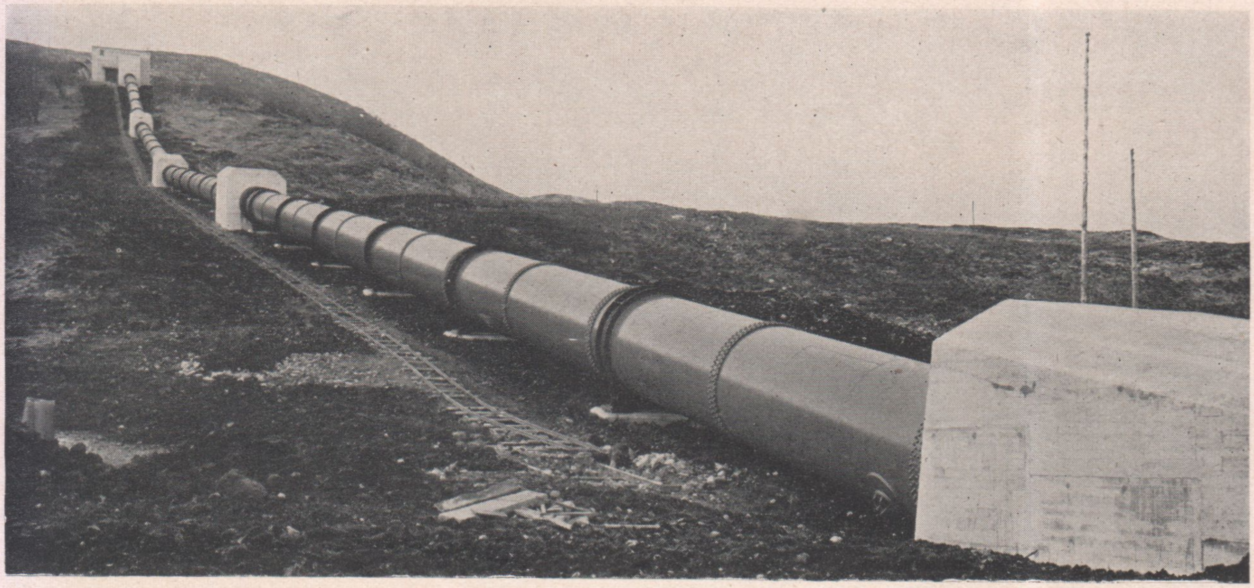

*Fig. 1. The pipeline leading from the tunnel to Grudie Bridge power station*

# Testing Hydro-Electric Generating Plant

A comprehensive account of the official efficiency tests at the Grudie Bridge power station of The North of Scotland Hydro-Electric Board is contributed by The Harland Engineering Co. Ltd., Alloa, Scotland

ON October 10 1951 the official efficiency tests were carried out on one of the two 12,000 kW Harland Bruce-Peebles turbo-alternator sets at Grudie Bridge power station, which was described in a previous issue of this journal* and which has been running almost continuously since it was commissioned in December 1950.

As will be shown later, the overall efficiency of a hydro-electric generating set at any particular load is a function of net head and water consumption. Although no great difficulty or controversy is attached to the measurement of head or electrical output, opinions differ widely as to the best and most reliable method of measuring the discharge or rate of flow of water. B.S. 353 states that the best method depends upon circumstances, and recommends, if feasible, that more than one of the following recognised methods should be employed, viz.: current meters *(a)*, pitot tube *(c)*, pressure-time (Gibson) *(d)*, salt titration *(d)*, salt velocity *(d)*, travelling screen *(b)*, venturi meter *(c)*, volumetric *(b)*, and weir *(a)*.

$P = \rho QH\eta$

The Swiss, on the other hand, go as far as to classify the above and four additional methods, into: *(a)* normal methods, *(b)* other methods suitable chiefly for laboratory measurements, *(c)* doubtful methods, and *(d)* methods not yet sufficiently tried out. The letters appended to the recognised methods listed above refer to this classification.

