plants were being built, Stone and Webster were designing for Henry Ford and Son a vacuum flume plant with four units which was installed and placed in operation in 1922 at Green Island, New York on the Hudson River. This plant is shown on Plate No. 11. It will be noted from this illustration that in this plant a scroll type of flume was used and in addition to extending the upstream wall below the water surface it was curved and extended toward the roof of the pit near the turbine. This lip arrangement tends to reduce eddies and increases plant efficiency. The Green Island plant, while one of the early plants of this type,

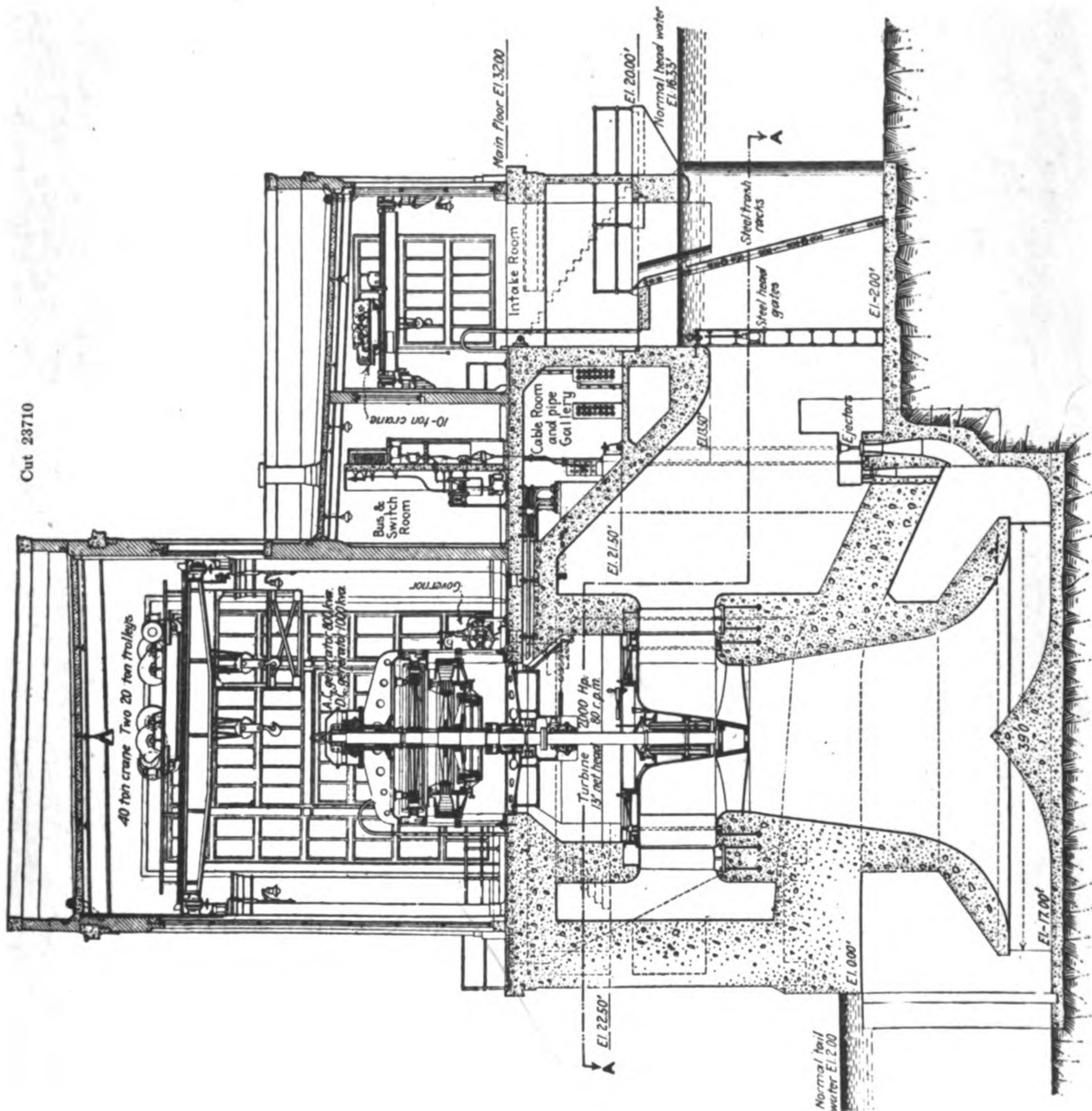
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PLATE N° 10



CROSS-SECTION OF PLANT AT OREGON ILLINOIS WITH
SIPHON SETTING BUILT IN 1921

Plate No. 11



Cross-section of Green Island New York plant
of Henry Ford and Son.

is the largest in h.p. capacity built so far in the United States. The turbines are rated at 2000 h.p. and operate at a speed of 80 r.p.m. under a head of 13 feet.

After the step had once been taken the number of plants operating with siphon settings increased rapidly. In Appendix No. II is given a chronological tabulation of such plants of this type as the author has been able to collect data on. The principle has been applied to a large variety of plants with heads from 7 to 18 feet and with capacities from 200 h.p. to 2000 h.p.

As has already been pointed out the application of this principle has made possible the installation of turbines of large size by providing the necessary submergence without placing the turbine so low that the cost of excavation is prohibitive and excessive operating and maintenance costs result. The large propeller type turbines now being used for low-head installations represent real economies over the smaller units formerly offered by manufacturers of power plant equipment and their use in the larger sizes is only possible by the use of siphon settings. The placing of these turbines at the higher elevations possible with the vacuum flume and the use of the hydraucone or spreading type of draft tube has reduced the excavations necessary for most installations. The placing

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of larger units in the plants has reduced the number of units necessary and while the flumes may be larger the net result is a shorter plant than one of equal capacity built with smaller units without the use of siphon settings. These features have tended to reduce the investment required per h.p. and with the reduced excavations and shorter power house design the construction costs for cofferdams and excavations have also been materially reduced. Still further reductions have been made in power costs by reductions in operating expenses.

It is not the purpose of this paper to compare costs of various projects in an effort to prove the economic value of siphon settings but rather to show by example, where savings have been made in plants that have siphon settings. No two projects are alike and direct comparisons of cost if they were available would not tell the story of economy. Labor costs vary from place to place, construction materials vary in price depending on their proximity to the project and the foundation conditions may affect materially the cost of the installation. Two plants built from the same set of plans at different localities might vary in cost to a considerable extent. It is rather the object of this thesis to show that by the use of the principle of the siphon in the design of low-head plants real economies have resulted. It will be shown that larger sized, high speed turbines are possible in siphon settings which has

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resulted in lower cost per h.p. Larger sized units have made it possible to equip plants with fewer generators and less auxilliary apparatus. The equipment being more compact, smaller power houses are required which has contributed to reduced construction costs. The above economies have not only resulted in lower fixed charges but also have made possible considerable reductions in operating and maintenance costs.

Reduction in Investment by the Use of Larger Sized Turbines Operating at Higher Speeds.

In the outline of the development of power plant design given above it will be noted that through the years engineers were constantly striving for increased size and speed of turbines as a means of simplifying the power plant layout and thereby reducing the plant investment. The progress made so far is due to a large extent to the efforts of turbine designers who have been working not only toward the improvement of turbine efficiency but also toward the increase of turbine speeds and capacities. The history of water turbine development as we know water turbines today is covered by the developments of the past thirty or forty years. This means that improvement in turbine design has gone hand in hand with the growth of the electrical industry which alone has made possible the utilization of high capacity units operating at high speeds. In the matter of speeds, electrical generator development has permitted of higher limits of r.p.m. than water turbine designers have been able to reach under low-head and large capacity conditions.

At the time the first hydro-electric plant was placed in operation in 1882, turbine designers had been able to build turbines that had efficiencies of nearly 90 % when tested at the Holyoke testing flume. Demands for high speed and large capacity were not made

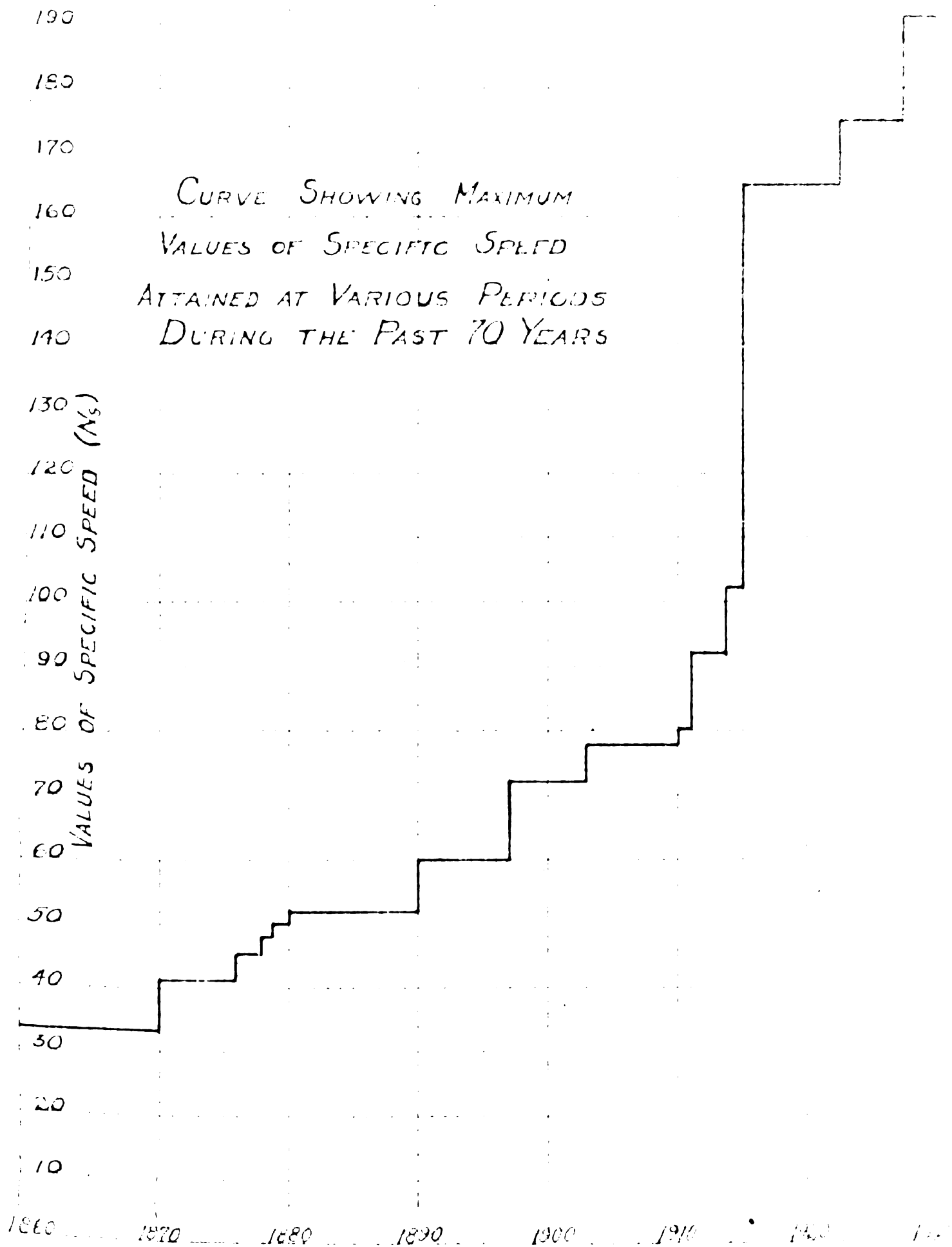
upon the designers and there were many turbines on the market under various trade names which gave good results when operating under conditions that required slow speed in r.p.m. In order to compare turbines of this early period with those manufactured today it is necessary to set up some standard of comparison so that their characteristics may be compared under identical conditions. Water-power sites are far from standard and no two of them are alike as to head, quantity of water available or foundation conditions. To compare any two runners of the same period or of different dates of manufacture some common ground is necessary. This can best be done by a comparison of "specific speeds" or "characteristic speeds" of the turbines. This term is defined in most text books on the subject of water power. Professor Mead in his text on "Water Power Engineering" defines it as:

"The number of revolutions per minute of a wheel of such size that it will produce one h.p. under a head of one foot."

Plate No. 12 shows graphically how this value has increased through the years as improvements have been made in turbine design. At the time of connecting the first generator to a water turbine in 1882 the value of this constant was only a little above 50 for the highest speed wheels then installed and this value was twice that of the early Francis turbines of 1849. During the period of the multiple runner developments speed was

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PLATE No 12



increased so that specific speeds of 75 to 80 were possible. Through the efforts of Professor Zowski of the University of Michigan and others, further increases in specific speed were made in the period from 1905 to 1915 and this increase in specific speed made possible the single runner direct connected plants for low heads. In the plant at Sault Ste. Marie, Michigan and the plant at Superior near Ypsilanti, Michigan designed by Mr. Gardner S. Williams the specific speed of the runners was about 74. The direct connected plants at Watertown, New York and at Sterling, Illinois have turbines with specific speeds of 93.4. In 1914 Professor Zowski published an article in which he described tests of a unit with a specific speed of 102 and with an efficiency of over 90 %. The high values of turbine efficiencies now possible leaves very little room for improvement in this direction but increases of even fractions of a percent are welcomed by plant designers.

The work of Larner, Moody, and Zowski was directed principally toward the improvement of the Francis type or mixed flow turbine. Improvements in specific speed of this type of turbine were accompanied by decreases in the top diameter of the runner and by a cutting back of the intake edge. This cutting back was carried to the ultimate in the Nagler or propeller type turbine which is virtually an axial flow turbine with specific speeds as high as 175 to 200. This turbine was

a radical departure from the accepted standards of the day but has become today the recognized standard for low heads and has been built for heads as high as 66 feet in this country and for heads as high as 75 feet in Europe.

In low-head plants where a large amount of power is to be developed it is desirable to make the units as large as possible. As an increase in size is accompanied by a decrease in turbine speed the lower limit of generator speeds becomes a limiting factor in turbine capacity and the short space between upper and lower pool levels places still further limitations on the size of units. The first limitation has now been raised by the increase in the specific speed and the space limitation has been practically removed by the application of the principle of the siphon setting which raises the water inside the wheel pit above the head water level before it enters the turbine.

Mr. Forrest Nagler first presented a description of this new type of turbine to The American Society of Mechanical Engineers at its annual meeting in December 1919. Several of these runners had previously been built and placed in successful operation. Mr. Nagler in his paper presented a history of the development of this runner and clearly set forth its hydraulic characteristics. The commercial advantages which he claimed for it were as follows:

- a. Lower generator cost due to an increased

speed of 50 % and over. This saving varies from 15 to 35 percent of the generator cost depending on the size and speed.

b. Lower turbine cost due to simpler runner. This averages around 10 percent of the turbine cost, the weight being about one-third the weight of the corresponding mixed flow turbine and much easier to build.

c. Smaller generator diameter which means a smaller power house.

d. Higher generator efficiency due to better design possible with higher speeds.

e. Greater turbine flexibility which permits the plant to give more power under flood conditions when the head is greatly reduced.

All of these advantages have been proved in practice as will be shown by examples of actual installations. These high speed runners are now designed by most turbine manufacturers and improvements in design have raised the efficiency of these turbines to a value above 90 percent.

New types of draft tubes have also been developed with these high specific speed turbines which have aided materially in improving efficiency and operating characteristics. As will be shown later these new type draft tubes have also helped considerably in reducing plant costs by a reduction in excavation necessary for

foundations and the draft pit.

When the speed in r.p.m. and the maximum h.p. which a unit will develop under a given head are known, the specific speed can be calculated by the formula

$$\text{Specific Speed} = \frac{\text{R.P.M.} \times (\text{H.P.})^{\frac{1}{2}}}{(\text{Head})^{5/4}}$$

From this formula it will be noted that for a given specific speed any increase in capacity, which means an increase in the physical dimensions of the unit, must of necessity mean a decrease in speed. Low specific speed units were built which would operate at speeds above 60 r.p.m. but the capacity was so low that generators of this size were impractical. Increases in specific speed were therefore an absolute necessity before the direct connected units at Sault Ste. Marie and Ypsilanti were possible. With propeller type units it was possible to increase both the speed and horsepower capacity of low-head units because of their high specific speed but for heads below 15 feet units of maximum size had already been attained due to the limitation of submergence required. While increases in speed and h.p. would result in decreased cost and increased efficiency larger units could not be installed in open flumes as they would not have sufficient submergence. To overcome this difficulty engineers revived the principle of the vacuum flume which, as has been stated above, was used by some manufacturers of water turbines previous to 1900. Siphon

settings therefore have made possible the use of high specific speed propeller type turbines in larger sizes than would have been possible in open flumes and are now almost universally used for heads below 15 feet. Some examples of the economies that have been effected by the use of these turbines will serve to demonstrate the economic value of the siphon setting which makes possible their use when the head is so low that sufficient submergence cannot be obtained in an open flume.

