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THE GARRY AND MORISTON HYDRO-ELECTRIC SCHEMES

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SYNOPSIS

The Paper describes briefly the Garry and Moriston Schemes of the North of Scotland Hydro-Electric Board and deals in more detail with certain aspects of the design and construction which represent new experience in Great Britain.

Particulars are given of the Quoich rockfill dam with up-stream reinforced concrete membrane, the use of Trief concrete in dams and tunnels, and of precast concrete facing blocks in place of shuttering for dams. The Taintor gates and a tilting gate for flood control at the Dundreggan dam are described together with the treatment of inverts in low-pressure tunnels throughout the Schemes.

Provisions for the preservation of salmon in the River Garry were extensive and their influence on design and construction is outlined.

A wide variety of power stations and surge control arrangements is incorporated in the Schemes and mechanical and electrical aspects are dealt with as well as problems of civil engineering design and construction.

INTRODUCTION

THE GARRY AND MORISTON SCHEMES of the North of Scotland Hydro-Electric Board, although promoted separately, have been constructed simultaneously and are being operated as one group with a control centre at Fort Augustus (Fig. 1, Plate 1). It is therefore appropriate to treat them as one scheme for the purposes of this Paper.

2. There were four earlier promotions of the combined scheme, prior to the

formation of the Board, each of which was rejected by Parliament. In these earlier promotions it was proposed to develop the Loch Quoich catchment towards the west so as to obtain the maximum head with a power station on the shore of Loch Hourn at sea level. Much opposition was raised to this, however, and the Board therefore decided to develop entirely within the natural catchment of the River Garry and thereby sacrifice about 150 ft of gross head.

3. Both the Rivers Garry and Moriston lent themselves to two-stage development. The layout of the works is shown in Figs 1 and 2, Plate 1, and hydraulic data are given in Table 1. The total average output is $339 \cdot 1 \times 10^6$ kWh/year and the installed capacity is 95,680 kW. The main power stations are connected into the 132-kV transmission system as shown in Fig. 1, Plate 1. It is hoped to develop the Livishie aqueduct at a future date, with a power station discharging into the Dundreggan head pond.

4. Many of the features of design and construction are common to other schemes and have been described elsewhere. Certain features, however, which are unusual in this country, are discussed in some detail in the Paper. They include:

(*a*) Quoich rockfill dam.
(*b*) Trief concrete in dams and tunnels.
(*c*) Precast concrete facing blocks in place of shuttering for dams.
(*d*) Control gates in Dundreggan dam.
(*e*) Inverts in low-pressure tunnels.
(*f*) Influence of provisions for salmon on design and construction.
(*g*) Underground power stations.

Some details of the generating plant are included in §§ 84–90.

QUOICH ROCKFILL DAM

Design

5. Several types of design for Quoich dam were considered and a rockfill type was selected for the following reasons:—

(i) Saving in cement, demand for which has exceeded supply since World War 2.
(ii) Economy. The price quoted was 10% less than for a gravity dam.
(iii) Reduction in shuttering, and therefore in the number of joiners required. These were scarce and difficult to attract and retain on hydro-electric work.

6. The dam, as constructed, has a maximum height of 126 ft; the crest length is 1,050 ft, and the maximum base width 336 ft. It contains 386,000 cu. yd of rockfill, of which tunnel and foundation excavations yielded 100,000 cu. yd and the rest was quarried from a site about ½ mile up-stream of the dam. Fig. 3, Plate 1, shows a cross-section of the dam. Salient features are now described with the reasons for their adoption.

7. The up-stream sealing membrane has merits over a central core wall; there is a substantial reduction in the quantity of rockfill; there are inspection facilities and, if the seal shows any sign of deterioration or failure, repairs can be made. Impermeable moraine as an alternative to concrete was not available near the site.

8. The proportions of the membrane concrete by volume are 4:1. The

standard size of slab is 20 ft × 20 ft, and the thickness is 15 in. in the lower sections and 12 in. in the upper. It is reinforced (0·4% in 15-in. slab and 0·5% in 12-in. slab) in two layers in both directions. The cover to reinforcement is 3 in. and the face of the concrete is painted with two coats of bituminous paint.

9. The joint seals are of annealed copper strip and rubber bitumen. The three types used are shown in Fig. 4, Plate 1, and the connexions between them in Fig. 5, Plate 1. The copper is itself protected against acid attack by the rubber bitumen. The horizontal joints provide for hinging only, the inclined joints for opening, closing, and hinging, and the joint adjacent to the cut-off wall for sliding, closing, and hinging.

10. The top of the dam is cambered in elevation and also in plan, in an up-stream direction, to counter any settlement following completion of the dam and filling of the reservoir. In each case the maximum offset is 1 ft at the deepest section, i.e. less than 1% of the depth. Hand-packed rubble ranging from 7 ft thick at the base to 3 ft thick at the crest provides a solid support for the up-stream slab and takes up any local settlements.

Construction

11. The specification for selection and placing of rockfill was stringent with the aim of reducing after-settlement to a minimum:—

(i) All rock from excavations which contained a high proportion of mica or hornblende was rigorously excluded from the rockfill.

(ii) All material below ⅜ in. in size was removed from the rockfill before placing in the dam to ensure rock-to-rock contact.

(iii) The fill was deposited in 2-ft layers dipping up-stream at 1 in 24. Material from the quarry was well graded from 2-ft blocks downwards, while that from the tunnel was mostly small. The up-stream slope of the tipped rubble was formed in steps 18 in. high with large blocks of stone. The steps were later incorporated in the hand-packed rubble, which followed with a specified lag of at least three months. The down-stream slope was stabilized by rough pitching 9 in. thick. The bulk of the fill was placed at an average rate of 17,300 cu. yd/month, with a peak production of 30,000 cu. yd.

(iv) Each layer was consolidated by (*a*) rolling with a 10-ton smooth roller —about twenty passes; (*b*) sluicing with a water jet at 40 lb/sq. in. (2 × volume of layer); (*c*) rolling with 10 passes of a vibrating roller; and (*d*) sluicing with water jet (2 × volume of layer).

Vibration was adopted after extensive tests had shown that it gave an additional compaction of 2% of the depth of rockfill in a 2-ft layer. The vibrating roller weighed 3½ tons.

12. Sluicing was done with a site-made frame on rubber-tired wheels carrying fifteen ½-in.-dia. nozzles directed downwards.

13. From test pits excavated it was found that the density of the consolidated fill was 119·4 lb/cu. ft and voids were 27%.

Settlement and deflexion measurements

14. A number of settlement- and deflexion-measurement stations were established in the dam. Readings taken during construction showed a small and fairly uniform compaction as the rockfill level rose; the maximum was 0·7%

TABLE 1.—HYDROLOGY AND CONSTRUCTIONAL DATA

	Garry Scheme		Moriston Scheme		
	Quoich	Invergarry	Loyne	Cluanie	Dundreggan
Hydrology					
Useful storage capacity in:					
(*a*) cu. ft × 10^6	12,500	825	1,600	6,090	negligible
(*b*) million kWh through assoc. stations	111·5	4·3	18·3	67·8	,,
Catchment area: sq. miles	52·2	147	26·5	74·5	155·1
Average annual rainfall: in.	125	101	90·2	95·5	81·1
Average annual run-off: in.	117	91	78·2	82·5	68·1
Spillage and compensation losses: cusecs	51	186	8	85	140
Average flow available for power: cusecs	399	806	128	367	642
Max. draw down: ft	85	12	39	67	4
Design floods					
Normal maximum: cusecs	6,000	13,000	2,400	4,200	15,000
Corresponding rise in reservoir over-spill level: ft	3	4·7	2·3	2·2	Nil
Catastrophic: cusecs	10,000	21,000	5,100	8,500	30,000
Corresponding rise in reservoir over-spill level: ft	4·1	10	3·9	3·6	2·0
Dams					
Type	Rockfill	Concrete gravity/buttress	Concrete gravity		
Max. height (Foundation to roadway): ft	126	50	58	128	55
Length: ft	1,050	150	1,745	2,220	400
Volume: cu. yd	386,000	8,560	66,000	232,000	35,000
Length of spillweir: ft	305	174 (+gates)	225	424·5	77 (gates only)
Low-pressure tunnels					
Length: ft	12,843	14,033	7,600	14,000	
Equivalent diameter	11 ft 6 in.	16 ft 6 in.	12 ft 0 in.	12 ft 0 in.	
Construction	Horseshoe section		Unlined horseshoe section	Horseshoe section	
Thickness of concrete lining	12 in.	12 in.		12 in.	

TABLE 1 (*cont.*)

High-pressure tunnels				Two	Two
Length: ft. . . .	1,440	344	—	100/111	100
Diameter	11 ft 6 in.	16 ft 6 in.	—	10 ft/5 ft	10 ft 0 in.
Construction . . .	Circular section concrete lined 12 in. thick		—	Steel lined	Steel lined
High-pressure pipes				Tail-race tunnels	
Length: ft. . . .	820 (140 ft in trench)	465	—	1,706	22,000
Diameter	11 ft 6 in.	16 ft 6 in.	—	19 ft 4¾ in.	20 ft 9 in.
Construction . . .	Welded steel pipe, 1 in. thick, backed with concrete	Welded steel pipe, 1⅛ in. thick, backed with concrete	—	Horseshoe section	
				Invert lined 8 in. thick	Unlined
High-pressure shafts					
Length	158 ft 6 in.	91 ft 5 in.	—	170 ft 6 in.	296 ft
Diameter	11 ft 6 in.	16 ft 6 in.	—	12 ft 6 in.	15 ft 0 in.
Thickness of concrete lining	10 in.	10 in.	—	10 in.	10 in.
Surge chambers					
Length ft	169	112	—	180	—
Diameter	30 ft	60 ft	—	45 ft	—
Construction . . .	Orifice type (orifice 8 ft 1½ in. dia.)	Differential shaft riser 14 ft 6 in. dia.	—	Circular section	Circular shaft with upper and lower galleries
Thickness of concrete lining	8 in.	10 in.	—	8 in.	12 in.
Side-stream intakes to		Aldernaig Tunnel	Doe Tunnel	Peathrain Tunnel	—
Low-pressure tunnels		Invergarry	Cluanie		
Length: ft. . . .	—	500	5,781	339	—
Equivalent diameter .	—	5 ft 10¾ in.	9 ft 6 in.	5 ft 10¾ in.	—
Slope	—	1 in 3	1 in 40·36	1 in 2·9	—
Additional catchment: sq. miles .	—	8·8	13·6	1·4	—
Construction . . .	—	Horseshoe section			—
Thickness of concrete lining		8 in.	12 in.	8 in.	

of the depth placed. Since completion of the fill any settlement has been negligible.

Up-stream facing slabs

15. The slabs forming the waterproof membrane rest on a square grid of horizontal and inclined concrete beams cast in chases left in the hand-packed rubble. The horizontal beams were monolithic with the slabs (section BB in

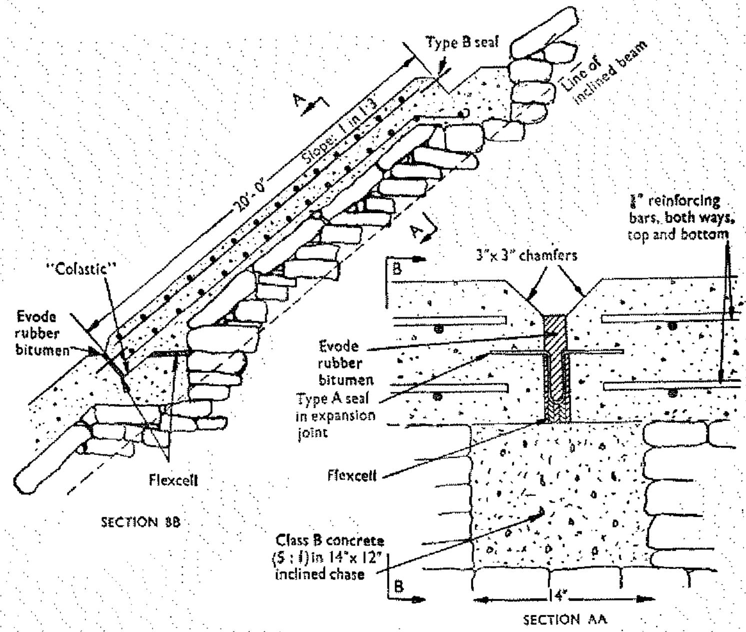

FIG. 6.—QUOICH DAM. UP-STREAM SLAB AND BEAMS

Fig. 6), but the inclined beams were cast first and used as a base on which to erect the slab shuttering.

16. The construction of the up-stream face posed a major problem in shuttering the inclined slabs. This was solved by using the vacuum-concrete process, which had not before been used on a large scale in Britain. A preliminary test, made on an area of fifteen slabs, proved encouraging. After some further experiments the sequence of operations was standardized as follows:—

(i) Cast inclined concrete beams in chases left in rubble. The shuttering was of two side forms, dowelled to the rubble, with top shutters laid in 4-ft lengths in advance of concreting.

(ii) Erect copper seals on the beams. Type A seals, in 20-ft lengths, were first set and type B welded to them (Fig. 4, Plate 1). At the bottom of the face the slabs butt against a seating in the cut-off wall. Type C spans this joint and is made in two sections, one cast in the concrete on each side, to allow for relative movement. The joint was made watertight by a layer of Colastic between the meeting faces.

(iii) Erect side and stop-end forms for slabs (Fig. 7, Plate 1). It was necessary to fasten these down and also the vacuum shutters to prevent them lifting during concreting.

(iv) Fix steel reinforcement in position.

(v) Place concrete in slabs, using vacuum shutters. Two vacuum units were used, each consisting of a rotary suction pump and motor, a separator tank with manifold, and four vacuum shutters (Fig. 8). Each shutter measured 20 ft × 2 ft. The vacuum chamber was formed by two layers of steel mesh, one coarse and the other fine, covered on the back by a ⅝-in. plywood screwed to the frame, and on the suction face by a filter cloth of unbleached linen (Fig. 8). Air was extracted from the chamber by eight connexions spaced along the back of the shutter. Concrete was placed in 2-ft stages behind each shutter, and by the time the fourth shutter was filled the first could be moved to the fifth position. The shutters weighed

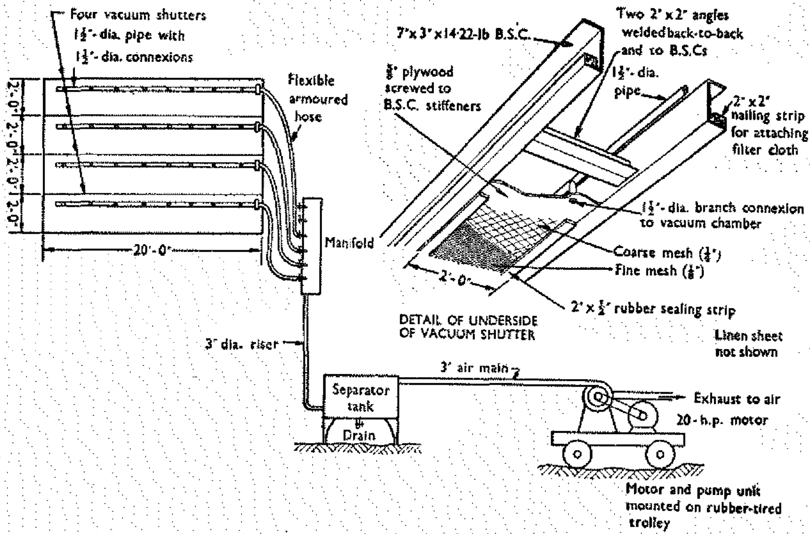

FIG. 8.—QUOICH DAM. ARRANGEMENT OF VACUUM EQUIPMENT

about 1 ton each and were handled by the derricks (Fig. 9a, Plate 1). In order to avoid loss of vacuum, poker vibrating was found to be necessary, and in addition one shutter was half filled with concrete ahead of the shutter being treated. Experience showed that a vacuum of 15 in. of mercury was required for satisfactory results. The time of treatment ranged from 20 min in hot weather to 40 min in cold weather. The casting of a 20-ft × 20-ft × 12-in.-slab took about 2½ hours. The shutters were cleaned by hosing down with an air-water jet.

