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The Paper, which was received on 2 September, 1955, is accompanied by eleven sheets of diagrams, from which the Figures in the text have been prepared.

Discussion

The Author, introducing the Paper with the aid of a series of lantern slides, illustrated recent progress in the development of reversible pump-turbine units. He also referred specifically to the use of various types of pumps in a newly-reclaimed desert area in Egypt.

The Chairman referred to the question of the flexibility of pumping schemes in terms of control of the amount of water being pumped. The pumps which the Author had described were capable of variation in discharge quantity by variation in speed, but it was possible to go further than that, and in the case of the axial-flow type of pump, whether single-stage or multi-stage, the variation in quantity could be controlled by varying the tip angle of the blades, even when running.

With a centrifugal type of pump, or even with the mixed-flow type, if the speed was varied the efficiency of the pump itself would remain at its maximum value if almost the whole of the head was due to pipe friction. On the other hand, if the total head against which the pump was operating included a large static part, then, as the speed was reduced, it would run away very quickly from the maximum efficiency point. Variable speed was most satisfactory, therefore, in the case of friction systems such as booster pumps, where there was not much static lift. It also followed that the variable speed was most satisfactory when the head against which the pump had to work was reduced. With axial-flow pumps, the varying of the blade angle had the effect of maintaining the efficiency at a high value for different quantities against the same total head. In other words, where the static head was very high in proportion to the total head, variable pitch axial-flow pumps were suitable, again with the limitations of the head which could be generated by the axial-flow pump.

The variation of speed was possible only at some cost. When considering only electric pumps, as he was doing at the moment, a reduction of speed could be achieved by losing energy in the rotor resistance of an induction motor, and it could be achieved by using a commutator-type a.c. motor in which most of the unused energy was returned into the main, and where the efficiency was therefore kept at a high value. It was necessary to pay, however, for that ability to control the quantity, and the more highly efficient it was the more costly the electrical plant which had to be used.

Mr W. E. Doran (Chief Engineer, Great Ouse River Board) said that centrifugal pumps had been in use for rather more than a century, but it appeared that engineers did not yet know how to design a sump. Recent Papers[17, 18] presented to the Institution of Mechanical Engineers contained much useful information on the subject, but there was still a great deal to be learnt.

In land-drainage pumps, a low value of the critical submergence of the suction inlet was very important, because of the small working range on the suction side of the pump. The lowering of the sump by quite a small amount—1 ft or 18 in.—would add quite considerably to the cost of the installation, and the cost of lowering the sump might be more than the difference in cost between two competitive tenders.

He felt that sump design had not received sufficient consideration from civil engineers, and it was becoming increasingly important with the use of the axial-flow type of pump. By keeping the suction inlet close to the wall and close to the floor, it was possible to discourage the formation of a vortex. It had been suggested that the distance between the end of the pipe and the floor should be about half the diameter of the suction inlet.

He would welcome the Author's comments on the plan view of the sump. The old-

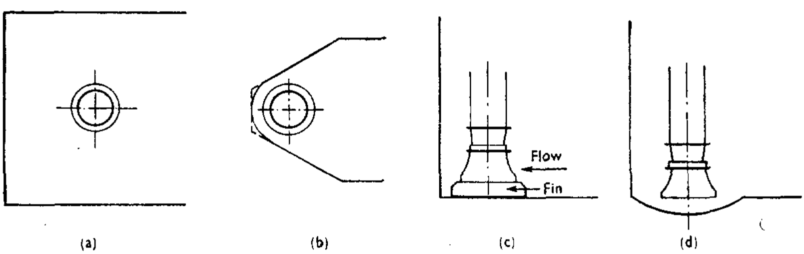


FIG. 12

fashioned sump was an open-sided box, with the width corresponding very often to the width of the inlet channel and with the suction pipe near the mid-point of one end as shown in Fig. 12a. That was very liable to vortex trouble. The modern idea was to

[17] References 17–25 are given on p. 699.

make the sump rather of the type shown in Fig. 12b but to avoid expensive formwork it could be made as shown by the broken line which would probably be equally effective.

The suggestion had also been made that a diametral fin should be put underneath, as in Fig. 12c. He did not like that suggestion, because the fin might gather weeds which would affect the operation of the pump. In a situation where it seemed desirable to keep the pipe as close to the floor as possible to avoid vortex formation, it might be possible to make a bowl-shaped depression underneath the suction inlet, as shown in Fig. 12d. Did the Author think that that would be a good compromise, to avoid the expense of dropping the whole sump floor?

Putting the suction pipe too close to the wall was likely to result in uneven velocity distribution in the pipe, and there might even be an uneven load on the bearings; it was necessary therefore to strike a mean between avoiding vortices and keeping the pipe so close to the wall as to cause trouble in other ways.

In dealing with drainage pumps, the Author had mentioned the probable development of weather-proof pumps which would make a pump-house unnecessary, because the pumps could be left in the open. Mr Doran felt that any saving which could be made in that way would be extremely small, and in any case it could apply only to quite small units, because the main item of the cost of a Fen pumping station of any size was not the building but the intake flume, the delivery flume, and the delivery pipes. The cost of the building was quite a minor matter, and its provision meant that when there was an overhaul or a break-down in bad weather there was a building in which to work. It would hardly be worth while to install weather-proof pumps and switchgear.

With regard to future trends Mr Doran thought that the most probable development in drainage pumps was towards the increased use of electric power. Electricity rates were now becoming very competitive in the off-peak periods, and the combination of a Diesel pump for use during peak hours and an electric pump with automatic control, which pumped during the off-peak hours, particularly at night, was almost ideal. With an ordinary Diesel set the natural tendency was for the pump attendant to run during the day, pumping his drains right down and letting them fill up at night. The constant fluctuation in the drain was not good from an agricultural point of view. If there was an electric set which looked after the situation automatically at night, and a Diesel set which operated during the day, it was a very good combination. There were certain direct advantages with electricity, such as the possibility of automatic control and a cheaper initial cost. The stations were usually smaller, and the cost was less provided a source of power was close to the pump. There was no need for constant attendance, and the overall maintenance costs were considerably less.