The first modern vertical unit with a siphon setting, as mentioned above, was at Plainwell, Michigan. The replacing of 7 turbines by 3 propeller type turbines represented not only a considerable reduction in the number of moving parts to be carefully machined and assembled but also because of the simplicity of the runner a considerable saving in the weight of the materials used. This saving as estimated by Mr. Nagler is about 10 % in the cost of the turbines. The higher speeds possible with the new runner at Plainwell made it possible to install direct connected generators of 400 k.v.a. capacity operating at 164 r.p.m. The saving in generator costs and the elimination of the cumbersome harness work and gearing all helped in reducing the investment in this installation. With the runner diameter of 6 feet the top of the turbine was too high for proper submergence and the siphon setting was used to raise the head-water inside the turbine pit to provide sufficient

cover over the top of the wicket gates. The specific speed of these turbines was 143 and with a speed of 164 r.p.m. much smaller generators were necessary than were usually employed. This reduction in generator size not only improved the appearance of the plant but also provides more space between the units.

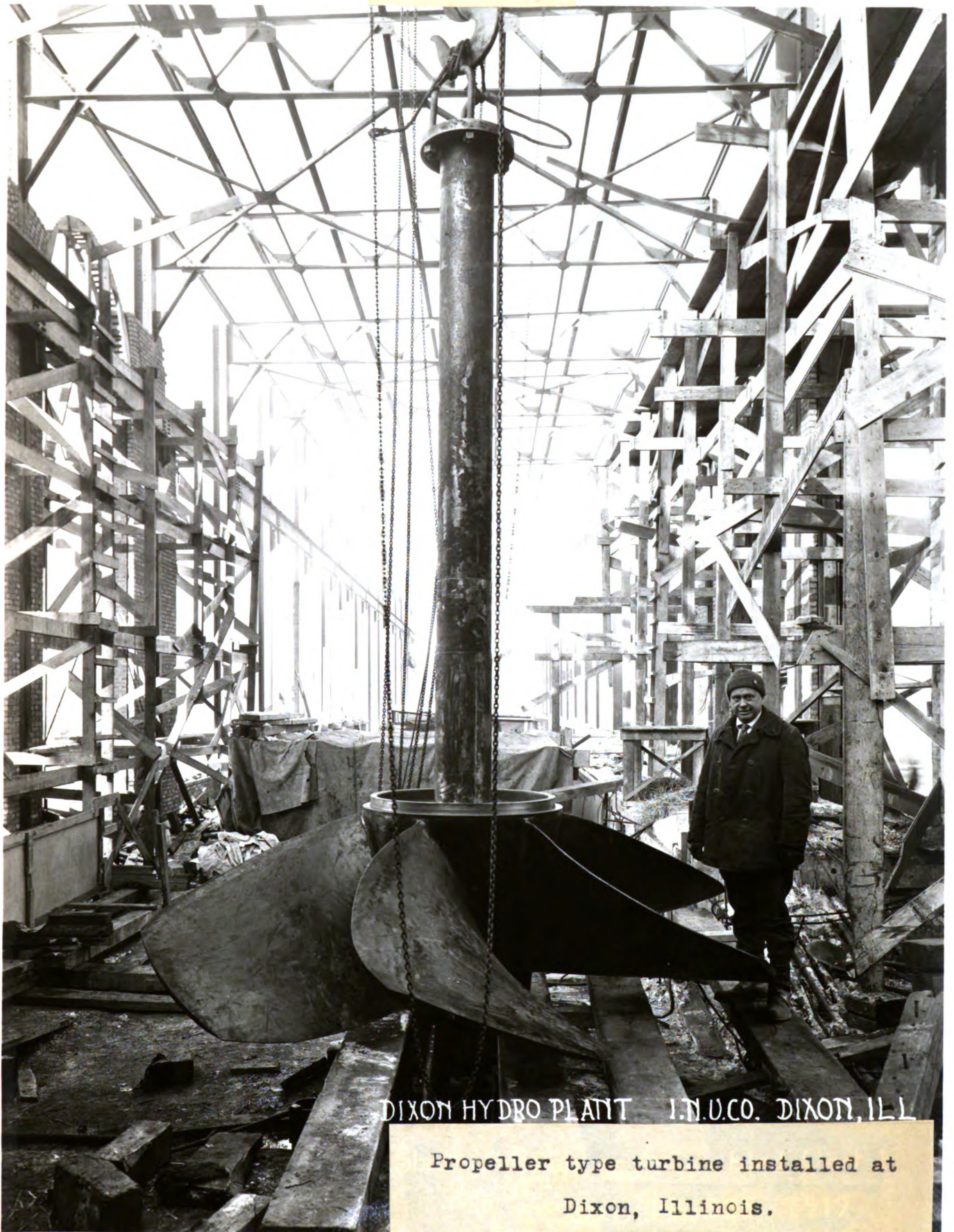
A considerable number of turbines of this type have been installed along the Rock River in Illinois and Wisconsin. The unit installed at Oregon, Illinois the year following the Flainwell installation was much smaller in capacity and the head being only 7 feet the use of the siphon setting was even more essential for a successful direct connected vertical unit. The Oregon plant in 1920 contained 5 turbines geared to a horizontal shaft driving a horizontal type generator direct. The speed of the shaft and generator was 200 r.p.m. but the turbines operated through gears with a three to one ratio so that their speed was about $66\frac{2}{3}$ r.p.m. Six wheel pits had been installed but only five of them were in use in 1921. To provide additional capacity and also partly as an experimental installation a unit with a siphon setting was installed in this idle wheel pit in 1921. The original turbines had specific speeds of approximately 60. The new turbine installed was one of the Zowski turbines manufactured by the James Leffel And Company. It had a specific speed of 80 and operated at 80 r.p.m. This unit had its top set at head water eleva-

vation and the roof of the wheel pit was about six and one-half feet above the head-water elevation. The small size of this unit made its cost per h.p. higher than some larger units but its satisfactory operation has demonstrated its economy.

The next installation on the Rock River was at Rockford, Illinois. Two units were installed for the Rockford Electric Company in a plant that originally contained four units. In the interests of economy as much of the original foundations were used as possible. The units were designed for operation at 100 r.p.m. and developed 750 h.p. under a head of 9 feet. The specific speed was 175. The replacing of four units by two units represented a considerable saving and the increase in speed made further savings possible in the cost of the electrical equipment.

The plant at Dixon was started in July 1924 and finished in June 1925. A view of the propeller type runner built by the I. P. Morris Department of the Wm. Cramp and Sons Ship and Engine Building Company and now a division of the Baldwin-Southwark Corporation is shown on Plate No. 13. The physical dimensions are comparatively large and the wide areas between blades permit the passage of large quantities of water. This type of unit has the further advantage of permitting a wider rack spacing and results in a reduction in rack losses. Plate No. 14 shows a cross section of the Dixon plant



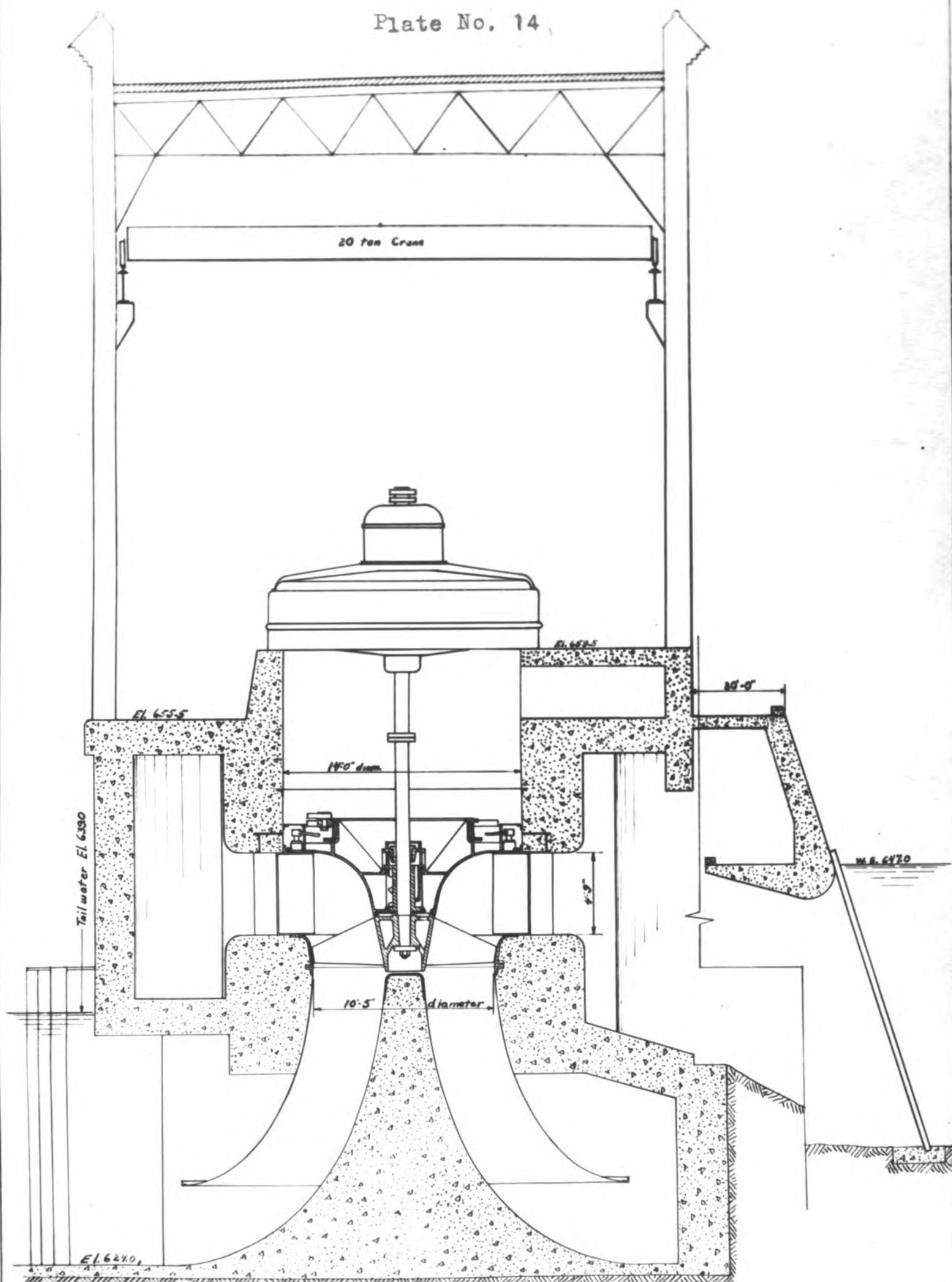


DIXON HYDRO PLANT I.N.D.CO. DIXON, ILL.

Propeller type turbine installed at
Dixon, Illinois.



Plate No. 14



CROSS-SECTION OF THE PLANT AT DIXON, ILLINOIS

which has wheel pits 43 feet wide. At the time this plant was built the average head was between 8 and 9 feet but dredging of the river below the plant has increased the head so that at the present time the average head is between 9 and 10 feet. The runner diameter is 125 inches or just equal to the maximum head on the plant. Units of this size would have been impossible at this site without the siphon settings in which they are installed. The top of the turbine is above the normal head water elevation and a view of the turbine setting is shown on Plate No. 15. The bottom of the runner is just above normal tail water elevation so that it can be inspected periodically a feature which is important if turbines are to be properly maintained. The Dixon units are rated at 800 h.p. when operating at 80 r.p.m. under a head of 8 feet. The specific speed is about 170.

The Sterling plant mentioned above, located about 14 miles down stream from Dixon, was built just 10 years before the Dixon plant. These turbines are in open flume settings and are about the maximum in size which can be installed in an open flume when the head is only about 9 feet. Some comparisons of these two plants will illustrate the economy of the high specific speed turbine with siphon settings. The Sterling units have a specific speed of 93.4 while the units at Dixon have a specific speed of 170 or almost twice as high. Both plants contained five units each until December 1930.

Plate No. 15

DIXON HYDRO PLANT I.N.U.CO. DIXON, ILL.

Wheel Pit. Unit 2

Jan. 6, 1925 7913

View of the turbine setting for the
plant at Dixon, Illinois.



The units at Sterling have a capacity of 550 h.p. under a head of 8.5 feet. The Dixon units have a capacity of 875 h.p. under a similar head which is a 60 percent greater capacity. It would have required eight turbines of the capacity of the Sterling units to equal the capacity of the Dixon plant. The Sterling turbines are the Francis type mixed flow runners and as stated above are more expensive to build. The high speed characteristics of the Dixon units makes it possible to operate at 80 r.p.m. while the Sterling units operate at 60 r.p.m. This higher speed at Dixon reduces the cost of generators as well as their size. The Sterling units are 18 feet $9\frac{1}{2}$ inches in diameter and the Dixon units are 15 feet 4 inches in diameter.

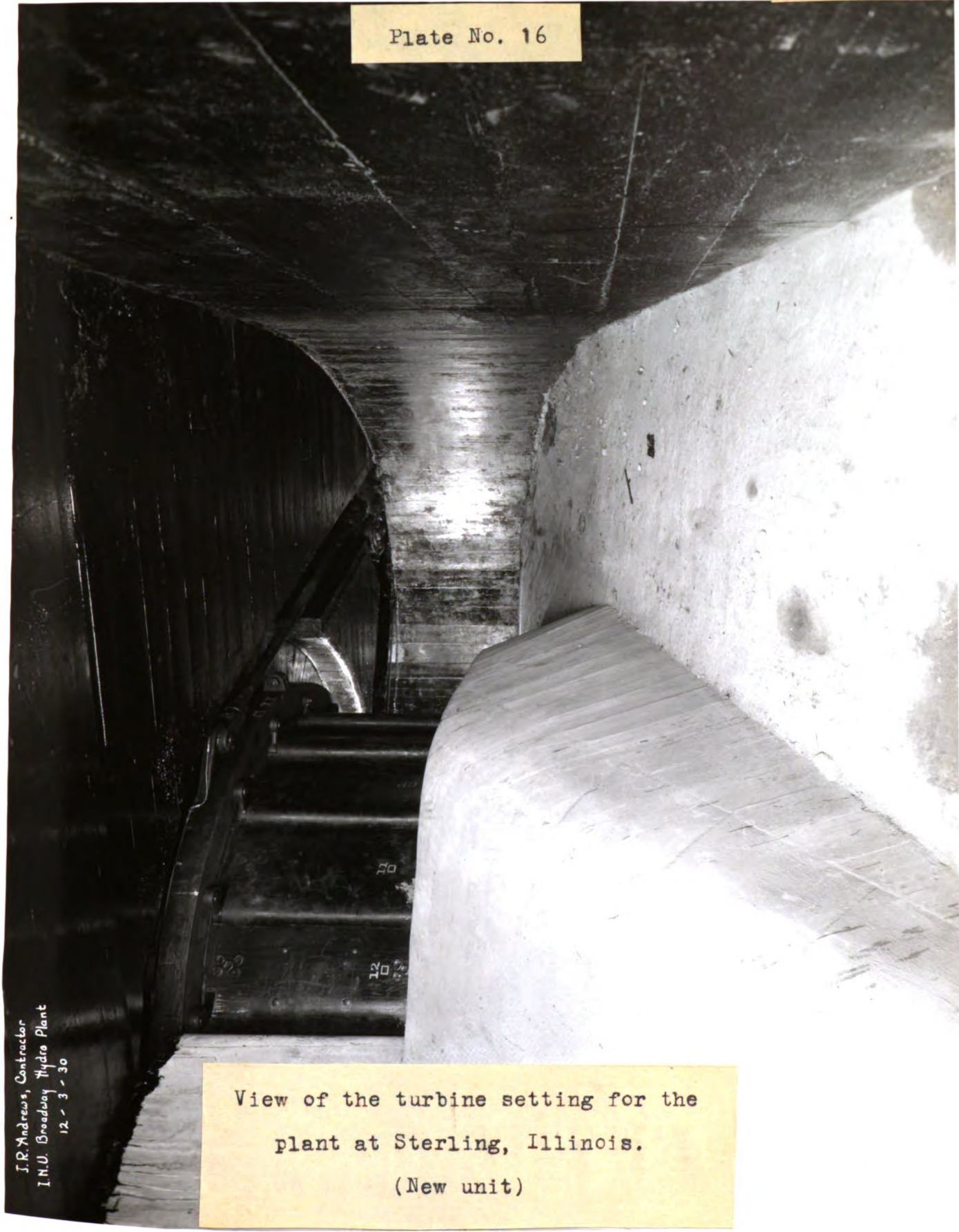
The higher speeds not only reduce the generator costs but also the turbine costs due to the fact that for a given runner diameter a larger quantity of water can be passed at a higher velocity and consequently a greater h.p. is produced. The runner diameter of the Sterling units is 122 inches or only three inches less than the Dixon units. The Dixon units, however, have about a $33\frac{1}{3}\%$ greater water capacity and about a 60 percent higher h.p. rating. The Sterling units were purchased prior to the World War and any comparison of costs must be adjusted to values such as would exist if the units were made at the same period of time. In 1925 the wholesale commodity index was 150 as compared to

1914. In other words the Sterling units might have cost 50 % more than they did cost if they had been furnished in 1925. The combined cost of generators and turbines at Sterling in 1914 was about 36 dollars per h.p. including the erecting. Based on 1925 price levels this cost would have been 55 dollars per h.p. The cost of the Dixon units in 1925 was only 47 dollars per h.p. including erection based on their capacity at an 8.5 foot head. The relative lower cost of the Dixon units is due to two things. First the units are of larger capacity and second the propeller type units are lighter and cheaper to build. Units of the size of the Dixon units are only possible for such a low head when installed in siphon settings. The actual savings at the Dixon plant were about 10 % of the Engineers' estimates on the turbines and nearly 30 % on the generators. The cost of the equipment was over \$50,000.00 less than the estimates and this saving is a rather large percent of the total cost of the project.

