

ACKNOWLEDGEMENTS

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The Paper is accompanied by seven photographs, one drawing, and nine diagrams, from which the half-tone page plates and the Figures in the text have been prepared.

Discussion

Mr H. D. Morgan, introducing the Paper in the absence of the Author, said that a previous Paper¹ by Messrs J. K. Hunter and R. W. Mountain, M.M.I.C.E., had dealt, on a very general basis, with the value of hydro-electric power as compared with steam power. The present Paper discussed some of the fundamental factors and variable conditions which were encountered in designing the civil engineering works of a hydro-electric scheme and also touched on some of the factors which entered into the methods of operation appropriate to the varying circumstances for which the power was required.

On p. 132 there was a remark about the size of generating stations and a reference to *Fig. 17*, which illustrated the Lochaber power house. It was not intended to imply that that was typical, because Lochaber was a low-voltage station with very high amperage used for furnaces, and the fact that the voltage was low increased the space occupied.

Any questions of economic design necessarily involved certain assumptions in regard to the variable factors concerned; for example, annual charges on capital, which might range up to 13 per cent. according to the rates of interest chargeable; friction coefficients, which could not be exactly determined; and many similar points.

Mr Morgan cited the case of the tunnel which conveyed water from Loch Laggan to Loch Treig in the Lochaber scheme. Extensive calculations had been carried out to determine the economic diameter of the tunnel, but Sir William Halcrow had decided to increase the figure by an apparently substantial amount. In operation it turned out that the flow conditions were less favourable than had been anticipated and the larger tunnel was completely justified.

¹ "Hydro-Electric Development: Some Economic Aspects." J. Instn. Civ. Engrs, vol. 19 (Jan. 1943), p. 135. *Discussion*, p. 161.

Methods of construction and the availability of material and skilled labour also entered into the picture. When considering a tunnel, it was necessary to take account of the improved methods of driving which could be adopted with larger diameters. In view of that and the shorter time of construction thereby obtained, a larger tunnel might prove more economical than would appear at first sight.

Similarly, in the case of dams, a buttress dam often showed itself to be very economical, on paper, but against the saving in concrete there was the larger consumption of timber and joiners' labour in the shuttering which, with present conditions in Great Britain, tended to offset the advantage. The position in those respects changed much more rapidly than used to be the case and further complicated economic calculations and considerations.

Mr Morgan then commented on *Fig. 9*, which had been drawn from observations at the Lochaber station. At Lochaber there had been quite significant apparent variations in efficiency from time to time and an intensive search for the cause had been made. As might be expected the main reason for the variations was found to be the number of machines in operation and holding the load at any given time. The specialized equipment required by the particular nature of the load served by the station made complete flexibility impossible, so that it was necessary at times to run sets at part load to a greater extent than would be normal in another type of station.

Mr R. W. Mountain confined his remarks to electrical considerations and commented on two general points which arose in pp. 119-124, *ante*. First, how was a decision made on the size of the dam for storage—the quantity of concrete which was put into it, if it were made of concrete; and secondly, how was the amount of plant to be installed for a given site and for given electrical requirements decided?

Fig. 6 concerned different sizes of conduit and plant over a wide range, and Mr Morgan had explained that that referred to a scheme in Portugal; *Fig. 7* concerned storage. The Author had shown that it was possible to decide how much concrete to put in a dam by considering the law of diminishing returns: only an economical proportion of the run-off should be used, and that was taken into account when deciding the level and size of the dam.

The second point—how to decide on the size of the plant and the tunnels and pipe-lines—arose in regard to *Fig. 6*. It appeared that the Author had restricted his basis for calculating that to the revenue which would be obtained from the electricity, simply expressed as units or kilowatt-hours. Had the Author taken into account what was, in effect, the capacity value of the scheme as distinct from the use value—the kilowatts of maximum demand as distinct from the units of electricity sent out from the scheme?

If those two factors—the economic cost of storage and the economic

amount of plant—were taken together, Mr. Mountain thought that they would be found to be interrelated; yet there was no suggestion in the Paper that that was so. Could the Author give some data on the essential factors which governed the amount of storage and the amount of plant in the Portuguese scheme shown in *Fig. 10* and also referred to in *Fig. 6*?

Mr J. Guthrie Brown said that it was essential, at the present time, to give special consideration to the economics of hydro-electric schemes, in view of the rapid increase in construction costs. Labour costs, which had been about 2s. 5d., would rise to 2s. 8d. in the near future—a 10-per-cent. increase, which would probably mean an overall increase in construction costs of about 5 per cent.

