Development of the Kaplan Turbine

by Hans G. Hansson

Mr. Hans G. Hansson, Chief Engineer of Karlstads Mekaniska Werkstad Kristinehamn Works, presents a chapter of hydro-electric engineering history with important contributions by Swedish engineers.

Water power today represents approximately 70 per cent of Sweden's electric power production and thus constitutes the safe basis for this important part of our energy supply. In most of the larger hydro power stations with heads below 50 meters the generators are driven by Kaplan turbines, which have proven to be superior to alternative types of turbines both from technical and economical points of view. Almost all of these turbines have been manufactured in Sweden. The first Kaplan turbines have now been in operation for more than 50 years and it may therefore be of interest to review the early history of this interesting machine and the main features of the technical development, which followed and to which Swedish engineers and Swedish industry made important contributions which have won recognition all over the world.

The first water turbines were, as their predecessors in the form of water wheels of different kinds, used for the direct driving of different kinds of machines, flourmills, sawmills, mining hoists, pumps, forge hammers etc. For this kind of operation it was generally no drawback but rather an advantage to have a prime mover with low speed. The introduction of electric power at the end of the 19th century meant that an increasing number of water turbines were installed for direct connection to electric generators, causing new requirements on the basic turbine characteristics. Besides increased efficiencies, higher speeds were wanted to match the new generator designs. The individual units were growing in size and especially at lower heads this led to certain design problems. What everybody was looking for was turbines with a higher specific speed which would, for given main data of head and power, result in smaller dimensions of the turbine proper and its waterways as well as the generators. Thereby it would be possible to reduce the investment cost per installed kilowatt.

Because the *specific speed* is a conception of basic importance for the correct understanding of the relationships here discussed, a brief definition and explanation is given as follows.

The specific speed n_s of a given turbine, operating under H meters head, and developing at its optimum speed of n rpm a nominal output of N metric horsepowers is the speed of a homologous turbine (unity turbine) so dimensioned as to give under 1 meter head and similar flow conditions an output of 1 horsepower. The mathematical expression for specific speed is

Viktor Kaplan, born 27th Nov. 1876 (Picture from around 1930)

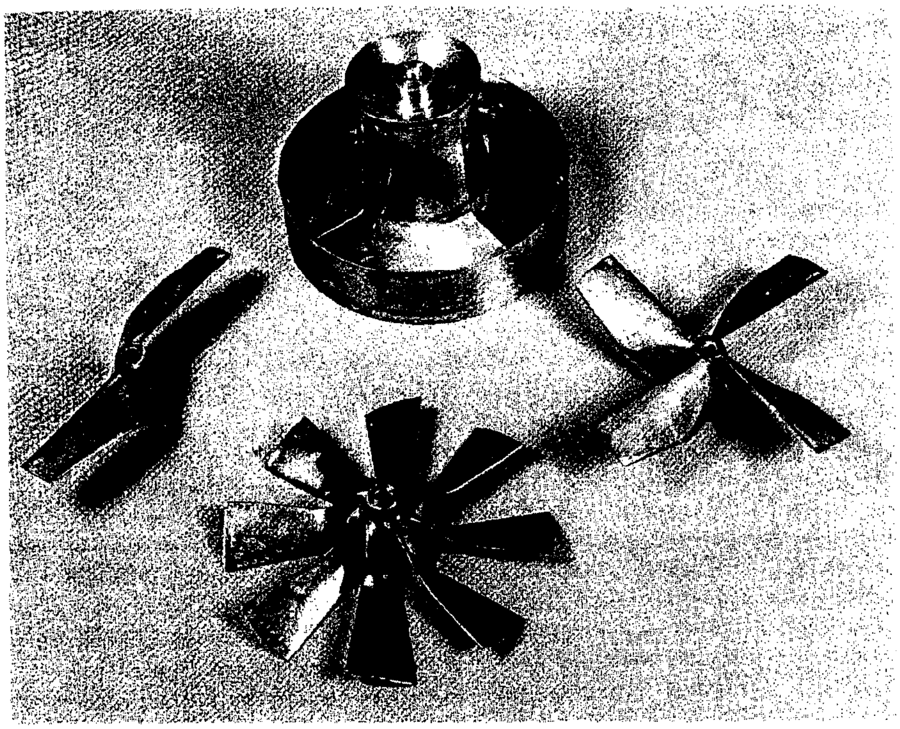
$$n_s = n \cdot N^{0.5} \cdot H^{-1.25}$$

A comparative analysis of a series of unity turbines will demonstrate that increasing specific speed is associated with generally reduced dimensions and increasing flow velocities. This affects essential design parameters and special attention must be paid to friction losses in the runner and kinetic outlet losses. Cavitation becomes a matter of importance.

Competition between the turbine builders around the turn of the century therefore essentially took the form of a contest between their design engineers, who were challenged with the task of developing new types of runners with higher specific speeds. Most efforts were devoted to improving the Francis turbine, which was at this time the generally adopted type. To further this development the more advanced manufacturers started systematic model testing. This was also the case with the three leading Swedish firms Verkstaden, Kristinehamn (KMW), Nydqvist & Holm (BOFORS-NOHAB) and Finshyttans Bruk, who all built new testing stations. The equipment and general layout of these facilities was of course rather primitive according to present standards, but offered satisfactory means for selecting the best designs and establishing their main characteristics. Soon specific speeds of 340 at an efficiency of about 85 per cent were reported. Some years later values of n_s equal to 450 or slightly above were achieved, but then the efficiency level came down to about 75 per cent with a very sharp peak of the curve, meaning that economic operation wold be restricted to a narrow band of output variation. It might be said that this was the price that had to be paid for the higher specific speed. During a period this problem was partly solved by the adoption of multiple runner turbines, meaning that two or more runners of moderate specific speed were coupled to the same shaft driving one and the same generator. The speed was thus increased to the benefit of a smaller generator, but the turbine was more complicated and expensive with requirements for larger space, reflected on civil constructions. Only partial progress could thus be achieved in this way.

Amongst those specialists, devoting their skill and efforts to solving the technical problems here discussed, was the Austrian engineer *Viktor Kaplan* (born in Mürzzuschlag, Steiermark 27th Nov. 1876 died 23rd Aug. 1934). He worked as an assistant professor at the Technical University of Brünn (now Brno in Czechoslovakia). Kaplan specialized on the design of water turbines. He worked out and published a new theoretical analysis of the hydraulic design of the high specific speed francis turbine and designed new runners, which he tested in a small and rather primitive laboratory, arranged in the cellar of one of the university buildings. He obviously was an ingenious research engineer with the exclusive ability of combining theory and simple but conclusive experiments in a very successful way.