17. The water extracted was measured and it was found that the process reduced the water/cement ratio by between 0·05 and 0·07. Comparative tests were made on some 6-in. cubes subjected to the vacuum process and others untreated from the same batch. The treated cubes showed an increase of strength of about 20% at 7 days and 4% at 28 days.

Effects of cold weather

18. The work programme necessitated some concreting of slabs during the cold weather. The aggregates and mixing water were heated and placing was

delayed till the air temperature rose to 32°F. Even so it was difficult to get satisfactory work on account of the freezing up of the vacuum pipes. It was concluded from this experience that the vacuum process should not be used in low temperatures unless unavoidable, and that vacuum pipes should be short.

Trief concrete in dams and tunnels

19. Owing to the shortage of home-produced cement the Cluanie and Loyne dams were constructed using Trief concrete.

20. The replacement of a proportion of ordinary Portland cement in concrete by pozzolanas is one of the methods which have been adopted at various sites to meet the shortage.[1] Blast-furnace slag in the vitreous form is a pozzolana, and has been widely used on the Continent. In Great Britain, B.S.146: 1947 specifies the requirements of an integrally-ground mixture of Portland cement clinker and granulated blast-furnace slag. Standards have been proposed by various authorities, but the main guide to quality is one which expresses the basicity of the slag. Langavant's has been mostly used, the chemical quality index being greater than 10 in the formula:—

$$\text{Chemical quality index} = 20 + CaO + Al_2O_3 + \tfrac{1}{2}MgO - 2SiO_2$$

where the figure for each constituent is its percentage of the whole.[2]

21. In the manufacture of Portland blast-furnace cement, the cement clinker, granulated slag and gypsum are ground together in a dry mill. M. Trief, in Belgium, devised a method to increase the efficiency of grinding by using a wet mill to produce a slurry, which was mixed with the cement in the concrete mixer. Wet grinding enables a finer particle to be obtained than dry grinding and reduces the power required. Moreover, fine slags give better mechanical strength after hydration than coarse. When ground, the slurry can be kept in storage vats without deterioration, if continuously agitated to prevent settlement.

22. The Trief process was investigated by a party of the Board's engineers, and tests were made on slags produced at Colville's Clyde Iron Works, the results of which were satisfactory. The quantities of concrete made with Trief cement on the Moriston Scheme were as shown in Table 2. The cement mix gives the percentage of ground slag, ordinary Portland cement, and calcium chloride. The water/cement ratios of the mixes, including the water in the slurry, were 0·6–0·8 in the 7:1 mix and, about 0·45 in the 4:1 mix.

23. Transport of the slag from Colville's works to the site was initially by road, but later it was railed to Spean Bridge and carried thence by road. Chemical analysis of each tapping was made at the furnace, with occasional independent checks. On arrival it was either stockpiled in the open or delivered direct to hoppers feeding two wet-ball mills. After grinding, the resulting slurry was discharged into storage vats, fitted with rotating agitator arms with compressed-air nozzles, and here samples were taken for testing. From the vats the slurry was drawn off either to the central mixing plant which served the Cluanie dam and Loyne dam and tunnel, or conveyed in a circulating tanker to

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[1] A. A. Fulton and W. T. M. Marshall, "The use of fly ash and similar materials in concrete". Proc. Instn civ. Engrs, Pt 1, vol. 5, p. 714 (Nov. 1956).

[2] J. C. de Langavant, "Theoretical considerations on the nature of slag for cement manufacture", p. 29.

TABLE 2

Location	Concrete mix by volume	Cement mix by weight	Concrete quantity: cubic yards
Cluanie and Loyne dams.	7:1	70/28·5/1·5	182,700
	4:1	70/30/0	40,200
Loyne, Ceannacroc, and Doe tunnels .	4:1	70/28·5/1·5	43,900
			266,800

the plant which mixed concrete for the other tunnels. Mixed concrete was transported by road to Loyne in transit mixers.

24. The bulk of the aggregate was granite, obtained from a quarry established at Cluanie and crushed on the site. Little stockpiling was done as the crushed aggregate was generally fed direct to the central mixing plant at Cluanie or transported to other sites. Two cableways at Cluanie linked the dam with the concrete plant, from which either batched aggregate, or mixed concrete could also be drawn off as required for other parts of the works. The aggregate for the dam hearting was up to 4 in. in size, and elsewhere up to 1½ in. Internal vibration was used throughout to help compaction, and the concrete in the walls and roofs of the tunnels was placed by pneumatic placer.

25. Concrete made with Trief cement had to attain the strength required for ordinary Portland cement, and to have a minimum density of 145 lb/cu. ft. The required strengths were as shown in Table 3.

TABLE 3

Proportions by volume	Max. size of aggregate	Cube size: inches	Min. comp. stress lb/sq. in.	
			7 days	28 days
4:1	1½	6	2,400	3,400
7:1	4	10	1,600	2,250

26. From initial tests it was found that a 70/30 mix of slag and cement was satisfactory for the 4:1 mixes, but the 7:1 mixes required the additional replacement of 1·5% of the cement with calcium chloride to attain the prescribed 7-day strength. A similar replacement was made in the 4:1 tunnel linings, so that the strength at 12 hours would allow the shutters to be stripped.

27. The following routine tests were carried out at site:—

(i) Physical tests on Portland cement.
(ii) Examination of slag for efficiency of granulation.
(iii) Examination of slurry for water content and fineness.
(iv) Crushing tests on 3:1 mortar cubes made with Trief cement (70 slag/28·5 Portland cement/1·5 CaC_2).

(v) Crushing tests on concrete cubes:—6-in. cubes for concrete with maximum aggregate-size of 1½ in. (4:1) and 10-in. cubes for 4-in. maximum aggregate-size (7:1). The average strengths of these cubes at various ages, with the number of cubes crushed in brackets, are shown in Table 4.

TABLE 4

Mixes	7 days: lb/sq. in.	28 days: lb/sq. in.	90 days: lb/sq. in.	180 days: lb/sq. in.	360 days: lb/sq. in.
4:1					
70/30/0	2,024(195)	4,173(195)	4,930(27)	—	—
70/28·5/1·5	2,643(114)	4,237(117)	(3½ years—9,080 (9))		
7:1					
70/30/0	842(69)	1,894(66)	3,518(54)	4,191(18)	4,785(12)
60/40/0	864(30)	1,922(36)	2,754(15)	—	—
70/28·5/1·5	1,720(327)	3,005(303)	4,167(24)	4,461(24)	4,909(21)

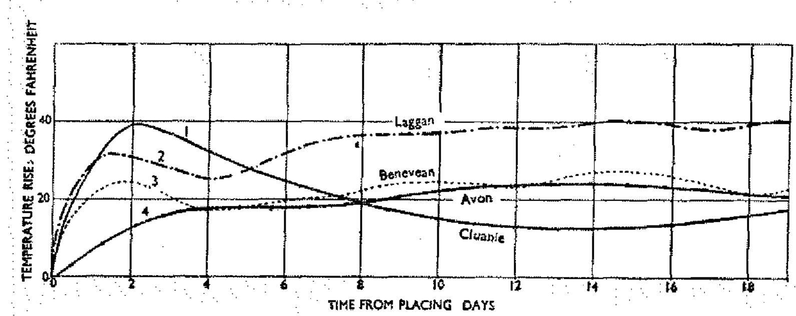
28. The fineness of the slurry varied between 2,800 and 4,300 sq. cm/g and was generally about 3,000. This compares with British Standard requirements of not less than 2,250 sq. cm/g for ordinary Portland cement and not less than 3,200 for low-heat Portland. The average initial and final setting times for accelerated Trief were 107 min and 154 min respectively, compared with 108 min and 156 min for Trief without accelerator.

29. Tests of the heat of hydration were made in a specialist's laboratory. The results obtained are shown in Table 5 and are compared with B.S. requirements for low-heat Portland cement. On the site, a measure of the heat of hydration of Trief cement was obtained by the readings of thermometers embedded in various positions in the Cluanie dam. This is shown in Fig. 10 alongside temperature curves obtained on other dams constructed with ordinary Portland cement (Laggan dam) and low-heat Portland cement (Benevean dam).

30. The Building Research Station tested Trief cement and found that the drying shrinkage, moisture movement, and thermal expansion were similar to those for ordinary Portland cement.

TABLE 5

Type of Cement	Heat of hydration: cal/g.	
	7 days	28 days
Portland cement .	—	91
Trief 70/30· . .	—	62
Trief 69/30/1· .	66	77
B.S.1370:1947 for low-heat Portland cement .	Not more than 65	Not more than 75



Dam	Cement	Cement/concrete: lb/cu. yd	Lift thickness: feet	Lift cycle	
				Adjacent blocks	Vertical lifts
1. Cluanie	Trief, 70/28·5/1·5	347	5	6 days	4 days
2. Laggan	Ord. P.C., coarse ground	375	4	2 weeks	6 days
3. Benevean	Low-heat Portland B.S.137/47	375	4	3 weeks	3 days
4. Avon	Trief, 70/30/0	400	4	8 days	4 days

FIG. 10.—CLUANIE DAM. COMPARISON OF TEMPERATURE RECORDS WITH THOSE OF OTHER DAMS

31. Measurements were carried out on the movements of the 45-ft blocks in the Cluanie dam, firstly, by measuring the overall movement by a block by means of a strained wire, and secondly, by measuring the openings of the contraction joints on each side of a block. The results are given in Figs 11 and 12.

32. If properly proportioned, Trief cement has no free lime, and should therefore be more resistant than Portland cement to acid water. So far there is no evidence to confirm this, but concrete cubes have been immersed in the water of the Tummel aqueduct and Loch Cluanie (average pH values of 6·0 and 6·6 respectively) and it is hoped to get information on the matter after an adequate lapse of time.

PRECAST FACING BLOCKS IN PLACE OF SHUTTERING FOR DAMS

33. The shortage of joiners led to consideration of methods of construction which did not involve shuttering, and with this in view the use of precast facing

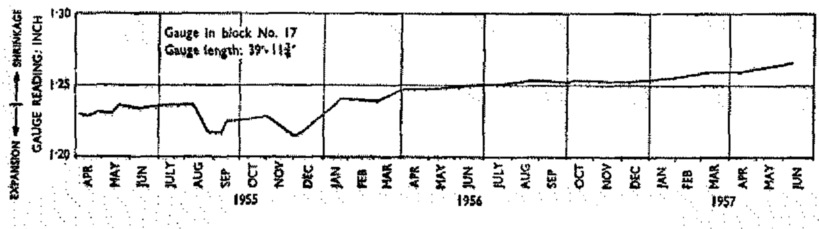


FIG. 11.—CLUANIE DAM. BLOCK MOVEMENT

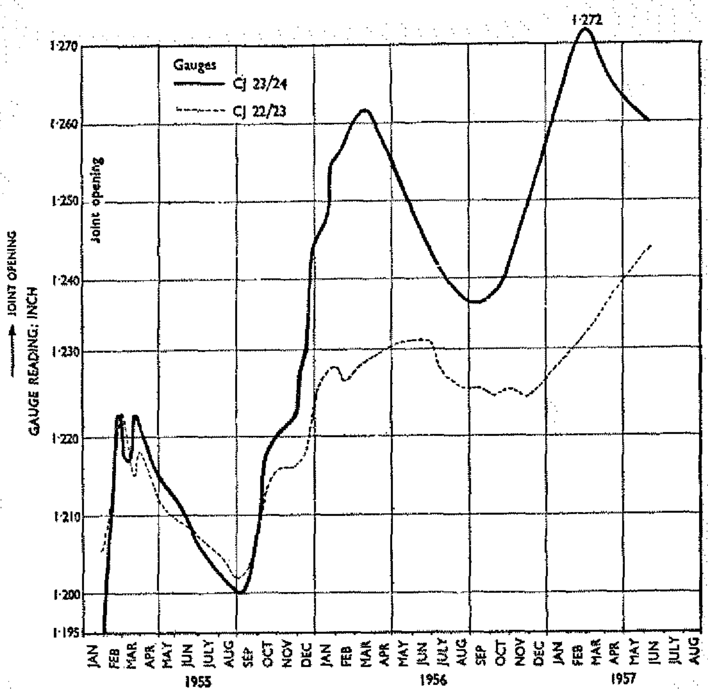


FIG. 12.—CLUANIE DAM. CONTRACTION-JOINT MOVEMENT

blocks was adopted. Although the idea is not new, it is believed that in Britain this is the first occasion on which the facing units, of too thin a section to be stable as gravity units, have been designed to be self-supporting.

34. For the Cluanie and Loyne dams three types of facing units were used as shown on Fig. 13. All units were designed to be adjustable by means of the concrete joggle blocks, housed in recesses in the top and bottom edges, which acted as hinges. The vertical height of each unit is about 5 ft, corresponding to the depth of a lift of concrete. The weight, and therefore the length, was governed by the capacity of the largest mobile crane that could work between the two faces at the top of the Cluanie dam.

35. Up-stream and contraction-joint units could be erected without reference to the level of the concrete behind them, but those on the downstream face were designed to be propped from the preceding lift of concrete.

36. The units were cast, face down, on a vibrating table. Ordinary Portland cement was used, the mix being 4:1 by volume. Reinforcement was provided only to the extent necessary for lifting the units. They were cast on a site adjacent to the Cluanie dam, and for that dam were transported by cableways to the required block, where they were set in position by a 3-ton mobile crane. Units for the Loyne dam were transported there by road and placed in position by derricks.