The use of electric pumps might entail the necessity for some kind of mechanical clearance on the trash racks. If the pumps were running without attendance, one could not risk having the trash racks choked with weeds, especially at night, or during the day when the attendant was not there. That was another development which Mr Doran could foresee, but he believed that electricity would be increasingly used for land-drainage pumps.

Mr H. R. Lupton (Consulting Engineer) said it had always struck him as a very clumsy and expensive method of storing energy to pump a bulky material such as water against the very feeble gravity of the earth through expensive pipes to an expensive reservoir, with losses in the pumps and pipes and further losses when the energy so bottled was used to get back heat or mechanical energy. He could not help thinking that within the next 50 years scientists would have found some more compact method of bottling energy, either chemically—as of course was done now in accumulators, when the energy was retrieved as electrical energy, not subject to Carnot's limiting laws—or, if heat was to be bottled, by the electrolysis of water. There must be, he thought, already existing methods of bottling energy very much less clumsily than by pumping water to an expensive reservoir. Very soon, no doubt, it would be possible to store the energy inter-atomically, when the bulk of the store would be very much smaller.

Looking still further ahead, he could not help thinking that Malthus's pessimistic prognostications were almost certain to be overcome by scientists, possibly in the near future. It seemed the reverse of wisdom to use a great deal of energy in irrigating areas where nature could not at present grow vegetation when that energy might be used for the direct synthesis of the products which were needed—a very much more direct method. That was already being done, for instance, with rubber, and he had no doubt that in the next 50 years scientists would develop other applications.

The Author, in his book "Land, Water and Food," had stated that it was estimated that of the increase in food needed by the world in the next 50 years, probably not more than 20% could be provided by large-scale engineering schemes of irrigation. That was a poor prospect, and emphasized Mr Lupton's contention that food, clothes, and other requirements for civilization should, in the course of the next 50 years, be increasingly provided not by irrigating land to help nature but, still using nature wherever nature worked efficiently, by synthesizing the products instead of bolstering up nature to grow them.

Mr Lupton regretted that the Author had not dealt more fully with the great increase in automatic working in pumping plants. It was particularly applicable, of course, to small installations; for instance, in the case of water supply, to small re-pumping stations, and still more, in the case of sewage plant, to small sewage stations, because generally the plant was of low horsepower, and the cost of attendance formed a very large proportion of the whole cost of the service. It was where that occurred that automaticity should be increased at an accelerating rate. In industry, of course, there were innumerable instances of automatic devices controlling processes of great variety.

The electronic control of water supply was no new thing, and it should be possible to develop electronic devices to a greater extent.

Coming to a small point of detail, he noticed that in Fig. 4 the delivery pipe from a pump ended above the water level. That was a great sin; that pipe should certainly dip into the water to get the benefit of siphon action, and he was surprised that it should have been shown otherwise. If it was desired to stop the water siphoning back when pumping was not taking place, a siphon-breaking air-valve could be arranged at the top of the siphon.

Dr D. F. Denny (Research Engineer, British Hydromechanics Research Association) observed that the hydraulic design of inlet structures was of primary importance to the successful functioning of the whole system. Particularly with the very large schemes which were in progress or envisaged for the future, it was es ential that the size of the intake structure and the depth of excavation be kept as small as possible. But at the same time it was necessary to ensure that that flow in the intake did not have an adverse effect on the performance of the pump. Large pumps could now be designed with efficiencies of the order of 90%, but in the case of high-specific-speed pumps, that performance very often depended on good flow conditions on the suction side.

To the sources of swirl in suction pipes listed by the Author, Dr Denny would add the sump itself; because, if the water swirled in the sump, that swirling motion persisted as the water flowed into the pump, and the effect was either to reduce the delivery of the pump or to overload the driving motor. Sometimes the swirl in the sump was localized into a vortex, the tail of which reached the suction pipe and allowed water to be drawn in. Most pumps did not like air, and experiments showed that 1% of air entering with the water could reduce the efficiency by as much as 10–15%. That decrease in efficiency could pass unnoticed if there was no means of measuring the flow through the pump. The one sure way to avoid swirl and vortices was to make the sump very deep, but that was a very expensive remedy. However, by careful attention to the shaping of the boundary walls it was possible to control the flow patterns even in shallow water.

Recent research had led to the framing of guiding rules for the design of sumps, but it was still difficult to predict the performance of individual sumps. For that reason it had become more usual, particularly with large schemes, to investigate the flow conditions in the sump by means of a scale model. Such models could provide fairly accurate quantitative data for the design of an inexpensive sump which at the same time would not adversely affect the performance of the pump.

Dr Denny then showed an illustration of a 48-in.-dia. pump inlet submerged in a power-station cooling-water sump. A 10–15-in.-dia. vortex had formed in the sump and the pump ran very roughly. He then illustrated a $\frac{1}{12}$-scale model which almost exactly duplicated (to scale) the vortex formation and flow patterns. The model had been used to find means of avoiding the swirl and the vortex. The erection of steel baffle-plates in the sump had prevented the vortices both in the model and in the full-scale installation.