Taking 1 kilowatt of installed plant in the power station as an approximate guide, hydro-electric schemes in Great Britain before the 1939–45 war had cost from £25 to £35 per kilowatt. The Galloway power scheme, completed in 1936, had cost £28 per kilowatt. At present hydro-electric schemes in Britain were costing from £80 to £130 per kilowatt, or three or four times the pre-war cost. From the point of view of the hydro-electric engineer, it was fortunate that thermal stations were showing a corresponding increase. Before the war, the cost of a thermal station had been about £15 per kilowatt, and it was now between £50 and £60. The advantage to the hydro-electric engineer was that, in addition to those increased costs of the thermal station, coal was increasing in price at the same rate, whereas for the hydro-electric scheme water was still as cheap as before.

He was glad to see that the Paper had brought out the advantages of arch-dam construction, because in his opinion that was one of the most economical and reliable designs which could be adopted. He had never heard of a major failure of an arch dam, and in certain cases of model arch dams there had been the greatest difficulty, at the end of the experiments, in breaking them by overload. Unfortunately, the number of suitable valleys or ravines in which arch dams could be constructed was limited.

With regard to the multiple-buttress type of dam, he confirmed the Author's conclusion that it was an economical design, though admittedly Mr Morgan had qualified that by reference to a possible shortage of joiners. Mr Guthrie Brown was at present dealing with a diamond-headed buttress dam, 130 feet high and 1,300 feet long. Before deciding on the type of dam to be adopted, a close study had been made of two alternative types, the gravity dam and the rock-fill dam. So far as the rock-fill dam was concerned, it had seemed to be an obvious economy to make use of the stone removed from tunnels, which would provide a cheap form of rock filling; in the case of the dam under consideration, 700,000 cubic yards of broken rock would have been required and the tunnel would have provided only 15 per cent. of that quantity. Moreover, the tunnel spoil would have been obtained very slowly—at the rate of, perhaps, 1,000

cubic yards a week—and the slow delivery would have increased the cost appreciably.

The analysis of costs of the three different designs gave the following results. Taking the figure for the multiple-buttress dam as 100 per cent., the figure for the gravity dam was 120 per cent., and for the rock-fill dam, 166 per cent. Those results were not dissimilar to those to which reference had been made in the Paper. In considering the higher cost of the rock-fill dam, it should be borne in mind that the methods of dealing with the temporary and permanent control of floods were more expensive than for the other types. Apart from the question of economy, the multiple-buttress dam had certain other advantages. It had a lower intensity of loading on the foundations, a higher factor of safety against sliding than the gravity dam, and also greater flexibility, which allowed for any slight settlement in the foundations under full load.

With regard to tunnel construction, he had never seen any unlined tunnel excavated in Britain where he would permit water under high pressure and at high velocity to pass through it direct to the power station. In the Scottish Highlands most of the schist rock was unreliable, and he thought that risks of major falls would make the use of an unlined pressure tunnel too serious to contemplate. In Sweden, on the other hand, where there was high-quality granite, unlined pressure tunnels were common practice. The Swedes also built large underground stations. The slight additional cost of those—about 5 per cent.—was fully justified in view of the greater protection which they gave against the risk of bombing.

Mr P. A. Scott said that in hydro-electric works the question of economics was doubly important, because not only was it necessary to consider the economics of the design of each individual structure in the scheme but also—before it was possible even to start on the design of those structures—it was necessary to prepare a whole system of operation; in other words, it was necessary to design the hydro-electric scheme. The charge was commonly levelled against civil engineers that they represented spending departments and that, although they knew that everything they built had an economic value—however much it might be hidden—hydro-electric work was one of the few branches of civil engineering which did show some obvious return.

Perhaps the Author had been carried away by that idea, because on p. 121 and in *Fig. 6* the word “profit” had suddenly occurred, although it was not used elsewhere in the Paper. Mr Scott did not subscribe to the modern idea that profit was something to be abhorred, but he suggested that a better term could be found for that case. The net profit was the difference between the selling price and the production cost; but the selling price did not enter into the present discussion since, for the purposes of the Paper, it was a constant and could therefore be ignored. Instead of “profit” he suggested the unit cost of production, and that the

curve for the economics of conduit capacity (*Fig. 6*) should be plotted against the cost of production instead of the annual net profit.

On p. 124, the Author had stated: "Unfortunately, it is not yet possible to predict weather sufficiently far ahead to enable storage to be operated at the maximum possible efficiency. . . ." That was very true, and in a recent issue of *Water Power*¹ the Editor had raised the point of the increasing need of long-term meteorological forecasts. Great strides were being made in that direction. Clearly, it would be of great assistance to the designers of hydro-electric schemes if they were able to draw on reliable long-term weather forecasts. In Britain that might seem impossible, but Mr Scott had no doubt that in the future, if sufficient attention were focused on the need for long-term forecasts, they would be produced, thus making it possible for more economic schemes to be designed.