Very soon Kaplan came to the conclusion that in order to make decisive progress towards higher specific speeds, it would be necessary to adopt radically new principles. After a few less successful attempts with extreme types of francis runners he finally turned over to runners of the propeller type with mainly axial flow, having a smaller number of relatively short blades. With such runners, installed in a model turbine with a normal radial-flow guide apparatus, he achieved specific speeds of 600—700. However, efficiencies were fairly low and the



Some of Viktor Kaplan's first experimental runners, demonstrating the step from mixed-flow to axial-flow layout.

curve showed a sharp peak. Now he got his revolutionary idea of making the blades movable in the central hub, thereby combining an unlimited number of propeller runners with different optimum capacity in one single runner, provided with a suitable mechanism to control the blade position during operation. As a result he had a high specific speed and a flat efficiency curve. Kaplan, who was fully convinced of the importance and usefulness of his ideas in the years 1912—1913, made patent applications for three main principles, which then constituted the basis for the initial development of the new type of turbine which since carries his name.

These original basic principles for the Kaplan turbine were:

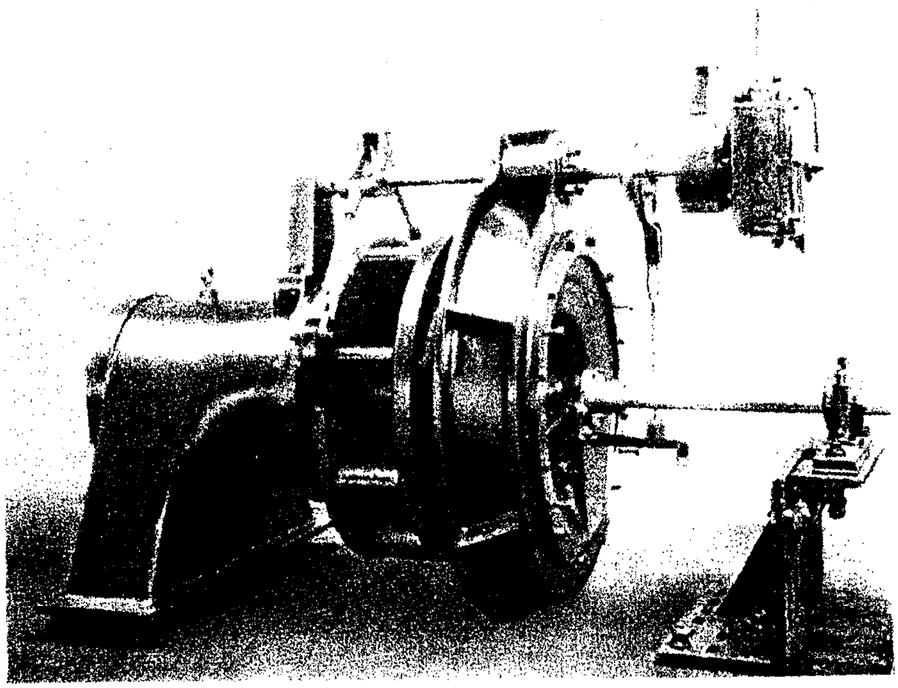
1. A radial flow guide apparatus, followed by a vaneless transition, deflecting the slightly rotating water flow into mainly axial direction before entering the runner.

2. A runner with relatively few radially orientated blades, attached to a central hub in such a way that they can be given a continuously variable pitch.
3. The profile length of the individual runner blade to be shorter than the peripheral distance between the blades (equal to a negative blade overlap and no pronounced channels between the blades).

Kaplan, who was eager to see his new ideas come into practical application already in the spring of 1913, made approaches to a number of well-known European manufacturers of water turbines, offering them the licence rights to his inventions. Unfortunately, his proposals were met with some scepticism with respect to the correctness of the test results and the possibilities of transposing the ideas to full scale turbines.

The model tests by which Kaplan tried to support his claims had very modest data. The runner was 100 mm in diameter and operated under 0.6 m head. It should therefore not surprise if the accuracy of the test results was questioned. Several firms also opposed the patent claims and refused to accept the royalties proposed by Kaplan.

One of the early interested parties was the Swedish water turbine manufacturers Verkstaden, Kristinehamn (KMW) and their managing director at that time, Hans Th. Holm, visited Kaplan in Brünn and made a preliminary agreement with him. This led to a model test in Verkstaden's testing station carried out in December 1914, probably the first test besides those initial ones made by Kaplan himself. The model turbine recorded as "Kaplan-Versuchsturbine" was in all details designed according to Kaplan's intentions and instructions. It had a runner diameter of 700 mm and was tested under 4 m head, thus more assuring with respect to accuracy than previous tests. The runner blades were fixed. The test results, came out with a rather low efficiency level of only 73 % and were not particularly encouraging. The first world war caused an interruption of the communications with Kaplan and this first test did not lead to any immediate practical result. However, Verkstaden during the following years independently carried on a certain development work on high specific speed turbines according to the basic principles of Viktor Kaplan.

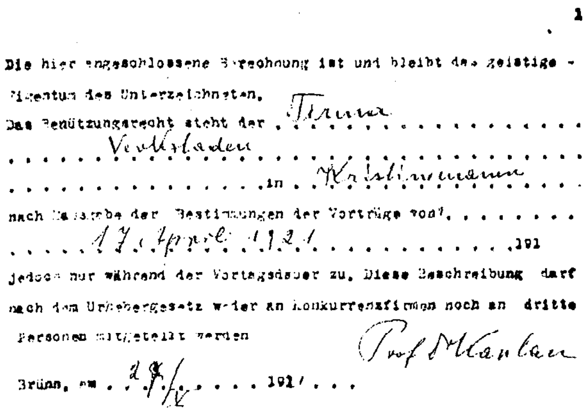


The first Kaplan turbine for industrial operation. The turbine was installed in Velm, Austria, in 1919 and produced 25.8 hp metr. under 2.3 m head.

Kaplan himself also continued his work and amongst other things developed a new type of draft tube, adapted for the special requirements caused by the high specific speed with high discharge velocities at the runner outlet.

In 1919 the first Kaplan turbine was put in practical operation at a textile factory in Velm in Austria. This firstling, which had been manufactured by the firm Ignaz Storek in Brünn, had moderate dimensions and produced under 2.3 m head 25.8 metric horse powers. The full load efficiency was measured to 84 % per cent and the specific speed was approximately 700. The turbine, which attracted great attention by the profession, was followed by several others of similar size. Kaplan of course was greatly encouraged and began to see the beginning of a success. However, already the following year new technical problems appeared. The turbine efficiency in some installations came down to about 60 per cent and the runners were severely damaged by a phenomenon which to begin with could not be explained. Cavitation, which had earlier not been known to water turbine designers, had become a factor of significance which had to be taken into account. The basic reason for cavitation troubles obviously was that in his efforts to reduce friction losses in order to increase optimum speed, Kaplan had reduced the blade surfaces of the runner too much in respect of the chosen setting of some of the turbines. As a consequence of these difficulties the continental group of turbine manufacturers, who hade formed together the so called Kaplan-Konzern, began to hesitate about the possibilities of using Kaplan's inventions and slowed down their work. Even Kaplan himself was shaken in his belief and had a rather difficult time. This was the situation when the Swedes re-entered the scene in a way which later on should prove to be of decisive importance.