In this instance, it was agreed with the clients (The North of Scotland Hydro-Electric Board) and their engineers (Messrs. Merz & McLellan) that the salt velocity method, devised by the late Prof. Charles M. Allen of Worcester Polytechnic Institute, Worcester, Massachusetts, U.S.A., which has been successfully applied on a great number of hydro-electric installations in the United States and elsewhere (including Scotland) should be used, and The British Pitometer Co. Ltd., whose former managing director, Capt. E. R. Howland, holds the British rights for this method, were engaged to provide all the necessary instruments and equipment for the water-quantity measurements, and carry them out in the capacity of an impartial, independent authority.

This method of water measurement in closed conduits is based on the fact that salt in solution increases the electrical conductivity of water. Thus, if a quantity of salt solution is injected into the penstock upstream of a pair of electrodes, the time of passage of the brine may be recorded graphically on the chart of a recording ammeter equipped with one pen to record the injection and, at regular intervals, the timing signals from a precision clock, and another pen to record the increase in conductivity of the water produced by the passage of the brine past the electrodes. If the volume of the penstock between the brine injection point and a point midway between the electrodes has been accurately determined, the rate of flow may be calculated from the equation:

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* WATER POWER, November 1951, page 424.

$$Q = V/t \quad \ldots\ldots\ldots\ldots \quad (1)$$

where $Q$ is the discharge in cubic feet per second,
$V$ is the volume in cubic feet, between the brine injection point and the point midway between the two electrodes,
$t$ is the time in seconds, of passage of the brine between the brine injection point and the electrodes.

**Measurement of Pipe Dimensions**

As the pipe consists in the main of 23 ft. 9 in. lengths of fabricated tube, it was decided to number these lengths consecutively from the bottom, the length containing the electrodes being called No. 1. At length 31 the pipe is tapered to reduce the diameter from 7·700 ft. upstream to 7·330 ft. downstream.

The diameter of the pipe was measured by means of an expanding point gauge, calibrated in decimals of a foot. The divisions were such that it was possible to measure accurately to the nearest 0·002 ft. Two readings at right angles to each other were taken at the bottom (just clear of the rivets), centre and top of each length, i.e., six readings per length with approximately 11 ft. between each set of readings. The slip joints, just below each anchor block are flanged at each end, and no readings were taken at the slip joint itself—only at the flanged ends of the adjacent fabricated sections.

The diametrical measurements as far as the top end of length 44 were taken after the pipe had been painted. Subsequent measurements were made on unpainted pipe. A specimen plate which had been half-painted with the same number of coats as the inside of the pipe was lent by the civil engineers in charge of that section of the work, and it was found that the average total thickness of the four coats of paint was not more than 0·0065 in. The error, therefore, in neglecting the thickness of paint was no more than 0·028 per cent. on a diameter of 7·700 ft.