37. When lifted into position the units were adjusted to correct alignment,

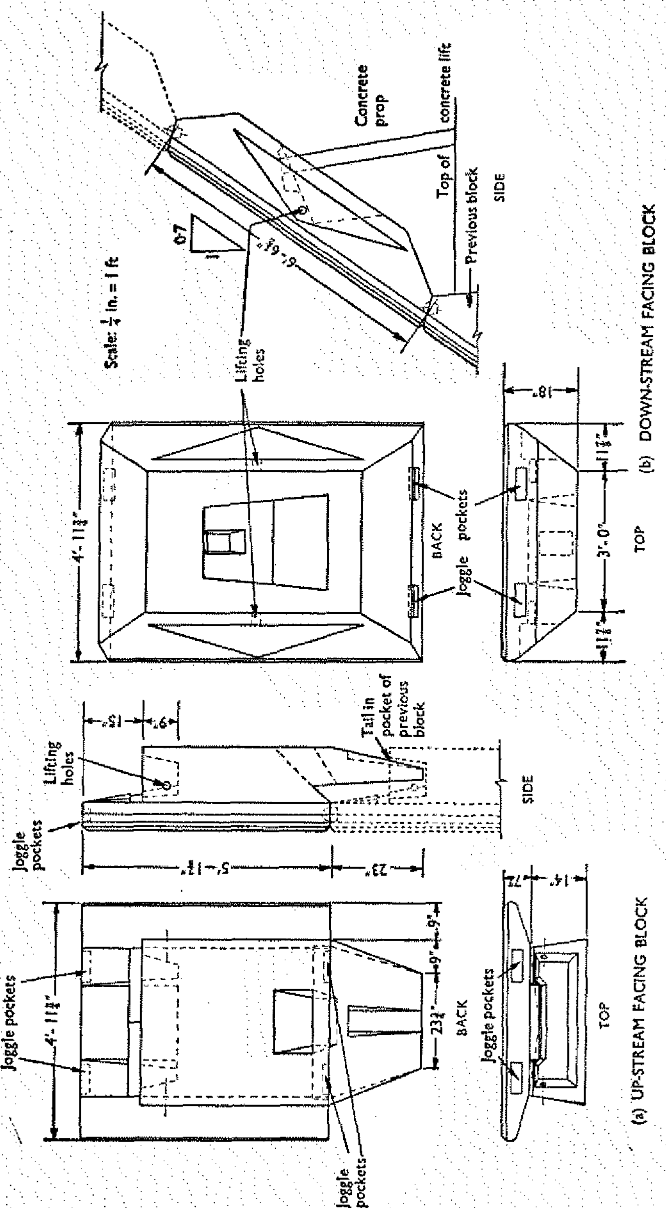


FIG. 13.—CLUANIE DAM. FACING BLOCKS

wedged, and grouted. The following day the concrete filling was placed, each lift finishing about midway up the vertical units. Later the joints were pointed from the outside to exclude water. On completion, the up-stream faces of both dams were given two coats of bituminous paint as an added protection.

38. The labour used to make and place the units was much less than the number of joiners that would have been required for conventional shuttering, and the rate of progress much quicker. In the light of this experience the Authors consider that the method used has great possibilities.

Control gates in Dundreggan dam

39. At the Dundreggan dam (Fig. 14, Plate 2), the rise in water level must be kept to a minimum in order to preserve agricultural land, and the pondage is therefore small. The dam has to pass, through gates only, an estimated maximum flood of 30,000 cusecs. In addition, artificial spates of 370 cusecs must be passed as part of the compensation water arrangement, and provision has to be made to discharge the full flow of the turbines should load be rejected. One gate must dip below the water surface to pass floating debris and the others must lift clear to pass flood-borne debris below the surface.

40. Various types and combinations of gates were examined, and Table 6 gives a comparison of costs. The cheapest combination to fulfil the requirements was two 28½ ft × 27 ft Taintor (radial) gates, and a 20 ft × 10 ft tilting gate. To give balanced flow conditions the tilting gate is placed centrally. (Fig. 15, Plate 2).

Table 6

Type and size of gate	Total cost	Cost per sq. ft
Drum gate 27 ft × 12 ft	£25,000	£76
Tilting gate 20 ft × 10 ft	£8,000	£40
Fixed roller drop gate 19 ft × 19 ft	£11,000	£31
Vertical lift, fixed roller 27 ft × 27 ft	£13,500	£18 14*s.*
Taintor 28½ ft × 27 ft	£11,250	£14 12*s.*

41. Model tests were carried out on site, on a scale of 1/60, to determine the discharge through the gates at various openings, and any work which might be required to ease the passage of fish to the fish lock.

42. All the gates are electrically operated, but to avoid dependence on the power line, power is derived from batteries. There is also provision for manual operation in the event of electrical breakdown.

43. Operation can at any time be effected by means of push-buttons at each gate. Remote water-level and gate-position indicators are provided in the generating station. An alarm in the station indicates if any gate has failed to operate.

44. The Taintor gates are mainly of welded construction and of conventional design while the tilting gate is of riveted construction. This gate is controlled independently of the Taintor gates which in turn can be operated together or

individually. The operation of the tilting gate is linked with the main turbines and control is partly by water level in the reservoir and partly according to the flow through the turbines. The operation of the Taintor gates is controlled by the water level in the reservoir in such a way that the outflow during floods approximates to the inflow.

Inverts of low-pressure tunnels

45. In the Mullardoch tunnel on the Affric project the rock spoil on the invert was not completely removed before placing the concrete invert, except for short sections at the intake portal, the intake gate-shaft, and the outfall, and at some intermediate sections where the rock was unsound. The minimum thickness of concrete was 8 in., but continuously along each side and transversely at 50-ft centres, a trench was excavated and the concrete carried down to solid rock. This resulted in savings in labour, materials, and time, as complete mucking-out of the invert has to be done by hand and is tedious and costly. This tunnel was put into service in 1951 and inspected in 1955 when some rockfalls from the unlined roof were found, but even under the falls the invert was undamaged.

46. Because of the savings effected, the inverts of the Ceannacroc, Invergarry, and Quoich tunnels have not been completely excavated, but that of the Doe tunnel was carried to rock, as here the water is liable to high-velocity flow and surging. Weepholes of 1½-in. dia. were formed in the invert slabs at 10-ft centres and provided with filters of clean gravel.

47. The Loyne tunnel of the Moriston project was driven large enough to keep the water velocity within 5 ft/sec at maximum flow through the turbine. The invert of the tunnel was unlined except for short lengths at the up-stream end and at the outfall gate-shaft and portal. Spoil was removed to formation level, the invert being roughly graded for drainage purposes. Sections of the walls and roof were lined at both ends of the tunnel and where the rock was unsound. In December 1955, a sudden flood caused the River Loyne to overtop the coffer-dam at the dam and pass through the tunnel. The water velocity was slightly over 5 ft/sec but, although some scour was caused at most sections where the walls were lined, it was still easy to walk through the tunnel.

48. At Glenmoriston the invert of the tail-race tunnel is not lined, apart from a short length down-stream of the station where turbulence is expected. Maximum water velocity is about 5 ft/sec and an access road has been formed at the outfall to provide easy entry in the event of a rockfall.

49. At the up-stream end of the Loyne tunnel some short lengths of invert were lined experimentally with a new type of bituminous macadam, named Compomac. Only a light vibrating roller could be used for consolidation, but nevertheless the macadam was undamaged by the flood water. It is too early yet to draw definite conclusions, but, if successful, this type of macadam, which can be laid in water, might prove very useful, especially in large tunnels where its use would provide a smooth invert both for transport and the flow of water.

50. The experience gained from these tunnels, and from tunnels in other countries, indicates that whenever the rock is suitable it is definitely cheaper to adopt unlined tunnels and there is also a saving in time which, in the client's interest is important. There is, however, a feeling that lining should not be omitted up-stream of turbines because of the possibility of damaging the machines, either by large pieces of rock or by abrasion from fine particles.

INFLUENCE OF PROVISIONS FOR SALMON ON DESIGN AND CONSTRUCTION

51. The preservation of salmon was of prime importance in the design and construction of the hydro-electric works on both the Rivers Garry and Moriston, and the measures required cost a considerable sum. When deciding to proceed with development the Board took care to ensure that the stock of salmon would not suffer and would if possible be improved.

52. The Garry is the more important river for fish, and the particulars given here of the chief protective measures taken are confined to this catchment. These measures are as follows:—

(i) Minimum compensation flows between Invergarry dam and power station of 28 cusecs in winter and 120 cusecs in summer, with seasonal freshets to bring fish up the river.
(ii) A fish pass through Invergarry dam.
(iii) A screened intake to the power tunnel at Invergarry dam.
(iv) A fish stopper and trap down-stream of Quoich power station.
(v) Minimum compensation flow of 37 cusecs released from Quoich dam.
(vi) Hatchery at Invergarry.

53. Quoich dam, in the upper part of the catchment, raises the loch level by over 100 ft, thus drowning the best spawning reaches: hence the need for a stopper and trap to take and strip the fish, and a hatchery to deal with the spawn.

Invergarry dam and tunnel intake

54. The dam is sited in a narrow gorge. It is provided with two lifting flood gates, two compensation-water turbines (one for summer and one for winter flows) and a Borland-type fish pass, which functions on the principle of a canal lock and is automatic in operation. The range of reservoir levels is 12 ft, and the maximum lift is 33 ft. There is no room for spillway accommodation in the gorge and for this a side-channel spillway is provided which discharges into a large spillway tunnel by-passing the gorge. The original layout is shown in Fig. 16a but this was revised to that shown in Fig. 16b in which the power-tunnel intake is placed between the spillway and the dam, so that smolts and kelts attracted by the flow into the intake would have but to drift across the fine screens to find themselves at the up-stream end of the fish lock. The screen structure shown in Fig. 28 is an extensive one and constant maintenance is required by the operating staff in keeping screens clean at certain times of the year. The power tunnel passes under the spillway tunnel (Figs 16b and 17).

55. Passage through the gorge had always been difficult for fish, and some improvement was needed to provide for their easy access to the fish lock. In view of unstable conditions on the south side of the gorge, which might at some future date cause a blockage, a small tunnel was excavated through good rock on the north bank, with six low weirs to raise the water level in 12-in. steps.

Quoich fish stopper and trap

56. The programme of the works required that the fish stopper and the trap should be built two years before impounding began, so that the last smolts bred in the upper waters would pass down-stream before the dam was closed.

57. A bar-screen type of stopper was adopted, and designed to be stable even if completely choked with grass and over-topped. It has a minimum overfall