The Swedish State Power Board was during the years 1919—1921 preparing an exploitation of the remaining waterfall in the Göta Älv at Lilla Edet. The low head of 6.5 m and the limited space for the power station caused exceptional requirements on the compactness and performance of the turbines to be chosen for this application. Many alternatives were studied and preliminary proposals were worked out by different manufacturers. Already in 1919 the Board had preliminary contacts with professor Kaplan and the firm Ignaz Storek in Brünn, who presented project drawings for a Kaplan turbine, intended to produce the maximum output of 10 000 hp, as specified by the Board. Surprisingly, when the Board's engineers asked the Austrians to put at their disposal a model turbine to be tested in the newly arranged testing station in Lilla Edet, there was no response and the contact was broken. Verkstaden in Kristinehamn, who were busily working with the turbine problems of Lilla Edet at this time had started to reconsider the possible application of the Kaplan turbine and its usefulness for the Lilla Edet project in particular. New discussions with professor Kaplan, carried out by Messrs. Englesson and Molinder, the 27th of May 1921 resulted in a final licence agreement. A both funny and moving episode from this historical event is worth of being referred. Mrs. Bertha Englesson, who accompanied her husband and participated in the celebration of the concluded collaboration agreement, has afterwards told that when the family Kaplan had put on the table the bottle of wine the house could produce, this was insufficient to offer everybody a glass.



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Die hier eingeschlossene Berechnung ist und bleibt das geistige Eigentum des Unterzeichneten.
Das Benützungsrecht steht der Firma Verkstaden in Kristinehamn
nach Massgabe der Bestimmungen der Verträge vom 17. April 1921
jedoch nur während der Vertragsdauer zu. Diese Beschreibung darf nach dem Urhebergesetz weder an Konkurrenzfirmen noch an dritte Personen mitgeteilt werden

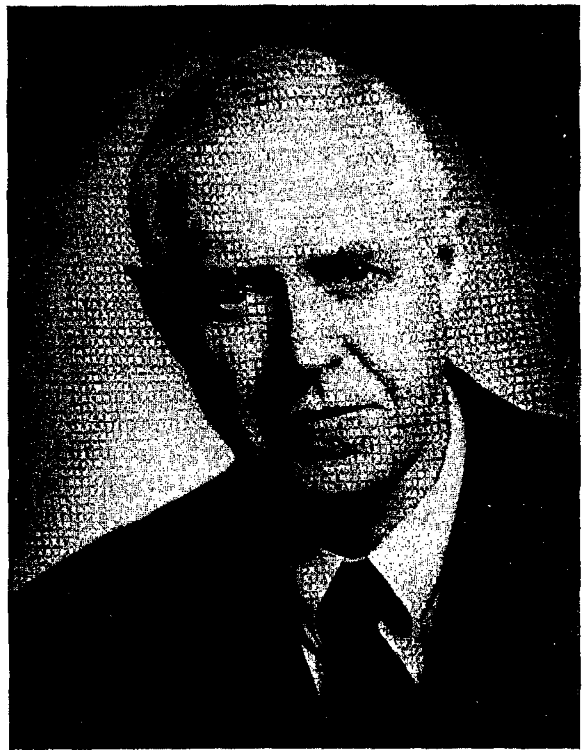
Prof Dr Kaplan

Brünn, am 27/V 1921

Copy from the first page of professor Kaplan's technical instruction file for his Swedish licensee, Verkstaden, KRISTINEHAMN, signed 27.5.1921.

Then Mrs. Margarethe Kaplan took a lighted candle in her hand, which she held forward, when the others raised their glasses for a common toast, saying: "Dies passt mir, ich bin mehr für das Geistliche!" (This suits me better — I am more for the spiritual than the spirits!). If one has, as the author of this article 48 years later, heard this intelligent and warmhearted lady tell personal memories from the period of the creation of the Kaplan turbine, one understands what the woman in the background has meant, as in so many other cases of stimulator and support to the hardworking inventor.

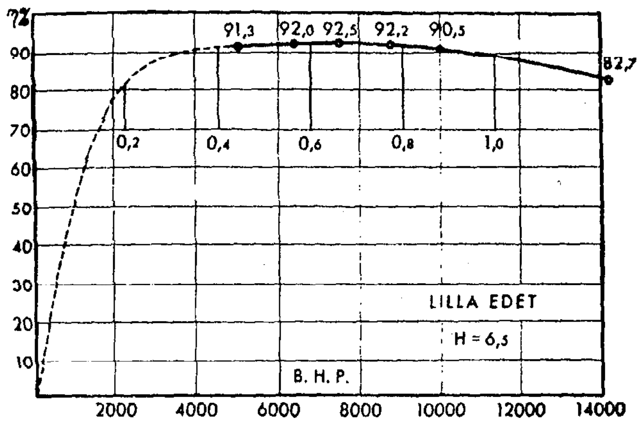
As soon as the agreement with professor Kaplan was signed an intensive development work was started up by Verkstaden with the aim of bringing the turbine out on the market. The first important application they had in mind was for Lilla Edet, but also a project for the Assuan Dam in Egypt was studied seriously. Already in September 1921 the first tests were made and on the 1st of December a tender was presented to the Swedish Power Board for the Lilla Edet project. The very daring proposal, which was for a turbine with 5.8 m runner diameter, was together with other competing proposals subject to a very careful analysis and evaluation. As a result it came out, that the Kaplan turbine proved such obvious overall merits that it ought to be chosen for Lilla Edet. In order not "to put all eggs in one basket" the Board in the beginning of 1922 ordered one Kaplan turbine from Verkstaden and at the same time a so called Lawaczeck turbine from Finshyttan. Although the latter type was also new with



Elov Englesson, born 17th June 1884, Chief Engineer and designer of the Lilla Edet Kaplan turbine. Active at KMW between 1906 and 1953.

respect to the shape of the runner blades and the omission of a band on the runner, it did not actually comprise any new features which made it radically different from the conventional Francis turbine. It was therefore considered as less risky than the Kaplan turbine. With regard to the employment situation a second Lawaczeck turbine was latter on ordered also for the third unit of Lilla Edet.