In the Paper the Author had rightly concentrated his attention on the economics of a hydro-electric scheme by comparing the costs of building the scheme, and running it, with the numbers of units of electricity produced. That was the first thing that had to be done; but even in a small country such as Scotland, where there was so much hydro-electric work going on, the fact of starting a power scheme and controlling the waters often brought with it attendant benefits, such as the control of floods in the lower valleys, where the flood plains could, after the construction of the station, be brought into agricultural use.

That was a benefit which accrued more noticeably in the bigger schemes carried out abroad, where it was usually necessary to consider not only hydro-electric development but also the attendant benefits of flood-control down below, and often the benefits of the provision of long navigable waterways as a result of building the reservoir, with the resulting benefits of opening up the country and, frequently, irrigation. The control of floods, and the benefit to agriculture generally, had to be considered when developing a power scheme in a country which would benefit by those attendant improvements in its economy, and that allowed a much greater capital sum to be expended on the hydro-electric power scheme, provided that the Government concerned would allow credit to be taken for those other developments to offset the expenditure involved.

Mr Henry Headland thought that, in times of heavy capital expenditure and shortage of power plant, as at present, such schemes could not be considered solely from the view-point adopted by the Author. For example, many of the conceptions given in the Paper could be qualified to a large extent by the market value of "firm" and "non-firm" outputs on an interconnected system, and those two components might vary in value during working hours and at night, or over week-ends, or from month to month over the hydrographic year.

Mr Headland had recently compared quite a number of project reports,

¹ "Prediction." *Water Power*, vol. 2 (Nov.-Dec. 1950), p. 223.

and they had led him to conclude that there was a great need among hydro-electric engineers to develop a uniform economic treatment, if it were to be possible to compare several schemes on a proper basis. That comparison should include the winter and summer output related to guaranteed and run-of-river production, and it should be coupled with an established value for firm capacity in terms of the ratio of energy in storage to the minimum production in the critical season.

In connexion with annual charges, the question of running costs, in particular, was influenced largely by the quantity of installed plant, the cost of storage, the number of hours of operation per annum, the operating head, and whether or not pumps were included for purposes of providing storage.

Another factor which entered into the economic question was transmission. That was often disregarded, but it should be possible to relate the cost of delivering energy to the load centres to the market value, in terms of transmission-voltage, capacity, route-length, and number of circuits.

In the absence of a detailed analysis of *Fig. 8* and a specific definition of station efficiency, the implied criticism in the Author's conclusions would not be accepted by operating engineers without considerable protest. It was stated in the Paper that *Fig. 8* was based on spot checks; but there was no information about how those spot checks had been made, nor had the Author stated the frequency at which those lower efficiencies occurred or the number and loading of the machines in service.

Quite a number of factors entered into the question of efficiency but, considering only the impulse machines, on which presumably *Fig. 8* was based, those machines were particularly sensitive to head variations, of which the Author had not given any indication. Another serious source of loss of energy might result from aeration, caused by heavy discharges from side streams into the pressure tunnel. That resulted in the jets of the machines spreading out and thus caused loss of energy. A factor which might not apply to the particular installation in question, but which was common in mountainous country, was erosion of the nozzles, spears, and buckets by granite particles. That loss of efficiency could easily arise, even where there were stainless-steel buckets and other components, if the intake design were not properly conceived.

A source of energy loss which was not always appreciated, even by operating engineers, applied where it was demanded that the governors of the turbines should regulate over the full range of load; whilst another source was unstable governing, particularly where governors were called on to regulate on a direct-current resistance load, which was always difficult to govern from the point of view of stability.

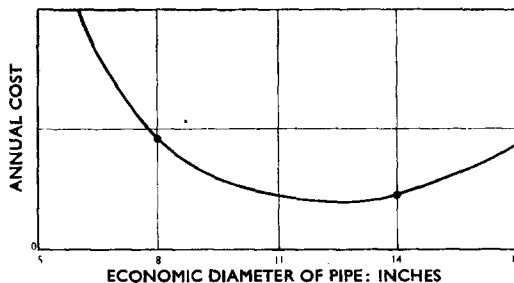
From *Fig. 9* it might be inferred that the multiple-machine station would give better results than one with only one or two units; but that was an economic question and could be solved only if the efficiency of the

combination were related to the load/duration curve. In general, the difference between the output of a station with one machine and a station with two machines might be about 5 per cent. in energy, whilst if a third machine were added the output might be increased by 7 per cent. ; so that the additional output for an increasing number of units was relatively small. The method of determining the zone wherein a given arrangement would ensure high efficiency was not so simple as it might appear from what was said in the Paper—apart from the daily load fluctuations and station interconnexion, which had to be considered. Individual turbine characteristics were seldom known precisely, and marginal losses due to differences were greater for higher-specific-speed machines such as the Francis than for Peltons, when the load was not correctly allocated.