Fig. 13 showed an unusual view of a vortex, taken through the glass side of the tank. The vortex, which appeared as a trumpet on the surface, had an air core stretching down

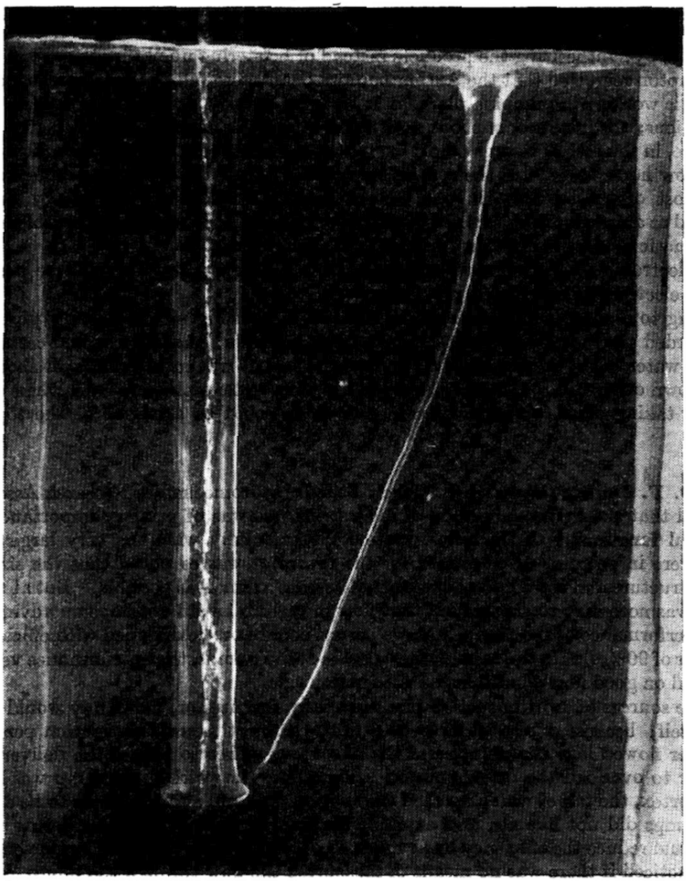


FIG. 13

to the bell-mouth, and air was entering the pipe. It illustrated how deep the vortex core could go if the flow conditions in the sump were bad.

Mr Gerald Lacey (Consultant, Drainage and Irrigation Adviser, Colonial Office) said that the Author had listed, amongst the various uses to which pumps could be put, the augmenting of agricultural production. So far as irrigation was concerned, engineers were faced nowadays with the larger problem of integrating land, water, and power resources. Of those power resources, a part could be devoted to pumping, either for drainage or for irrigation, and both were very frequently required.

The Author had referred to the exploitation of underground water resources for irrigation in India and Pakistan. That had been done in the United Provinces, and the first large project of that kind had been due to the vision and energy of the late Sir William Stampe, under whom Mr Lacey had had the privilege to serve. Twenty years ago there had been no fewer than 1,500 of the tube wells to which the Author had referred in the United Provinces, and all those wells had been operated by power derived from falls on the Ganges canal. It went further than that, however, because in addition to those falls on the canal there had also been thermal stations. There had been a grid extending over a great part of the province, and that grid also supplied power to pump water from the Ramgunga river to the Ramgunga canal. In fact the first base load had been the Ramgunga canal pumping station and the large-scale development of tube wells had followed. That grid was still expanding, and it was an early example of the integration of land, water, and power resources.

In many countries water was pumped from rivers for irrigation, the Nile in Egypt and the Sudan, and the Tigris in Iraq being notable examples. In the near future there would in all probability be two or three new major canal systems constructed in Iraq. When large sums were to be spent on projects of that character, and when there was soil of which the full productivity had not been tested, it was always advisable when possible to have a pilot scheme to try out in advance and on a small scale what it was hoped to achieve when the gravity canal works were ultimately constructed. For that purpose, a pumped pilot irrigation project from the nearest river was invaluable. As the Author had pointed out, there were many cases where pumping was decidedly more economic than a gravity system, particularly for small works, or when a gravity canal involved a long haul for the water over difficult country.

One thing which had not been emphasized in the Paper was the extent to which pumping through pipes should be cut down whenever possible. If the levels permitted, it was much better to pump in a number of stages, giving the effect of a staircase with open channels between the steps, than to have a long delivery pipe, because a great deal of head was lost in the latter process. During the war Mr Lacey had been concerned with a water supply system for Jodhpur, where water was brought from a range of hills some 90 miles away, 80–90 cusecs of water being taken across country in a lined open channel, siphoned under a number of rivers and finally pumped up in step-by-step fashion into a storage reservoir. The method had been adopted during the 1939–45 war when pipes had been unobtainable; it had proved to be cheaper and more economical in power.

The Author had referred to Diesel engines as being very useful for small pumping schemes. Mr Lacey suggested that so far as possible a Diesel-electric system should be used, with a Diesel-engined central power house and pumping stations tapping a small local grid.

Iraq was very fortunate in having two sources of power—oil and water. There were no large falls on the canals, but large storage works now under construction would provide power, and in any future overall power development a compromise between oil and water had to be made.

Mr M. R. James (Planning Engineer, Metropolitan Water Board) quoted from p. 666 and said that to the words "right size of pump, the right number of pumps, and the right place to put them" he would like to add "the right types of pump".

Every drop of water used in London had to be pumped at least once—most of it twice and some more often. The extent and complexity of the distribution system made it essential to ensure that the right types of plant were employed and that head losses were reduced to the minimum.

Pumping in London was not confined to distribution and Mr James described with the the aid of a wall diagram (reproduced as Fig. 14) an installation at the Hampton works of the Metropolitan Water Board for pumping raw water to storage reservoirs by utilizing available excess head.

It was the normal practice for all water which had to be purified to receive its first stage of purification by passing through open storage reservoirs, which had been built primarily for the purpose of storing water against drought. In its passage through those reservoirs it underwent sedimentation, equalization of quality, and the reduction of pathogenic bacteria.

A substantial proportion of the water which was purified at the Hampton works came from an intake on the River Thames about 1½ mile above the works, at Walton, where it was pumped into a couple of storage reservoirs with a top water level at 65 O.D. and then flowed by gravity down to the inlet of the rapid filter plant at Hampton, which was at a level of 33 O.D.