Amongst the continental competitors prophets of evil were heard to predict a catastrophe with the large Kaplan turbine, but in Kristinehamn the design team was working hard and conscious of the purpose under the dedicated leadership of Elov Englesson. A number of alternative runners were tested and No. 42 was finally selected. Well informed about previous failures on the continent the Swedish engineers paid the greatest attention to the cavitation problem. In order to advance the right understanding of the phenomenon itself and to

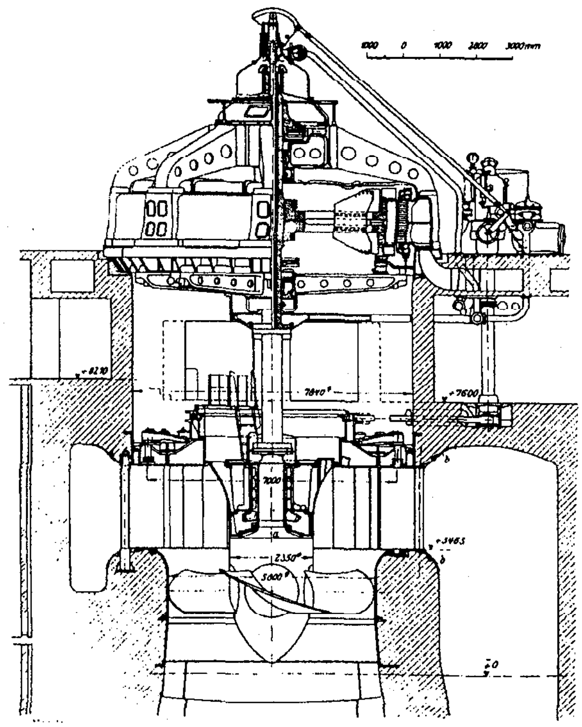


Efficiency curve from contractual acceptance test at site with the Lilla Edet Kaplan turbine (1926).

establish the cavitation characteristics of new runners, a special test tunnel was built and taken into operation in 1924. This was probably the first cavitation test stand in the world for cavitation research with a turbine manufacturer. In this connection it is proper to emphasize the very valuable contributions made by Mr. Hadar Lind, a very talented engineer, for many years in charge of the hydraulic laboratory of Verkstaden.

The mechanical design was developed according to completely new principles. No master design existed and the advice given by professor Kaplan in this respect proved to be less useful for a turbine of Lilla Edet's dimensions. Particularly the runner hub with its mechanism and servo system, required to support the movable blades and to control their position to suit in every moment prevailing operating conditions, was subject to very thorough studies. The resulting design comprised a number of new inventions.

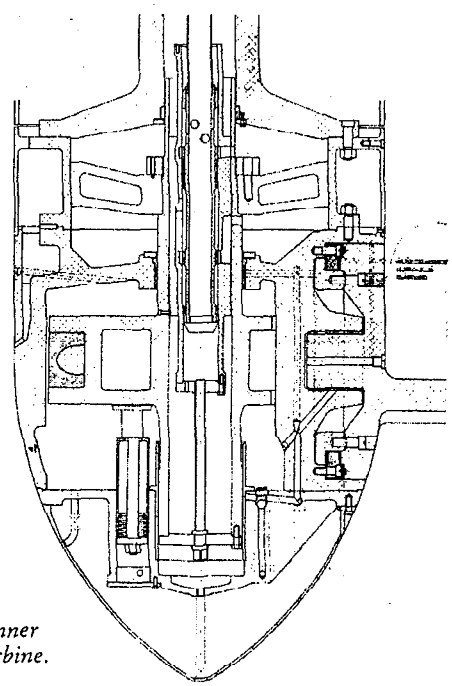
The Kaplan turbine in Lilla Edet was delivered and installed as foreseen in the contract and was tested in the plant by professor Hjalmar O. Dahl and the Board's turbine engineer Hugo Munding. The results, which appear from the diagram above, gave evidence that contractual performance guarantees had been exceeded and as the mechanical function of the turbine also proved to be according to expectations, the success was complete. This meant, that the ice was broken and the Kaplan turbine could start it victorious progress over



Vertical section through the Lilla Edet Kaplan turbine.

the world. An ingenious idea by a dedicated researcher and inventor working in small scale had been brought to maturity in full scale by an energetic and skillful contribution of Swedish engineers, supported by a knowledgeable and farsighted Power Board.

A brief description of the mechanical design of the Lilla Edet turbine may be of interest. The cylindrical runner chamber with an inner diameter of 5.8 m, made of cast iron, is supported on a lower foundation ring also made of cast iron downwards connected to the draft tube cone. The upper foundation ring is mounted on 12 stays interconnecting the ceiling and bottom of the concrete spiral casing. The guide apparatus has 24 vanes made of cast steel. The mechanism is protected against overstressing by means of shearpins. The runner consists of a cast steel hub of cylindrical shape, to which the four blades also of non-alloyed steel are attached by a bronze coated bearing ring screwed on to the hub body. Inside the bearing rings are crank rings bolted to the blades and connected to the piston of the servomotor, controlling their position. The servomotor is located in



Sectional view of the runner hub of the Lilla Edet turbine.