Table 3 was based on a length/head ratio of about 1.12 : 1, but it was not often that such a favourable case presented itself ; often the ratio was nearer 10 : 1, and that in itself created problems in the field of water-hammer, stability of turbine governing, and spiral flow, all of which could have an unfavourable effect on plant efficiency and costs. An economic study of a pipe-line design, therefore, would not necessarily finish with the assessment of loss of revenue due to friction, or with the annual charges on the pipe-line.

Mr R. C. S. Walters compared the fundamental economics of hydro-electric design with those of waterworks design, since they had much in common. For instance, the mass diagram (*Fig. 3*) and the connexion between storage and yield (*Fig. 7*) were similar to those used in waterworks practice. The methods used for the compilation of the Lapworth diagram, connecting storage and yield, were similar, and the flow/duration curve in *Fig. 4* was a very useful method for cutting off the maximum floods and arriving at the curve in *Fig. 5*. In waterworks practice the same type of curve was used for determining the economic

Fig. 18



size of a catchwater ; the whole annual flow was not taken because that was not economical—about 90 per cent. was sufficient.

In *Fig. 6* the capacity of the conduit divided by the average flow was

plotted against the annual net "profit"; Mr Walters was a little mystified by the wording and by the shape of the curve; but the corresponding curve used in waterworks practice for arriving at the economic diameter of a pipe-line was as shown in *Fig. 18*. If the diameter were made too small, the cost would be higher than it would be if the diameter were too large by the same amount, because the steeper part of the curve was on the left; it was better to err on the side of largeness.

Mr Walters added that he was doubtful about the relative cost of the buttress and mass dams; but the need for caution had been emphasized by the explanation that it depended on many other factors, which might vary from day to day.

Mr P. O. Wolf suggested that the yardstick of economy was the cost of electricity produced by thermal power stations. Except for atomic-energy plants, the economics of which could not be discussed at the moment, thermal power stations were fuelled chiefly by coal. The cost of coal was, therefore, the most important factor on which the economics of hydro-electric development had to be based. In the discussion on an earlier Paper¹ presented to the Institution on that subject, the view had been expressed that the rise in the cost of coal would never make a hydro-electric development relatively more economical. Mr Wolf agreed with that view so long as the rise in the cost of coal was part of the general inflationary movement to which the national economy appeared to be subject. The prices of coal, cement, and labour might all increase and yet leave the relative merits of thermal and water-power schemes quite unaltered. He thought, however, that that was not a correct view of the situation. Since economic analyses usually assumed the life of a hydro-electric scheme to be from 50 to 100 years, it was justifiable, and indeed necessary, to look so far ahead. In that period, the price of coal, relative to the prices of other non-wasting assets, was sure to increase as the better seams were worked out and the quality deteriorated. Similar considerations applied to oil.

If the present cost of building a steam station were taken as a basis, it would be found that many hydro-electric schemes were economical to develop, both for base-load and for peak-load supplies. In addition they brought in their train great ancillary benefits, such as flood-control and safety from interruptions by such causes as strikes. The Author had shown that very economic schemes could be built if the degree of utilization of a catchment were, perhaps, 60 per cent.; Mr Wolf was perturbed by the impression which that analysis might give. He agreed with Mr Morgan that the achievement of a high degree of utilization was a public-spirited act on the part of the electricity authorities. At present, there were many upland valleys which would lend themselves to hydro-electric development. On a short-term basis, those valleys could be developed one by one, to perhaps a 60-per-cent. degree of utilization which would give a speedy