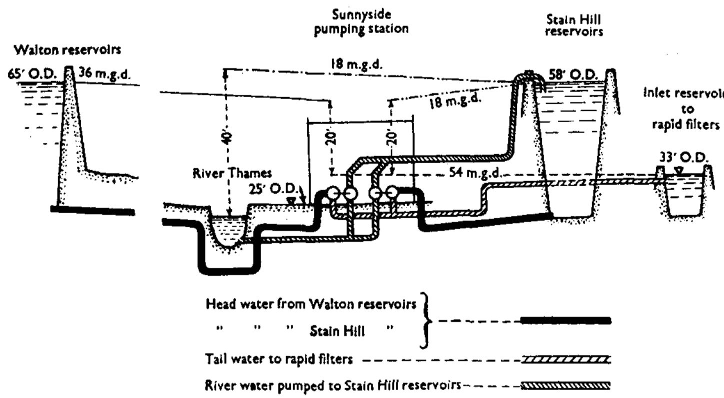


FIG. 14.—HAMPTON WORKS. SUNNYSIDE PUMPING STATION

There were also at Hampton two much smaller reservoirs (known as the Stain Hill reservoirs) with a top water level of 58 O.D., which could also discharge to the rapid filters at 33 O.D. In both cases there was about 20 ft of excess head. Adjacent to the intake was a small pumping station with five rather comprehensive units, each consisting of a water turbine, an electrical machine which could be used either as a motor or as a generator and a pump. The suction of each pump was connected to the intake, and its delivery to the inlet main of the Stain Hill reservoirs. The overall efficiency of the turbine-driven pumping sets was approximately 66%.

Assuming that 18 m.g.d. was allowed to flow by gravity from the Stain Hill reservoirs through one of the water turbines to the filtration plant, that quantity would pump 6 m.g.d. from the river to the reservoirs. That meant that 18 m.g.d. had come out and only 6 m.g.d. had gone in, and so in a few days the reservoirs would be empty and they would have lost all their head unless something else was done. To make up the difference of 12 m.g.d. 36 m.g.d. flowing from the Walton reservoirs to the filters at Hampton was made to pass through two more water turbines, which operated two 6-m.g.d. pumps to lift the balance of 12 m.g.d. to the Stain Hill reservoirs.

Reduced to its simplest terms, the installation enabled 18 m.g.d. to be lifted from the Thames at Hampton for circulation through the Stain Hill reservoirs and saved the fuel which would otherwise be necessary to lift an equal quantity of water from the intake at Walton into the Walton reservoirs. With present-day prices of coal and electrical energy—the plant at Walton was either steam or electrically driven—the annual saving in energy, if the plant were kept in operation throughout the year, would be about £12,000.

The station ran unattended except for a cleaner during the day. The electrical machine on each set had two main purposes. The first was to assist the water turbine to work the pump should the water level of the reservoirs fall below the normal, and eventually to take over the whole of the pumping from the turbine if the reservoirs had to be completely depleted. The second was to make use of a larger amount of excess head which would become available when a new reservoir was built, close to the existing Walton reservoirs but farther south, having a higher top water level. The turbines would not only do the pumping but also generate current which would be fed to the bus-bars of the main pumping station.

The electrical machines had hollow shafts and three clutches, which enabled any of the following combinations to be used:

The turbine to drive the pump with the electrical machine idle.
The turbine and the electrical machine to drive the pump together.
The turbine to drive the pump and also the electrical machine as a generator to supply current to the works.
The turbine to drive the electrical machine as a generator, without the pump.
The electrical machine to drive the pump with the turbine idle.

The plant had been installed in order to make use of excess head which existed to satisfy other requirements. It would not have been advisable for the Board to have the reservoirs designed with their present top water levels solely to provide pumped storage with all the disadvantages enumerated by Mr Lupton.

Mr G. A. Bonnyman (Sir Alexander Gibb and Partners, Consulting Engineers), referring to the irrigation scheme at Goneid illustrated in Fig. 10 of the Paper, said that the scheme had been installed to pump water from the Blue Nile up to the distribution channels at a higher level, and it was the largest irrigation scheme in the Sudan.

At Goneid a large proportion of the water for irrigation was required when the river was in flood; however, when the river was at a low level a small quantity of water was also required, so that there was the problem of ensuring that the pump suction would work satisfactorily under those conditions. The Author had stated that the first essential was to ensure that the suction was not surrounded by a wide, unbroken expanse of water surface. At the station in question, the location of the intakes sufficiently far out in the river to obtain adequate submergence at low Nile, resulted in just the condition to which the Author referred. The presence of silt and sand had ruled out a number of alternatives. Accordingly, after a model test it had been decided to arrange a wall close to the back of the intake pipes. The screen installed in front should also have a beneficial effect. The present season was the first for which it had been in operation, and it was working quite satisfactorily. There was only another month to go before the lowest river level was reached, and then all would be well.

The general layout was very favourable to the installation of a surge tower. In order not to exceed the maximum permissible suction head for the pumps, it had been necessary to install them about 22 ft below ground level, and therefore the height to the top of the tower above ground level was relatively small; it had been possible in that way to provide an inexpensive solution of the problems of surge and water-hammer.

As was well known, the axial-flow pump was suitable for low heads and the centrifugal pump for higher heads. What did the Author consider to be the most suitable change-over point from the one type to the other?

Mr M. W. Leonard (Soil Mechanics Ltd) used a series of slides to illustrate various methods of ground-water lowering in general use by civil engineering contractors.

Mr K. H. Tuson (Partner, Messrs Mackness and Shipley, Consulting Engineers) referred to the difficulties which appeared to exist in the design of a combined pump and turbine for pumped-storage schemes. Could the Author say why the design had not progressed further than it seemed to have done? In view of the amount which would be saved, on machinery, building, and excavation and of the complication of three clutches and so on, it seemed that it was a study which mechanical engineers might find it well worthwhile to pursue with vigour.