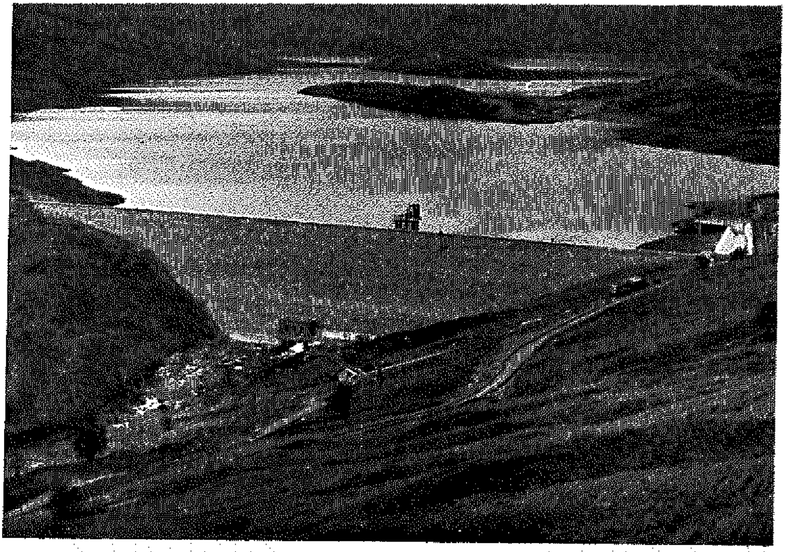


FIG. 28.—QUOICH DAM

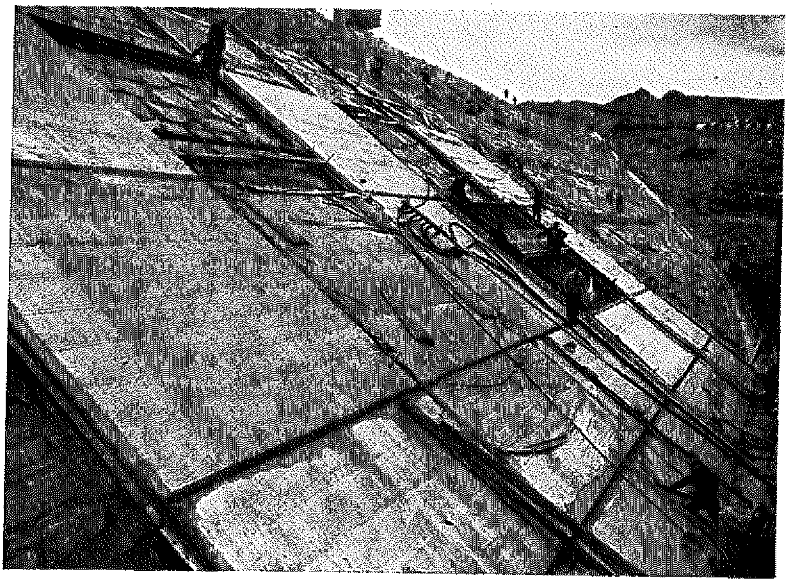


FIG. 29.—QUOICH DAM. UP-STREAM MEMBRANE DURING CONSTRUCTION

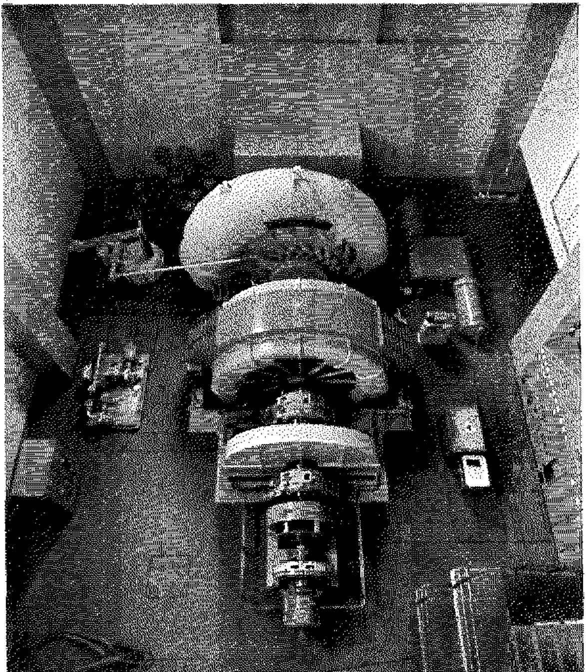


FIG. 30.—QUOICH POWER STATION. INTERNAL VIEW

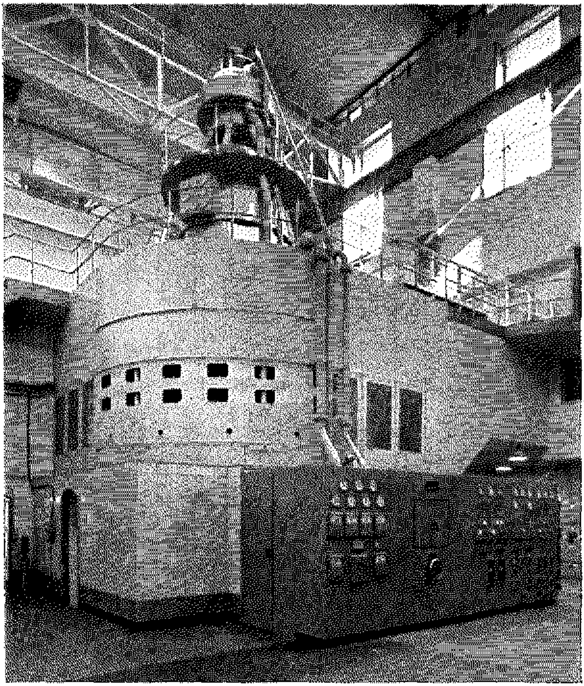


FIG. 31.—INVERGARRY POWER STATION. INTERNAL VIEW

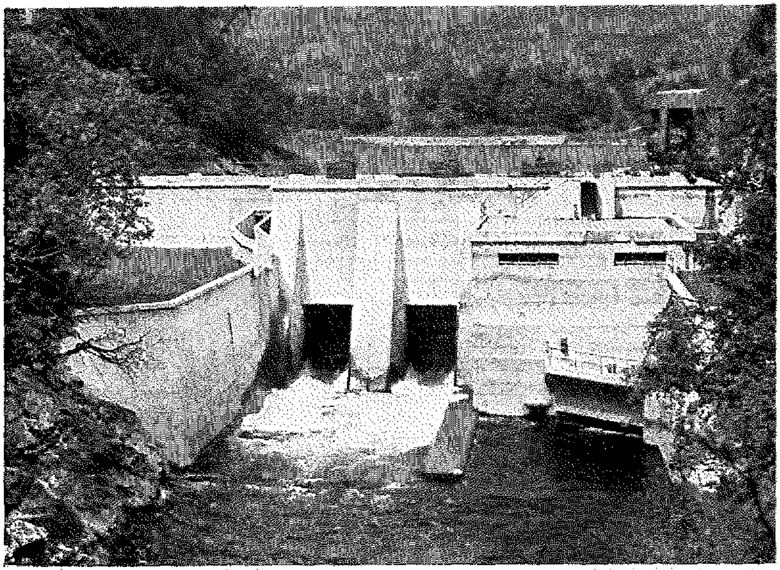


Fig. 32.—Invergarry dam

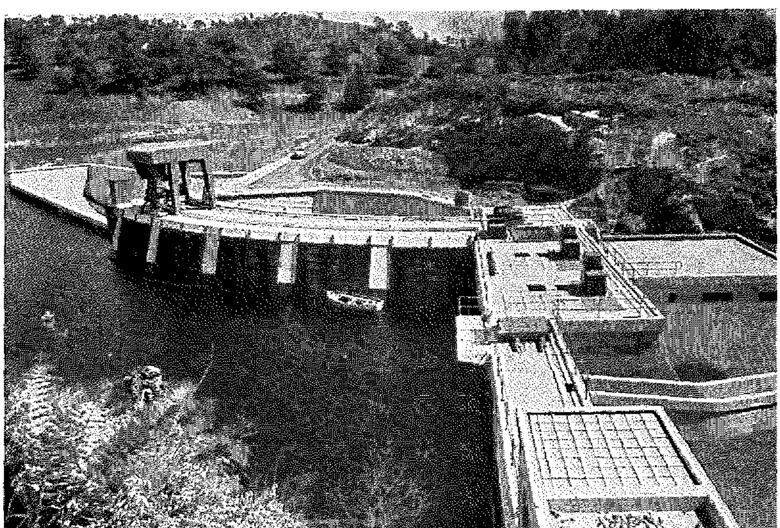


Fig. 33.—Invergarry dam and tunnel intake

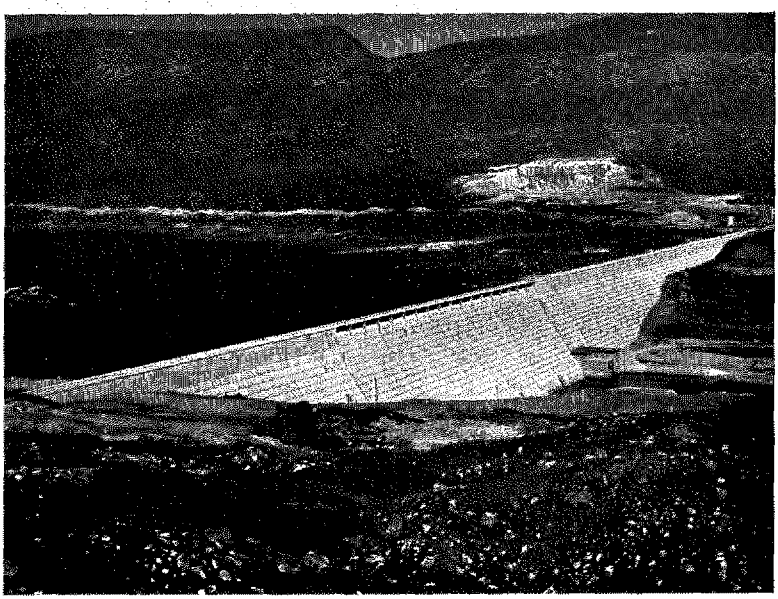


FIG. 34.—CLUANIE DAM

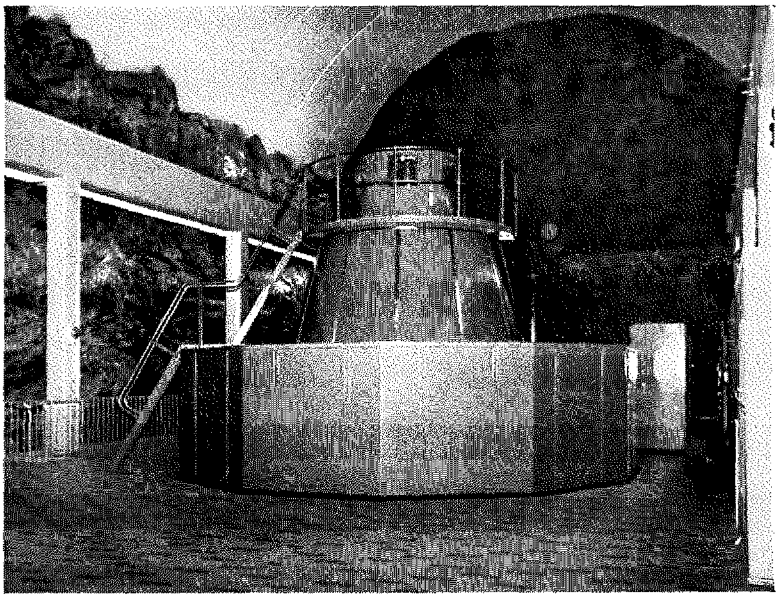


FIG. 35.—CEANNACROC POWER STATION. 16-MW SET

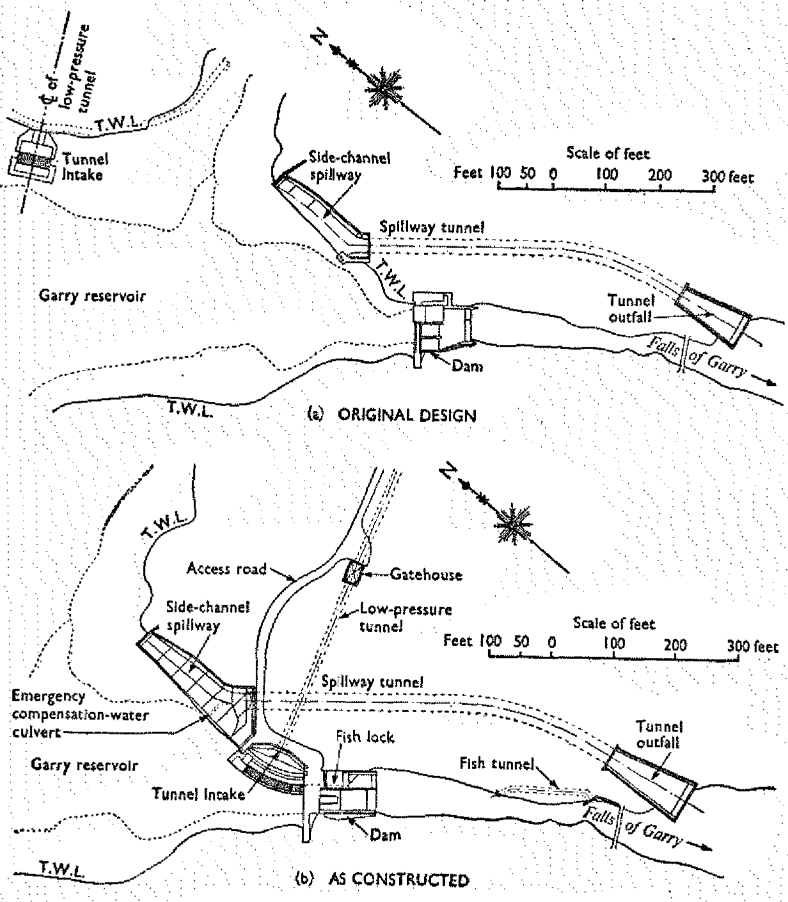


FIG. 16.—INVERGARRY DAM AND TUNNEL INTAKE

height of 8 ft. Three traps were finally provided, to give access for fish at all levels (Fig. 18, Plate 2).

58. In order that immature fish could be kept until ripe for spawning, holding tanks were formed on the river bank and a wired-in area provided down-stream in Loch Poulary.

59. An experimental electrical fish stopper was also constructed about ½ mile down-stream and this is capable of controlling the movement of fish up-stream.

Anti-pollution measures

60. Temporary works needed to prevent damage to fish during the construction period included oil traps in all burns passing through working sites, and settling bays and filter banks to remove rock flour from the effluent from stone crushers and from the water used for washing the rockfill material at Quoich.

Power station design

61. The power stations were designed to meet diverse engineering conditions, with maximum water utilization consistent with compensation water and other obligations. The principal features are summarized in Tables 7 and 8.

62. Underground power stations have been constructed on the Continent since 1910. They were gradually adopted by the Board as shown in Table 9.

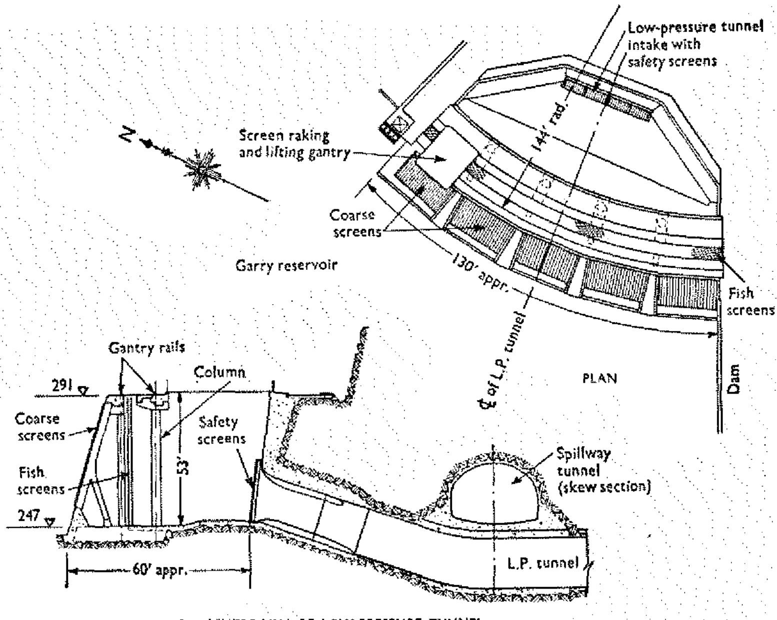


Fig. 17.—Invergarry tunnel intake

In the later developments, improved subterranean excavation techniques permitted economic realization of the advantages obtained in underground stations elsewhere, which included:—

(i) Freedom, in site and plant selection, to take maximum advantage of head and ground conditions.
(ii) Short high-pressure intake shafts in rock with no up-stream surge chambers.
(iii) Elimination of tunnel lining except at points of weakness and special junctions, etc.
(iv) Protection from surface-rock falls and floods.
(v) Simplified construction in foundations, walls, and crane runways.
(vi) Freedom from effects of weather during construction provided ground water is controlled.
(vii) Low maintenance costs.

The extent to which these advantages could be utilized at each site will be seen from the descriptions which follow.

63. Plant selection created no special problems. System demand, load factor, hydraulic and manufacturing considerations justified a maximum of two units in any station. The main features are described below.

Quoich

64. As shown in Figs 19 and 20, Plate 2, a surface station was adopted. For easy erection it was decided to use a horizontal Francis turbine with butterfly inlet valve and open-circuit alternator ventilation. The velocities and penstock length/head ratio necessitated a turbine relief valve and flywheel for satisfactory governing.

Invergarry

65. Fishery and topographical considerations resulted in the adoption of a semi-underground station (Figs 21 and 22, Plate 2) with one Kaplan instead of the two Francis turbines originally contemplated. The unit is unusual in that the head is high for this type of turbine and the oil-operated relief valve discharges into the underground tail race. The alternator has open-circuit ventilation.

Ceannacroc and Glenmoriston

66. These stations have comparable heads but differing flows. At Ceannacroc (Figs 23 and 24, Plate 2) compensation flow demanded a 4-MW unit and at Glenmoriston (Figs 25 and 26, Plate 2) limited storage made two units preferable to one. Total capacities required were 20 MW and 32 MW respectively, and it was decided to order three similar 16-MW machines, one for Ceannacroc to be installed along with the 4-MW unit, and two for Glenmoriston.

67. *Station location.*—The River Doe diversion fixed Ceannacroc station near the down-stream end of the tunnel. Siting the station virtually below the surge shaft resulted in a considerable saving of steel and concrete at no extra cost over other sites.

68. Three schemes for Glenmoriston were examined as follows:—

(i) Low-pressure tunnel, surge chamber, and high-pressure shaft with:—
  (*a*) a high-pressure tunnel and surface station at Invermoriston.
  (*b*) an underground station at the foot of the high-pressure shaft and free flowing tail-race tunnel.

(ii) High-pressure intake shaft, underground station, and unlined pressure tail-race tunnel with surge chamber.

A study of the merits of the three schemes, including the generating plant, showed that, subject to geological investigation, the third was the best. It avoided a 132-kV transmission line between Invermoriston and Dundreggan dam. With the station 150 ft from the intake shaft, ensuring structural strength and low leakage, the turbine inlet-flow conditions were acceptable and much steel and concrete lining to conduits was avoided.

69. Speed- and pressure-regulation conditions at Ceannacroc and Glenmoriston made relief valves unnecessary and governing stability satisfactory with the same alternator-flywheel effect. It was thus possible to provide similar machines for each station except that, at Glenmoriston, it was necessary to strengthen turbine covers to resist tail-race surge pressures. Humidity and other factors demanded closed-circuit alternator ventilation.

TABLE 7.—MAIN POWER STATIONS

SUMMARY OF GENERATING PLANT DETAILS

	Quoich	Invergarry	Ceannacroc	Glenmoriston
Type of station	Overground	Semi-underground	Underground	Underground
Type of turbine	Horizontal Francis	High head vertical Kaplan	Vertical Francis	Vertical Francis
Capacity: MW	1×22	1×20	1×16 1×4	2×16
Av. gross head: ft	312	169	276	310·5
Design head: ft	255	146·4	250 254	285
Mean annual output: kWh ×10[6]	74·4	81·0	60·8	120·2
Annual load factor: %	40	47	40	41
Flow at rated capacity and mean head: cusecs	1,034	1,737	1,070	1,720
Waterways	High-pressure tunnel and restricted orifice surge chamber	High-pressure tunnel and differential surge chamber	High-pressure tunnel and simple surge chamber	High-pressure shaft, Low-pressure tail-race with compound overflow surge chamber
High-pressure system				
Conduit length/head ratio	9·48	6·15	1·08	1·39
Speed of turbine: r.p.m.	300	250	375 500	375
Alternator flywheel effect: WR^2 × lb × ft^2 × 10^6	4·06	6·35	1·90 0·20	1·90
Machine speed and pressure control	Relief valve		Governor alone	
Speed rise for load rejection: %	22·0	21·0	18·0 18·0	19·0
Pressure rise for load rejection: %	25·0	16·0	18·0 10·0	18·0

Transformers	Quoich Main	Quoich Unit	Invergarry Main	Invergarry Unit	Ceannacroc Main	Ceannacroc Unit	Glenmoriston Main	Glenmoriston Unit
Voltage ratio	All main transformers 132/11 kV; All unit transformers 11,000/433V							
Capacity: kVA	Main 25,000	Unit 50	Main 25,000	Unit 100	Main 30,000	Unit 40	Main 2× 25,000	Unit 2× 40
Connection	All star/delta							
Insulating medium	Oil	Oil	Oil	Oil	Oil	Resin	Oil	Resin
Location	Compound		Compound		Compound	Alternator cubicle	Dundreggan headworks	Alternator cubicle

Table 7 (*cont.*)

11-kV Switch-gear				
Current rating: amperes . .	1,600	1,600	3,000	2 × 1,200
Rupturing capacity: MVA . .	250	250	500	500
110-V Station Batteries				
Type . . .	Lead acid	Nickel Cadmium	Lead acid	Lead acid
Rating: ampere hours . .	240	275	350	400
Charging . .		Trickle charging		Constant voltage

TABLE 8.—AUXILIARY POWER STATIONS

Dam location	Turbine type	Capacity: kW	Output: kWh × 10^6/year	Design head: ft	Speed: r.p.m.
Quoich . .	Horizontal Francis	1 × 350	2·6	113	762
Invergarry .	Vertical Francis	1 × 285		27	230
		1 × 30	1·4	27	762
Loyne . . .	Vertical Kaplan	1 × 550	1·2	39	434
Cluanie . .	Horizontal Francis	1 × 300	2·1	86	507
Dundreggan .	Vertical Propeller	1 × 165	0·6	42·5	1,020

TABLE 9

Station	Capacity: MW	Type	Completed
Morar . . .	0·6	Cut and cover	1948
Mullardoch .	2·4	Underground	1954
Clachan . .	40·0	Cut and cover	1955
Invergarry . .	20·0	Semi-underground	1956
Ceannacroc .	20·0	Underground	1956
Glenmoriston .	32·0	Underground	1957
St Fillans . .	21·0	Underground	1958

70. *Geology*.—The rock consists of psammitic and pelitic schists with injections of igneous rocks. Two borings were put down at each site.