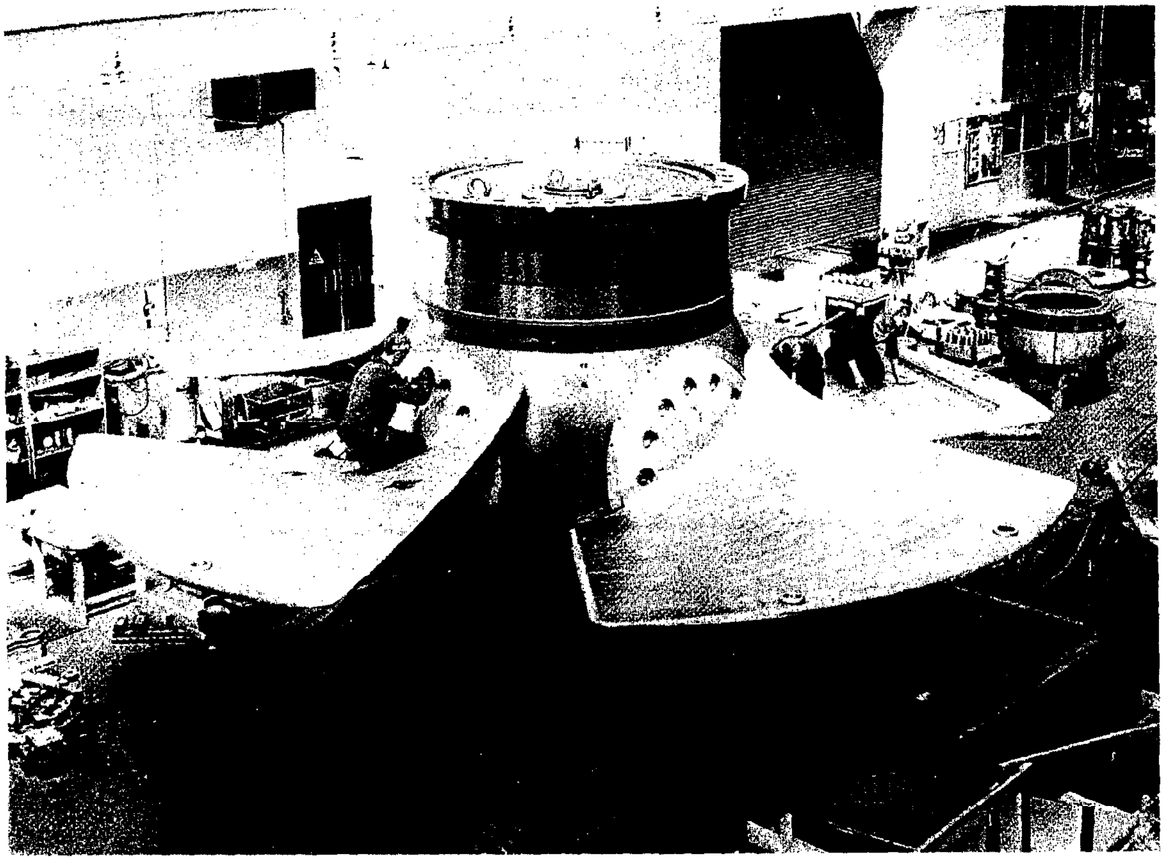
the upper part of the hub. The pressure medium is oil, supplied at a pressure of 20 bar through a steelpipe in the central bore of the shaft. The control valve is located inside the piston and actuated from the combinator on top of the generator by means of the oil pipe. The lower part of the runner is filled with low pressure oil, which is by means of an integral piston pump by the movements of the blade mechanism brought to circulate through all bearings, including the blade pivoting bearings. At the blade flanges there are double acting lip seals of leather which effectively prevent oil from leaking out and water from entering the hub. The above mentioned combinator with its mechanical cam constitutes the coordinating link between guide vanes and runner blades. The shape of the cam is empirically adjusted to give a runner blade position which for every guide vane position (load) results in the best turbine efficiency.

The turbine guide bearing, which is placed in the lower part of the inner cover is a white metal clad journal bearing with relatively great length in relation to the diameter. The bearing is lubricated with selfcirculating oil. The shaft seal below the bearing is of the labyrinth type. Although the thrust bearing belongs to the generator and is placed on a spider above the rotor, it is worth mentioning here because its design is greatly affected by the turbine characteristics. The bearing bigger than any other bearing previously made. The load is carried on 16 segment pads, supported on a great number of springs. The average oil pressure on the bearing surfaces corresponding to maximum load is 25 bar. There is external pump circulation of the lubricating oil.

From the intake the water is conducted into the turbine through a semi-spiral casing of reinforced concrete. The draft tube is of the elbow type with oval sections in the outlet of the bend. Like the spiral it is built in reinforced concrete with a plate lining only in its upper conical part. The shape of these external waterways was finally determined by extensive comparative model tests, partly carried out in the Board's testing station in Lilla Edet.

The hydrodynamic qualities of the Lilla Edet Kaplan turbine are in the first hand demonstrated by the previously mentioned results of the contractual field tests. Furthermore, it should be noted, that the runner blades after 4 years of operation near the periphery of the suction side showed only minor pitting from clearance cavitation. These defects, like similar pittings on the runner chamber, have been durably repaired and further cavitation damage eliminated by the insertion of stainless steel plates in the affected areas. The reliability of the mechanical design, had been greatly questioned by the critics and caused the Board to load their evaluation of the Kaplan alternative with a special amount of money set off to cover expected exceptional maintenance costs. Experience has proved these worries to be completely unjustified and the mastership of the designers appears from the fact that the turbine has now given more than 50 years troublefree operation. The hub with its permanently operating mechanism has never had to be opened and the vital blade seals are still completely tight. There is no wear in the guide bearing. Only recently an internal oil leakage in the hub has had to be reduced by readjustment of the control valve clearances.

Already the early experience with the Lilla Edet turbine was convincing and was noted with admiration by the water power experts all over the world. This caused a complete revision of all previous judgements about the suitability of the Kaplan turbine for big power



Runner for the Rusfors power station under shop erection. Diameter 8.1 meters.

stations. The pioneer plant was therefore on continent as well as in Sweden followed by other low head installations of Kaplan turbines of corresponding or bigger dimensions. In Sweden, besides a great number of medium size Kaplan turbines, eight big turbines were manufactured during the years 1929—1933 for the Russian Ladoga power station SWIR. These turbines, designed and manufactured by KMW, were mainly built according to the same principles as the Lilla Edet turbine but considerably bigger. The runner diameter is 7.42 meters and the output per unit is 28 MW at 10 meters head. At the time of the commissioning this was again a record, superceeded the following year by the turbines for Vargön in Sweden, which were with their runner diameter of 8.0 meters for a long time the biggest in the world. It should be noted that from Vargön and onwards there were two manufacturers of Kaplan turbines in Sweden, since also NOHAB had entered the field by manufacturing one of the two turbines for that power station. However, as the basic patents were still valid, the contribution of NOHAB was in collaboration with KMW. The large units in Vargön are technically interesting insofar as there are no intake gates. Another feature of particular interest with the Vargön units is the fact that the intake gates have been omitted. This is possible because the upstream waterways, including intake and concrete spiral, have been given the form of a siphon with the intake section totally submerged and the treshold of the stayring above the highest intake water level. This makes it possible to control the flow to the turbine by evacuating the top of the spiral casing respectively let in air for stopping the flow. Evacuation is accomplished by means of large water driven ejectors.

The general trend of the further development of the Kaplan turbine was towards higher heads and greater outputs. It was obvious that the particular advantages of the Kaplan turbine were not exhausted within the head range below 10 meters. By a gradual adaptation of turbine design and general layout of the stations by means of careful calculations and extensive laboratory testing new types of machines could be built with maintained or improved performance and operational safety. With increased heads followed a greater number of runner blades and relatively bigger hub diameters. Although this inevitably led to a gradual reduction of the specific speed, this was still higher than for corresponding francis turbines and there was still the advantage of the flatter efficiency curve. In order to reduce the hydraulic clearance losses and cavitation at the periphery of the runner blades, the runner chamber was given a spherical shape in its lower part. Because it is not economically feasible to choose a setting of the turbine or size of the runner which would completely prevent cavitation on blades and runner chamber, stainless steel was introduced as a construction material for these parts. This was made as a result of extensive systematic tests with a range of different materials carried out by KMW in a special model turbine installed for long-term operation at the power station MUNKFORS. The tests conclusively demonstrated the superiority in comparison to other available materials of the cast stainless steel which was therefore introduced for application in prototype turbines already in 1927 and have since then become standard for European Kaplan turbines in general.