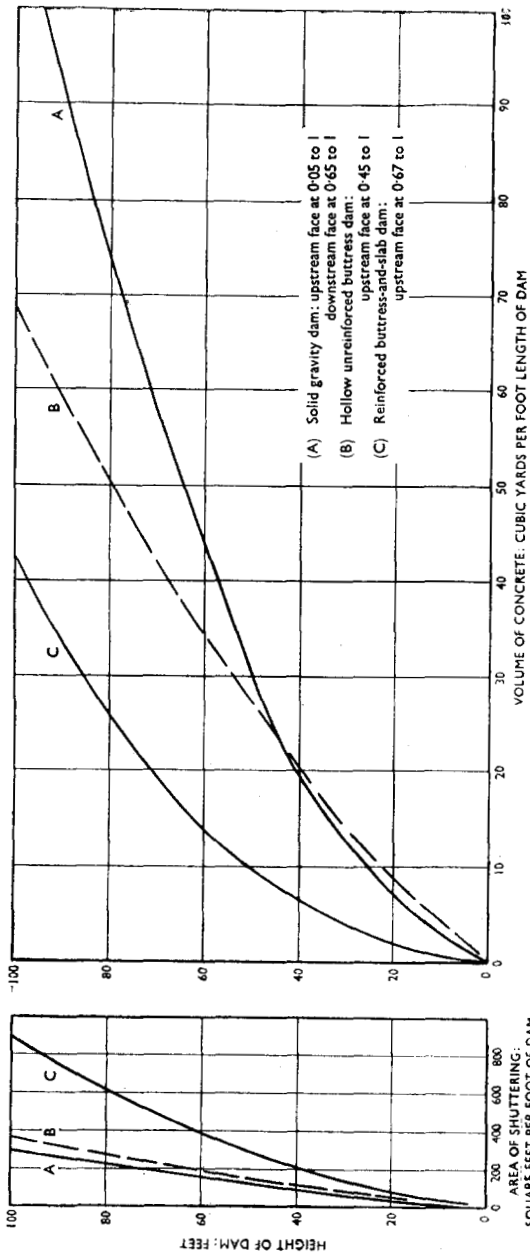
¹ See footnote on p. 133.

return. When more power was required, another catchment could be used, as suggested in Table 1. When no more undeveloped catchment areas were available, however, it would be necessary to consider raising the degree of utilization of the partly-developed ones. Alterations to existing schemes were extremely costly and extensions to dams, tunnels, pipe-lines, and power stations would cost several times the amount for which similar work could have been done at the time of the first development. In that sense, Table 1 might be extended to show the cost of obtaining the larger storage capacity in the first instance. That might, perhaps, have been between £200,000 and £400,000 in the present case, increasing the number of firm units per annum by 20 millions. Moreover, in most schemes, a heightening of the dam increased the average head on the turbines, thus increasing the long-term average output. In that respect a high degree of utilization was of greater advantage in a hydro-electric scheme than in a water-supply or similar project.

Mr Wolf understood that several countries overseas, including some of the Dominions, had decided to work on the basis of maximum initial development in each valley.

With regard to design problems, the discussion had emphasized the fact that not only the general arrangement but also many details of each project had to be studied on their merits and designed anew. With the aid of some lantern-slides (for which he was indebted to Dr Charles Jaeger), Mr Wolf discussed the alternatives to the plain gravity dam, the plain arch dam, and the roundhead-buttress dam, quoting as examples the solid-buttress and arch dam, the hollow-buttress dam, the domed (or cupola) arch dam, and the very slender reinforced-concrete dams of buttress-and-arch or buttress-and-slab construction. All alternatives to the solid gravity dam proved to be more economical in the quantity of concrete used (see *Figs 19*), whilst the quantity of shuttering increased with decreasing concrete volume. Although it was easy to arrive at a stage of each design type at which the cost of concrete plus shuttering was the minimum, there were other considerations than that of simple first cost of concrete and shuttering. Where a site did not lend itself to the construction of an arch dam, he favoured an open type of dam, preferably with walls and buttresses thick enough to require neither steel reinforcement nor lateral struts. All open types of dam had the advantage of restricting the area on which uplift pressures could be expected to act, and so made it possible to analyse the concrete stresses with great accuracy. The hollow-buttress type, in particular, was attractive, for its horizontal section, which was essentially a box, combined great rigidity with an economical distribution of material. Each wall of the "box" was thick enough to require several concrete mixes to fill the shutters, so that the effect of one weak or permeable batch of concrete was neutralized by its better-quality neighbours. That would take care of the difficult problem of concrete control at a remote site. He did not think the strategic argument should

Figs 19



override every other consideration. In the unreinforced open type of dam the concrete section was not likely to be less than 15 feet thick, which was adequate to withstand small bombs. However, no practicable thickness of concrete was proof against carefully aimed bombs; that had been demonstrated by the bombardment of the Möhne dam, which had caused a breach about 250 feet wide and 70 feet deep in a gravity dam, the thickness of which at the bottom of the breach was nearly 60 feet.

The pair of curves in *Fig. 1* might, on the basis of more recent work,¹ be supplemented by other but similar graphs. It had been observed that the probable variations from the mean in tropical climates were much greater than those in the equable British climate. It had also been found that large catchment areas were subject to smaller rainfall variations than isolated rainfall stations. Interesting attempts were being made to analyse the curious phenomena of the "grouping together" of a number of dry years, and of a subsequent number of wet years.

The variability of stream flow from year to year or season to season also arose in a discussion of the flow/duration curve in *Fig. 2*, the value of which lay chiefly in the aid it gave in preliminary investigations.