Mr I. C. Forbes (Engineer, Dorchester R.D.C.) put two questions to the Author. Some time ago he had been interested in a water-supply scheme, where the top water level of the distribution reservoir was 786·00 O.D. The length of the rising main was 4¼ miles, and the standing water level in the borehole was 220·00 O.D. with the station floor level 256·00 O.D. (Fig. 15). The station had turned over from Diesel-engine drive to

FIG. 15

electrical power, and there had been trouble at once when the current failed. The sudden cessation in flow had caused a pressure drop in the main, and the pressure wave, whose initial point was at the impeller tip, had travelled the whole length of the rising main, with a velocity of approximately 4,600 ft/sec. It had been found by calculation that the time lag between the times when the pump cut out and the back surge from the reservoir occurred was 4½ sec, and the conclusion had been reached that no surge suppressor would be able to act quickly enough to prevent damage. On those grounds it had been decided not to install a surge suppressor. Would the servo-mechanisms mentioned by the Author act sufficiently quickly to overcome that surge and resurge? Mr Forbes then referred to the Humphrey gas pump which had been popular about the year 1910. It had struck him as being a very capable pump for handling large volumes of water, but since it had been installed in a reservoir for the Metropolitan Water Board, he had never heard much about it, and wondered whether or not it had fulfilled what had been claimed for it at the time.

Mr M. R. James, replying to Mr Forbes's question about the Humphrey pumps at Chingford, said that they had been quite successful in the work for which they were designed; their load factor had been low, because their duty was to refill the King George Reservoir whenever it had to be used to supplement the flow of the Lea so as to maintain the supply to the Lea Valley works. Periods of drought occurred relatively infrequently and the result had been that the Humphrey pumps had not worked a great deal. Their load factor over the past 43 years had been only about 2½%.

*** **Mr P. Dériaz** (Chief Designer, Water Turbine Department, English Electric Co. Ltd) referred to the Author's mention of dual-duty runners, capable of running as turbines and as pumps. Examples of such reversible pump turbines were the Colorado–Big Thompson, the Flatiron, and the Hiwasse pump turbines. Reversible pump turbines with movable blades of the Kaplan type had also been considered for very low heads (especially in France for tidal schemes).

The origin of the mixed-flow variable-pitch reversible pump turbine, now being installed at Niagara Falls was worth mentioning. Early in 1952, it had been noticed that some of

*** This and the following contribution were received after the closure of the oral discussion.—SEC.

the largest Francis turbines were being run continuously at very low gate opening with consequent wastage of water. The possibility of disturbances on the extensive distribution network had made it necessary to provide for emergency power supply at the very shortest notice and that was the reason which had been put forward by the operating engineer for such unorthodox procedure. To the designer of the turbines, that state of affairs was very disappointing. To remedy it would require a turbine having its maximum efficiency at small gate opening instead of the usual seven-eighths of full rated load for a Francis turbine of medium specific speed. Reference to Fig. 16 would show that the Kaplan turbine approached that requirement. On the other hand, the Francis turbine of medium specific speed ($n_s = 216$(metric)) gave, at 0·4 of rated power, an efficiency 9 points below the Kaplan of $n_s = 420$. The shaded area illustrated the importance of the improvement required. The diagram also showed why the Kaplan turbine had

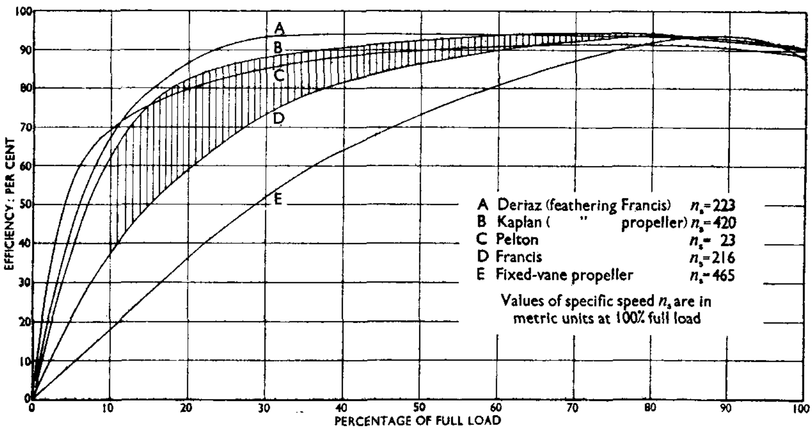


FIG. 16.—COMPARISON OF RUNNER EFFICIENCIES

ousted the propeller-type fixed-blade turbine in so many cases. Now it was particularly the Francis turbine, associated with storage, short pipelines, and heads ranging from 200 to 700 ft, which was interesting.

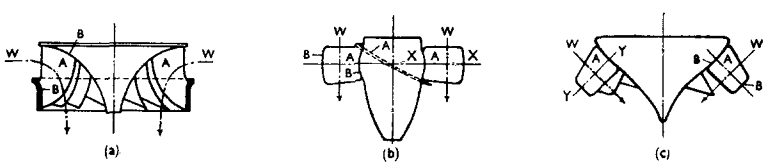


FIG. 17.—COMPARISON OF FRANCIS, KAPLAN, AND DÉRIAZ TURBINE RUNNERS

(a) Francis (inception about 1870, Swain)	(b) Kaplan (inception 1913)	(c) Dériaz (1952)
A. Fixed vanes	A. Adjustable vanes about axis XX	A. Adjustable vanes about oblique axis YY
B. Toroidal surfaces of hydraulic profile	B. Spherical surfaces of hydraulic profile	B. Spherical surfaces of hydraulic profile
W. Direction of flow: radially inwards, axially outwards	W. Axial direction of flow	W. Oblique direction of flow

In 1952 Mr Dériaz had set himself the task of investigating the possibilities of applying the principle of the Kaplan turbine with its feathering vanes to a head of 300 ft, i.e. exceeding anything which had been attempted so far. The Kaplan turbine had so far been developed to a maximum head of 200 ft. Attempts to exceed that head had encountered very serious difficulties:—

1. A lower specific speed was necessary than that of a normal Kaplan turbine because of cavitation conditions and efficiency. The hydraulic requirements of a lower specific speed was the short expanse in a radial direction of the inlet edge of the turbine runner vanes. Compared with a Kaplan runner, there had to be more vanes and an increased ratio of vane length to pitch. The inevitable result was the mixed-flow layout, Fig. 17c.
2. Mechanically the enormous loads to be supported by the runner-vane pivots required a very large hub diameter, to locate large bearings.