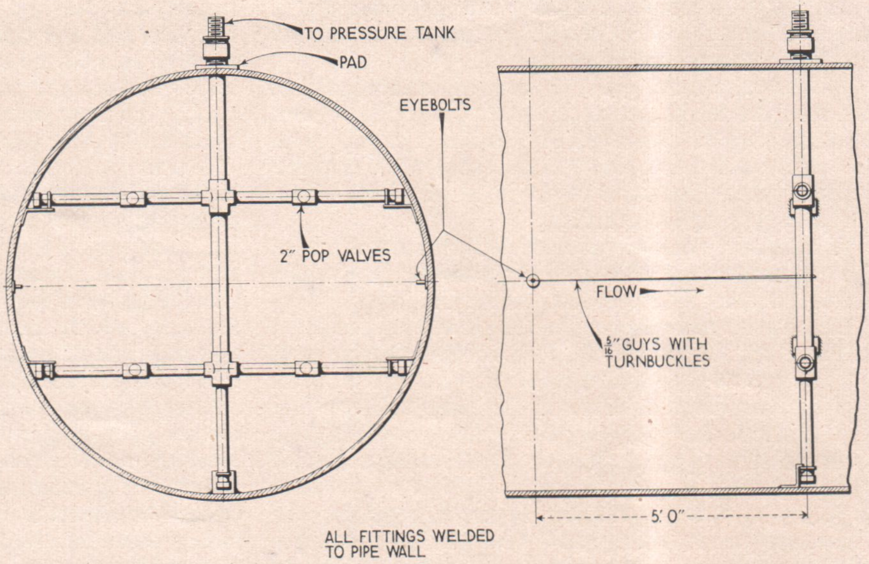

*Fig. 3. Arrangement of brine pipes and nozzles at upstream end of penstock*

The readings of pipe diameters taken by the foregoing procedure were tabulated, and the positive or negative deviation from the nominal diameter calculated in each case. These deviations were then summated and the average diameters for the two sections of penstock on either side of the taper piece determined. These were found to be 7·3394 ft. and 7·7043 ft. respectively.

The distance between the midpoint of the electrodes and the injection point was measured as follows. The origin was taken as the point midway between the two electrodes, and measurement was made along the bottom of the pipe right to the end of length 53. The point of injection was determined by measuring along the top of the pipe to the centre-line of the 4 in. gas hole from the end of length 53, and subtracting $2\frac{9}{16}$ in. from the length so determined. The length of the smaller-diameter section was found to be 638·250 ft. and of the larger-diameter section 466·386 ft.

The volume of the pipe was then calculated from the pipe lengths and average diameters thus determined, and found to be 48,745 cu. ft.

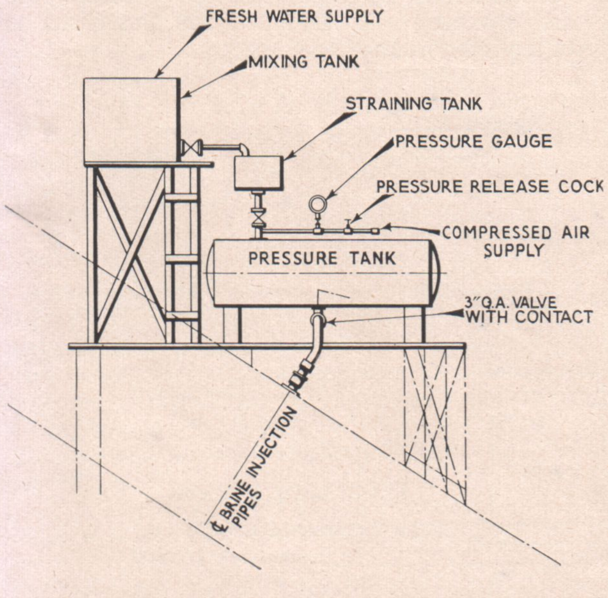

*Fig. 2. Apparatus for injecting brine into penstock*

**Determination of Time of Passage of Brine**

For the determination of the time of passage of the brine $t$, a set of tanks and fittings, as shown in Fig. 2, was erected on a wooden platform at the brine injection point. A manhole and pressure tapping were provided on the penstock, the former to permit the assembly, inside the penstock, of the brine-injection pipes and pop-valves, shown in Fig. 3, and the latter to receive the pipe from the 3 in. quick-acting valves. A compressed-air cylinder (a total of 1,980 cu. ft. of compressed air was provided for the tests) was connected to the 1 in. socket shown in Fig.