71. At Ceannacroc the cores showed undisturbed rock, confirming surrounding geological indications and the nearby tunnel excavation.

72. At Glenmoriston the cores showed complex jointing and some shattering. For fuller information a shaft was sunk on the line of the proposed intake shaft and from it a gallery was driven to enter and traverse the station, following the

line of one of the pipe tunnels. This confirmed what the borings had shown, but the rock was considered stable enough to excavate without undue difficulty.

73. *Access.*—This plays an important role in underground station layout and certain criteria have to be taken into account. Tunnels with a gradient of about 1 in 10 are preferable to shafts for machinery transport. Small service tunnels and shafts are expensive and should be large enough to accommodate ventilation ducts, generator cables, pipes and, in the case of shafts, lifts, and stairways.

74. At Ceannacroc the most economical form of access was a tunnel. This was left unlined except for a short length at each end.

75. At Glenmoriston the choice lay between a vertical shaft incorporating service ducts and a tunnel together with service shaft. The costs were comparable but the requirements of the surge gallery gave some advantage to the second scheme which was adopted. The tunnel was lined over part of its length by means of the Aliva gun.

76. The dimensions fixed by machine-component transport on low loader are shown in Table 10.

TABLE 10

	Width or diameter	Weight: tons
Spiral casing . .	16 ft 10 in.	13
Alternator rotor .	11 ft 6 in.	62
	Height: road to soffit	Max. width
Access tunnels .	15 ft 8½ in.	17 ft 4 in.
	Gradient	Length
Ceannacroc . .	1 in 9	620 ft
Glenmoriston .	1 in 12	2,200 ft

77. *Construction.*—The intake-shaft designs assumed that the rock, reinforced by grouting, takes the entire water pressure and that the concrete lining resists external loads when the shaft is dewatered. Similarly the steel linings of the short high-pressure tunnels are designed to resist external loads when empty. The mass-concrete arches forming the station roofs were designed to carry a 15-ft-thick rock load, which was considered adequate for any grouting pressures to be used.

78. At Ceannacroc the rock in the side walls was stable enough to be left unlined but on the north-end wall the "small" rock was gunited to prevent minor falls. The south-end wall appeared unstable and a concrete lining was provided there with long bolts driven into the rock. The station was comparatively dry when completed and put into operation.

79. At Glenmoriston the rock was weaker and during excavation the inflow of ground water was about 50,000 gal/hour. The walls were strengthened by 9-ft Perfo rock bolts at 4-ft centres and a concrete facing was applied. The walls were subsequently grouted in three stages and pressure-relief holes were provided through the concrete facings. Construction and erection space was

limited and the operating floor was designed for completion before the spiral casings arrived.

Surge control

80. Waterway and associated surge-chamber design made allowance for system interconnection as well as load, machine, and governor stability characteristics, for which the data in Table 7 are appropriate. The governors were designed to limit the load acceptance rate.

81. Surge-chamber performance was determined analytically and confirmed by model tests in association with the tail-race tunnels for Ceannacroc and Glenmoriston.

82. Ceannacroc tail race was dimensioned for free flow, except for fast load acceptance during high river levels, which are unlikely since the discharge is controlled at Loyne and Cluanie dams.

83. The Glenmoriston tunnel can absorb load-rejection down-surges. The surge system was designed for machine coming on load 10 min after losing full output to avoid maximum surge when the return wave meets the increasing discharge.

Mechanical and electrical aspects

Station operation

84. Geographical and hydraulic considerations, as well as the installed plant, weather, and labour conditions, dictated the operating requirements which were:—

(i) Major stations with synchronous generators to be partially attended and started and stopped by local pushbuttons with provision for remote control from Fort Augustus.

(ii) Auxiliary stations with induction generators to operate unattended except for occasional visits for output adjustment and maintenance.

Underground station design

85. Comparison with practice elsewhere is instructive:—

(i) Flood outlets and highly stressed floor reinforcement for emergency conditions were deemed unnecessary but the turbine valves and spiral casings were given a high safety factor.

(ii) Underground transformer locations were avoided because of fire risks and need for larger access-tunnel and ventilation systems. At Ceannacroc and Glenmoriston, compounds near the access-tunnel portal and the service-shaft head respectively were suitable for naturally cooled main and auxiliary transformers.

(iii) Amenities are important since strong lighting, monotonous noise, and bad ventilation are depressing for personnel. For the stations in question:—

(*a*) Machine controls are at generator-floor level with the high- and low-voltage switchgear housed near the transformer compound.

(*b*) At Ceannacroc an impression of daylight was created by mounting continuous troughed fluorescent lighting behind the crane beams which, with light coloured switchboards, gives a restful appearance.

(c) The noise levels are below the 100 dB reported elsewhere. This was assisted by discontinuous wall surfaces and liberal alternator design with closed-circuit ventilation.

(iv) Abundant fresh air is essential. Continental experience and Highland climatic conditions indicated that natural ventilation was sufficient with short access and free flowing tail-race tunnels. Provision was nevertheless made for fan installations if necessary. The installations adopted were as shown in Table 11.

(v) The difference between the alternator and switchgear elevations necessitated mass-impregnated, non-draining power and control cables laid in road ducts at Ceannacroc and fixed to the lift shaft at Glenmoriston.

Space comparison

86. The assembly-bay dimensions (Table 12) were fixed by the physical size of the machine with (*a*) Access adjacent to the machine hall and serviced by the

TABLE 11

Station	Cold-air entry	Warm-air exit
Ceannacroc . .	Tail-race tunnel	Access tunnel
Glenmoriston .	Access tunnel	Roof extraction into lift-shaft trunking

TABLE 12

Station	Installation: MVA	Speed: r.p.m.	kVA/r.p.m.	Assembly-bay area: sq. ft	Crane	
					Capacity: tons	Span: ft
Quoich . .	23·2	300	77·5	1,060	110	45·0
Invergarry .	23·5	250	94·3	1,040	130	49·5
Ceannacroc .	23·6	375*	50·5*	1,140	80	41·5
Glenmoriston	37·8	375	50·5	890	80	38·0

* for 16–MV machine

station crane and (*b*) Space for entrance and unloading of road vehicles and working around the machine components. At Quoich the assembly-bay level was fixed by the catastrophic-flood level.

87. Invergarry is unusual in that the assembly bay is above the turbine inlet butterfly valve and extends to the alternator centre-line. This resulted from the relative elevations of the access road, inlet tunnel, turbine setting, and tail race.

88. Ceannacroc and Glenmoriston have the alternators above floor level and contiguous with the assembly bay, with turbine and inlet-valve access below.

89. Comparison of the machine hall dimensions (Table 13) illustrates the influence of (i) single- and double-unit installations, (ii) horizontal and vertical

TABLE 13

Station	Design head: ft	Power-station volume: cu. yd/MW			Typical 1944 figure
		Super-structure	Sub-structure	Total	
Invergarry .	146	274	394	668	675
Quoich . .	255	222	301	523	575
Ceannacroc .	250	204	301	505	575
Glenmoriston	285	132	197	329	575

Francis and Kaplan units, (iii) overground and underground construction, (iv) head, (v) total capacity, and (vi) previous experience.

Mechanical and electrical installations generally

90. Operational requirements and economy allowed minimum space for conventional mechanical and electrical auxiliaries, workshops, stores, and employees' and public facilities. The following notes amplify Table 7.

(i) At Quoich and Invergarry:—

(*a*) Station lighting is by fluorescent fittings below the crane runway.

(*b*) Open-circuit alternator ventilation required motor-operated air-inlet louvres in the station wall in front of the viscous filters, and manually adjusted high-level hot-air outlet louvres.

(ii) There is no machine-hall heating but:—

(*a*) Tubular heaters are installed in some switchgear and relay rooms.

(*b*) Alternator-winding heaters are provided to prevent condensation during shut-down except at Quoich where this is being examined.

(iii) Emergency lighting from the 110-V battery, on failure of the A.C. supplies, is installed at important locations.

(iv) Overlapping differential systems protect the alternator, 11-kV breaker, and main transformers. In addition, the alternators have over-voltage, negative-phase-sequence, and overcurrent protection and the transformers have Buchholz relays. On the high-tension side of the transformer are:—

(*a*) 132-kV motor-operated isolators with interlocked line-maintenance earthing contacts.

(*b*) Single phase fault-throwing switches for automatic tripping of the associated 132-kV circuit-breaker at Fort Augustus.

(v) Essential machine auxiliaries are fed from:—

(*a*) A unit transformer connected to each alternator.

(*b*) A stand-by supply with manual changeover to the station common-services board, which is fed from either a 200-kVA transformer on the 33-kV system or a 200-kVA earthing transformer.

(*c*) The station battery for those auxiliaries needed at starting, shut-down, or on A.C. supply failure.

(vi) All metal parts are bonded to embedded mats which are connected to the station earth buried near the transformer compound.

(vii) The alternators and transformers are considered to be covered by the general fire protection system which includes:—

(*a*) Hydrants fed from the pressure tunnels through reducing valves.

(*b*) A CO_2 installation for the 11-kV switchgear.

(*c*) Carbon tetrachloride extinguishers for cranes.

(*d*) Portable CO_2 extinguishers appropriately located.

(viii) Domestic water supplies are taken from the pressure tunnels and treatment was unnecessary.

(ix) The major stations communicate with the Fort Augustus group control centre *via* carrier channels using one of the 132-kV phase conductors and earth return (Fig. 27, Plate 2), giving the following facilities:—

(*a*) Telephone communications including connexions with the Board's main control centre at Port-na-Craig (Perthshire).

(*b*) Extensions to the head works and attendants' houses.

(*c*) Continuous output indication.

(*d*) "Urgent" or "Non-urgent" signals of alarms on the machine-gauge boards.

Conclusions

91. Large-scale civil engineering works, such as those associated with hydro-electric development, make a large demand on the national resources of materials and labour, and should be designed to absorb the minimum national assets. This can be done in various ways, some of which are described in the Paper.

92. Rockfill dams save cement and, where they are constructed in association with large excavations yielding good rock spoil, compare favourably in cost with concrete dams. The use of the $3\frac{1}{2}$-ton vibrating roller and the sluicing jets solved completely the problem of after-settlement which has caused sealing failures in other similar dams.

93. The vacuum process produced concrete of good quality in forming the up-stream slabs at Quoich in spite of the large working area and exposed site. It is important that the length of vacuum pipe should be kept short, and cold-weather working avoided.

94. The wet-grinding process used for Trief cement has advantages over dry grinding to B.S.146:1947. The fineness of the slurry can be accurately controlled and wet grinding absorbs less power. Wet grinding at site can only be justified for large quantities, but there are good possibilities for the erection of wet-grinding plant near the source of the slag, the slurry being dried and blended with ordinary Portland cement to comply with B.S.146:1947. Trief cement is eminently suitable for massive structures such as gravity dams. It has the attributes of a low-heat cement but, like it, is slow to harden in cold weather and may require an accelerator. In specifying the growth of strength, Trief should be treated as a low-heat cement. Theoretically Trief should be better than ordinary Portland cement in resisting attack by acid water, but experience so far is inconclusive on this.

95. The use of precast concrete facing blocks in place of shuttering saves joiners and gives faster progress. The pointing of joints between precast blocks demands careful attention.

96. Taintor gates of the size installed at Dundreggan have not previously been employed in Great Britain but they are extensively used elsewhere and are considerably cheaper than other known types of gate.

97. There seems to be scope for leaving muck under the concrete lining of tunnel inverts. In diversion and tail-race tunnels, if the flow velocity is not more than 5 ft/sec, a bituminous macadam invert, laid close behind the driving face, can save wear on rubber tires during construction, and resist erosion when the tunnel is in use.

98. The Garry project provides an example of one of the most comprehensive schemes of provision for fish and its effect on the design and construction of hydro-electric works. It has shown how important it is to formulate detailed plans and integrate them with the power requirements before work is begun. In any similar project the natural fish regime in the catchment area should receive the same degree of careful study as does the topography or hydrology. The problem of passing fish up and down through a dam economically appears to have been solved by the Borland fish-lock, or future adaptations. The problem of diverting ascending fish from normal channels is perhaps now nearer a reasonably cheap solution on the lines of the electrical stopper. Prevention of descending kelts and smolts from entering a power tunnel remains the most serious problem. From the hydro-electric point of view it would be most economical to stop the fish at the river mouth, trap them there, and hatch the ova, but other important interests are involved and must be taken into account.

99. When siting an underground station it is inadvisable to rely entirely on borings though they are useful as a check on known geological conditions exposed in nearby excavations. When such excavations are not available it is best to sink exploratory shafts and galleries on the site of the proposed works. The power stations on the Garry and Moriston Schemes appear to have achieved some reduction in plant-space requirements and show that the advantages of underground construction realized elsewhere are applicable in the Highlands without extra cost over that of surface stations.

100. The mechanical and electrical design was simplified to reduce capital and running costs, and operating personnel, to the minimum. While the machinery follows conventional practice the performance of the high-head Kaplan turbine at Invergarry and the combined plant and surge-control arrangements at all stations will be watched with interest.

Acknowledgements

101. The Authors wish to express their thanks to the North of Scotland Hydro-Electric Board for permission to publish the information given in the Paper and to Mr. A. A. Fulton, C.B.E., F.R.S.E., M.I.C.E., M.I.Mech.E., General Manager of the North of Scotland Hydro-Electric Board for his helpful comments in reviewing the draft.

102. They are indebted to Messrs Lemon & Blizard for permission to reproduce curve No. 4 of Fig. 10.

103. They also wish to thank those members of their respective staffs who gave valuable help in the preparation of the Paper.