Still further comparisons as to economy can be made at the Sterling plant for in 1930 a sixth unit was installed in an idle wheel pit. The original units were installed in wheel pits much too small for their capacity. In low-head plants water velocities must be kept as low as possible to reduce the drop in head in the wheel pit. Flume velocities at Sterling are too high for high efficiency operation and at times they

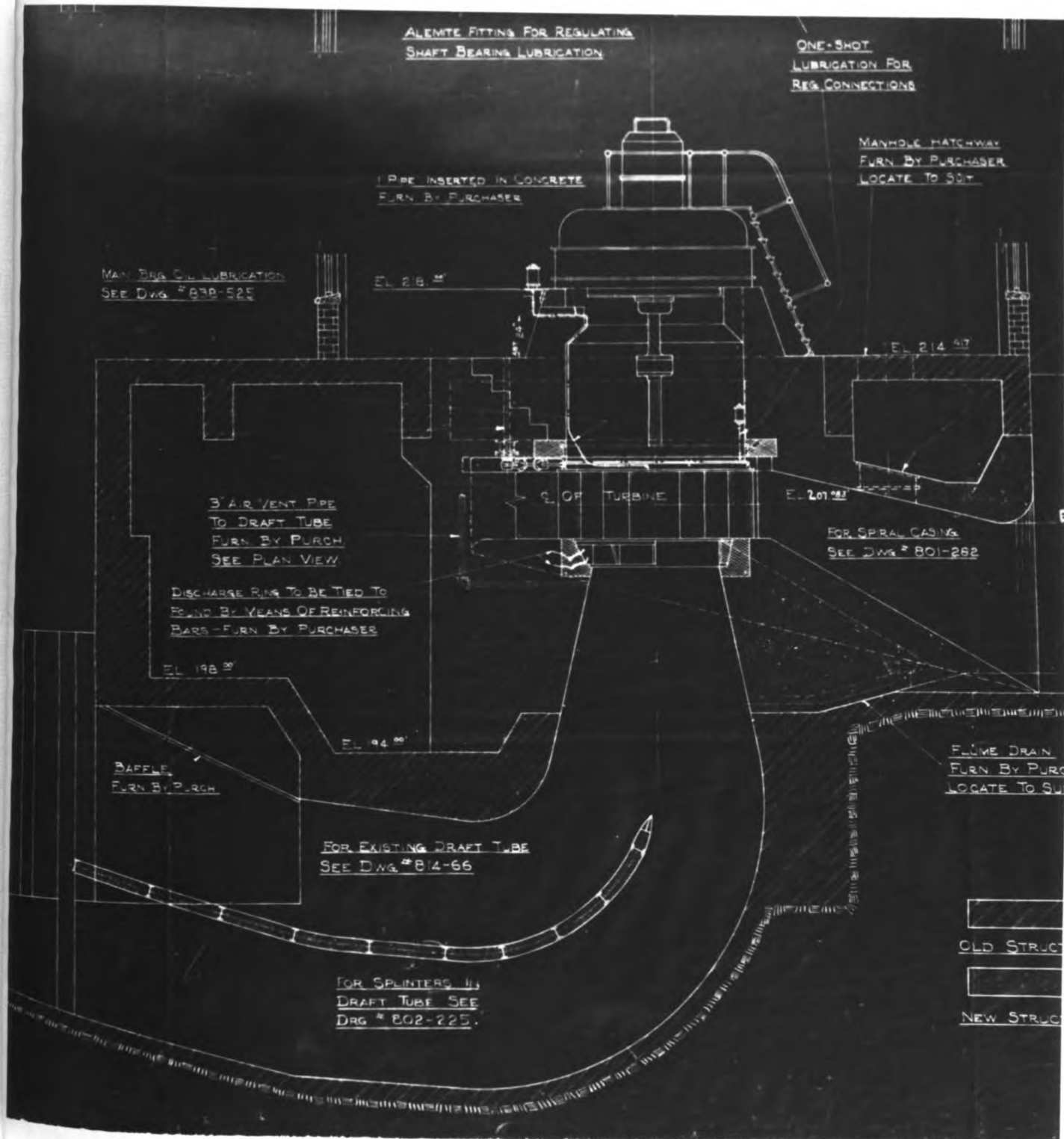
reach values as high as 5 feet per second. The new unit was selected with a capacity which would keep this value to about 2 feet per second. The water capacity for normal operation was therefore limited to 500 cubic feet per second. The normal capacity of the original units with a 9'0" head is about 800 c.f.s. The new unit was installed in a siphon setting with the top of the runner 2 feet above head water. Plate No. 16 shows the turbine setting for this unit and should be compared with Plate No. 15 showing the setting for the turbines at the Dixon plant. Plate No. 17 shows a cross section of the new unit and it is to be noted that there is no large air chamber above the unit as at Dixon. While this new unit is installed in a siphon setting it is of such size that it might have been installed without the siphon setting by placing it lower. Draft tube design however, raised the setting so high that a vacuum flume was necessary. The draft tube for the larger units having been installed in 1914 when the plant was built economy required that it be utilized by extending the upper part of the tube until its diameter conformed to the diameter of the turbine speed ring. Had units of this size been installed at Sterling originally it would have required 9 of them to have equalled the capacity of the Dixon plant. A comparison of the cost of this equipment with that at Dixon shows that the equipment for the Dixon plant with fewer units of larger capacity

Plate No. 16



View of the turbine setting for the
plant at Sterling, Illinois.
(New unit)

Plate No. 17



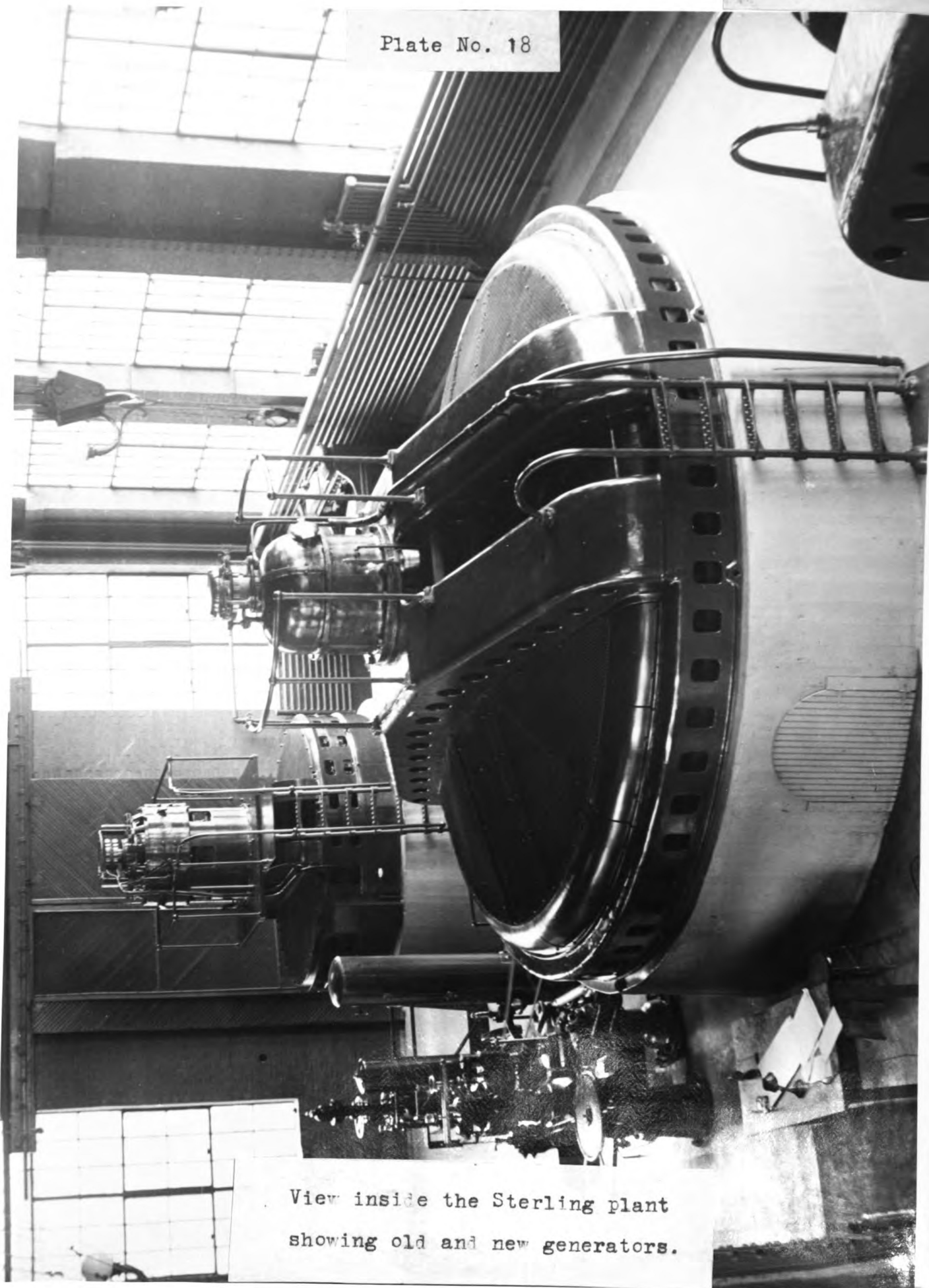
Cross-section of the plant at
 Sterling, Illinois, (New unit)

cost less per h.p. Plate No. 18 is a view inside the Sterling plant and shows the difference in the size of the generators for the old and new units. The new unit has a specific speed of 175 and operates at $128\frac{1}{2}$ r.p.m. and has the further advantage of having turbine blades which are manually adjustable for varying conditions of head and quantity of water available.

The water capacity of this turbine is about 50 % that of the Dixon turbines and its h.p. rating at 9 feet head is 450 as compared to 950 h.p. for the Dixon units at the same head. Due to the larger hub diameter required by the adjustable blade feature the turbine diameter is slightly larger than half that of the Dixon turbines. Its throat diameter is $81\frac{1}{2}$ inches. The cost of this unit for generator and a fixed blade propeller type runner would have been about 48 dollars per h.p. The adjustable blade feature added about 10 dollars per h.p. To the cost but this increased investment is justified by the additional kilowatt hour output possible from the turbine with adjustable blades.

While the Keokuk plant does not have a siphon setting some interesting facts as to the economy of the high specific speed turbines can be shown by comparing this plant with the Ohio Falls plant at Louisville, Kentucky which has propeller type turbines. The 10,000 h.p. turbines at Keokuk are 168 inches in diameter and operate at 60 r.p.m. The runners weigh 130,000 pounds.

Plate No. 18



View inside the Sterling plant
showing old and new generators.

At the Ohio Falls plant the 13,500 h.p. propeller type turbines are 180 inches in diameter and operate at 100 r.p.m. The runners in this plant, however weigh only about one-third as much as do the runners at Keokuk or about 40,000 pounds. The decrease in turbine weight means economy in the cost of the turbines and the increased capacity possible means that today a plant the size of Keokuk could be built with fewer units and the higher speed generators would not only cost less but would be much smaller in diameter and more efficient. These same comparisons are true with almost any low-head installation and because of the simplicity of the design of the runner and its real economy this type of turbine with high specific speed is now generally used for all low-heads. When these units have been built for heads of 15 feet or less their diameter and height of gates are usually so large that the siphon setting must be used to provide the necessary submergence for satisfactory operation.

The routine operation of any hydro-electric power plant requires that the current be generated to meet the demands for power. In an interconnected system the duty of the taking of the variations in load is usually assigned to the units having the best efficiency under part load operation. Economy of operation in a steam generating station is best obtained by a high load factor and where possible load changes are assigned to

the hydro-electric units. In run-of-river plants having no storage however, this plan of operation is impossible and the steam plant has to assume this duty of taking the variation in load. This leaves the hydro turbine to operate at its most efficient capacity. If it were possible to operate in this manner throughout the entire year a maximum of kilowatt hours would be obtained. Variations in water supply on rivers without storage, however, make it necessary to operate turbines at part-gate for considerable periods. This is especially true during years of drought such as was experienced in 1930 and 1931. The Francis type or mixed flow turbines had reasonably high part-gate efficiency but the new propeller type turbine was not so satisfactory for part-gate operation. This fact was brought out in the discussion of Mr. Nagler's paper in 1919 when he first described these turbines. He answered this objection by stating that the part-gate efficiency of the high-speed runner was 6 to 8 percent lower for half load than the mixed-flow low specific speed runner. He added that

"the real field for the runner is in such an installation as that at Keokuk or that on the St. Lawrence River, where with a large number of units, the part-gate efficiency would not be a deciding factor in the problem."