It became obvious for all those reasons that the axial-flow character of the Kaplan turbines (Fig. 17b) had to be abandoned and that the mixed-flow position of the Francis runner vane (Fig. 17a) associated with the feathering possibility for altering the pitch, provided the solution. The new turbine thus conceived was shown in Fig. 17c. Its principal features were as follows:—

1. The oblique "mixed flow" position of the runner-vane trunnions, with the advantage of the short radial expanse in the vane inlet edge, associated with larger distances between the bearings of the vane trunnions.
2. The spherical surfaces of the hub and skirt to permit rotation of the vanes whilst maintaining close clearances. (A departure from the corresponding toroidal surfaces of the Francis runner.)
3. The runner vanes were of simpler shape than those of the Kaplan and could be made to close over their entire length, where they met each other in the closed position, where the runner could act as an effective shut-off valve.

A turbine designed on those principles and tested gave remarkable results, the efficiency curve showing an improvement even on the Kaplan turbine (Fig. 16). There was no doubt that such a turbine had many striking advantages over the Francis which it would replace in many cases as the Kaplan had replaced the fixed-vane propeller runner.

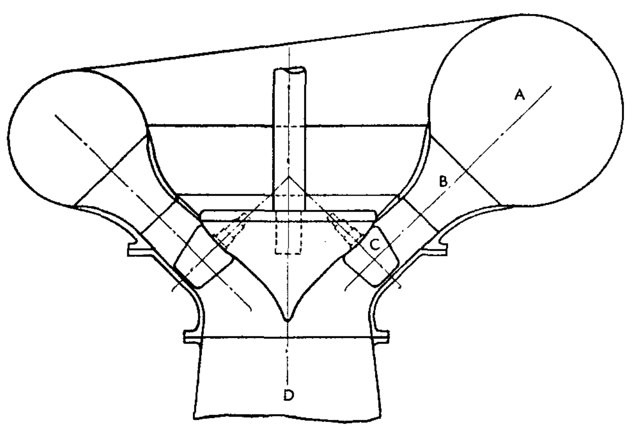


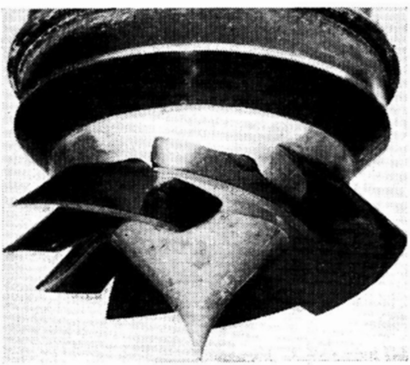
Fig. 18.—Revised form of spiral casing and diffuser
A. Spiral casing, oblique design. B. Fixed diffuser blades. C. Variable-pitch runner vanes. D. Suction pipe

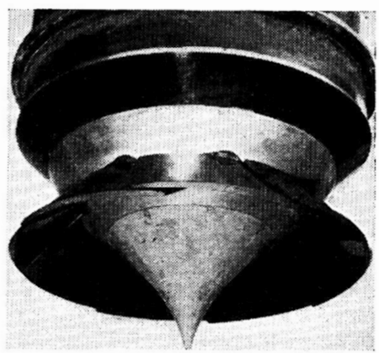
In the spring of 1953 The English Electric Company had decided to enter the new field of reversible pump-turbines and develop machinery for the hydraulic conditions set out by the Hydro-Electric Power Commission of Ontario for their pumped-storage scheme at Sir Adam Beck No. 2 generating station at Niagara. In view of the large fluctuations in head of that pumped storage, a feathering machine offered some definite advantage over the fixed-vane conventional pump-turbine because of its flexibility and it had been decided to go ahead on the design of an entirely new runner combining the characteristic of a reversible pump-turbine with the flexibility given by movable vanes.

In view of the very large size of the motor-generator, synchronous machines were the rule. They had a relatively low starting torque and might be difficult to bring to synchronous speed owing to the heavy torque required by a conventional pump, even with shut gate. That difficulty was obviated with the conventional pump by depressing the water level in the pump-suction pipe so as to permit starting the pump with the runner clear of the water. With the feathering machine that difficulty disappeared because the torque required to drive the turbine runner in shut position was a very small fraction of the normal torque. Provision for compressed air with its bulky tanks and compressors became unnecessary. The start would take place very much more quickly.

The reversible version of the new turbine had obviously to take into account the requirements of high efficiency when working as a pump as well as a turbine. To that effect a completely revised form of spiral casing and diffuser had been developed (Fig. 18).

The runner is shown in Figs 19a and b.





(a) VANES OPEN (b) VANES SHUT

FIG. 19.—DÉRIAZ RUNNER

Preliminary tests carried out on a 24-in. model under 12-ft head showed excellent promise. It had then been decided, at the suggestion of the Hydro-Electric Power Commission of Ontario, to repeat the tests under full prototype head, ranging from 90 to 30 ft. A model turbine pump of a smaller size had been used.

From tests under prototype head, it had become clear that full head could be developed by the feathering pump at any opening of the runner vanes. No instability had been observed. That was of considerable importance, since the starting operation of the pump could be carried out smoothly and the power input controlled to any desired load.

Whether running as turbine or as pump, the runner could be made to run at optimum efficiency. That was of great importance, especially for the pump which was efficient at full head also.

As a result of those tests the Hydro-Electric Power Commission of Ontario had ordered six units of 52,500 b.h.p. each for their Niagara pump-turbine station.

Dr Charles Jaeger (Consulting Engineer, English Electric Co. Ltd) believed that in the near future pumped-storage schemes would acquire considerable importance. His opinion was based on the probable increase in the cost of coal at a faster rate than that of the average cost of living, and even more so on the future development of nuclear power and new technical developments in pumped-storage schemes.

In spite of pessimistic basic assumptions a price estimate by Haldane and Blackstone[19] showed that pumped-storage schemes were a paying proposition for the conditions prevailing in Great Britain. For conditions obtaining in a power economy based mainly on water power, price estimates given by Musil[20] led to similar favourable conclusions.