APPENDIX

List of consultants and principal contractors

Consulting engineers:—	
Civil	Sir William Halcrow and Partners
Mechanical and electrical	Kennedy & Donkin
Architects:—	
Garry works	Gratton and McLean
Moriston works	Robert Hurd, Esq.
Principal civil contractors:—	
Quoich works	Richard Costain Ltd. Alex. Robertson (Roads)
Invergarry works	Whatlings Ltd
Upper Moriston works	Mitchell Construction Co. International Development Co. Ltd (Roads)
Lower Moriston works	Duncan Logan (Contractors) Ltd

Principal mechanical and electrical contractors

Station	Turbine contractor	Alternator contractor
Quoich	Boving & Co. Ltd	English Electric Co. Ltd
Quoich (compensation) water station)	Gilbert, Gilkes & Gordon Ltd	Bruce Peebles & Co. Ltd
Invergarry	English Electric Company Ltd	
Invergarry (compensation water station)	The Armfield Hydraulic Engineering Co. Ltd	Bruce Peebles & Co. Ltd
Loyne	Boving & Co. Ltd	English Electric Co. Ltd
Cluanie (compensation water station)	The Armfield Hydraulic Engineering Co. Ltd	Bruce Peebles & Co. Ltd
Ceannacroc 4 MW	The Harland Engineering Company Ltd	
16 MW	English Electric Company Ltd	
Dundreggan (compensation water station)	Boving & Co. Ltd	Bruce Peebles & Co. Ltd
Glenmoriston	English Electric Company Ltd	

The Paper, which was received on 20 September, 1957, is accompanied by eight photographs, twenty-nine sheets of diagrams, from some of which the half-tone page plates and the Figures in the text have been prepared, and Appendix.

Written discussion on this Paper should be forwarded to reach the Institution before 15 November, 1958, and will be published in or after March 1959. Contributions should not exceed 1,200 words.—SEC.

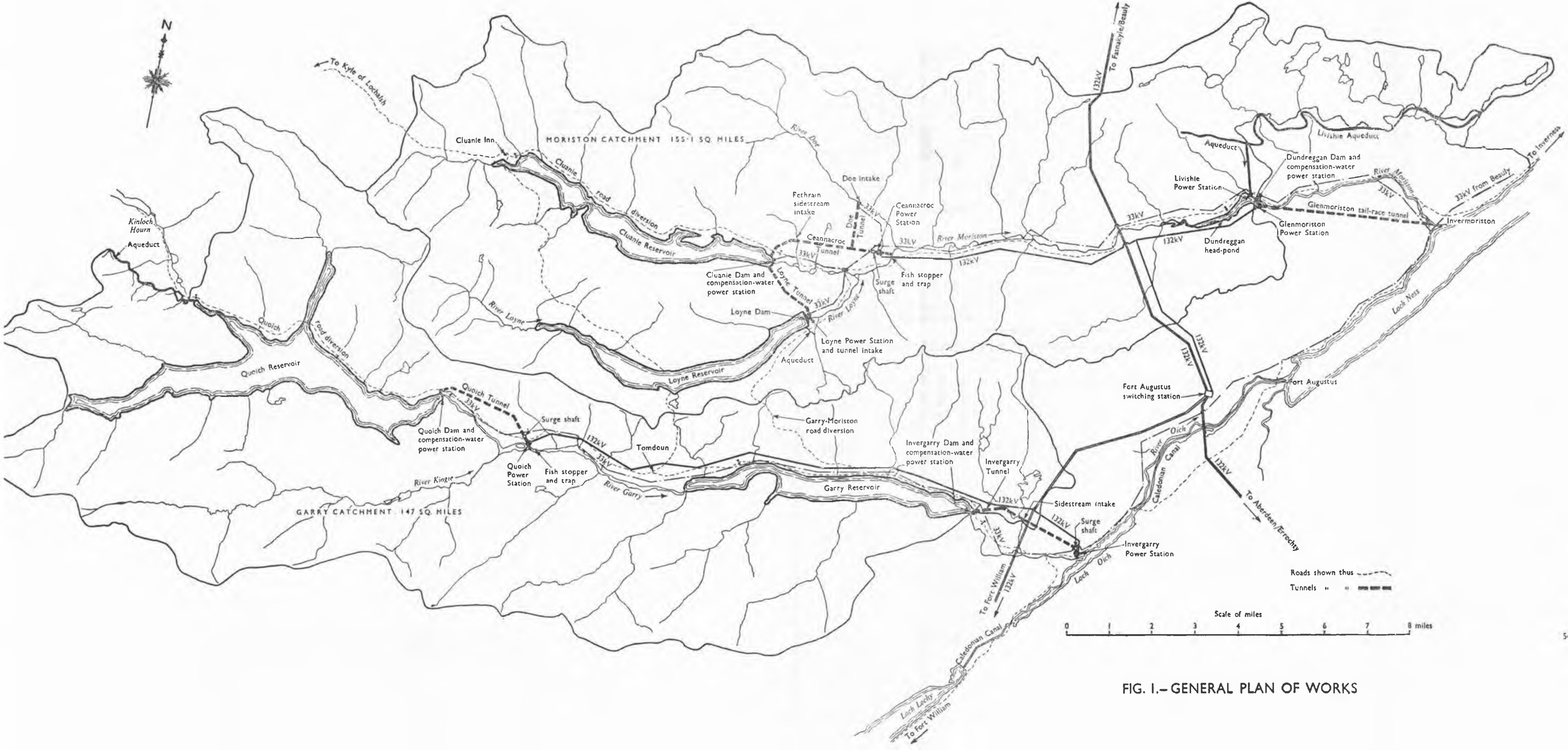


FIG. I.– GENERAL PLAN OF WORKS

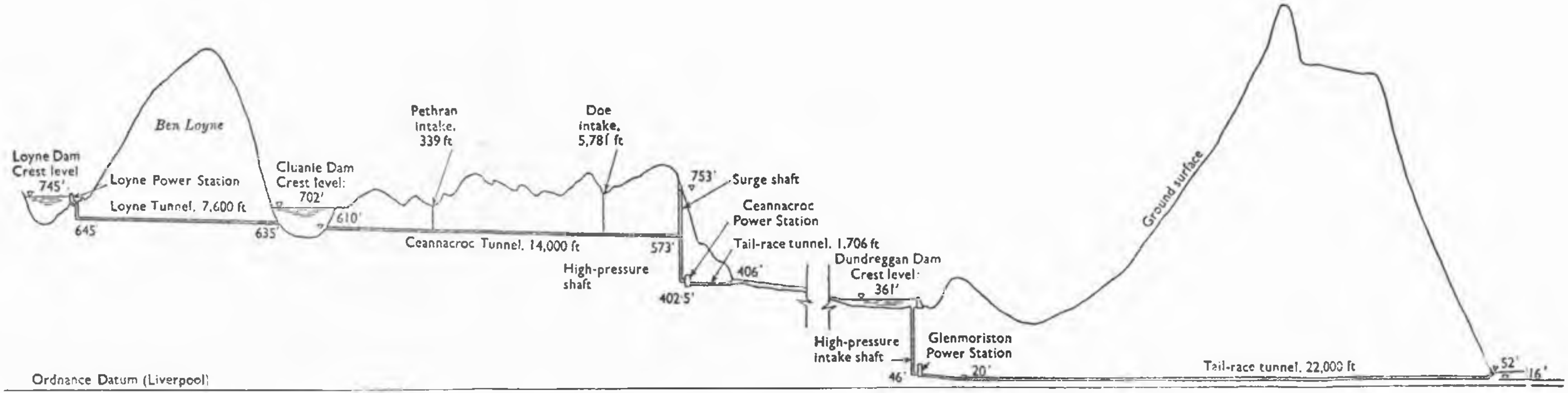


FIG. 2a. - LONGITUDINAL SECTION OF MORISTON SCHEME

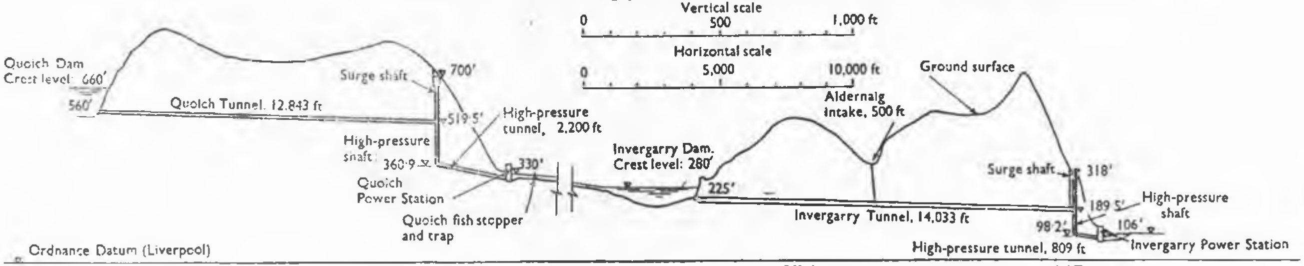
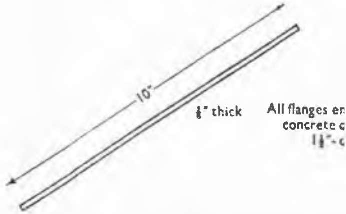


FIG. 2b. - LONGITUDINAL SECTION OF GARRY SCHEME



(a) SECTION THROUGH HORIZONTAL SEA

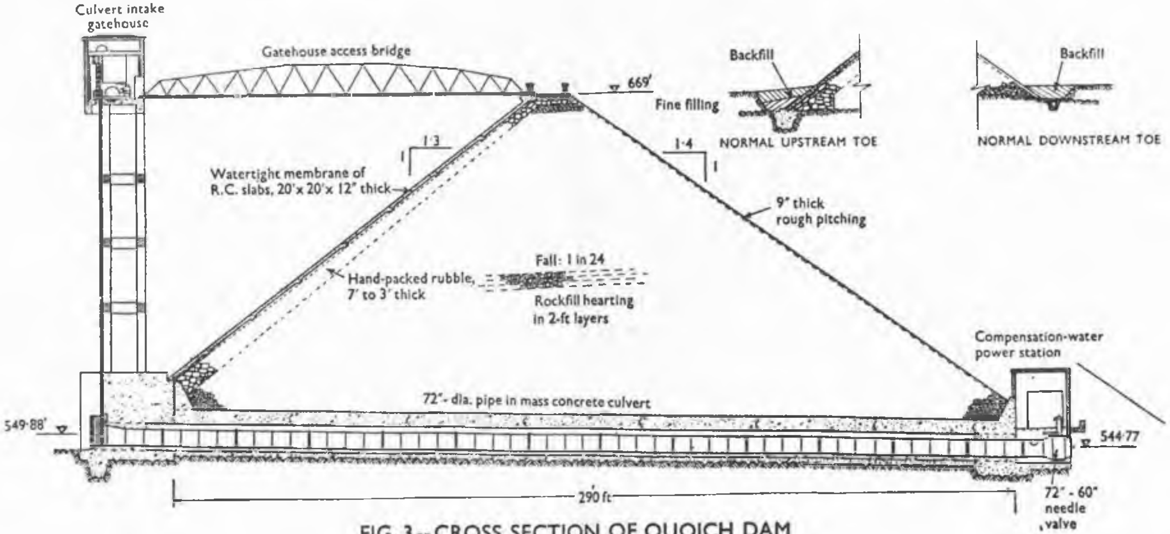
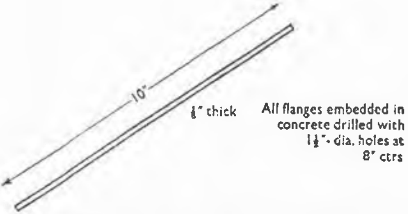