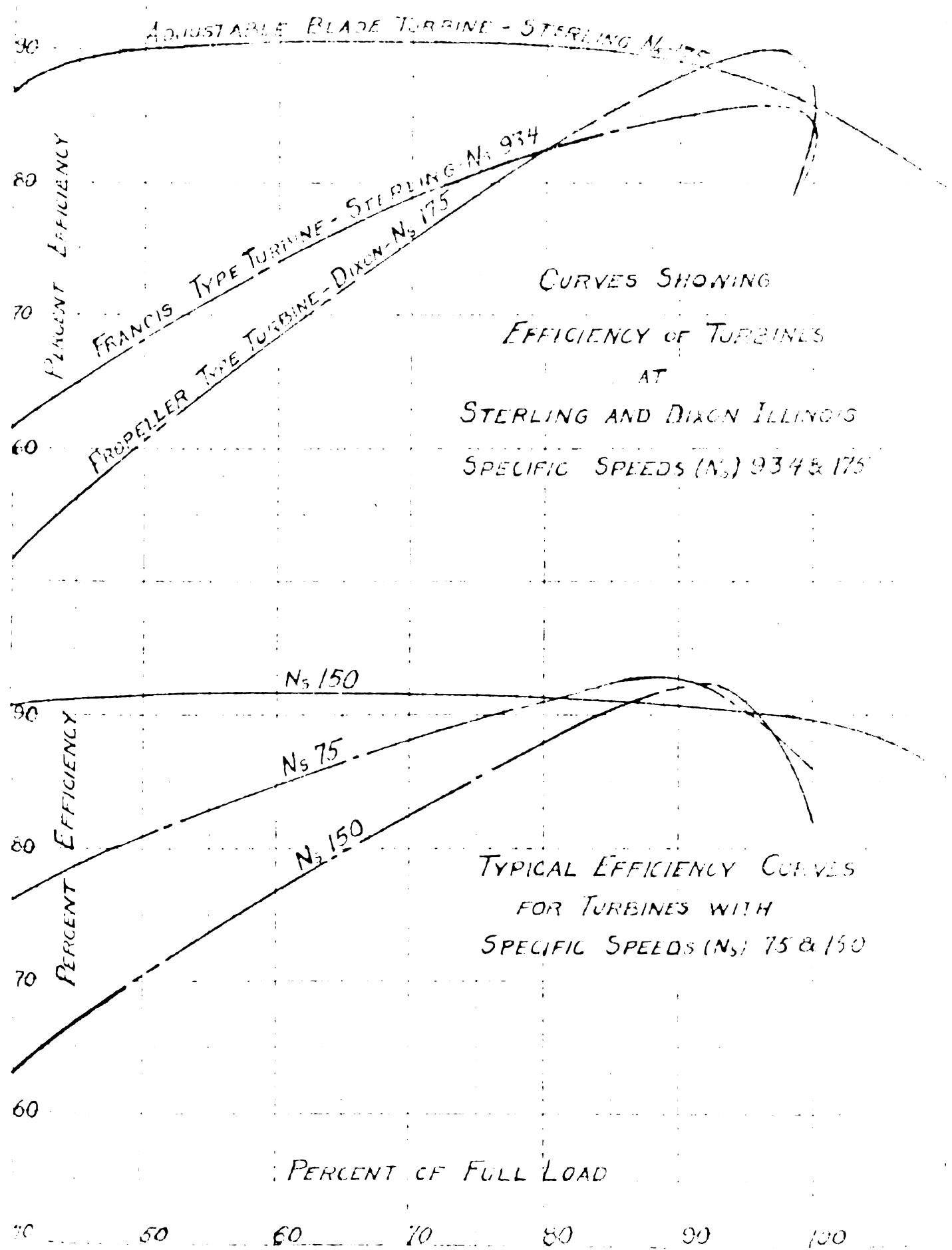
In his paper Mr. Nagler also stated that

"a runner may be taken out and another substituted for capacity variation under flood conditions without removing any other turbine parts except two or three

guide vanes. In two plants this was made use of to install a high-capacity runner for obtaining more power during flood periods."

The changing of turbine runners, however, was not a practical method of providing for variations in flow. Engineers who were concerned with the design of plants usually proportioned the size of units so that there would be as little operation of the turbines at part-gate as possible. In some plants units of different sizes were installed to overcome this difficulty of low efficiency at part-load. On the Flint River in Crisp County, Georgia two 10,000 h.p. units and two 1,400 h.p. units were installed to provide for the variations in flow and load. At the Dixon plant the turbines selected were of 800 h.p. capacity and utilized about 1,000 cubic feet of water per second. The lowest recorded minimum flow was about 800 cubic feet of water per second and it was thought that this size unit would require a minimum of part-gate operation. However, in 1931 even lower flows continued for long periods and considerable operation of the turbine at part-gate was necessary. Plate No. 19 shows an efficiency curve for one of the units at Dixon when operating with a head of 8.5 feet. The physical dimensions of the Dixon units are large for units for such low heads but even larger units might have been used and a plant of four or perhaps even three units to give the same total capacity might have been installed had it not been for this

PLATE NO 19



limitation of low efficiency. at part load operation. Limitations as to size of units has been removed as far as submergence is concerned by the use of the siphon setting.

Following closely on the development of the high specific speed propeller type turbine an even more radical step has been taken with the propeller type turbine itself by a design which permitted the articulation of the propeller blades at the hub to permit a change of blade angle under different conditions of operation, a thing that was impossible to attain with a Francis type turbine. In this country the first adjustable blade turbine was manually adjusted and required the unwatering of the wheel pit as the adjustment was made at the hub of the turbine. While this was an improvement over changing of the entire turbine for one with different blade angles it was nevertheless not an entirely satisfactory method of operation. Later improvements permitted the blade angle to be changed at the point where the turbine shaft and the generator shaft were coupled together. This was an improvement but still required the shutting down of the unit to make the change. Later improvements permit the articulation of the turbine blades while the unit is operating. This is done by means of an electric motor controlled at the switchboard. The new turbine at the Sterling plant, referred to above, has adjustable blades that are adjusted manually at the

coupling when the unit is at rest. In Europe the progress of the adjustable blade turbine design has been much more rapid and for several years they have had in successful operation units in which the blade angle is changed by oil pressure from the governor. For every change in load which requires a change in gate opening there is a corresponding change in the setting of the blade angle so as to provide efficient operation over a wide range of load change. Plate No. 19 shows a family of efficiency curves for these several types of units.

At the bottom of Plate No. 19 are shown efficiency curves for a turbine of the Francis type with a specific speed of 75 and a curve for a propeller type turbine with a specific speed of 150. It is readily seen that the part-load efficiency of the high specific speed turbine is considerably below that of the Francis type runner. The upper curve is for a Kaplan turbine with a specific speed of 150 and the high efficiency of this turbine at part-load is readily apparent. These curves are taken from an article published by George A. Jessop, Chief Engineer of the S. Morgan Smith Company, in *Electrical Engineering* for February 1931. These curves indicate clearly that additional kilowatt hours can be obtained from the adjustable blade turbine when part-gate operation is necessary. Just how this works out in practice is shown by the curves at the top of the curve sheet. The Francis type units at Sterling, Illinois

have not been tested but from test data on this runner, (Holyoke test No. 2122), the efficiency curve has been constructed. This unit is one of the early turbines built by the Allis Chalmers Manufacturing Company to meet the demands for higher specific speed turbines and has a specific speed of 93.4. While the efficiency is not as high there is a reasonable resemblance to the curve for a turbine with a specific speed of 75. An index test of one of the Dixon units provided the data for the curve for the unit with a specific speed of 170. This curve is for a head of 8.5 feet. Typical of turbines of this class the part-load efficiency is below that of the Sterling Francis type units. While the usual operation at the Dixon plant is with turbines operating at the best efficiency there are considerable periods when part-gate operation must be resorted to. Recognizing this loss as being considerable, the new unit selected for the Sterling plant in 1930 was designed for manual adjustment of the turbine blades. After installation this plant was tested by the index method. A current meter was installed in the flume about 8 feet upstream from the entrance lip and at mid-depth. Simultaneous readings of power output and flume velocities were taken and from later tests to calibrate the index meter sufficient data was provided to construct complete efficiency curves of reasonable accuracy for each setting of the turbine blades. The curve shown on the curve sheet for this turbine which has a specific speed of 175 is an

envelop of several efficiency curves obtained from these tests. The automatically adjustable blade turbine operates at efficiencies as represented by this type of curve if the proper cams have been worked out either by tests or from theoretical calculations but with the manually adjustable blade turbine it is necessary to set first the turbine blades and then adjust the turbine gates for best efficiency. Once the information has been worked out this is not a long or difficult process. Turbines of either type will give increased kilowatt hour output and the frequency of load changes determines the necessity for the automatic feature. Where changes are seasonal the manually operated turbine blades will give satisfactory results at a lower investment cost.

In this country the European type of turbine was first manufactured under license by the S. Morgan Smith Company of York, Pennsylvania. In paper entitled "Greater Efficiency for Low-Head Hydro" published in "Electrical Engineering" for February 1931 by George A. Jessop, Chief Engineer for the S. Morgan Smith Company, he states that

"Economy in first cost has stimulated 20 years of effort to secure a higher speed in hydro-electric units; principally because generator costs go down as the speed increases. Until recently an increase in speed has resulted in a reduction in efficiency - particularly at part loads - to a large extent offsetting the advantages of reduced investment. Improvement in generator efficiency with increased speed has only partially offset these reduced turbine

efficiencies. Turbine designers now have succeeded in maintaining the maximum or peak efficiency at a given figure over a wide range of specific speed and by means of the Kaplan or automatically-adjustable blade runner have improved the part-load efficiency far above that formerly obtained even in the slow-speed Francis turbines."

This development in turbine design has made available to engineers turbines with high efficiency over a wide range of load. Low-head plants, where propeller type units are applicable are usually on streams where little or no storage is possible and where the development, if made, must be a run-of-river installation designed to use a large percentage of the flow of water which is available for at least a part of the year. As pointed out above the high peak of the efficiency curve of fixed blade turbines requires that several units be installed and then the units either operated at the most efficient gate opening or not at all. On the other hand the adjustable blade turbine has an efficiency curve of such shape that it is almost ideal for a run-of-river plant. Variations in load can thus be provided for without a serious departure from peak efficiency.

Just what bearing this development in turbine design has on the economic value of the siphon setting is best shown by the fact that it is now possible to build hydro-electric plants with still larger units than have been used heretofore for the low heads and for this reason fewer units are required for the same

total capacity. The high efficiency at part load makes it possible to obtain an even greater number of kilowatt hours from an installation than would be possible with fixed blade propeller type units of equal capacity. If siphon settings were necessary for the successful utilization of the propeller type turbines for low-head plants they are even more essential for the settings for adjustable blade turbines whether manually or automatically controlled.

Mr. L. F. Harza, Consulting Engineer of Chicago, was responsible for the installation of one of the first Kaplan turbines in this country. This plant was located on the Devils River in Texas. In writing about these turbines in an article entitled "Water Turbines of the Propeller Type" published in Electric Light and Power for April 1931, Mr. Harza states that

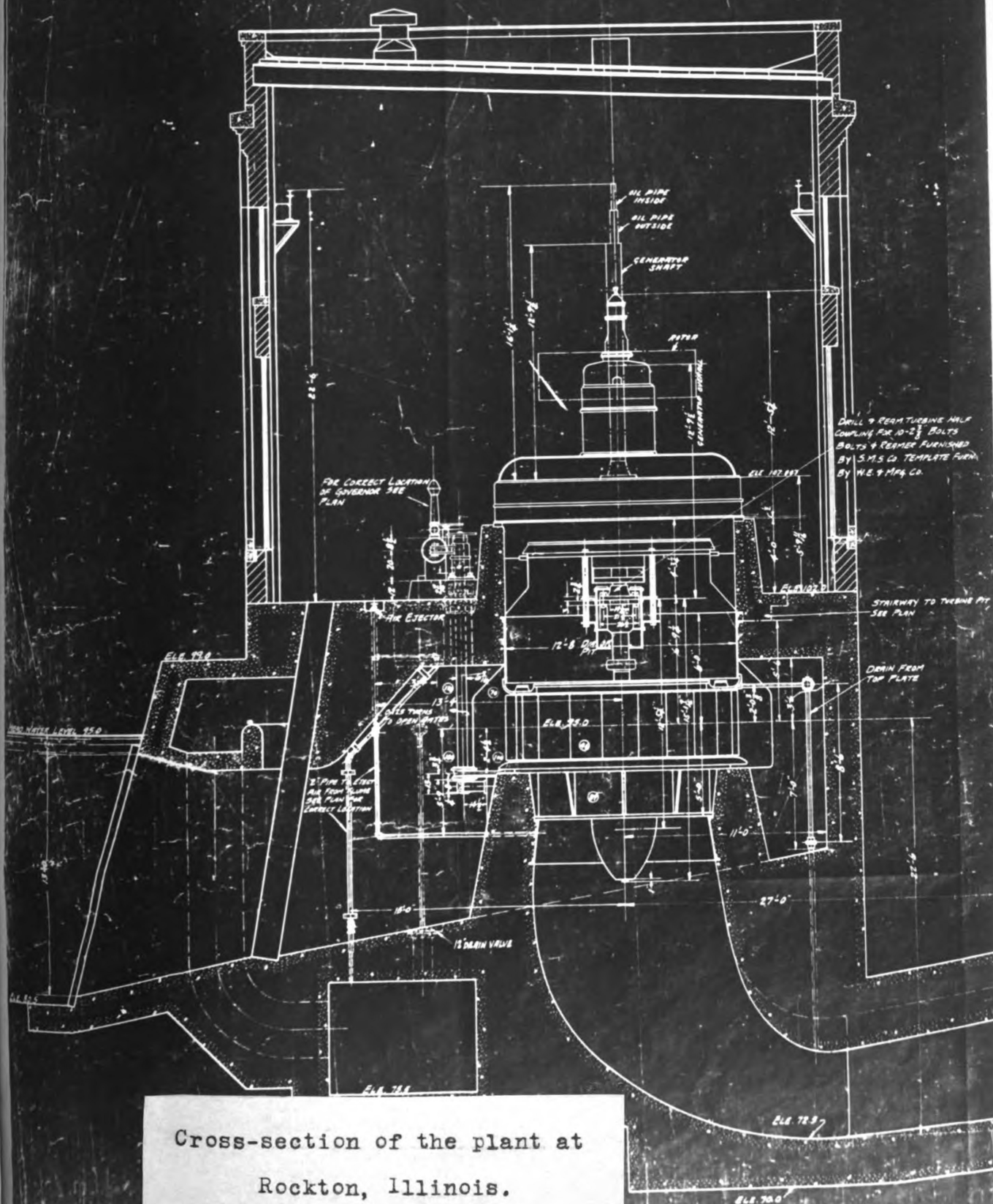
"Although the Kaplan turbine costs more than either the Francis or fixed blade propeller types, for fairness the comparison must be made on the same total capacity, but a smaller number of units, thus tending toward a reduction in cost. The alternative procedure is, of course, to put in part fixed-blade propellers and part Kaplan units, the former to be operated at best efficiency or not at all, and the latter to handle the variations in load."

In the spring of 1930 a plant was placed in operation on the Rock River at Rockton, Illinois in which this latter procedure was followed. The plant contains one fixed blade propeller type turbine of 725 h.p. capacity and one Kaplan turbine of 994 h.p. capacity.

The head is 11 feet and both turbines are in siphon settings. Had it been necessary to install only fixed blade turbines the installation would no doubt have been made with three turbines and even turbines of this size would not have been possible for such a low head were it not for siphon settings. Plate No. 20 shows a cross section of the Rockton plant along the centerline of the adjustable blade unit. So far as the author has been able to learn this is the first automatically adjustable blade turbine installation in this country in a siphon setting. Several manually adjustable blade turbines, however, had previously been installed in siphon settings.

The high efficiencies obtained with adjustable blade turbines over the wide range in power output and the increase in the size of these turbines built in 1931 indicates that even larger units will be built in the future for low-head plants than have been considered practical in the past. As the size increases it will become increasingly necessary to apply the principle of the siphon setting to even higher heads than heretofore has been considered necessary. At Ottumwa, Iowa three units were installed in 1931. The head at this plant varies from 12 feet to 14 feet. The units are 1,400 h.p. capacity under a 12.25 foot head. The turbine pit is sealed to form a siphon setting but under certain conditions of high head-water the turbines may be operated under pressure. It can readily be seen that increases

Plate No. 20



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in size and capacity of turbines for heads between 15 and 20 feet will require siphon settings for their economical installation. The 21,000 h.p. turbines for the Rock Island Development of the Washington Electric Company to operate under a head of 32 feet. and the 42,000 h.p. units for the Safe Harbor Water Power Corporation on the Susquehanna River in Pennsylvania to operate under a head of 55 feet which were installed in 1931 and which have automatically adjustable blade runners, indicate the trend in turbine design toward larger and larger adjustable blade turbines. The economic value of increased capacity per unit and decreased number of units in an installation has been clearly demonstrated by the installations of the past few years. Combined with the siphon setting this economy can be extended to those low head installations which lie on the borderline of practical development.

In Sweden where there exists abundant water power with high heads there is at the present time under construction a plant that will utilize the principle of the siphon setting to develop power with a head of only 14 feet. The turbines to be installed will be the largest ever installed in a siphon setting being 26 feet three inches in diameter and will develop 16000 h.p. maximum. The runners will be of the Kaplan type and will weigh 150 tons each. It is expected that this plant will be placed in operation sometime in 1934 and

is known as the Vargon plant. It is located on the Gotha River at the outlet of Lake Vänern and is being built by the Royal Board of Water Falls.