The following Swedish made Kaplan turbines may be regarded representative for the technical development that followed:

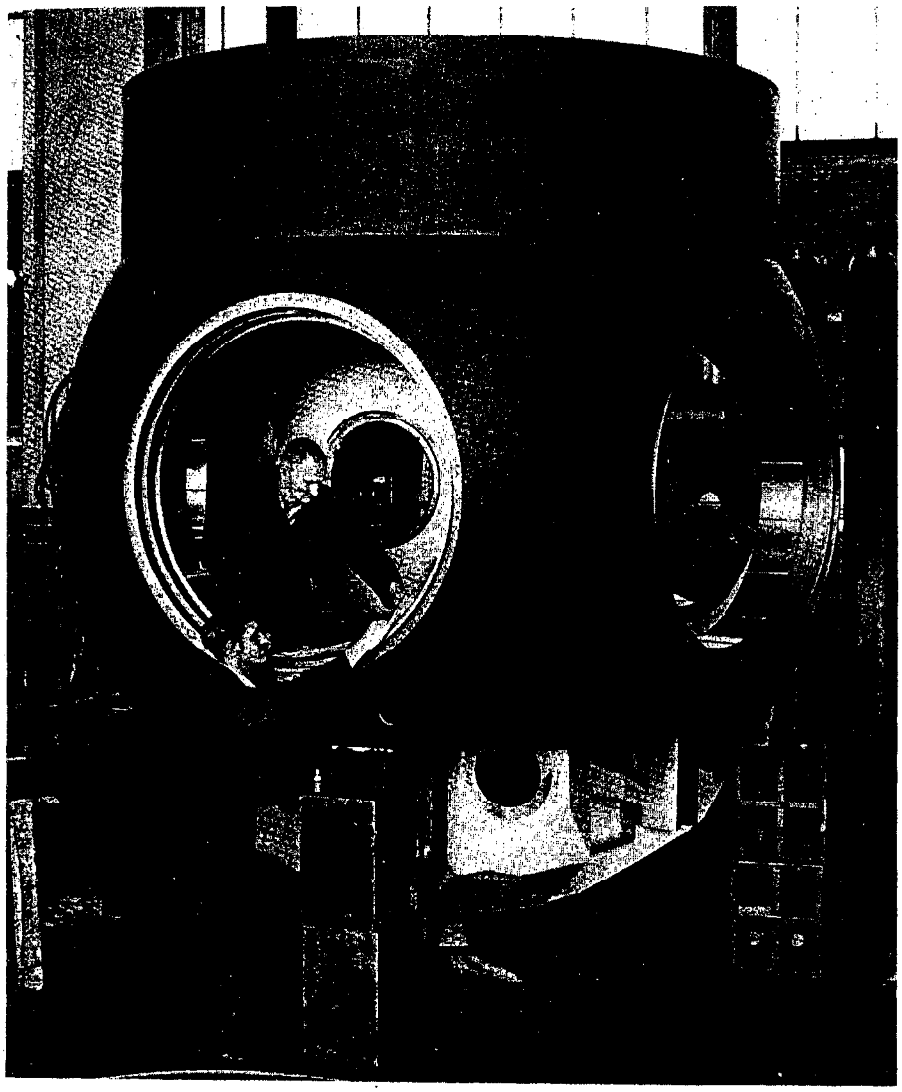
1937	Stadsforsen	2 × 35 MW at 28 m head, 5-bladed runner with spherical hub. Plate spiral casing.
1939	Hojum	2 × 47 MW at 31 m head.
1947	Aswan (Egypt)	5 × 48 MW at 27 m head. Great variation of head between 6 and 36 m imposes unusual requirements on the design, especially with respect to highest possible outputs in the lower head range.
1950	Ligga	2 × 78 MW at 39.5 m head. The world's most powerful Kaplan turbine at the time of commissioning. 6-bladed runner.
1953	Lasele	64 MW at 52 m head. 8-bladed runner.
1957	Kvistforsen	68 MW at 49.3 m head.
1958	Rusfors	47 MW at 11.7 m head. With a runner diameter of 8.1 m this is the biggest Kaplan turbine in Sweden.
1961	Krokströmmen	50.5 MW at 57 m head. 7-bladed runner. The highest head so far for a Kaplan turbine in Sweden.
1969	Akkats	153 MW at 42.8 m head.
1976	Ligga III	190 MW at 39 m head. This will probably be the most powerful Kaplan turbine in the world. The complete runner with its 5 blades will have a weight of 210 tons and the maximum load on the thrust bearing will be 2700 tons.

Apart from the referred development of designs towards increasing heads and modifications in detail of the mechanical construction most of the basic outlines of the design of the Lilla Edet turbine have been maintained during the years. As an example the runner blades are still attached to the hub by means of bolts in such a way that they can be dismantled without taking into parts the hub with its complete mechanism. Another advantage which is gained at the same time is that blades without an integral trunnion are more suitable for casting from the metallurgical point of view. It is easier to obtain a casting free of defects in the most highly stressed part near the junction of the blade and its flange. This is important with respect to strength and durability. The location of the blade servomotor in the hub is nowadays standard also with foreign manufacturers. In order to improve the accessibility of the control valve of the runner servomotor this has been moved to the combinator on top of the unit or in certain cases been placed outside the rotating system. This has also brought about a higher precision in the governing and a more reliable indication of the actual position of the runner blades. In the interest of easier replacement and maintenance the blade seals have been placed under gland rings around the blade flanges in such a way that exchange of seals can be made without dismantling of the blades. The arrangement of bearings for the support of the blades in the hub has been modified and there are now journal bearings with smaller diameters. This leads to lower friction torque and less deformations, which is particularly wanted with turbines designed for higher heads. It also makes it possible to control the blades at runaway conditions.

The confidence in the operational reliability of the Kaplan turbine is nowadays well-founded and this is best demonstrated by the fact that many power stations in rivers with small or non-existent storage possibilities have been equipped with only one single unit.

Licencing of Swedish Kaplan turbine engineering, in the first hand by KMW, to foreign manufacturers have been made already since beginning of the thirties. Generally speaking this has broadened the basis for technical development but has also meant a valuable feedback of experience and stimulated to new designs, adapted for the special requirements of foreign customers.