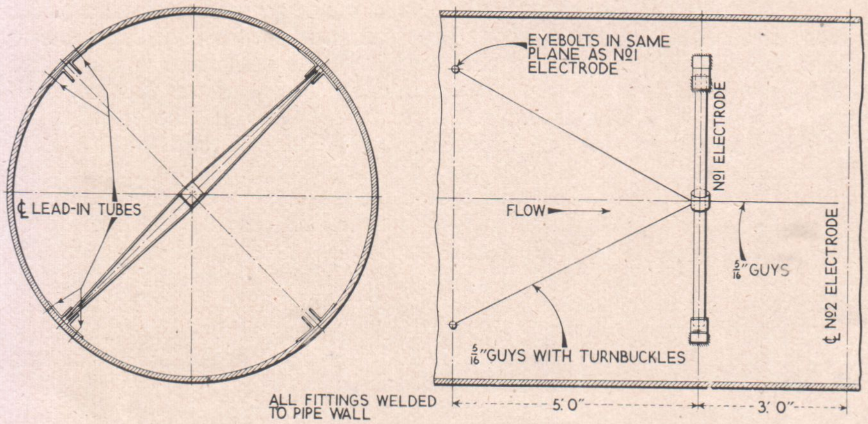

*Fig. 4. Arrangement of electrodes at turbine end of penstock*

2, and a 10 per cent. brine solution prepared in the mixing tank. 10 cwt. of undried vacuum salt was provided for this purpose. The injection pressure was adjusted to approximately 50 lb. per sq. in. above the pipeline pressure at that point.

At the electrode point a pair of electrodes was installed inside the penstock, as shown in Fig. 4, and connected up as shown in Fig. 5. The a.c. supply to the electrodes was taken from the 240 V station supply via a 200-440/110 V 2 kVA single-phase variable-tapping transformer.

A temporary shelter was erected in the vicinity of the electrodes for the recording ammeter, ballast board, switches and precision pendulum clock.

One of the recording-ammeter pens was connected in the electrode circuit and the other in series with a 6 V dry battery and with either the contacts on the precision clock or those on the quick-acting valve, depending on the position of the selector switch. The recorder chart was clockwork driven at a speed of 12 in. per min.

Following the installation of the equipment, the electrodes were "meggered" and the penstock refilled. The supply to the electrodes was switched on and the voltage varied by means of the variable tapping transformer until the required deflection of the recorder pen was obtained. A trial injection was then made to check the recording of the injection, electrode and timing signals, and thereafter the tests were proceeded with on the following lines.

The required load was applied to the generator, which was paralleled on to the grid, and as soon as load conditions were steady, the electrode point (which also acted as control station for the entire tests) instructed the injection point to inject in exactly one minute's time. A few seconds before the expiration of that minute, the chart of the recording ammeter was set in motion and the selector switch thrown over to the left (see Fig. 5) thus enabling the time pen of the recording ammeter to record the 2 sec. timing signals given by the contact on the precision pendulum clock. Just before the precise moment when the injection was due, the selector switch was thrown over to the right for the time pen to record the injection signal, on receipt of which it was returned to the left-hand position to enable the time pen to continue recording the timing signals. Upon arrival of the brine at the electrodes, the increase in conductivity of the water caused the electrode pen on the recording ammeter to deflect; due to the variation of water velocity over the pipeline diameter and also to partial dissolution of the brine in the course of its passage down the pipeline, this signal was not instantaneous but long drawn-out, thus describing a "cocked hat" curve on the recorder chart.

The electrode supply being a.c. (d.c. would cause electrolytic action on the electrodes), the deflection of the electrode pen is not a linear function of the current, thus necessitating the replotting of the curve to a linear scale. The time of passage of the brine $t$ is then taken as the time interval represented by the distance between the centre of the rectangular diagram obtained from the 1 sec. brine injection and the centre of the area enclosed by the curve drawn by the electrode pen, redrawn to a linear scale. The centres of these areas were determined by cutting them out of heavy squared paper and balancing them on a knife edge.

It was decided to test the machine at six different loads and between three and six runs were taken at each load, with a total of 24 runs. At the higher loads, at which the rate of flow was relatively high, and the time of passage of the brine correspondingly short, runs were taken consecutively, but at the lower loads, at which the rate of flow was relatively low and the time of passage of the brine correspondingly long, considerable saving in time was achieved by overlapping the runs at each load (i.e. injecting a further shot of brine before the previous one had reached the electrodes). In view of the above procedure for determining the centre of area of the recorder diagrams, it was not possible to calculate the cusecs immediately, and therefore, in order to make certain that the readings were all of the right order, a rough check was made after one of the runs; from an approximate estimate of the time of passage $t$, in conjunction with the other relevant readings, the overall efficiency was calculated and was found to be of the right order.