Very little information was available on the probable structure of prices for nuclear energy. It was assumed that capital costs would be high and that that type of energy would be base load. Most experts were of the opinion that even in countries now widely depending on steam power the production of additional peak-load energy would be by hydro-power of the more flexible type and/or by pumped-storage power.

When comparing thermal peak power and pumped-storage power,[21] the possible improvements in the overall efficiencies in the near future for both types of schemes should be considered. It was to be expected that thermal-power efficiency would be steadily increasing at a slow rate. The overall efficiency of a pumped storage scheme was given by the formula:

$$\rho_1 = \frac{H_T Q_T T_T}{H_P Q_P T_P} \eta_T \eta_P$$

where H = gross head,
Q = maximum discharge,
T = time during which station runs loaded at full capacity,
$QT = V$ = the total volume of water passing through the runner,
η = an overall efficiency factor including pipe losses.
The subscripts P referred to pumps and T to turbines.

True pumped storage corresponded to the conditions: $V_P = V_T$, $H_P \simeq H_T$, and therefore $\rho_1 = \rho_1^* = \eta_T \eta_P$ (as in the Ffestiniog project in Wales).

For true pumped storage a value of $\rho_1^* = 0{\cdot}6 - 0{\cdot}70$ was often assumed, neglecting the friction losses in the pipes, which should be kept as low as possible for that type of station.

Mixed pumped storage corresponded to the case where $H_T > H_P$ and/or $V_T > V_P$. The case $H_T > H_P$ was illustrated by the Sron Mor pumping station[22] (Scotland) where the water pumped from the lower reservoir up to the higher larger reservoir flowed back and through the turbines and also through the turbines of Clachan power station (Fig. 9). For Sron Mor, $H_P = 138$ ft and $H_T = 138 + 956 = 1{,}094$ ft. The Niagara Falls pumped-storage scheme also worked economically with $H_T = 292$ ft and $H_P = 90$ ft.

That definition of ρ_1 showed how, given favourable natural conditions, the overall efficiency could be improved.

If $$\rho_2 = \frac{P_{\text{peak}}}{P_{\text{off}}} = \frac{\text{Value of on-peak energy in pence per kWh}}{\text{Value of off-peak energy in pence per kWh}}$$

the P_{peak} value denoting the value of power (usually given in £ per kW) expressed in pence per kWh, then the simplified expression $\rho_2\rho_1 \geqslant 1$ represented the conditions for a pumped-storage scheme to be economical, provided that capital charges and operation costs were being neglected. (A value of ρ_2 from 2 to 3 could be assumed for normal present-day conditions but higher values could be foreseen when nuclear energy developed.) The condition $\rho_2\rho_1 \geqslant 1$ would approximately apply to the hypothetical case when a pump-turbine could be installed in an existing hydro-power station, where dam, reservoir, tunnels, and pipelines already existed, and were paid off by running the station on conventional lines without pumping.

More generally:

$$\rho_2^* = \frac{P_{\text{peak}} - P^*_{\text{charges}}}{P_{\text{off}}} = \frac{\text{Value of on-peak energy} - (\text{capital charges} + \text{operation charges})}{\text{Value of off-peak energy}}$$

and the more general conditions for a true or a mixed pumped-storage scheme to be economical were:

$$\rho_2^*\rho_1^* \geqslant 1 \text{ or } \rho_2^*\rho_1 \geqslant 1$$

Capital charges, operation charges, and all types of losses were included in ρ_2^* and ρ_1.

Turning to modern trends in pumped-storage design, the average turbine efficiency η_T, under varying conditions of head, could be vastly improved if a Dériaz variable-blade impulse turbine[23] was substituted for a conventional Francis turbine. It had been shown that the efficiency curve of a Dériaz turbine was flatter than that of the Kaplan turbine and its overall efficiency was high when compared with the accepted values for a conventional Francis runner.

A similar observation applied to the Dériaz pump runner, giving high average η_P values.

Finally, under special conditions a Dériaz reversible pump-turbine with movable blades could be considered.

A reversible pump-turbine had been developed for heads ranging from 43 ft to 90 ft for the Niagara pumped storage station. The Dériaz turbine had been designed for heads

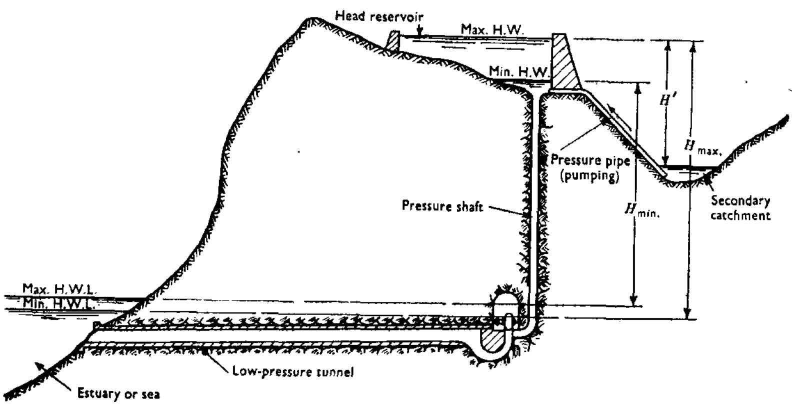


FIG. 20.—POSSIBLE APPLICATIONS, TO A COASTAL RIDGE OF HILLS, OF A PUMPED-STORAGE SCHEME WITH UNDERGROUND POWER STATION

of up to 300–350 ft, and higher heads were being considered. It had been objected that —for the time being—no design existed for a wider range of heads; that objection lost some of its strength when it was considered that the range which was already covered by existing designs was by far the most important for pumping purposes. Many large rivers were dammed by 300 to 350-ft-high dams where pumping stations with short pipes (reduced cost and reduced friction losses) could be established.

Whenever reservoirs were to be built in the near future, the possibility of further pumped storage to be added later should be borne in mind at an early stage. Tunnels, pipes, and surge tanks had to be built accordingly.

The advantages of underground power station designs for pumped-storage schemes should be closely investigated. Fig. 20 showed some possible applications to a coastal ridge of hills.