The adoption of more advanced theoretical analysis and services of new hydraulic laboratories with sophisticated measuring technique were new tools which came to the disposal of the designers from about 1950 and onwards and which made possible considerable progress in the hydraulic designs of new Kaplan turbines. The later introduction of new theories and methods for stress analysis have naturally also been to the benefit of the Kaplan turbine as well as other types of



Hub body for a large, modern Kaplan turbine for the VAMMA power station in Norway. Weight of hub only — 57 tons. Weight of complete runner — 175 tons. Max. turbine output 153 MW.

hydraulic turbines with respect to safer mechanical designs and optimum utilization of construction materials.

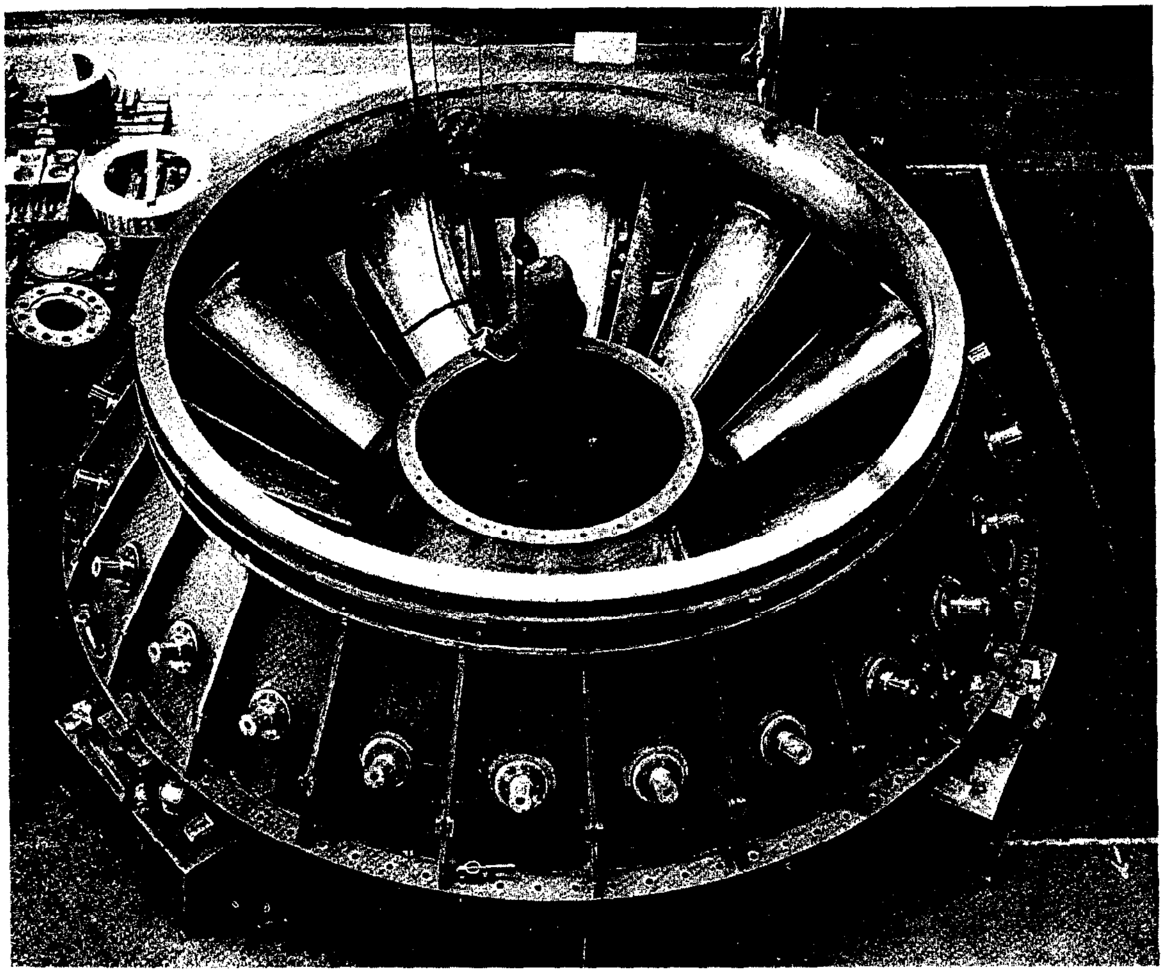
Another circumstance that at the end of the fifties and beginning of the 60th stimulated to a further raising of the performance level of the Kaplan turbines was the establishment of the Swedish Power

Board of a new testing station for water turbines in Motala. In conjunction with tender competition for new projects comparative model tests were arranged with model turbines supplied from different Swedish and foreign manufacturers. This was no doubt a very good initiative by the biggest Swedish purchaser of power equipment and it had positive effects for all parties involved. It may be said that the Swedish manufacturers managed to defend their technical position very well, challenging each other to new development efforts and further strenghtening their already high international reputation in this field.

A special type of Kaplan turbine, which has won recognition during later years, is the tubular turbine, especially the so called bulb turbine which is combined with a generator installed in a bulb shaped housing in the waterway. This type has appeared as a result of a development mainly carried out in Germany during the second world war and later on in France. The aim of this latest development has been to further reduce the costs of hydroplants for the lowest range of heads by means of very compact and possibly even more efficient types of Kaplan turbines. In the early German cases also military defence aspects had an influence, as it proved possible to combine the low civil constructions of the turbine with the spillways in such a way that if necessary the whole plant could be covered with flowing water to prevent discovery. Another special application of the tubular turbine is the French tidal power station RANCE, equipped with 24 reversible Kaplan turbines of the bulb type with 10 MW capacity each.

Through their French licensee, Schneider-Creusot, KMW already 25 years ago were given an incentive to contribute actively in the development of tubular and bulb type Kaplan turbines and thus successfully participated in the design and execution of several important installations in France.

The first Swedish bulb turbine was built for the Skogsforsen power station, commissioned in 1960, and followed by a few minor installations of similar type. About 10 years later the first big Swedish unit of the ordinary bulb type was built for the State Power Board's plant Parki. The turbine has a runner diameter of 4.9 m and yields a nominal output of 21.2 MW under 11.0 m head. Altogether 23 bulb units are now in operation or will be commissioned in Swedish power



Guide wheel apparatus for large bulb turbine under shop assembly—Parki power station, Swedish State Power Board. Runner dia. 4.9 m.

stations in the near future. Swedish bulb turbine technique, apart from the above mentioned French applications, is today represented in a number of foreign countries, like Norway, Austria and South Korea.

Generally speaking the bulb turbine is now recognized as being the primary choice for most low-head hydro projects. Except for the lower total capital investment per kW, mainly achieved due to the simpler and less voluminous civil constructions of these units as compared to conventional vertical shaft Kaplan units even better efficiencies are obtained. This is particularly apparent in the high-load region, where the straight waterways with smaller friction surfaces lead to reduced hydraulic losses. Assuming a given maximum capacity of the unit this can of course be exploited by selecting a smaller runner diameter, which in turns will further reduce the total costs of the whole power station.