For low-head hydro-electrical developments there is now available equipment which can be operated over a wide range of load without a serious reduction in efficiency. This type of turbine permits the installation of larger units than have heretofore been considered practical because of this feature of high part load efficiency. The increase in turbine size with fewer units in an installation tends toward reduced cost per h.p. installed and the wide range of operation at high efficiency provides a means of increasing the kilowatt hour output when part gate operation is necessary. The higher speeds available with the fixed as well as the adjustable blade turbines has reduced generator sizes and the cost per kilowatt and at the same time increased the generator efficiency. These advantages which were predicted for this equipment by Mr. Nagler in his paper before the American Society of Mechanical Engineers in December 1919 have been proven in practice and are not only available for heads above 20 feet but also for lesser heads when the turbines are installed in siphon settings.

Reduction in Investment by a Reduction in the Size of the Power Plant.

In the preceeding pages we have considered the economies made possible by improvements in the hydro-electric equipment. Increases in efficiency are desirable when they can be obtained at little or no increase in cost. We have seen that while Kaplan turbines are more expensive than fixed blade turbines of equal size their use can be considered economical when the size is increased and the number of units reduced. Fifteen years ago the open flume was considered the practical and logical setting for low-head turbines. Improvements in the hydro-electric plant equipment have demanded changes in plant design and as the cost of the plant for low-head developments may exceed the cost of equipment by a considerable amount it will be well to give some consideration to this item of investment.

For the small Francis type turbines of low specific speed the open flume setting offered the most economical type of installation. Some attempts were made to improve on this type of turbine setting in the early days and for the smaller units steel jackets were provided instead of the wooden flumes or flumes of ashlar masonry. At Sterling, Illinois there can still be seen almost all these types of turbine settings. The earliest plants had timber flumes, later plants had ashlar masonry walls and one such plant is still operating after not less

than 40 years of service. This plant represents an economical use of the materials available at the time of its construction but is hardly to be recommended as a modern installation. As the use of cement concrete came into more common use it was applied more and more to power plant construction. In 1904 the plant shown on Plate No. 1 was built at Sterling, Illinois. It was designed by Professor Mead and the three turbines were placed in separate wheel pits with concrete walls between them and an attempt was made to improve the hydraulic conditions by making the downstream wall of plate steel and semicircular in shape.

As turbine speeds increased engineers began to improve flume designs. The improved turbines would take almost twice the water through the same throat diameter and one of the mistakes of the early designs for high specific speed turbines was failure to take into account the flume velocities. The units at the Government dam at Sterling were placed in open flumes and the average water velocity at the intake is about four feet per second. At the Dixon plant the design is such that the flume velocity is about two feet per second and in addition scroll type flumes were employed. It cannot be denied that improved flumes with scroll type walls cost more but as the art of concrete forming has improved the building of these curved surfaces does not present the problem that it formerly did. As with the turbine costs

the fact that fewer units are required to make up a given capacity the total plant cost may even be less for the improved flumes than for a greater number of box flumes.

The redevelopments of the past few years in which propeller type turbines have been installed in scroll type cases with siphon settings emphasize the economy of fewer units for a given capacity development. In most cases even greater capacity has been achieved, within the same space limitations by fewer units of larger capacity. In Plate No. 2 there was illustrated the saving possible with a single large unit to replace a quadruplex horizontal runner. In the building of the first vertical type unit in a siphon setting seven units were replaced by three larger units. In the rebuilding of the plant on the Rock River at Rockford, Illinois two units replaced four and the old substructure was used by removing the concrete in the intermediate walls. Illustrations might be cited without number to show the tendency during the past few years to decrease the number of the units in an installation and increase the plant capacity. The result of this change in plant design has been to reduce the plant cost by a decrease in materials required per kilowatt of plant capacity.

There are certain necessary parts of a power plant installation which contribute to the cost of the installation but not in proportion to the capacity. This auxilliary apparatus can be reduced in quantity and cost

by a decrease in the number of units for a given capacity. If we first consider the switchboard and electrical wiring for a small hydro plant it is evident that one panel must be required for each unit installed and conduits for wiring placed in the concrete must be run to each unit. If the number of units be reduced one-half by making their capacity twice as large it is evident that there will be a considerable saving in this item of equipment alone. The wire and conduit for the larger unit might be increased slightly but the labor and materials for the switchboard would be cut in two. In a large installation the switchboard cost is not a large percentage of the total cost of a hydro development but for the small low-head plant such as is usually built with siphon settings the cost of the switchboard in percent of the total cost is much larger. A saving such as has been suggested above will materially reduce the investment in any low-head hydro-electric development.

The cost of the governor for the turbine is another item of plant cost that is reduced by the reduction in the number of units. A larger governor may be required for the larger turbine but the cost of the turbine governor does not increase in proportion to the capacity in h.p. of the unit to be governed. The cost of this equipment is sufficiently large to affect materially the investment in a plant and in some plants in order to keep the investment down to a value low enough so that

a fair return might be earned, the governors have been omitted entirely. The unit installed at Oregon in 1921 is small and has no governor. The run-away speed is not high and usually the operators who are on duty are able to close the gates before the full run-away speed is attained. This unit has operated successfully for 10 years without a governor. Considerable study has been given to this subject of reducing plant costs by omitting the governors and several small units and some larger ones have been so installed without depreciating the value of the plant as an operating unit where it is operated on base load with no load changes to provide for and where operators are on duty to shut the unit down in case of trouble. At the plant located at the Government dam in Sterling this item of cost was given considerable study and as a means of reducing the investment the units were so designed that one governor controlled two turbines. At the Dixon plant smaller capacity governors are controlling units with capacities nearly equal to two units at the Sterling plant.

The necessity for a governor to control the hydro unit is not determined by whether the unit is in a siphon setting or not. That is a problem of engineering and is determined largely by the size of the system with which the unit is connected and the method of operation. If governors are required in the hydro-electric plant it is evident that when larger capacity

units are installed in siphon settings the cost of governors per h.p. installed will be less than with a greater number of units installed in open flumes.

The exciter is another plant auxilliary that can be reduced in cost by the increased speed and larger size of units now possible for low-head installations. Several illustrations of typical power plants included in this thesis show exciters direct connected to the main shaft and mounted on top of the generator. In larger power plants separate water wheel driven exciter units are sometimes provided but in smaller plants it is a more common practice to make the exciter an integral part of the machine which it serves. For slow speed machines the cost of this type of exciter is high and as with generators the cost reduces and efficiency increases as the speed increases. Where the speed is too low for economical exciter units direct connected on the machines, motor generator sets are employed. As this involves generating the current and then passing it through a motor to operate the exciter the losses make it less efficient than the direct connected type of exciter. With speeds of 100 r.p.m. or over satisfactory direct connected exciters can be built at reasonable cost. At the Sterling plant excitation was first supplied by exciters driven by belts from a jack shaft geared to the vertical water wheel shafts. This arrangement was not very flexible and later a motor generator set was installed. The speed of 60 r.p.m. at which the

generators operated was too slow for economical exciter design. Even the 80 r.p.m. generators at the Dixon plant do not have direct connected exciters and motor generator sets supply the excitation in this plant. The new unit at Sterling operating as it does at $128\frac{1}{2}$ r.p.m. is supplied with exciting current from a direct connected exciter mounted on top of the unit as shown in Plate No. 18.

The advent of the high specific speed turbine which has made possible higher operating speeds also made it possible to design direct connected exciters for generators connected to them. As with the governors the increase in unit capacities reduced the number of units required and so the plant investment can be reduced by considerable savings on the excitation equipment. It is true that as the units increase in size the capacity of exciters connected to them must also increase but the cost does not increase in proportion to the capacity and even reduces with an increase of speed.

One of the major items of cost of a power plant is the building which houses the generators. Below the generator floor all of the space is utilized for water passages and very little of the area can be considered as useless or waste space. Above the generator floor however, questions of crane clearance and size of the equipment determines the size of the building necessary. In some of the larger plants for higher heads

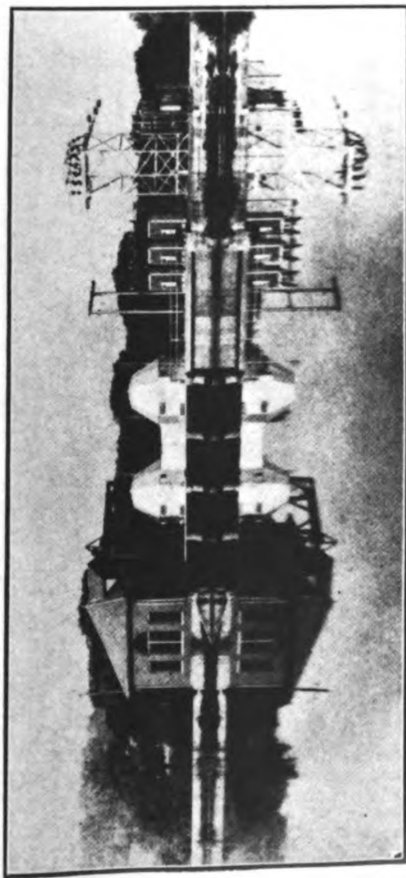
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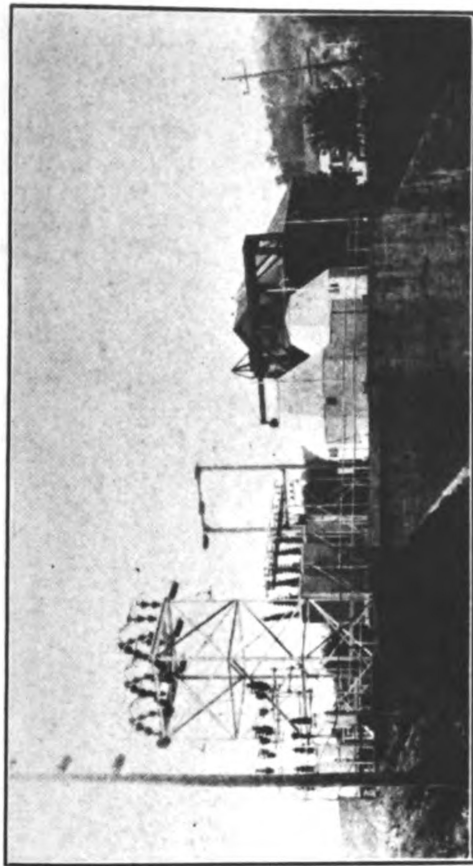
the building has been dispensed with and protection only provided over the generators. These generator covers are removable and gantry cranes are provided for installing and maintaining the equipment. A plant of this type with siphon settings was installed at Otsego, Michigan in 1925 (Plate No. 21). It is not always practical to dispense with the building for low-head hydro plants but any savings made possible by reduction of the space necessary will tend to reduce the plant investment. While the building of larger and higher speed turbines has had a tendency to expand the size of the plant somewhat in its dimension from intake to discharge, the reduction in generator diameters due to increased speed has reduced the width of power house necessary to house the generators.

In the past some plants have been built to include inside the building not only the generator room but also the rack structure and raking platform. This is not a common practice however. In the more modern plants the generating room is designed to cover only the generators and auxiliaries. The switchboard, transformers, and the other equipment being placed in a separate room built either at one end or as a wing to the main plant. Crane clearances usually control the height of the power house although other considerations such as appearance or materials available may enter into the design. It is evident that generators of large diameter with large rotors will require wide power house super-

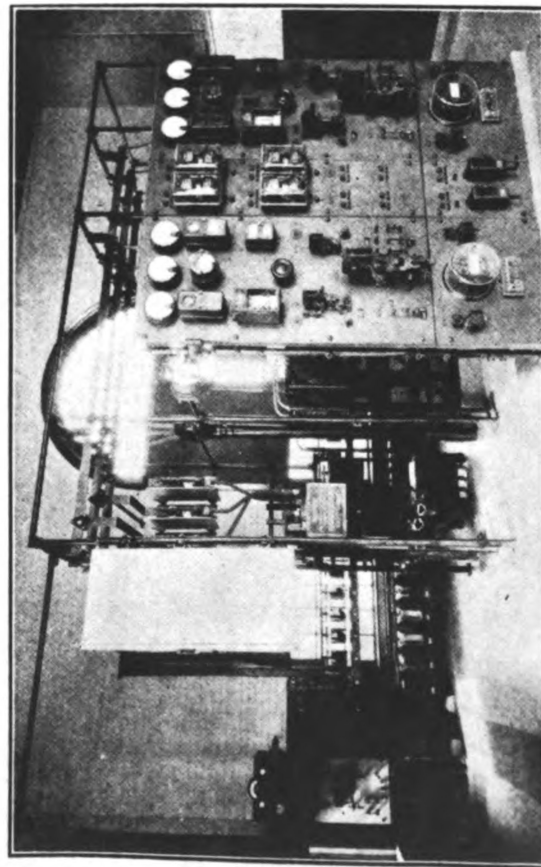
VIEWS OF AUTOMATIC HYDRO ELECTRIC GENERATING STATIONS



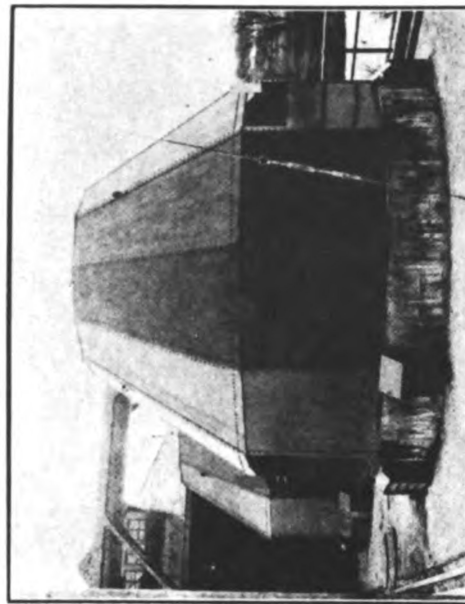
Otsego Automatic Hydraulic Station view from upstream



Otsego Automatic Hydraulic Station. View from Downstream



Otsego Automatic Hydraulic Station. View of Switchboard.



The Otsego Penstock Deck Showing Steel Houses over Generators.

structures and that high speed units of much smaller diameter will require somewhat smaller buildings.

At the Sterling plant the generators have a diameter of 18 feet 9 $\frac{1}{2}$ inches. The power house superstructure is 35 feet wide.

At the Dixon plant the generators are 15 feet 4 inches in diameter and the power house is 32 feet wide. Such relative small savings may not seem important especially when the floor area per h.p. installed is almost the same for both plants. Savings other than brickwork and concrete are involved in this reduction in width of the plant. The roof trusses being almost 10 % shorter will be lighter and cost less and the span of the traveling crane being less its cost will also be reduced. Architectural considerations may determine the type of building to be built if it is in a town or city and usually the low-head plants that are redevelopments of former mill sites are in such locations. The savings possible by shorter spans over the generating room made possible by smaller diameter generators are of real value, however, and regardless of the type or kind of the exterior superstructure, help to keep down the costs of the low-head power development.

It must be remembered that these savings and reductions in plant costs are the direct result of utilizing higher speed turbines of larger capacities than were possible 15 or 20 years ago and that their use

in the low-head power plant today is only possible by use of siphon settings. This principle makes possible their installation above tail water level without loss of power due to lack of submergence. The questions of lower cost and increased economy of design of hydro-electric plants are becoming increasingly important as steam plant efficiencies increase and power costs decrease. Since the cost of the building in which the plant is housed and the cost of the equipment used are a major part of the investment any savings in these items will have its effect on the cost per kilowatt hour of the power produced.

Reduction in Investment by a Reduction in Construction Costs.

The planning of the construction of a hydro-electric plant must be more carefully worked out than for most building structures if real economy is to be effected. The fact that the substructure work is always done within cofferdams, a feature which involves special hazards, and the necessity for considerable excavation in solid rock for water passages, makes it necessary to plan the structure with special consideration of these construction details. Low-head plants are usually built on streams where the slope of the river is not great but sudden floods even on these streams are a constant menace and may do considerable damage in the destruction of completed work as well as delaying the completion of the plant. Any saving in excavation, cost of cofferdams, or reduction in time required for construction will have an effect on the investment in the plant and lack of careful planning of these items may increase the cost to a point where it is impossible to earn a fair return on the investment in competition with other sources of power.