Pumped-storage developments would require the most economical designs to be adopted: very light buttress dams, prestressed concrete dams, etc., would have to be considered for daily or weekly reservoirs for peak-energy prices to be kept as low as possible.

It was commonly argued that most of the resources of new hydro-power still available on the continent of Europe would be exhausted within the next 15 or 20 years.[24] Before that, a new trend would be set into motion and existing conventional hydro-power schemes would be turned into mixed-storage schemes.

The Author, in reply, said that Mr Lupton made a number of very interesting points, and in particular had commented on the automatic working of pumping plants. In a Paper of rigidly defined length it had been necessary to omit many such topics. With regard to the absence of siphonic action in the Tarraleah plant, Fig. 4 had been taken from the constructional drawings supplied by Mr Knight, of the Tasmania Hydro-Electric Commission, for whose energy and ability the Author had the greatest respect. He had seen the plant, and he had no doubt that the siphon pipe had been omitted because it was a temporary installation, and it might have been considered better to leave the plant as it stood rather than to use a reflux valve or something of that sort. The question of the submerged delivery pipe had often caused comment. On one occasion in Egypt a salesman had tried to convince a landowner of the advantage of a submerged delivery pipe as against allowing the irrigation water to splash many feet below the pump outlet, whereupon a rival salesman had tried to sway the landowner the other way by saying "Pasha, what do you feel when you put your hand over your mouth?" "I feel suffocated," said the Pasha. "So does the pump," replied the salesman.

Dr Denny had given an admirable exposition of his work, which made very clear the necessity for careful study in designing sumps.

Mr Lacey had spoken of the use of canals instead of pipes. Very often a combination of the two was used. Mr Bonnyman could explain that in the Goneid scheme there was a relatively short delivery pipe and the main canal began as soon as the necessary height had been reached. Mr Lacey had spoken of competition between Diesel and electric plant, and there was a fascinating range of opinion on that subject. Mr Doran had also referred to that matter. By avoiding the peak-load periods it might be possible to use electricity where before it had not been competitive.

Mr James had described a very interesting project. It was surprising to learn that in the Metropolitan area there was a pumped-storage scheme actually at work. It showed the great attention that the Metropolitan Water Board paid to making the most effective use of water power and not wasting energy if they could possibly help it.

Mr Tuson had spoken of the difficulty in pumped-storage plants of using the same machine both as pump and as turbine. The Author thought that the difficulty did not lie in actually using a single machine, but in getting it to work at the highest possible efficiency; because storage pumps must work at a high efficiency all the time if the scheme was to be economically sound. Comparing a given rotor working first as a pump and then as a turbine, at a given speed and discharge, it could be shown that the head generated by the pump would be less than the head applied to the turbine. That was because of the reversal of the direction in which the internal energy losses operated. There was a corresponding difference in the direction of the external energy losses, e.g., friction losses in the conduits between the upper and lower reservoirs. Nevertheless, if regard were paid to the normal head-discharge characteristic curve of the pump, it was true that at a *reduced* discharge it might be possible to generate the desired head, but because of the shape of the efficiency curve, the machine would be working at a much lower efficiency. That was the basic difficulty of getting the same constant-speed machine to work as pump and as turbine. That was why in one of the schemes mentioned in the Paper there was a two-speed motor-generator, which worked at a high speed when pumping and at a lower speed when generating.

With regard to the Ffestiniog pumped-storage scheme, Mr Tuson had pointed out that its development would interfere with the Ffestiniog railway. In reply, the Author said that when he had made his reconnaissance in 1955 to see the site, he had been duly sentimentally affected by the deserted railway, but he would point out that with existing schemes in Scotland there had been railway lines which had had to be rebuilt at a higher level. At Loch Treig on the Lochaber scheme that had had to be done, and if there were sufficient enthusiasts to support the Ffestiniog Railway he thought that it could be done there also.

Mr Forbes had asked whether a surge suppressor could be designed to operate in a very small period such as 4½ sec. The Author thought that it could, having regard to the very powerful servo-motors used on American schemes.

In reply to Mr Doran's questions about suction sumps, the Author thought that either of the types represented in Figs 12b and d would be advantageous. Where multiple pumps were concerned, information had recently been presented in American Papers.[25, 26] As for the possibility of installing mechanical self-cleaning trash-racks in drainage pumping plants, perhaps advantage could be taken of the performance of similar but larger self-cleaning devices in sewage works, circulating-water pumping systems in steam power-stations, and in water-power plants. There might be difficulties in designing an apparatus that would be sufficiently simple and inexpensive for the proposed new duties.

Mr Lupton's advocacy of direct synthesis as opposed to pumped irrigation for the production of food and clothing raised questions that could hardly be answered in a few paragraphs. Quite often, the object of a land-reclamation scheme was not merely to grow food: it was to furnish a livelihood. As world population expanded, more and more thousands of people would want new lands where they could build towns and villages for themselves, and fields where they could work. Even if energy had to be expended in pumping water on to those lands, it made available vastly greater supplies of energy, that was, the energy of the sun without which nothing would grow. Moreover, an indispensable prerequisite to any process of food synthesis was a supply of raw material of various kinds, ready to be synthesized. If those materials were mineral in origin—say oil or coal—they would eventually be exhausted as mines or oil deposits were worked out. If vegetable matter was needed, then the search for that would take us back to the starting point—the land.

Mr Bonnyman had asked about the most suitable head which marked off the operating zone of axial-flow pumps from that of centrifugal pumps. Although there was no rigid limit, a figure of 20 ft head might tentatively be offered. In particular circumstances the choice of pump might be guided by other considerations than the total head, e.g., the maximum suction lift might be decisive.

Mr Forbes had referred to the Humphrey internal-combustion pump, and Mr James had mentioned the Chingford installation. Similar pumps had been used for lifting irrigation water from the Murray River in Australia; but perhaps one factor that restricted their field of action was their preference for a fairly constant suction-water level and total lift.

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Correspondence on this Paper is now closed.—Sec.