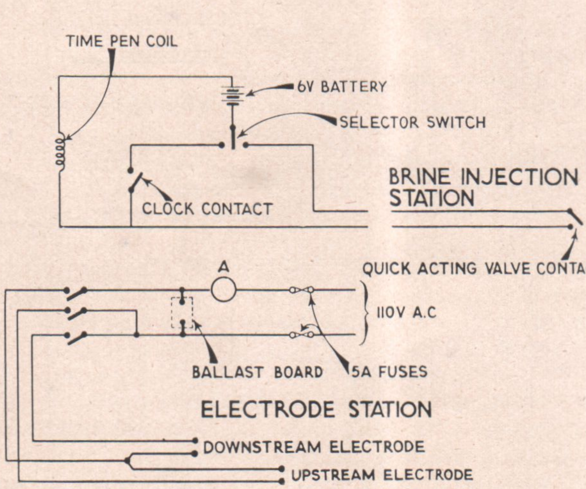

*Fig. 5. Diagram of electrical circuits*

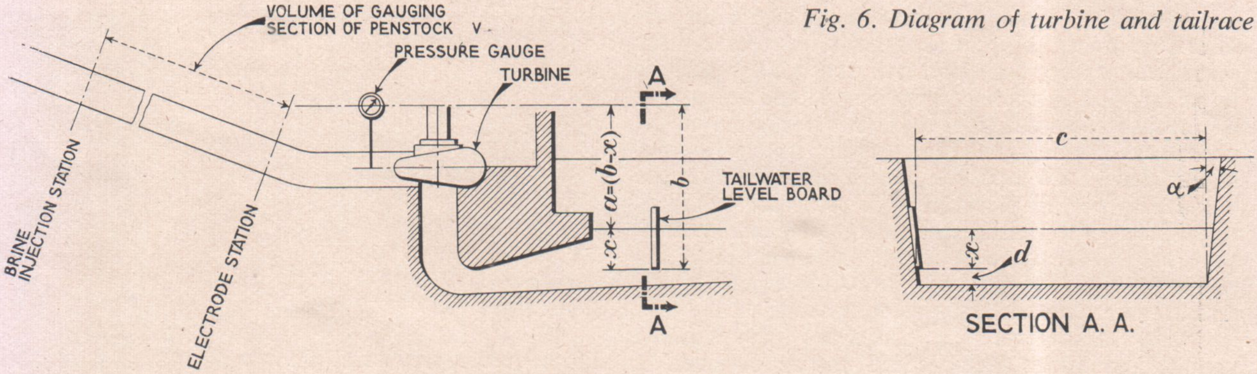

*Fig. 6. Diagram of turbine and tailrace*

The effective net head $h$ is the sum of the pressure head $P_e$, the velocity head $\frac{v_e^2 - v_a^2}{2g}$ and the height of the centreline of the pressure gauge above tailwater level $a$.

where $v_e$ is the velocity of the water at the pressure gauge tapping (feet per sec.).

$v_a$ is the velocity of the water at the tailwater level gauge (feet per sec.).

$g$ is the acceleration due to gravity ($=32{\cdot}2$ ft. per sec. per sec.).

The pressure head was measured on a 10 in. standard pressure gauge, reading 0-1,000 ft. head of water. A special teepiece was inserted in the pressure pipe leading to the turbine-panel pressure gauge, in the vicinity of the tapping on the turbine spiral casing. A gauge cock was provided and adjusted to give the best possible stable reading consistent with accuracy of measurement. The standard pressure gauge was calibrated by deadweight tester in The Harland Engineering Co. Ltd.'s works immediately before and after the tests, and exactly the same readings were obtained in both cases. A calibration curve was plotted enabling the conversion of the pressure-gauge readings $P$ to correct values of pressure head $P_e$.

The velocity of the water at the pressure gauge tapping $v_e$ is given by:—

$$Q / \frac{\pi}{4} D^2 \quad \ldots\ldots\ldots (2)$$

where $D$ is the pipe diameter at the pressure-gauge tapping (feet).