Referring to the Author's pipe-line analysis, Mr Wolf suggested that a similar analysis was required for each variable in the case, in turn, and the complete study should consist in finding the total flow required for economy of the whole project, varying the number of pipes, varying the diameters of those pipes, and possibly investigating whether a change in diameter from one end to the other of each pipe would be preferable to keeping the diameter constant. That process could be carried out mathematically, but was usually quicker by graphical or tabular methods. Having found the optimum pipe arrangement, the designer might find that it would slightly alter his assumptions for storage, tunnel, and power-plant calculations (and vice versa), and he might decide to repeat the process to obtain a better overall arrangement. There were several examples of the excellent results obtained by careful design of small details, such as the economy resulting from the alteration of the section of screen bars so as to offer the minimum of resistance to the flow.

A competent engineer had to be both an applied scientist and an economist in order to give of his best. In the end it was the engineer's client, be he administrator or businessman, who initiated action on the basis of the engineer's advice; but Mr Wolf felt strongly that in the preparatory work and in the formulation of the advice, as well as the execution of the work, it was necessary for the engineer to take full charge and not to relinquish half of his responsibility to the accountant.

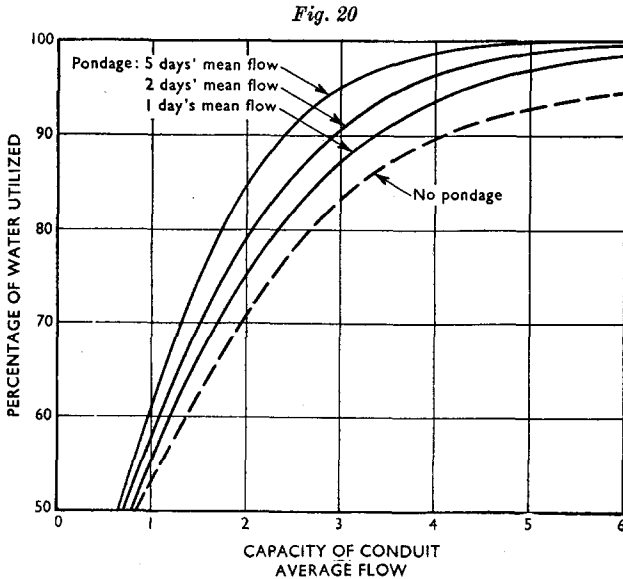
* * Mr J. H. Fleming thought that the upper curve in *Fig. 7*

¹ W. N. McClean, "Graphical Record of Rainfall in the Thames Basin." *J. Instn Wat. Engrs*, vol. 4 (August 1950), p. 432.

H. E. Hurst, "Long-Term Storage Capacity of Reservoirs." *Proc. Amer. Soc. Civ. Engrs*, vol. 76 (April 1950), No. 11 separate.

* * This contribution was submitted in writing.—Sec. I.C.E.

was misleading, because it appeared to indicate, for example, a 45-per-cent. flood loss from a reservoir storing 10 per cent. of the annual run-off. That presumably applied in the case of a plant whose capacity was only a fraction of the average flow, utilizing water corresponding to the area CDEO in *Fig. 4*. In the more normal case of a plant whose capacity was greater than the average flow, the number of unguaranteed or "spill" units would be determined by the plant and conduit capacity, as shown in *Figs 4 and 5*, as well as by the reservoir capacity, so that *Fig. 7* was perhaps an undue simplification of the problem.



Similarly, the utilization curve for a run-of-river scheme might be considerably affected by a small amount of pondage which, whilst not providing firm units, would increase the utilization by reducing flood loss. In the case of flashy mountain rivers, the difference between the flood losses over diversion dams with 1 or 2 days' pondage was considerable.

In making estimates for a subsidiary run-of-river scheme, it was found useful to prepare a series of utilization curves for different pond capacities, as shown in *Fig. 20*. It was assumed that 1 day's pondage was to be used to balance load requirements and that additional pondage would reduce flood loss. The curve for "1 day's pondage" was obtained as in *Fig. 5*; the other curves were derived from modified flow/duration curves—as mentioned in the note on *Fig. 4*—using the average of several days' discharge instead of the daily discharges themselves. Those curves were checked by determining the actual flood loss for a given conduit capacity,

using 1 year's daily discharge figures. The approximate curve for "no pondage" was derived by extrapolation.

Those curves were an aid in finding the economic combination of dam height and plant capacity; although based on only 1 year's flow records, they were mutually comparable.

It would be interesting to have figures for utilization percentages which had been realized in practice on schemes of different storage on pondage, plant capacity, and type of load, to compare with the percentage utilization derived from flow/duration curves and hydrographs for the rivers concerned, as a check on reservoir operation similar to the check on machine operation shown in *Fig. 8*.