One of the advantages claimed for the turbine when it was first introduced was that it could be operated entirely submerged. This is a distinct advantage especially in times of high water when the tail water may often rise to levels well above the normal turbine setting. In normal times however, when it may be neces-

sary to do maintenance work on the runner there is a considerable advantage in locating the runner well above the normal tailwater elevation. The area beneath the turbine is known as the draft pit and into this area must be discharged all the water which passes through the turbine. The early turbines of low specific speed absorbed most of the energy of the water as it passed through the runner and the discharge velocity was not high. As turbine speeds increased and the runner was placed at higher elevations above the tail water it was necessary to provide a connection between the turbine and the draft pit which would aid in the complete utilization of the energy in the water. The draft tube was next added to the turbine to meet this need.

The draft tube serves two purposes. The first of these is to maintain at the discharge of the runner passages a suction action equivalent to the difference in elevation between the runner and the level of the tail water thereby providing for the use of the total head. The second purpose is to transform the velocity head in the water as it is discharged from the runner into pressure head by the time the water reaches the end of the draft tube and thus maintain at the discharge of the runner a suction action equivalent to at least a portion of the velocity head available in the discharged water. This later purpose is accomplished in the draft tube by a gradual increase in the cross-sectional area

and a consequent decrease in water velocity as the water passes from the top to the bottom of the tube. The early tubes used were short conical sections of doubtful value as velocity head regainers but serving very well as suction tubes to permit the use of the entire head of water. Prasil, an experimenter of Switzerland, worked on this problem of the draft tube and as a result of his investigations he developed a tube with a flare at the bottom in which the change in the velocity of the water was constant for each unit of length or in other words the velocity variation was a straight line function. The form of the curve for the sides of the tube was that of a hyperbola which is asymptotic to the plane of the bottom of the draft pit. For reasons of simplicity and cheapness however, the hyperbolic draft tube was not often used and the truncated cone made from cast iron or steel plate was generally furnished as the standard draft tube. Various relations of diameter to length of tube have been used. Experiments by Venturi showed that for diverging tubes a maximum discharge was obtained when the length was 9 times the smallest diameter and the divergence or flare was equal to 5 degrees. The National Electric Light Association has suggested that for the purpose of testing model draft tubes a standard reference tube be used, the length of which is 5 times the diameter and the flare 5 degrees. Some tests have been made where reference tubes have been used and in these tests publish-

ed by the N. E. L. A. the straight conical tube gives the best results when compared to other forms of draft tubes.

It can readily be seen that for the larger sized turbines such a draft tube would have considerable length. The logical reason for not using the long straight conical tube is found of course in the excessive excavation that would be required in vertical plants. To overcome this objection engineers a few years ago attempted to make use of the conical tube by bending or turning it through a 90 degree angle and discharging the water downstream instead of against the bottom of the draft pit. The fallacy in this design lay in the fact that the water would not follow around this bend in parallel elements. Where the bends were short the draft tubes were not very effective. Where longer sections, which continued to flare after the bend was made, were used a reasonable draft tube action resulted. Elbow draft tubes have been considerably improved and are used today with very satisfactory results when properly designed.

In May 1921 Mr. W. M. White presented before a meeting of the American Society of Mechanical Engineers a paper entitled "The Hydraucone Regainer, Its Development and Applications in Hydro-Electric Plants". This paper brought out considerable discussion as there was at that time, and still exists, some conflict of opinion as to the relative merits of this and a similar type of

draft tube known as the Moody Spreading Tube or Whirl Regainer. Both of these tubes however, were developed to meet the conditions of the high specific speed turbine which discharges the water from the runner at a much higher velocity than the lower specific speed turbines. These draft tubes were of especial interest to designers of low-head plants as the depth of draft pit below the runner was considerably reduced by these designs. Their use permitted the placing of the turbine runners well above tailwater level and when used with plants having siphon settings the necessary excavation was reduced by a considerable amount.

An examination of the illustrations of some of the typical plants which are included in this thesis will show just how this saving has been effected in these low head plants. At the Edison Sault Electric plant (Plate No. 4), which was the first plant to have a single runner direct connected unit, one of the elbow type draft tubes was used. The runner diameter was 71 inches and the lowest excavation was 20 feet below the centerline of the runner. The ratio of depth to the diameter of the runner in this plant is nearly 3.4. At the Sterling plant (Plate No. 5) the lowest point of the excavation is $25\frac{1}{2}$ feet below the centerline of the runner and the ratio of the depth to the diameter of the runner is 2.5.

Two plants built almost at the same time with

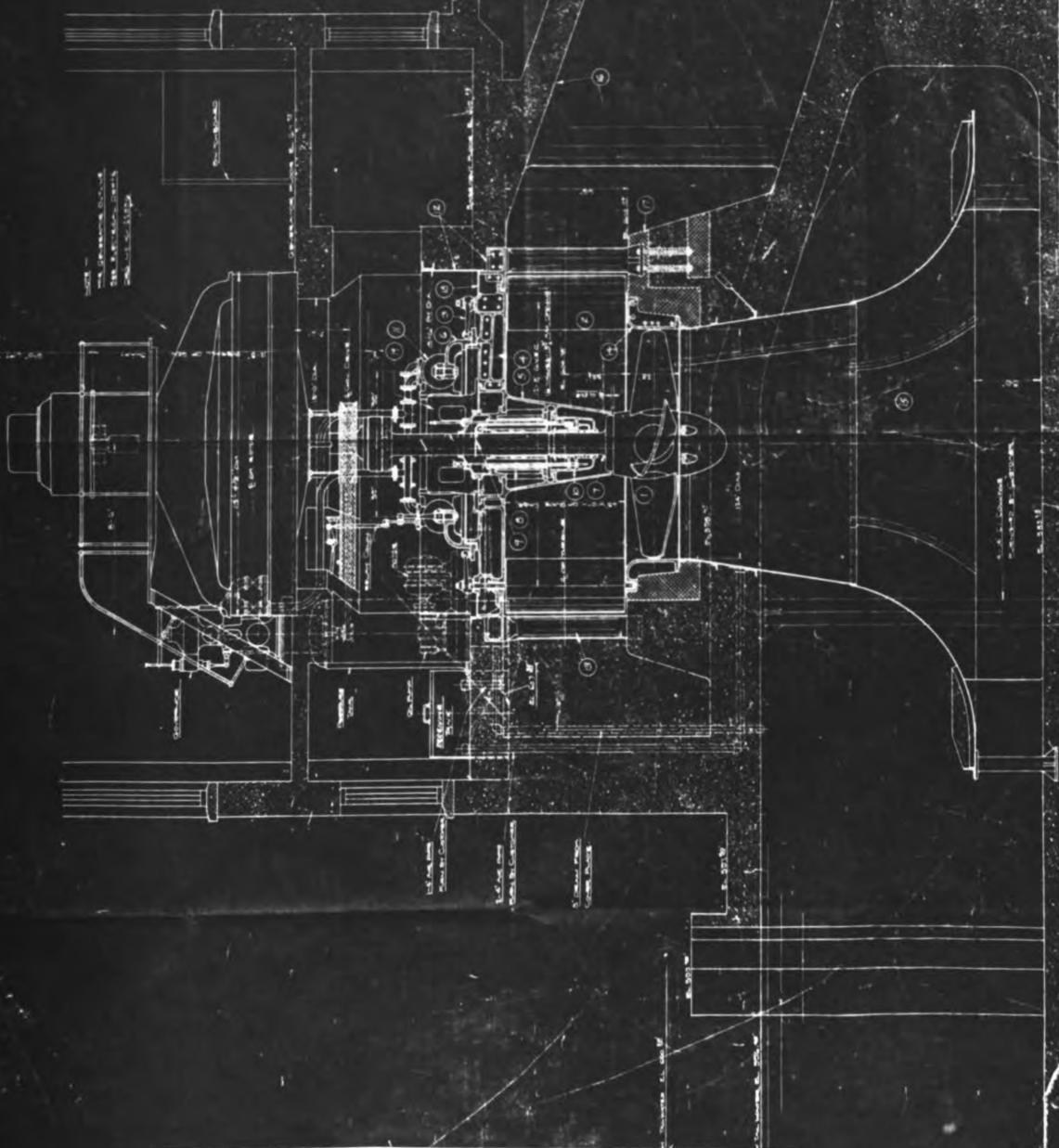
siphon settings and with units of about equal capacities are the plants at Dixon, Illinois on the Rock River and at Appleton, Wisconsin on the Lower Fox River. The former has a Moody Spreading type of draft tube (see Plate No. 14) while the later has a hydraucone type of draft tube (see Plate No. 22). The Dixon units are 125 inches in diameter and the Appleton units are 124 inches. The operating heads are about the same. The units with Moody spreading draft tubes have the lowest excavation 21 feet below the centerline of the units and the ratio of depth to the runner diameter is 2.02. The runners with hydraucone draft tubes are set 2 feet higher than the ones at Dixon and the lowest excavation is $21\frac{1}{2}$ feet below the centerline of the unit. The ratio of depth to the runner diameter is 2.08. Because of the lower setting of the units at the Dixon plant the excavations are about $1\frac{1}{2}$ feet deeper than at Appleton.

Looking at the above types of drafts tubes from the construction angle any reduction in depth of excavation such as is possible with either of these types of draft tubes is certainly a valuable consideration. Deep excavations are not only very expensive but the element of risk is always that much greater. The improved elbow type tubes also effect savings in excavation and do not require as wide a draft tube discharge as do the concentric type of tubes. At Rockton, Illinois (Plate No. 20) the unit is about 110 inches in diameter

Plate No. 22

DATA

EFF. HEAD	— 8½ FT.
CAPACITY	— 800 HP.
SPEED	— 90 RPM.



Cross-section of the plant at
Appleton, Wisconsin.

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and the lowest excavation is 2.45 times the diameter below the centerline of the runner. Because of the somewhat higher head at this plant a higher setting was effected so that the depth of excavation below tail water was about equal to that at plants mentioned above.

While designing engineers have improved the draft tubes to be used with the high specific speed runner so as to reduce the excavation necessary for the larger units these savings would be of little value for low-head plants were it not for the still further saving of placing the turbine higher which is made possible by the use of siphon settings. Without siphon settings the turbines for the three plants at Appleton, Rockton, and Dixon which have modern draft tubes of different types, would have to be lowered a distance at least equal to their diameter if a reasonable submergence in an open pit were to be obtained. This would add at least 700 cubic yards of excavation per unit at the Dixon and Appleton plants and at Rockton the excavation would be increased by about 550 cubic yards. The values given are for plant foundations only and the ramp necessary downstream from the draft tube exit would involve a quantity of excavation equal to if not greater than the extra required for foundations. From the above data it can be seen that the savings possible in excavation alone by the higher setting of the turbine is enough to make a considerable difference in the construction cost

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of a low-head hydro-electric power plant.

It is true that by the use of smaller units the depth of excavation could be materially reduced but as has already been pointed out this would require a larger number of units which would add to the cost as well as extend the excavation over a wider area. This might involve an even greater yardage of excavation.

In making the estimates for any particular hydro-electric plant the engineer must consider all costs in order to arrive at a complete economical design. To purchase machinery of smaller capacity to save expense of siphon flumes and deep excavation only to spend the possible savings in additional units to be installed in a longer power house involving an even larger quantity of excavation for foundations would hardly be considered true economy. The trend of the designs for hydro-electric plants is toward the installation of fewer units of larger capacity placed well above tail water to reduce the draft tube excavations to a minimum. The maximum height to which the turbine can be raised above the tail water level is determined by the draft head. High draft tube vacuum induced by high settings in higher head plants has caused some trouble with pitting of turbine runners but so far as the writer has been able to learn these troubles have not occurred in low-head plants with high specific speed runners in siphon settings. In this country there has been no attempt to

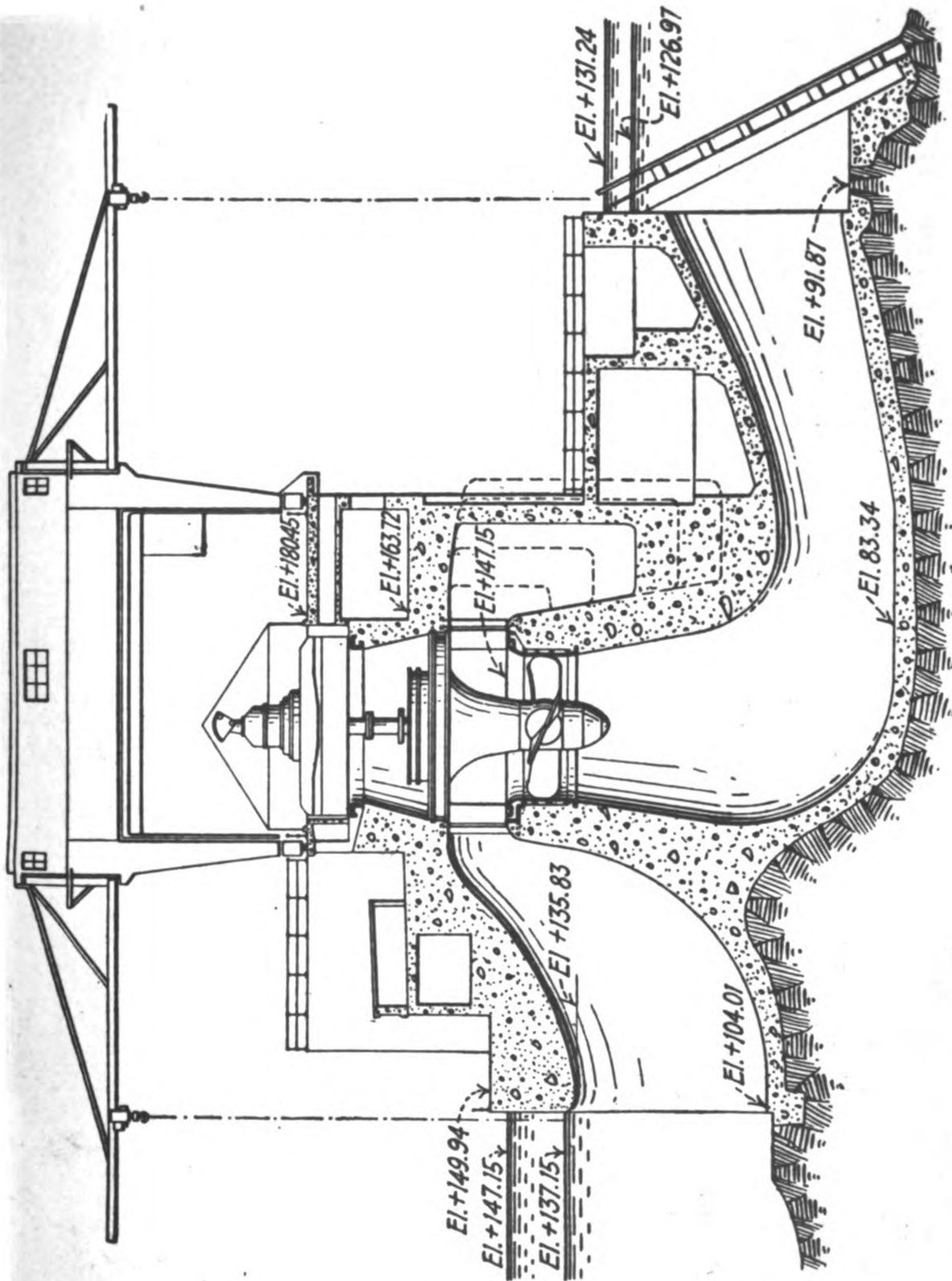
raise the runner above tailwater level by any considerable amount. The Green Island development with 2000 h.p. turbines has the runners about 10 feet above tailwater level and this is about the maximum in this country for plants with siphon settings.

There is at the present time under construction at Vargon, Sweden a plant of very large capacity in which the siphon setting principle is being used to effect considerable savings in excavation by the setting of the turbine even above the head water elevation. The head on this plant is 14 feet and Kaplan turbines 26 feet 3 inches in diameter are being used. Due to the extremely large size of these runners the lowest point of excavation for the elbow draft tubes is about 65 feet below the turbine and even with a turbine setting nearly twenty feet above low tailwater the excavations will extend to a considerable depth. Such an installation would be impossible without a siphon setting. Plate No. 23 which is reproduced from Power of September 8, 1931 shows a cross-section of this plant and in the article describing it the following paragraph appears:

"Several advantages are cited for this unique installation. Placing the turbines above the head-water level will eliminate the necessity for sluice-gates at the entrances to the scrolls and will materially reduce the cost of excavation. Furthermore it makes the development of very low-head falls economically possible."

One of the main items of expense in hydro-electric power plant construction is that for cofferdams.