$D$ was obtained from the drawing of the inlet taper pipe, on which the pressure-gauge tapping is situated.

The velocity of the water at the tailwater level gauge $v_a$ is given by:—

$$Q / A \quad \ldots\ldots\ldots (3)$$

where $A$ is the cross-sectional area of the tailrace at the tailwater level gauge (sq. ft.).

It is important that only that part of the tailrace width should be taken into account which corresponds to the unit on test, but since only one machine was running, the full width of the tailrace was taken in this case. From the diagrammatic representation of the turbine installation and tailrace (Fig. 6), the cross-sectional area of a tailrace of trapezoidal section $A$ is given by:—

$$x^2 \tan \alpha + x\,(2d \tan \alpha + c) + d\,(d \tan \alpha + c) \quad \ldots (4)$$

where $x$ is the reading of the tailwater level gauge (feet).

$c$ is the width of the bottom of the tailrace (feet).

$d$ is the height of the bottom of the tailwater level gauge above the bottom of the tailrace (feet).

$\alpha$ is the slope of the tailrace walls.

In actual fact the cross-section of the tailrace in question was not a true trapezium, and an appropriate correction had to be made to equation (4) above.

It will also be seen that the height of the centreline of the pressure gauge above tailwater level $a$ is given by:—

$$b - x.$$

where $b$ is the height of the centreline of the pressure gauge above the bottom of the tailwater level board.

The tailwater level was read on the existing tailwater level gauge, which is situated on the left-hand bank of the tailrace (looking downstream), and calibrated in fifths of a foot; observations were taken from the right-hand side (looking downstream) of the draught tube and relief-valve gate hoisting gallery (tailrace platform). $c$ and $d$ were obtained from drawings, and the height of the centreline of the pressure gauge above turbine floor level was measured to enable $b$ to be determined. Thus it will be seen that the only variables in the determination of $h$ are $P$ and $x$. Readings of these two quantities were taken at half-minute intervals from receipt of the "start" to the "stop" signal from the test control point (electrode station), and the mean of each set of readings was used for the efficiency calculations.

Tests were carried out at 113·4, 100, 83·33, 75, 66·67 and 50 per cent. full load, and the exact generator output $W_G$ at these nominal loads was taken as the mean of half-minute readings of the wattmeters for each run, using the two-wattmeter method.

With the exception of the copper losses, which were calculated from the currents and winding temperatures actually obtained during the tests, the generator losses were determined by the generator manufacturers and main plant contractors, Bruce Peebles & Co. Ltd., from works tests, and the generator efficiency $\eta_G$ calculated by the "summation of losses" method. This enables the turbine output $W_T$ and turbine efficiency $\eta_T$ to be calculated.

B.S. 353, the Swiss Rules for Hydraulic Turbines, and the Test Code for Hydraulic Prime Movers published by the American Society of Mechanical Engineers, all lay down different rules as to whether or not such auxiliaries as bearing-oil pumps, governor-oil pumps, cooling-water pumps, etc., should be charged to the turbine, so that it is necessary to specify the basis on which the efficiencies are calculated. In this instance, it was agreed that all measurements of output should be made as near to the alternator terminals as practicable and that the power required for auxiliaries, except for excitation of the alternator, is to be supplied independently of the turbine under test. Since on this installation, with the exception of the permanent-magnet generator (which has an output of less than 1 kW and was therefore negelected) the auxiliaries are all electrically driven, and since, as mentioned above, all measurements of electrical output were in fact made at the generator terminals, the power required for the auxiliaries formed part of $W_G$ and was therefore not charged against the unit.

Owing to adverse line conditions the specified voltage and power factor could not be obtained in every case, so that the best possible combination of voltage and power factor had to be contended with. Once set, the load setting was not changed throughout each run (or set of runs), and as a precaution the load-limiting device on the governor was set to the appropriate gate opening.

Successful intercommunication was achieved by interconnecting six field telephones, located at the following points: (1) brine injection point, (2) generator floor (electrical instruments), (3) control room (load adjustment), (4) electrode station, (5) turbine floor (pressure gauge), and (6) tailrace platform (tailwater level gauge).