The Author, in reply, observed that the discussion had emphasized the necessity for full consideration of economic aspects of design and, at the same time, had served to demonstrate the complexity of such studies. In a Paper of necessarily restricted length, it had not been possible to set down all the factors that affected the economic design of hydro-electric schemes, and its scope had therefore been limited to a review of the fundamental factors only. Any inaccurate impression that might have been conveyed to a layman by such a simplification of the problems involved would have been dispelled during the course of the discussion. The basic features of any economic considerations were given in the Paper but, of course, they had frequently to be qualified or were subject to limitations owing to other numerous and often conflicting factors.

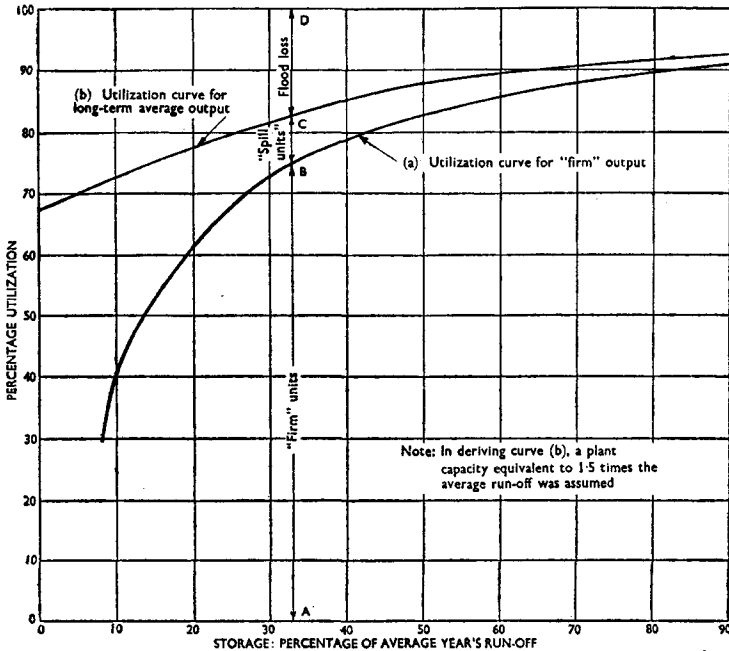
Mr Mountain, in order to illustrate a rather more general question, had asked for particular information about the Portugese scheme referred to in the Paper. Unfortunately the Ceira development was not a complete hydro-electric project in itself, its purpose being to divert water from a further catchment area into the over-reservoired Santa Luzia Scheme. The extra water so obtained allowed full advantage to be taken of the available storage. In that case, the value of one unit of electricity at the switchboard was known and it was merely a question of determining the best size of tunnel and of finding the percentage of the run-off which it was worthwhile to divert from the second basin. A description of the scheme had been given elsewhere.¹

With regard to the more general question, the economic amount of storage and the capacity of plant and conduits were, of course, interrelated. Indeed, *Fig. 7* served to indicate that relationship. Unfortunately, as Mr Fleming had pointed out, that graph might itself prove misleading, since the upper curve had been plotted assuming a varying plant capacity. The curve had been re-plotted (*Fig. 21*) for the same case but assuming a constant plant capacity equivalent to 1.5 times the average flow. A given degree of utilization could be obtained by providing a large storage volume

¹ H. D. Morgan, "Hydro-Electric Developments in the Serra da Lousan of Portugal." *Water Power*, vol. 2, No. 4, p. 154 (July-Aug. 1950).

with minimum plant capacity or otherwise a considerable plant capacity with little or no storage. The "firm" units would be more in the first case than in the second. The practical arrangement usually fell between the two extremes and was dependent upon other factors apart from purely economic considerations; for instance, the nature of the site, the requirements of the electrical demand in respect of peak load, the minimum permissible capacity value within the limitations of the scheme, the ability of the electricity-supply system to absorb excess power, etc. Those were

Fig. 21



UTILIZATION CURVE FOR STORAGE SCHEME

points which, incidentally, civil engineers did take into account when given the necessary data.

The civil engineer approached the problem by asking his clients what they wanted and what they were prepared to spend to get it. It might be that the clients wanted continuous generation, or that they wanted the electricity for normal factory purposes; it did not necessarily have to serve a system load. The procedure was, therefore, to ascertain the firm output available and then to ask the clients to what extent they wanted to install further capacity in excess of that, in order to take advantage of more

water when it was available. That depended, of course, on the purpose for which the electricity was required.

Mr Guthrie Brown had mentioned that an unlined pressure tunnel to a power station would be inadvisable unless in extremely sound rock. That was quite true. The unlined tunnels that had been referred to did not communicate directly with the power station but were driven for the purpose of connecting separate reservoirs.