Plate No. 23



Cross-section of turbine installation in Vargon plant

Cross-section of the plant under construction at Vargon, Sweden.

We have seen in the previous pages that the concentration of the plant capacity in fewer units has resulted in a saving in cost of excavation. As practically all of the excavation for powerhouse foundations must be made within cofferdams it can be shown that a reduction in the amount of excavation will result in a saving in the cost of the cofferdams. Each power site is a special problem and there may be cases where little or no savings can be made in the cost of the cofferdam by reason of reduced length of power house. It may also be true that a type of cofferdam which would be practical for the construction of a long power plant with 8 or 10 units would be entirely impractical for the construction of a plant in which an equivalent capacity was developed with three units of large diameter and an entirely different type of cofferdam construction costing more money might have to be employed. In general, however, a reduction in power house area does result in reduced cofferdam expense.

To maintain the average velocity at the intake of the plant at a value low enough to prevent undue loss in the flume requires a large area of intake. As the size of units is increased with the use of the siphon setting the depth of water also can be increased. This increased depth results in a reduced total flume width. At the Dixon plant the depth of water below the entrance lip is 13 feet while the depth of water at the plant at Sterling is only 10 feet. At Oregon, Illinois with

still smaller turbines the flume depth is only 8 feet. At Dixon the total intake area is a little over 2500 sq. ft. Had the plant been developed with units of the size of the Oregon units and the same intake area maintained the power house would have been nearly 40 percent longer. Had units of the size of the Sterling units been used and flumes 10 feet deep installed the plant would have been 15 to 20 percent longer. The length of the powerhouse at Dixon was largely determined by the draft tube width. With the elbow type draft tubes a somewhat shorter plant is possible because of the relatively narrower draft tube design.

Many examples such as the above might be cited to show that the modern plant with a siphon setting does require less cofferdams due to the shorter power house, for a given capacity. This saving in cofferdams may amount to a considerable sum on a large project and this is especially true where units the size of these at Vargon are installed. Where the plant and dam are built at the same time the savings may not be as much as the plant foundations usually form a part of the dam, but where the plant is a redevelopment at an existing dam the saving in the size of the cofferdams may be considerable and may also result in still other savings in construction cost in addition to the direct savings in the cofferdam.

Time is an important element in power plant

construction. Every river is subject to seasonal floods and construction work that extends through this period of high water is accompanied with additional risk as well as additional expense. A wise contractor will include in his bid a liberal sum for such contingences. If the work can be so planned that the time necessary for the construction can be materially shortened the risk is reduced and a considerable saving results. There will be not only a saving in direct cost but the item of interest on idle investment during construction is usually a large one and considerable savings may be made by so planning the project that a minimum of time will elapse between the starting of the work and the placing of the plant in operation. At the Dixon plant construction was started in July 1924 and nine months later on March 24th, 1925 the first unit was placed in operation. The entire project was completed in about 11 months and this short construction period resulted in a saving of nearly \$9500.00 in interest during construction which is about 52 percent of the total amount estimated for this item.

In planning the construction of a hydro-electric plant it is well to so schedule the work that the period of construction will not extend over the spring flood season and if this is impossible to include in the construction period as few flood seasons as possible. It is expected that in the construction of the Hoover Dam,

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at Black Canyon on the Colorado River, the cofferdams will be overtopped at least five times and they must be constructed so as to withstand this flooding. The usual construction period for low-head hydro plants is not as long and will seldom include more than one flood season. With the shortening of the construction period possible by means of modern power plant design involving fewer units of large capacity it is even possible to complete the underwater work in those months which come between the usual spring flood periods as was done at the Dixon plant. Even with such planning there is still a risk involved and further savings in time will reduce the construction risks and save expense. At the Dixon plant the cofferdams were overtopped twice in August and September when usually the river was at its lowest stage and an early spring breakup in 1925 delayed the erection of the turbines nearly a month. Such contingences cannot be foreseen but expenses which result from these acts of nature can be reduced by shortening the period of time over which the work extends.

It has been shown that with the siphon setting larger capacity units can be installed. These units can be built at the factory in less time than a larger number of smaller units and also can be assembled in the field in less time. The reduction in the size of the powerhouse required also helps to shorten the construction period. The reduction in excavation and the fact

that somewhat smaller cofferdams are required for the plants with large capacity units in siphon settings also help to reduce the construction period. The savings possible in reduced risk and in the interest on the idle investment made possible by a shorter construction period are sufficient to make a considerable reduction in the investment necessary for a low-head hydro-electric plant.

Reduction in Power Costs by Reduction in Operating Expenses

Previously we have discussed the effect on the plant investment by the use of large capacity units in siphon settings for low-head power plants. Because of the large investment required for hydro-electric plants the annual fixed charges per h.p. are high and any reduction that is possible in the investment required will affect materially the cost of the power which is produced by the plant. The term "fixed charges" is applied to those costs which remain constant or practically so during the life of the plant and they include such items as interest on the investment, depreciation reserve, taxes, and insurance. Operating expenses are made up of labor, supplies, maintenance of building and machinery, management, etc. Operating expenses in a high-head plant are relatively small in comparison to the fixed charges but in plants with low heads they are a relatively large proportion of the total power cost. It has been shown above that the application of the principle of the siphon setting has reduced the investment and consequently the fixed charges for low-head hydro-electric plants. In plants where this principle has been used operating costs have also been reduced either by a reduction in the number of operators required or by their elimination altogether by the installation of automatic equipment. Maintenance costs are reduced because of the fewer moving

parts which wear out and require replacement in the larger capacity units.

The number of operators required or the possibility of reducing the operating force by installing automatic equipment may depend largely on the location of the plant and plan of operation. A plant removed from a town or city will require operators quarters if manually controlled which adds to the investment and in such a case automatic control will save this investment. The investment necessary for the automatic features is usually less per unit than the cost of the house for an operator and the cost of at least part of the labor is saved. A plant located in a town or city where operators quarters would not be required may have distribution circuits running from it that makes it necessary to have manual operation so direct comparisons are not possible unless conditions are identical.

The plants on the Rock River in Illinois operated by the Illinois Northern Utilities Company are located in towns and distribution from these plants makes it necessary to have operators on duty at all times and for this reason automatic control is not practical. These plants range in capacity from 575 K.W. to 2800 K.W. They include plants of the old type with bevel mortise gear drives, vertical direct connected units without siphon settings and vertical direct connected units in siphon settings. Operating experience with these plants has demonstrated the economic value

of the siphon setting type of plant as far as operating costs are concerned. The old geared type of plants could never be converted to automatic control as they require constant supervision by the operators and constant maintenance. Costs are high in these plants partially because of their small size but even if the size of the plants were to be increased to equal that at Dixon their operating costs would be higher than at the Dixon plant. The plant at the Government dam at Sterling with vertical direct connected units requires fewer operators per unit of capacity than the geared type of plant and the operating costs are lower. This is due to larger capacity of the direct connected units. At the Dixon plant with its siphon settings the number of operators required per unit of capacity is still further reduced. The old geared type of plants require one operator for each 175 K.W. of capacity. The plant at Sterling require an operator for each 300 K.W. of capacity and at the Dixon plant there is one operator for each 400 K.W. of capacity.

The savings in operating costs and the economy of the Dixon hydro plant can best be shown by comparing operating costs of the hydro plants with steam plant costs on the same system. The operating costs in the steam generating plant in 1921 are taken as the basis of comparison. There has been a steady decline in these costs during the past ten years due to plant improvements which have increased the efficiency of the steam generat-

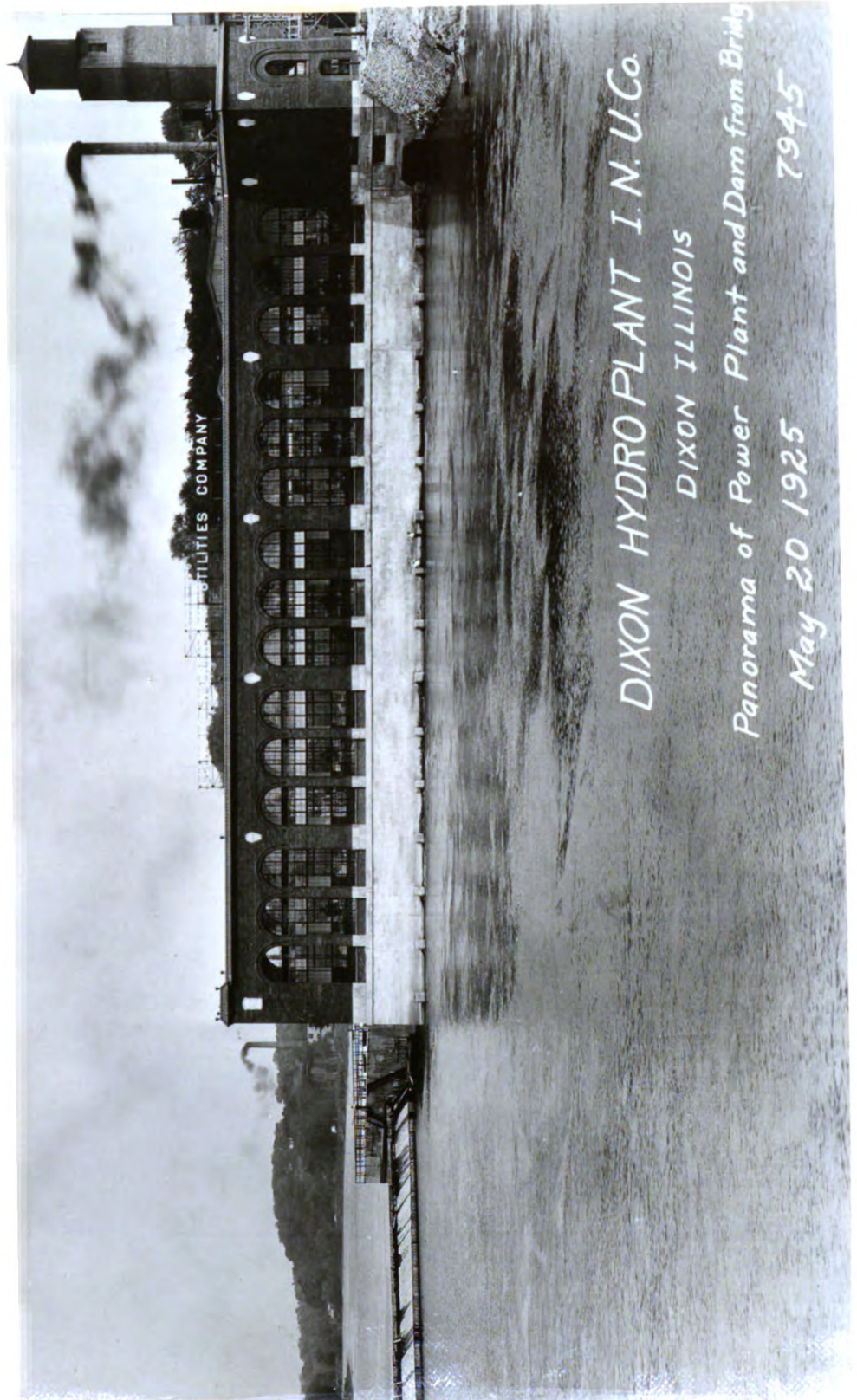
ing station. In 1931 the operating costs at the steam generating plant which now has triple the capacity it had in 1921 has been reduced to 42 % of the 1921 costs. The average operating costs in the geared type of plants in 1921 were about 50 % of the steam plant costs and these costs have been reduced in 1931 to about 28 %. The costs in the plant at Sterling with vertical direct connected units were about 13 % of steam plant costs in 1921 and they have remained practically constant during the past 10 years. The 1931 costs at the Dixon plant with siphon settings were about 11 % of 1921 steam plant costs and this in spite of the fact that the production was at least 20 % below normal due to the drought. The economy of operation in a modern hydro-electric plant is obtained by the reduced plant forces required where the power is concentrated in fewer units of larger capacity. An interior view of the Dixon hydro plant is shown on Plate No. 24 and when this view is compared with Plant No. 1 which shows the interior of a plant with gear drive some idea can be obtained of the relative simplicity of the modern plant. Plate No. 25 which is an exterior view of the Dixon plant shows how the appearance of the modern plant has been improved at only a moderate expense per kilowatt of capacity. At this plant seven men operating on 10 hour shifts are able to take care of all electrical operations both for the plant and the distribution system running from the plant. This force also takes care of

Plate No. 24



DIXON HYDRO PLANT I.N.U.
DIXON ILLINOIS

Interior view of hydro plant at
Dixon, Illinois.



Exterior View of hydro plant at
Dixon, Illinois.

all necessary maintenance, cleans trash racks, scrubs and cleans the building regularly and takes care of the yards and grounds about the plant.

The reduction in the number of units required for an installation when siphon settings are used for low-head hydro-electric plants reduces the automatic equipment required and the economies possible by its use will reduce the operating costs at these plants. The plant of the Consumers Power Company near Otsego, Michigan (see Plate No. 21) is an example of such a plant and cost data for this installation showing the savings made is available. This plant is located on the Kalamazoo River and only 5 miles from the first modern plant with siphon setting at Plainwell, Michigan. The original installation at Otsego contained 8 turbines, 56 inches in diameter which were connected through gears to a 1500 K.W. generator. The new installation contains two direct connected units with 110" diameter turbines and the combined capacity of the two generators is 1700 K.W. This new plant was built in 1925. Construction was started in May 1925 and completed in November of the same year. This plant has complete automatic operation and the following extract from an article appearing in the Au Sable News shows the savings that are possible in the operating costs of low-head hydro-electric plants.

"Because the Otsego automatic hydro station is operated in the same manner as when under manual control, namely, as a run of river plant, the kilowatt hour outputs of the old and new in-

stallation are comparable. In 1926 and 1927 the outputs were 8,947,120 and 8,161,200 kilowatt hours respectively, while in 1928 the output was 8,924,600 kilowatt hours. These years have, however, been abnormal water years and the above figures cannot be taken as a true criterion of normal output. Another plant on the same river had increased outputs of 23.6 percent for 1926 and 11.6 percent for 1927. Applying these percentages, and taking into account normally spilled water at the other plant which would be fully utilized at Otsego, the normal output of the Otsego plant under the new conditions is about 7,600,000 kilowatt hours. This is an increase of about 2,830,000 kilowatt hours, or 830,000 kilowatt hours more than the estimate made for the original proposal.

Labor cost has been reduced approximately two-thirds by the installation of automatic equipment. The new construction has done away with much of the maintenance costs heretofore taken into consideration. Operation and maintenance costs were reduced from .25 cents per kilowatt hour in 1924 to .048 cents per kilowatt hour in 1928.

Manual control required the time of two and one-third operators as well as the use of two houses. Automatic equipment cut this to one man and one house with an annual saving of \$2,660.00. The extra equipment demanded by automatic control cost approximately \$6,500.00, which at 7 % interest results in an annual charge of \$445.00. Annual net operating savings, therefore, are \$2,205.00.

Operating costs have been reduced over 50 % by the whole development. The total costs in 1928 were \$4,230.00 as against \$10,970.00 in 1924. The saving, then, is \$6,690.00, of which \$2,200.00 is directly apportioned to automatic equipment. The remaining \$4,690.00 has been saved through reduced maintenance made possible with the modern, up-to-date equipment."

The above article clearly states the savings that were made at the Otsego plant. This plant is automatically controlled, a feature which would have been impossible in the plant which preceded it. The modern-

ization of low-head hydro-electric plants which has been taking place during the past 10 years has been entirely due to the demands for lower cost electric current. As was pointed out above the cost of steam generated current has been steadily reducing and to keep pace with this tendency it has been necessary to also seek means of reducing the cost of hydro generated current. As a measure of economy in some plants it has been necessary to utilize automatic control to save labor expense. This feature is estimated to have saved over \$2,000.00 annually at the Otsego plant. An even greater saving, however, was made in the cost of power at this plant by the reduced maintenance costs.