The electrode station, which, as mentioned previously, acted as control point for the entire tests, was thus able to call up all stations simultaneously, and having ascertained that they were all "netted in," instructed them to stand by for the "start" signal. The brine injection point was then instructed to proceed with the injection, and receipt of the injection signal on the recording ammeter was immediately relayed over the telephone to all stations, who, while still listening in, proceeded to take their readings until receipt of the "stop" signal from the electrode station on completion of the run. The distances between the various test points, the number of quantities to be measured, the exact timing and synchronisation required, and the limited time available, made first-class intercommunication essential. Only one of the 24 test runs had to be repeated owing to failure of telephone communications, and on the whole the system adopted proved very successful in that it helped to keep delays between runs to an absolute minimum.

**Calculations**

The overall efficiency of the turbo-alternator set is given by:—

$$\eta_O = \frac{\text{generator output (kW)}}{\text{turbine input (H.P.)} \times 0{\cdot}746} \times 100\%$$

The input to the turbine is given by:—

$$\frac{Qwh}{550} \text{ H.P.}$$

where $w$ is the weight per cubic foot of water ($=62{\cdot}4$ lb. per cu. ft.).

Therefore

$$\eta_O = \frac{100 \times 550\, W_G}{0{\cdot}746 \times 62{\cdot}4\, Qh} \%$$

$$= \frac{1181\, W_G}{Qh} \%$$

But $Q = V/t$

and $h = a + P_c + \dfrac{v_e{}^2 - v_a{}^2}{2g}$ ft. of water.

whence from equations (1), (2), (3) and (4),

$$v_c = V/\frac{\pi}{4}D^2 t \quad \text{and}$$

$$v_a = \frac{V/t}{x^2 \tan\alpha + x\,(2d \tan\alpha + c) + d\,(d \tan\alpha + c)}$$

Also, from Fig. 5:—

$$a = b - x$$

and therefore, expressing the overall efficiency in terms of the known constants and measurable variables, we get:—

$$\eta_O = \frac{1181\, W_G t}{V \left\{ 6 - x + P_c + \dfrac{V^2}{64{\cdot}4\, t^2} \left[ \dfrac{1{\cdot}62}{D^4} - \dfrac{1}{[x^2 \tan\alpha + x\,(2d \tan\alpha + c) + d\,(d \tan\alpha + c)]^2} \right] \right\}}$$

The turbine efficiency is given by:—

$$\eta_T = \frac{\eta_O}{\eta_G} \times 100\%$$

and may be calculated from the above and a knowledge of the generator efficiency $\eta_G$.

If, as was the case in this instance, the efficiency guarantee takes the form of a weighted efficiency, computed from three or more different loads, the efficiencies at the specified loads are taken from a curve plotted from the test results.

**Correction for Head**

At the time of the tests, the specified net head for which the guaranteed efficiencies applied was not available, and the unit had to be tested on a net head in excess of the agreed permissible 3 per cent. tolerance limit. If the speed of the unit can be varied, then it is possible to compensate for this discrepancy by varying the speed in the ratio of the square roots of the heads. In this case, however, the generator was synchronised on to the Highland grid for loading purposes, which made it impossible to vary its speed. An attempt was made, however, to analyse the test results in such a way that such valid deductions could be made from the results available as are required to prove that the efficiency guarantees given had, in fact, been met.

This was done in two different ways.

Method 1 consisted of drawing a curve of turbine efficiencies against turbine output, multiplied by the ratio of the rated net head to the test head, to the power 3/2. It may, however, only be considered a partial correction since it takes account of differences in head only and not of the effect of change in unit speed on efficiency.

It so happened that expected efficiency curves were originally submitted for three different heads and that one of these heads was approximately the same as the mean head prevailing at the time of the tests. Method 2 therefore consisted of comparing the weighted test efficiency with that derived from this efficiency curve.

A field test such as this requires a considerable amount of preparatory work and full co-operation

(*Continued on page 236*)