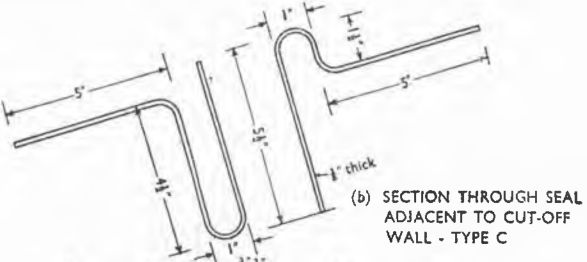
FIG. 3 -- CROSS SECTION OF QUOICH DAM THROUGH SCOUR CULVERT

h-pressure
shaft

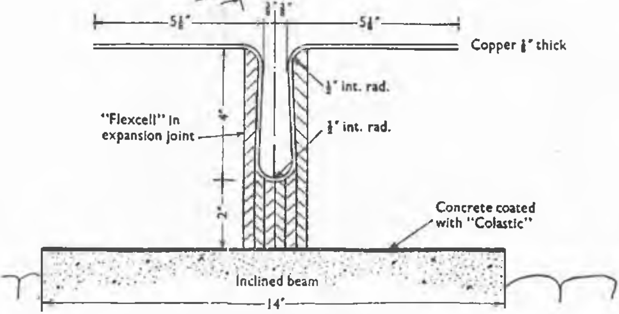
garry Power Station



(a) SECTION THROUGH HORIZONTAL SEAL - TYPE B



(b) SECTION THROUGH SEAL ADJACENT TO CUT-OFF WALL - TYPE C



(c) SECTION THROUGH INCLINED SEAL - TYPE A

FIG. 4. – QUOICH DAM. COPPER SEALS

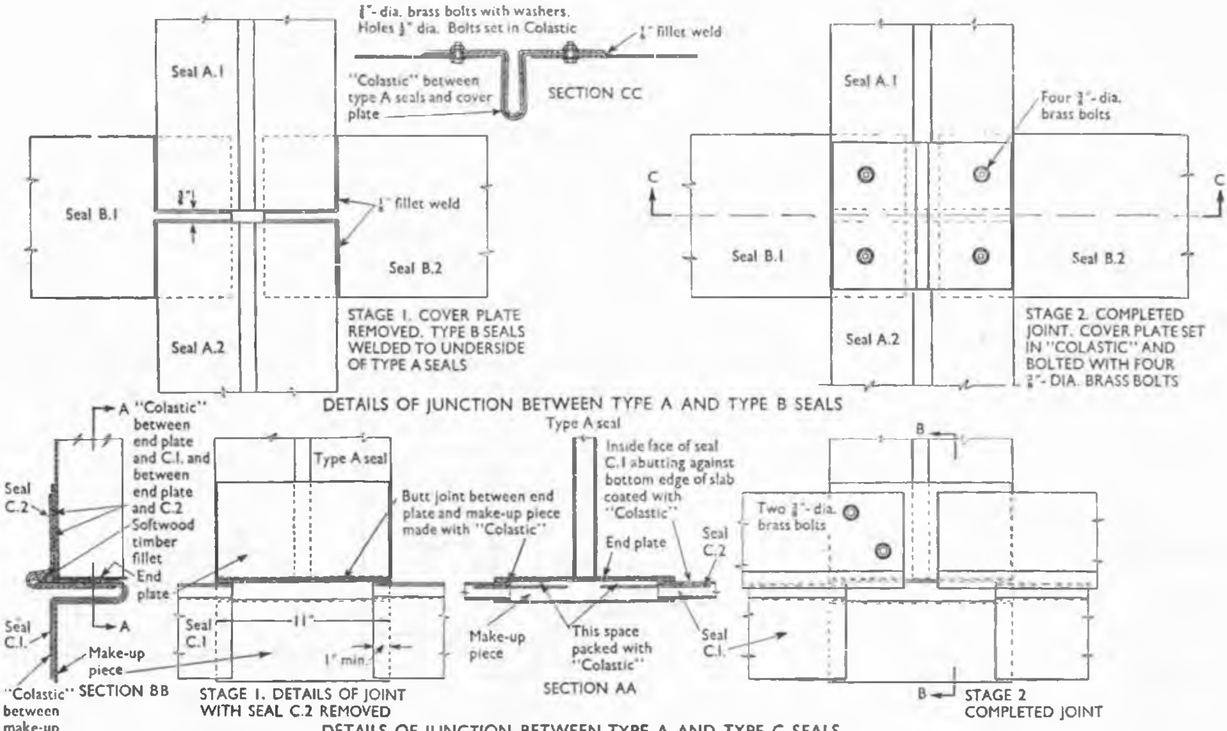


FIG. 5.– QUOICH DAM. JUNCTION OF COPPER SEALS

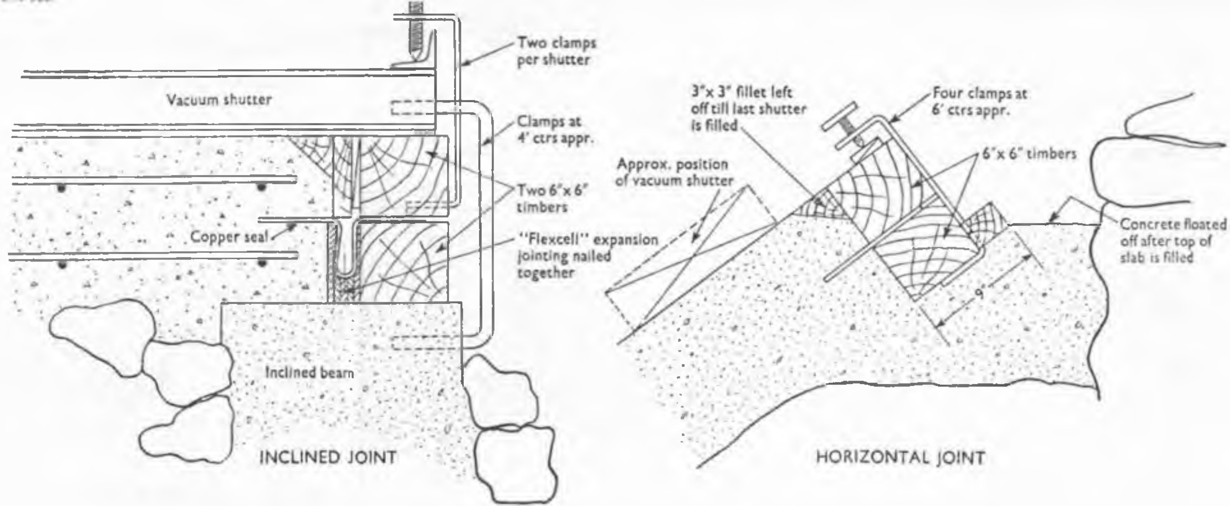
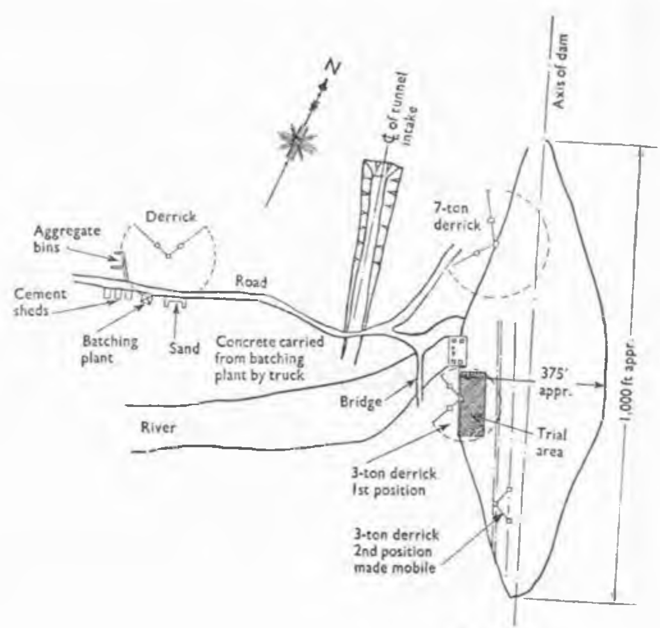
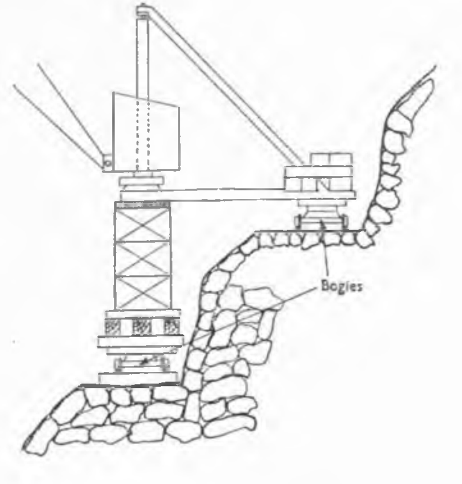