The old type turbines with bevel mortis gear drives seem always to be needing repair and modernization of these plants at once reduces the maintenance costs. At the hydro plant at Dixon which was removed to permit the building of the present plant the annual maintenance charges amounted to over five dollars per kilowatt of capacity. At the plants at Sterling and Oregon, Illinois where the older type small capacity units, we still operating, the maintenance charges average between four dollars and five dollars per kilowatt per year. The plant at the Government dam in Sterling was new in 1914 and because of its larger capacity direct connected units, the maintenance costs were considerably less than in the plants with gear

drives. During the past seven years, considerable deferred maintenance was completed the maintenance costs have averaged less than one dollar and twenty-five cents per kilowatt of capacity per year. At the Dixon plant which was new in 1925 these costs are even less than at the Sterling plant. In 1931 the annual maintenance charge was less than fifty cents per kilowatt of capacity.

If the fixtures were available for other plants which have been modernized with siphon setting installations there is no doubt that they would show like savings in maintenance expense. Operating companies with hydro-electric plants at low dams are not only reducing their operating expenses by building modern plants with siphon settings but the increased kilowatt hour output of these plants with increased capacities and improved efficiencies means a considerable reduction in the unit cost of the power produced. If the project has been carefully planned and the capacity properly proportioned for the water available the savings in cost of fuel alone will be ample to pay the fixed charges on the investment. Since it was built, the hydro plant at Dixon has produced on an average more than 12,000,000 kilowatt hours per year. At two pounds of coal per kilowatt hour this represents a saving annually of 12,000 tons of coal. This saving, based on the present day price of coal, has been sufficient to provide for the fixed charges on the plant. The total cost of current from this low-head

hydro plant has been low enough so that in competition with steam generated current there is a sufficient margin of cost in favor of the hydro plant to justify the investment as an economically sound one. Low-head hydro-electric plants usually lie on the border line between sound and unsound investments and it is necessary to take advantage of every means possible to effect economies in operating costs as well as in the plant investment. The siphon setting makes these economies possible by the utilization of larger capacity units which means less equipment to be maintained and operated for a given plant capacity.

Conclusions

The present day demands for low-cost power is bringing about the development of many power sites that could not be developed a few years ago because of the fact that there was no market close at hand. The network of interconnected transmission lines, which now forms a grid system over the eastern part of the United States at least and to some extent over the area west of the Mississippi River, has largely removed the problem of a ready market for power close at hand. Power is now generated at the mouth of the mine and transported over wires instead of in freight cars as coal. Power sites on our rivers far removed from centers of population are now being developed and the water power which once had to be used in a plant adjacent to the dam can now be carried by wire to cities or rural communities many miles away. Hydro-electric plants of larger and larger capacity are being built each year. No sooner is one large plant completed than another is started which eclipses it in size. The development of these large plants has demanded the best of engineering skill in the designing of the plants as well as the power plant equipment. For low-head installations the four greatest contributions to the art of hydro-electric power development in the past fifteen years have been as follows:-

First: The high specific speed or propeller type turbine which made possible the direct connected

type of unit operating at higher speeds than was possible with the Francis type turbine and this has made possible the use of higher-speed lower-cost generators.

Second: The hydraucone or spreading type of draft tube which reduced the cost of the excavation without impairing the turbine efficiency.

Third: The siphon setting which permitted taking full advantage of the modern draft tubes in saving excavation as well as the utilization of larger capacity units either partially or entirely placed above head water elevation.

Fourth: The adjustable blade runner which has made possible an increase in the horse power capacity for a given diameter as well as further increases in the specific speed, and high efficiency over a wide range of power output.

The above items are given in the order of their development and not in the order of their importance or value. While the siphon setting was used nearly 50 years ago its application to modern plants did not come until after the development of the propeller type turbine and the draft tube forms which are used with it. The siphon setting does not generate power nor does it increase the efficiency of the turbine with which it is used as does the draft tube. Its chief value in contrib-

uting to the improvement of power plant design lies in the fact that it makes possible the fullest use of modern type turbines at low-head sites without a serious loss in efficiency and that by its use there can be a considerable saving in the cost of low-head power plants.

The reduction in the investment is quite important as the fixed charges for a hydro plant are much larger than the operating expenses. Increases in the investment are justified if a sufficient reduction in operating expense results. The addition of automatic equipment does increase the investment but the saving in operating expenses more than offsets the fixed charges on this equipment. There may be some features of the siphon setting which involves some added expense but the savings on other items by its use far out weigh this extra investment. It has been pointed out above that by the use of this principle many savings in the investment are possible such as savings on turbines and generators by fewer units of larger capacity, reduced excavation by setting of the turbine at a higher elevation as well as other reductions in construction costs and as a result of the above savings the operating expenses have also been reduced. Low-head hydro-electric plants can only be justified so long as the total cost of current including fixed charges and operating expenses are kept at a minimum. The cost of current in competitive steam generating plants is reducing year by year. Any feature

of power plant construction which will aid in reducing the cost of hydro-electric current is a real contribution to the electric industry. The economic value of siphon settings for low-head hydro-electric power plants lies in the fact that they have made possible a reduction in plant investment and the fixed charges thereon as well as a reduction in operating expenses.

A P P E N D I C I E S

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APPENDIX NO. 1

The Economic Value of Siphon Settings for
Low - Head Hydro - Electric
Power Plants.

Outline of Thesis

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 - b. Modern type of plants.
 - c. Low head developments.
 1. Redevelopment of old sites.
 2. Development of new sites.

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 - b. Application of the principle of
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 - c. Value of the principle as used in
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 - b. Larger units are more efficient.
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 - c. Reduces construction period.
5. Reduction in power costs by reduction in operating expenses. 102
 - a. Fewer operators required.
 - b. Reduces maintenance costs.

Conclusions

- The application of the principle of the siphon setting for low-head hydro-electric power plants is economical because it makes possible.
- a. A reduction in fixed charges.
 - b. A reduction in operating costs.

APPENDIX NO. II

Hydro Electric Plants Using Siphon Settings

The following is a partial list of plants using siphon settings which have been installed during the past ten years. Their location is indicated on the map following.

Abbreviations of Manufacturers

A. C. M. Co. - Allis Chalmers Manufacturing Company.

S. M. S. Co. - S. Morgan Smith Company.

J. L. & Co. - James Leffel & Company.

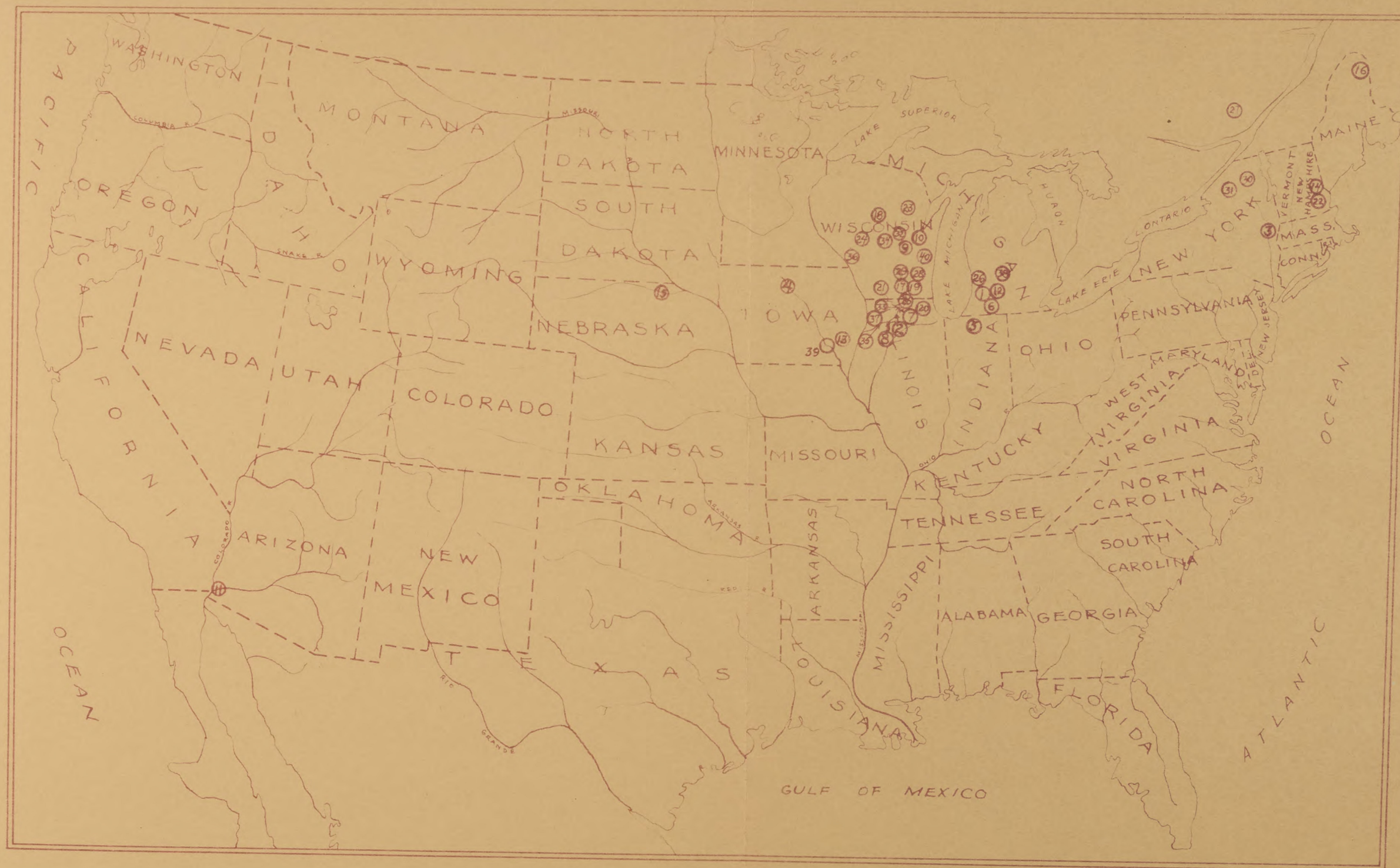
I. P. M. Co. - I. P. Morris Division
Baldwin-Southwark Corporation.

No.	Date	Company	Location	River
1.	1920	Consumers Power Co.	Plainwell, Michigan.	Kalamazoo
2.	1921	Illinois Northern Utilities Co.	Oregon, Ill.	Rock
3.	1921	Henry Ford & Son	Green Island, New York.	Hudson
4.	1921	Union Electric Co.	Humbolt, Ia.	Des Moines
5.	1922	Indiana & Michigan Electric Co.	Elkhart, Ind.	St. Joseph
6.	1922	Michigan Gas & Electric Co.	Constantine, Michigan.	Portage
7.	1923	Rockford Electric Co.	Rockford, Ill.	Rock
8.	1925	Illinois Northern Utilities Co.	Dixon, Ill.	Rock
9.	1925	Kimberly Clark Co.	Kimberly, Wis.	Lower Fox
10.	1925	Green Bay & Miss. Canal Co.	Appleton, Wis.	Lower Fox
11.	1925	U. S. Reclamation Service.	Yuma, Aris.	Gila
12.	1925	Consumers Power Co.	Otsego, Mich.	Kalamazoo
13.	1925	Iowa Electric Co.	Mt. Pleasant, Ia.	Skunk
14.	1926	Laconia Car Co.	Laconia, N. H.	Winnisquam
15.	1926	Nor. Nebr. Power Co.	Spencer, Nebr.	Nebraska

Turbine Manufacturer	Size in Horsepower	Head	Speed r.p.m.	Specific Speed	No. of Units
A. C. M. Co.	380	12.0	164	143	3
J. L. & Co.	199	7.0	80	100	1
A. C. M. Co.	2000	13.0	80	150	4
A. C. M. Co.	570	13.0	180	175	1
S. M. S. Co.	1900	18.0	120	Quadruplex Hor	1
S. M. S. Co.	302	12.0	100	77	1
A. C. M. Co.	750	9.0	100	175	2
I. P. M. Co.	800	8.0	80	175	5
A. C. M. Co.	900	9.0	94	180	3
A. C. M. Co.	1100	8.5	90	205	4
S. M. S. Co.	1160	14.0	112.5	140	2
S. M. S. Co.	1150	14.6	138.5	165	2
J. L. & Co.	415	12.0	164	148	1
	700	12.0	120	140	1
S. M. S. Co.	127	8.5	200	155	1
S. M. S. Co.	1520	15.0	120	157	2

No.	Date	Company	Location	River	Turbine Manufacturer	Size in Horsepower	Head	Speed r.p.m.	Specific Speed	Page No. 121 No. of Units
16.	1926	Caribou Water Lt. & Power Co.	Caribou, Maine	Aroostook	S. M. S. Co.	520	12.0	164	165	2
17.	1926	Wisconsin Power & Light Co.	Janesville, Wis.	Rock	A. C. M. Co.	240	8.5	150	160	2
18.	1927	Wausau Paper Mills	Brokaw, Wis.	Wisconsin	S. M. S. Co.	1400	17.5	100	105	1
19.	1927	Wisconsin Power & Light Co.	Janesville, Wis.	Rock	J. L. & Co.	384	9.0	120	150	2
20.	1927	Illinois Iron & Bolt Co.	Carpentersville, Ill.	Fox	S. M. S. Co.	230	7.0	64	85	1
21.	1927	Wisconsin Power & Light Co.	Blanchardville, Wis.	Pecatonica	J. L. & Co.	75	8.0	150	97	1
22.	1927	Public Service Co. of N. H.	Hookset, N. H.	Merrimac	I. P. M. Co.	2150	14.0	100	170	1
23.	1927	Wisconsin Power & Light Co.	Shawano, Wis.	Wolf	A. C. M. Co.	900	14.0	150	165	1
24.	1928	Wisconsin Power & Light Co.	Necedah, Wis.	Yellow	A. C. M. Co.	390	12.0	200	175	1
25.	1928	Wisconsin Power & Light Co.	Beloit, Wis.	Rock	A. C. M. Co.	550	9.0	109	165	1
26.	1928	Consumers Power Co.	Allegan, Mich.	Kalamazoo	S. M. S. Co.	730	11.5	128.5	165	1
27.	1928	Regent Knitting Mills	St. Jerome, Que.		S. M. S. Co.	600	14.0	164	148	1
28.	1928	Wisconsin Power & Light Co.	Indian Ford, Wis.	Rock	J. L. & Co.	281	6.0	90	160	2
29.	1928	Wisconsin Power & Light Co.	Fulton, Wis.	Yahara	J. L. & Co.	400	14.0	200	148	1
30.	1929	Malone Light & Power Co.	Hogansburg, New York.	St. Regis	S. M. S. Co.	754	11.0	100	135	1
31.	1929	St. Lawrence Valley Power Corp.	Potsdam, N. Y.	Raquette	I. P. M. Co.	1350	12.5	100	155	2
32.	1929	Wisconsin & Mich. Pr. Co.	Weyauwega, Wis.	Waupaca	A. C. M. Co.	600	12.0	150	165	1
33.	1930	Wisconsin Power & Light Co.	Rockton, Ill.	Rock	S. M. S. Co.	725 994	11.0 11.0	100 100	135 160	1 1
34.	1930	Wisconsin Power & Light Co.	Neshkoro, Wis.	White	S. M. S. Co.	150	12.0	150	80	1

<u>No.</u>	<u>Date</u>	<u>Company</u>	<u>Location</u>	<u>River</u>	<u>Turbine Manufacturer</u>	<u>Size in Horsepower</u>	<u>Head</u>	<u>Speed r.p.m.</u>	<u>Specific Speed</u>	<u>No. of Units</u>
35.	1930	Lawrence Bros. Mfg. Co.	Sterling, Ill.	Rock	J. L. & Co.	366	8.0	120	170	1
36.	1930	Neshonic Light & Power Co.	West Salem, Wis.	LaCrosse	J. L. & Co.	170	8.0	138.5	135	1
37.	1930	Illinois Northern Utilities Co.	Sterling, Ill.	Rock	A. C. M. Co.	450	9.0	128.5	175	1
38.	1931	Village of Portland	Portland, Mich.	Grand	J. L. & Co.	200 400	11.0 11.0	200 138.5	140 138.	1 1
39.	1931	City of Ottumwa	Ottumwa, Ia.	Des Moines	A. C. M. Co.	1400	12.25	112.5	170	2
40.	1932	Patten Paper Co.	Appleton, Wis.	Lower Fox	A. C. M. Co.	<u>950</u>	11.0	112.5	175	<u>1</u>
						55,147				67



Map of
THE UNITED STATES SHOWING LOCATION
OF PRINCIPAL HYDRO ELECTRIC POWER
PLANTS USING SIPHON SETTINGS.

APPENDIX NO. III

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APPENDIX NO. IV

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