An interesting illustration of the technical advancement made with the Kaplan turbine over the last 50 years, elapsed since its actual introduction in large size power stations, is obtained by comparing the above described original Lilla Edet turbine with a modern bulb turbine, having the same runner diameter of 5.8 m. It is then assumed, that both turbines are designed for and operating under the same head, 6.5 m. The nominal output of the bulb turbine will then be abt. 13.5 MW as compared to only 7.5 MW for the "firstling". The optimum synchronous speeds will be 83.3 and 62.5 rpm respectively. Efficiencies are as an average abt. 2 per cent higher with the new machine. As a matter of fact the Lilla Edet power station will now be extended with a fourth unit. The bulb type Kaplan has been selected for this purpose.

A summary of the deliveries made up to date, August 1977, shows rather impressive numbers. In Swedish works abt. 470 Kaplan turbines of different types with an aggregate nominal capacity of 9 000 MW have been manufactured. If also Kaplan turbines made under Swedish licence are included, these figures will raise to 710 units and 12 500 MW. Practically all these turbines are still in full commercial operation, contributing to the efficient conversion of low-head hydropower into electric energy. To make the Kaplan history complete there should of course also be added an unknown number of Kaplan turbines made by non-Swedish, mainly continental European firms. In any case the Swedish technique maintains a paramount position.

As a conclusion it may be said that the results of the creative basic work, which was performed by Viktor Kaplan half a century ago and matured for practical use by other pioneers, collaborating with Kaplan, some of them prominent Swedish engineers, have been well taken care of by following generations of researchers and designers to the benefit of power companies and power consumers all over the world. It seems proper to predict that the basic principles of the Kaplan turbine will find many applications also in the future exploitations of the vast hydro-power resources, which are still available, particularly in the developing countries.

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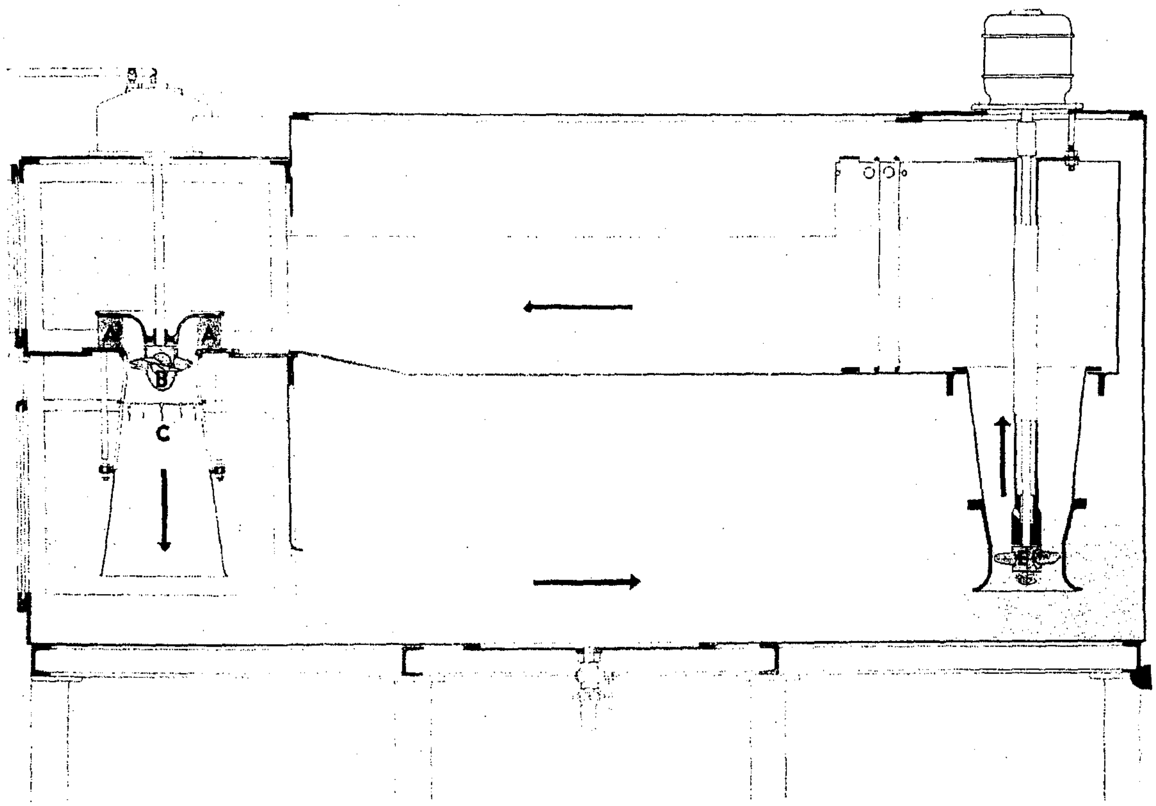
In Honour of Professor Victor Kaplan

After the death of Viktor Kaplan in 1934, the Austrian Research Institute for the History of Technology (Österreichische Forschungsinstitut für Geschichte der Technik) appointed an Extraordinary Committee in 1935 to honour the memory of Dr Kaplan and his contributions to the development of turbine technology. The *Rektor* of the *Technische Hoschschule* in Vienna, Dr A. Kann, was appointed Chairman of this Committee, and among the fifteen members was also Mr Elov Englesson, Kristinehamn, Sweden. The first action of the Committee was to set up a Memorial Plaque on the house in Mürzzuschlag in Steiermark where Kaplan was born. Memorial exhibits were also arranged at the *Technisches Museum* in Vienna, and the *Deutsches Museum* in Munic. Further, a biography on Dr Kaplan was published by the Committee in 1936 (Alfred Lechner: *Viktor Kaplan.* Julius Springer Verlag, Wien 1936).

In 1937, Frau Margarethe Kaplan took the initiative to donate to the Tekniska Museet in Stockholm a collection of experimental models of turbine runners, made by Viktor Kaplan in his private laboratory. This representative collection goes back to the early 1910s when Viktor Kaplan began to test his new concept on a model scale. Of special interest is, of course, the early experimental runners on which Viktor Kaplan tried out various solution sto vary the pitch of the blades. The first method used was to move the blades by means of levers, with obvious difficulties to obtain uniform movements on the blades.

As a complement to this collection of artefacts, the Karlstad Mekaniska Werkstad built a demonstration model of a working Kaplan turbine, which showed how the original ideas had developed into a usable source of power. This model was first exhibited at the International Water Power Exhibition in Liège in 1939, and was later set up in the Machinery Hall of the Tekniska Museet.



Demonstration model of a Working Kaplan turbine.