In considering the economics of individual works of a scheme, it was no doubt better, as suggested by Mr. Scott and mentioned by Mr Walters as being the water engineer's practice, to plot the capacity of the work against the unit cost of production rather than against the anticipated profit. With regard to the whole scheme, however, a client would be interested in the annual revenue that could be derived from a certain outlay. In the case of the Ceira scheme, upon which *Fig. 6* had been based, the conduit size was really the only variable factor.

Mr Headland had suggested that, in the consideration and comparison of hydro-electric schemes, there was considerable need for a uniform economic treatment. That was true to a limited extent; for instance, the examples given during the discussion to illustrate the rise in construction costs in recent years could not be considered complete without some details about load factor or annual output. There were, however, certain difficulties, and a somewhat different approach would be required from that adopted for steam stations, on account of the natural limitations involved in the case of hydro-electric schemes. The variations in type of development and nature of load supplied made a uniform basis of comparison impossible. Surely, the correct procedure was for the scheme promoter or his advisers on electrical matters to specify the requirements in any particular case. The civil engineer could then be certain of formulating his reports and subsequently designing the scheme on the correct bases. In the case of interconnected steam and hydro-electric stations, where the load on any particular station could not be defined initially, the matter should be worked out by the civil and electrical engineers together and in co-operation with the promoter.

It had not been the Author's intention, when including *Fig. 8*, to criticize the operation of the particular station. The purpose of the graph was to illustrate, from a case in practice, the possible loss in efficiency that might arise with incorrect allocation of load between machines. The problem of load allocation would appear where several stations were interconnected to serve a single load and especially, as in Scotland, where some of the stations were only partially regulated.

Fig. 8 had been plotted from several daily records of flow, head at the machines, and output—admittedly chosen at random from a series of records but considered to be representative of the true picture. As mentioned in the Paper, the average efficiency had been found to be approximately 75 per cent.

There was little doubt that the main cause of that poor efficiency lay in the allocation of load between the machines. The point that Mr Headland had made about the loss of efficiency owing to head variations did not arise in that particular case. The machines in question were generating direct current and it was a perfectly simple matter to adjust the turbine speeds to give maximum efficiency and then to alter the excitation to give the voltage that was wanted. It was, of course, a special case.

Mr Headland's remarks about aeration were interesting. Very little trouble had been caused by sand erosion, but there had been some with very fine grass which came off the sidestream intakes at Lochaber and got on the star guide of the spear and built up there, until cavitation caused a shriek and dismantling and cleaning became necessary. It was very difficult indeed to prevent that fine grass getting in, and it had not been done successfully yet. It might be that a very expensive mechanical apparatus would succeed, but when dealing with large quantities of water the expense involved would be considerable.

The Author felt that Mr. Wolf's suggestion, that the yardstick of hydro-electric economy was the cost of electricity produced by thermal stations, was not necessarily correct. It was so, no doubt, in England, inasmuch as the selling price of electricity was generally dictated by the production costs at thermal stations. In other countries, however, which had no coal and were more reliant on hydro-electric power, it was a different matter.

The large hydro-electric schemes in Scotland were in themselves quite profitable concerns but it might be argued that the capital, labour, and materials involved could be better applied to the interests of the whole country in the construction of steam stations. It was questionable, however, whether that would enable the rate of installation of steam plant to be increased. In addition, there were the attendant benefits of hydro-electric schemes such as the considerable saving in coal consumption and, for Scotland in particular, the encouragement of industry in the Highlands.

It was agreed that, in general, individual catchments should be fully developed in one stage in order to reduce the ultimate capital expenditure. It might well be, however, that the demand for electricity would be insufficient initially, or that alternative means of generating the power would make full and more expensive development unnecessary. There was another aspect, in that the promoter might not have sufficient funds to carry out full development in the first place or that he might wish for the quickest return on his capital outlay.

Referring to Table 1, Mr Wolf had taken the cost in column 2 as applying to the heightening of a dam which had been built to an initial level at an earlier date. The heading of that column might, perhaps, have been better worded, for the study referred to the preliminary investigation of a scheme before any building had been done, and the figure of £1,000,000

quoted was the estimated extra cost of the higher dam. That cost was therefore directly comparable with the costs of Schemes A, B, and C in column 3.

Mr Fleming had rightly drawn attention to the considerable increase in utilization that could be obtained with even a small amount of pondage in a run-of-river scheme, and his utilization curves were very interesting.

The Author agreed that some comparisons between the degree of utilization realized in practice and the figures calculated beforehand for various schemes would be of great interest. It was probable that sufficiently comprehensive records would be maintained by the North of Scotland Hydro-Electric Board on certain of their schemes to enable such an analysis to be made, but such records would be of real value only when taken over a number of years.