FIG.7.– QUOICH DAM. ARRANGEMENT OF SIDE FORMS FOR INCLINED AND HORIZONTAL JOINTS

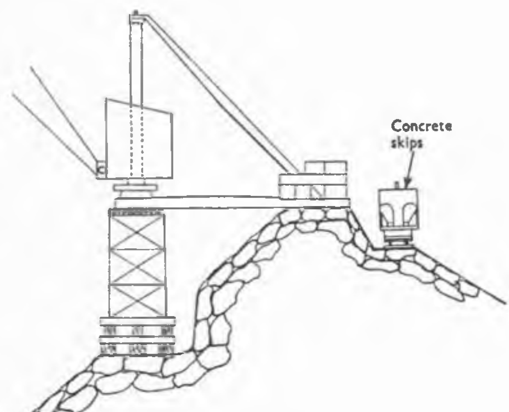


(a) STAGE 1



3-TON DERRICK IN 2ND POSITION OF STAGE 1

(b) STAGE 2



7-TON DERRICK OF STAGE 2

FIG. 9.— QUOICH DAM. LAYOUT OF PLANT

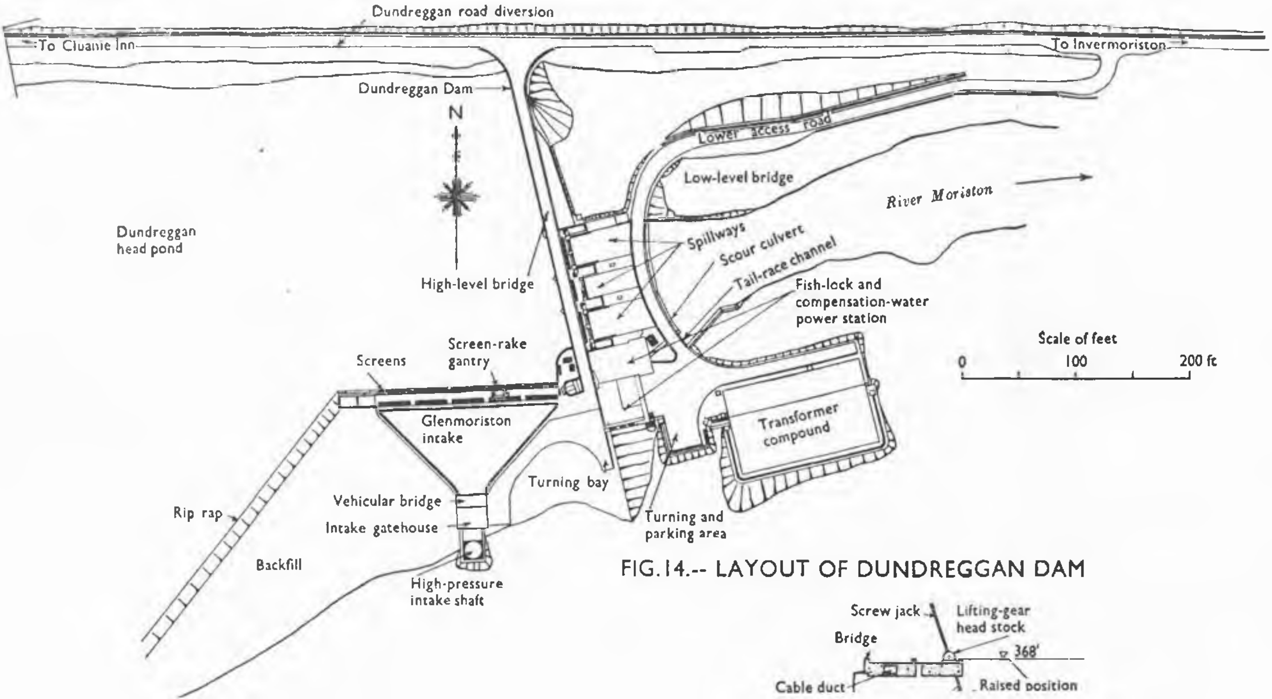


FIG. 14.-- LAYOUT OF DUNDREGGAN DAM

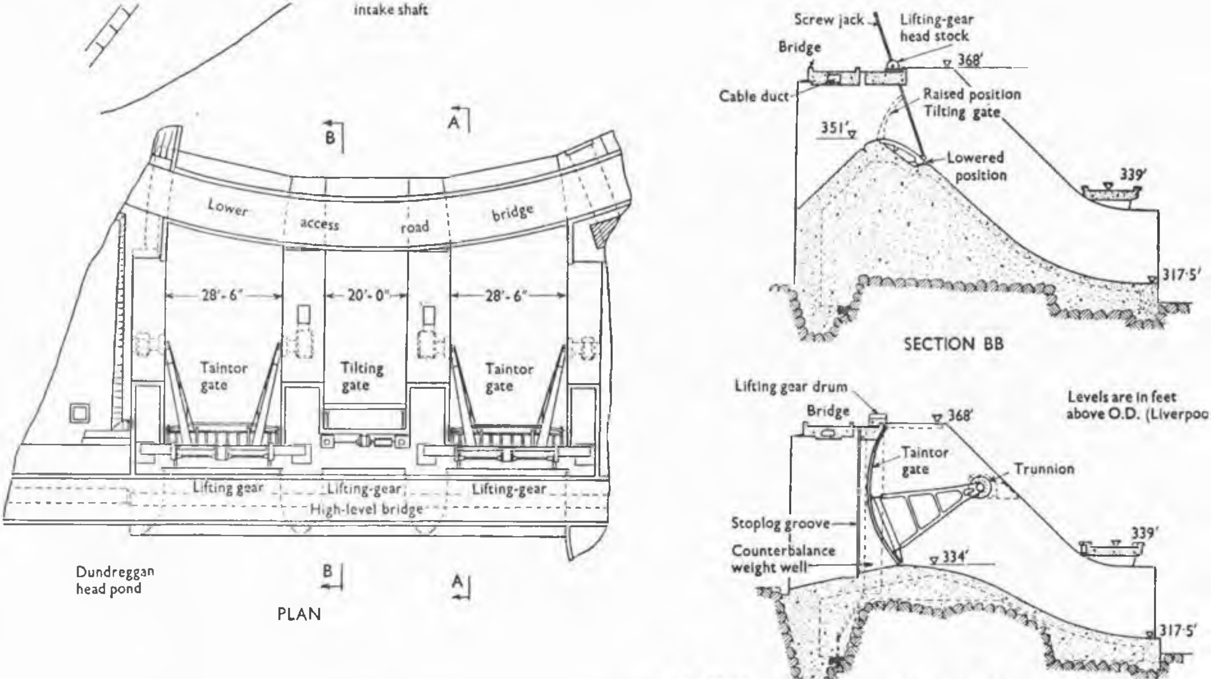


FIG. 15.-- DUNDREGGAN DAM GATES

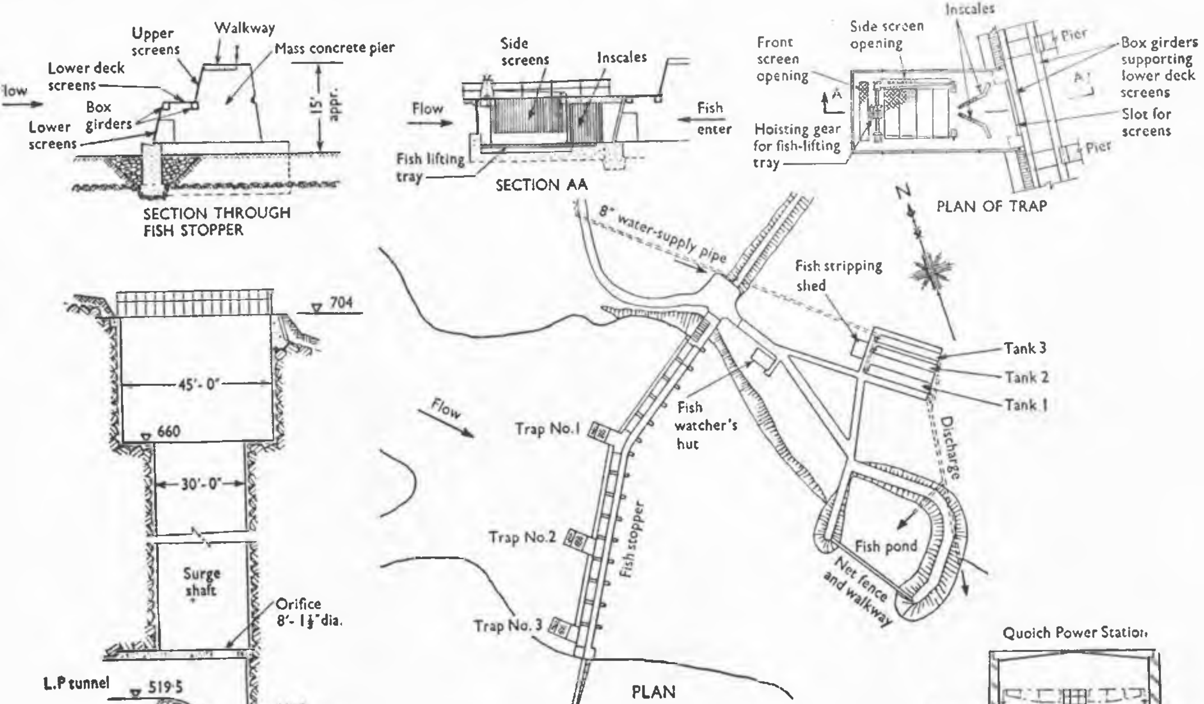


FIG.18.– QUOICH FISH STOPPER AND TRAPS

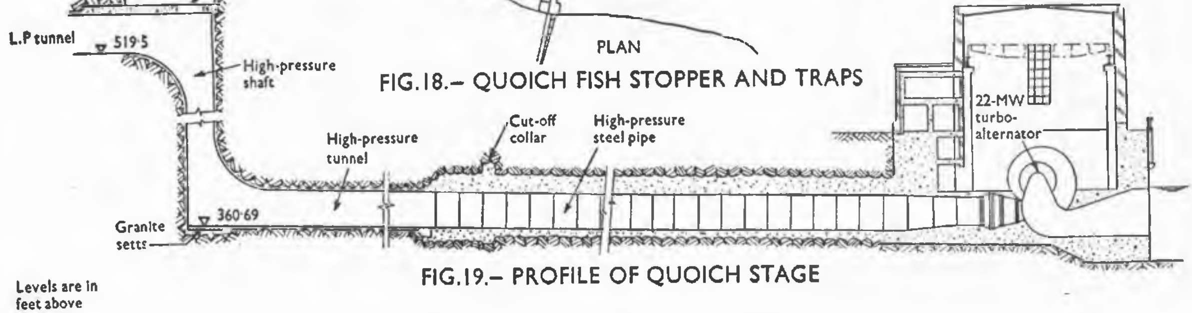


FIG.19.– PROFILE OF QUOICH STAGE

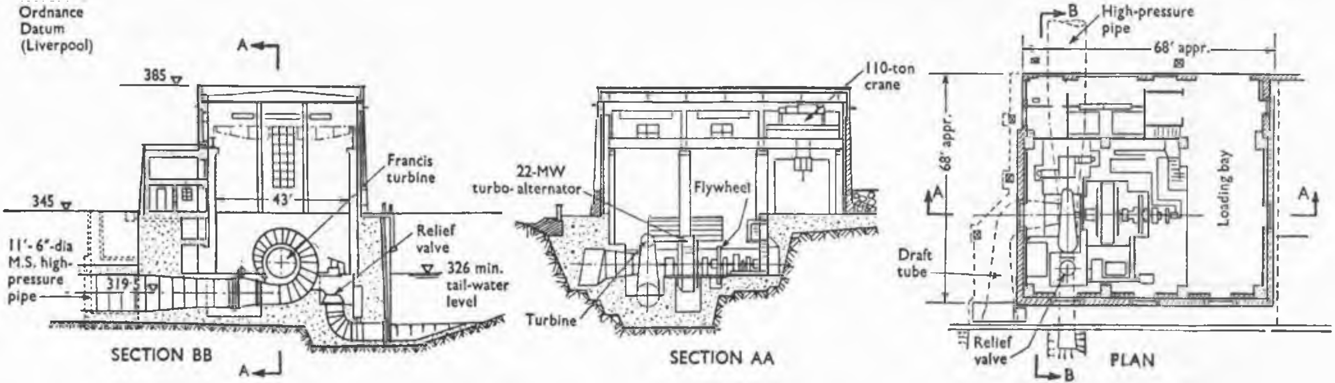


FIG.20.– LAYOUT OF QUOICH POWER STATION

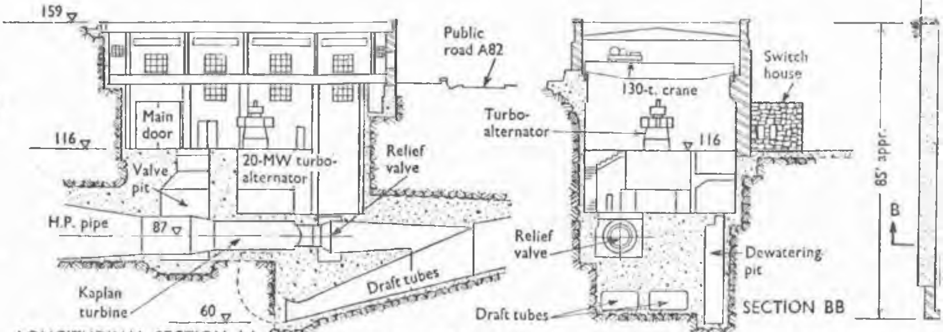


FIG.22.– LAYOUT OF INVERGARRY POWER STATION

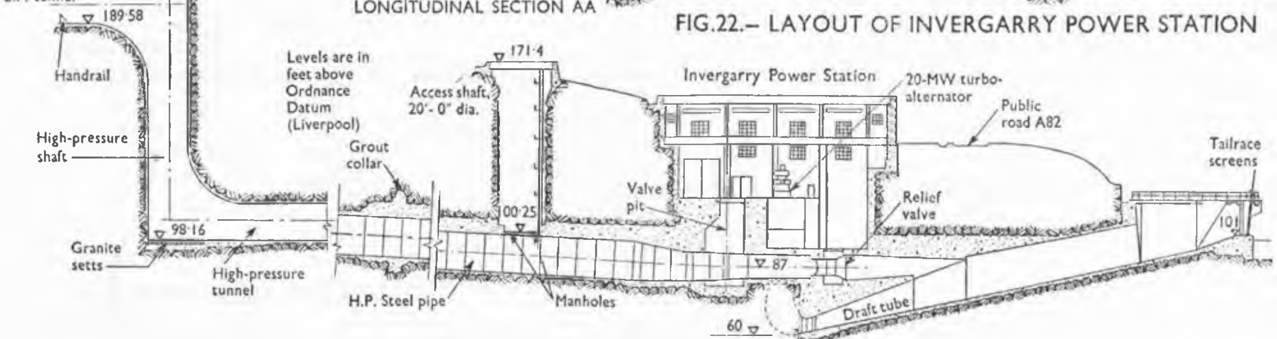


FIG.21.– PROFILE OF INVERGARRY STAGE

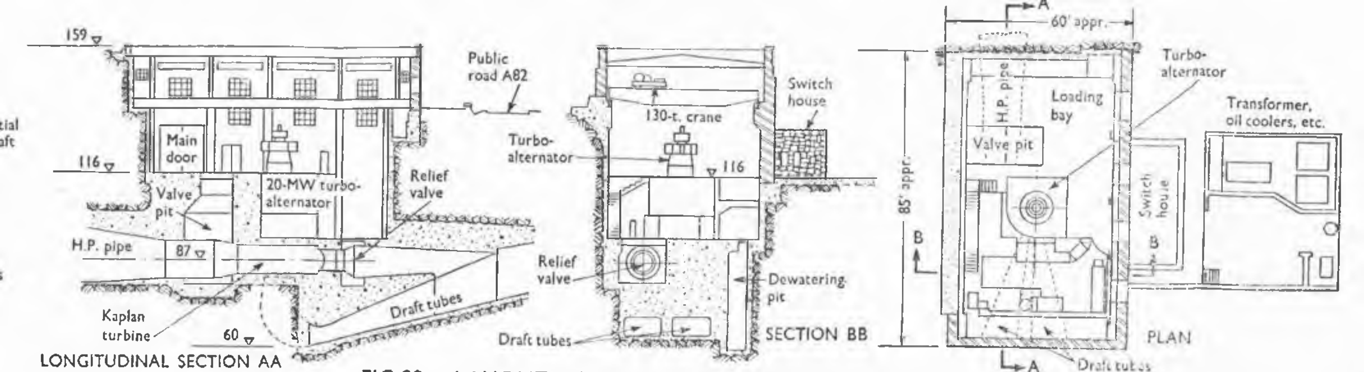


FIG.22.– LAYOUT OF INVERGARRY POWER STATION

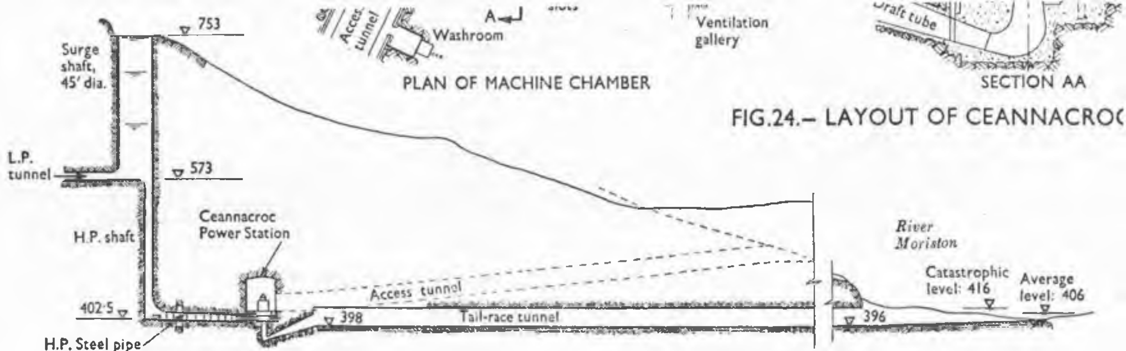
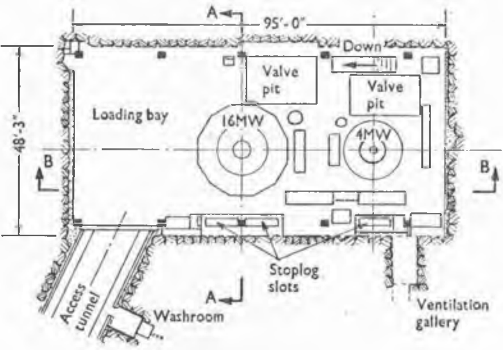


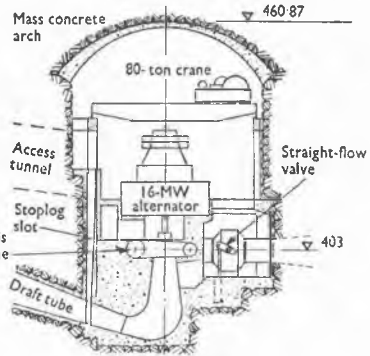
FIG.24.– LAYOUT OF CEANNACROC

FIG.23.– PROFILE OF UPPER MORISTON (CEANNACROC) STAGE



PLAN OF MACHINE CHAMBER

FIG.24.-



SECTION AA

- LAYOUT OF CEANNACROC POWER STATION

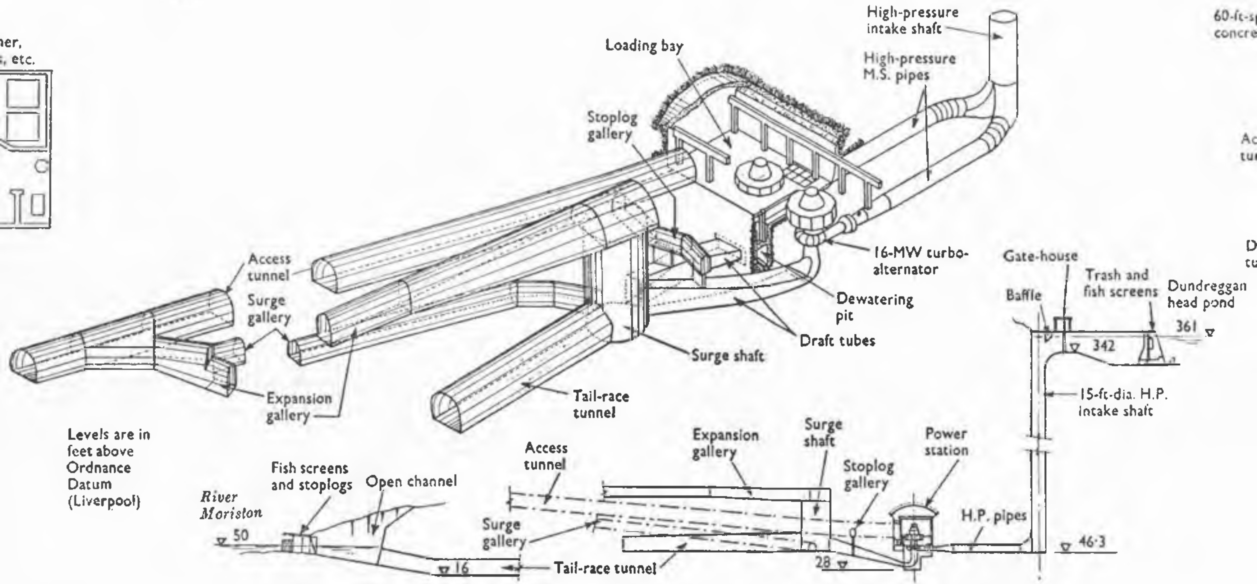


FIG.25.– SURGE ARRANGEMENTS AT GLENMORISTON POWER STATION

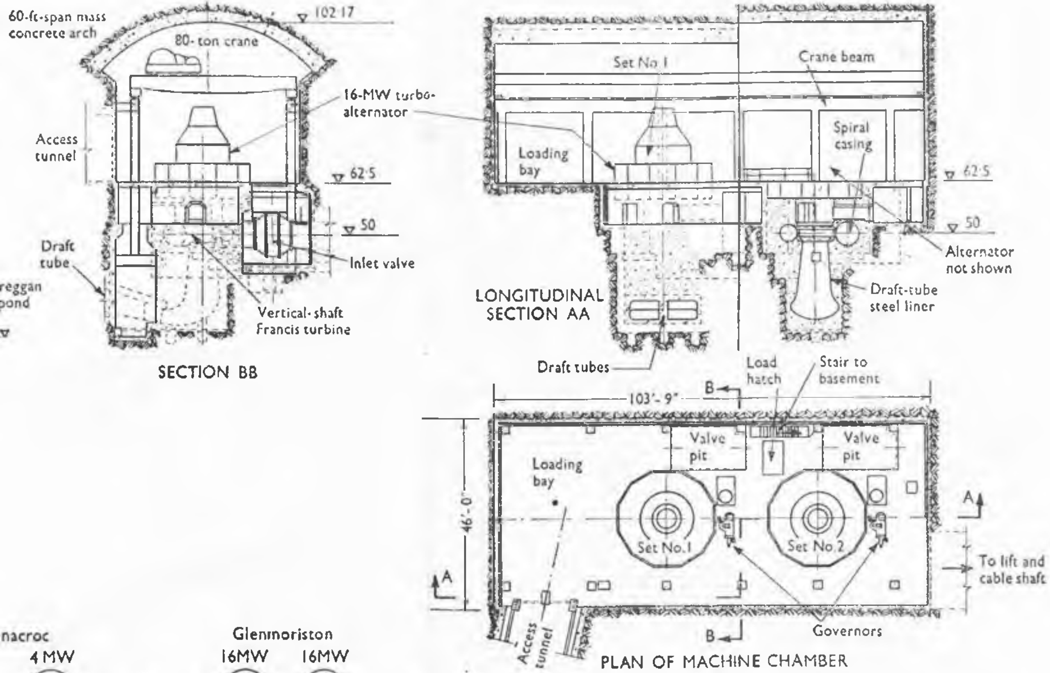
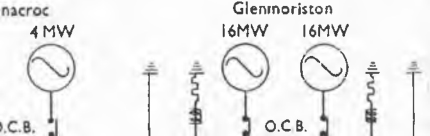
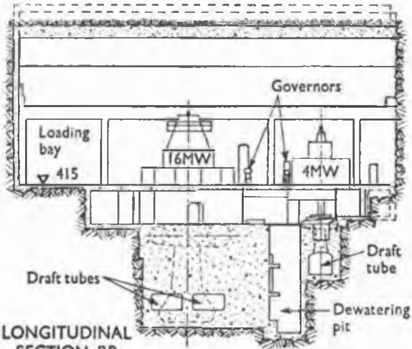


FIG.26. – LAYOUT OF GLENMORISTON POWER STATION





LONGITUDINAL SECTION BB

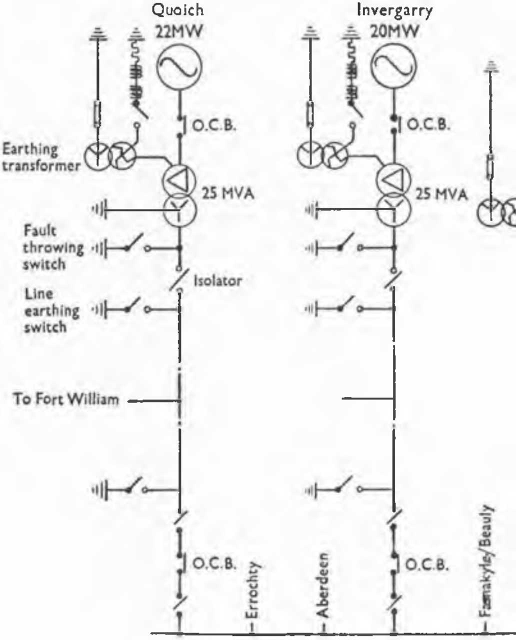


FIG.26. – LAYOUT OF GLENM
POWER STATION

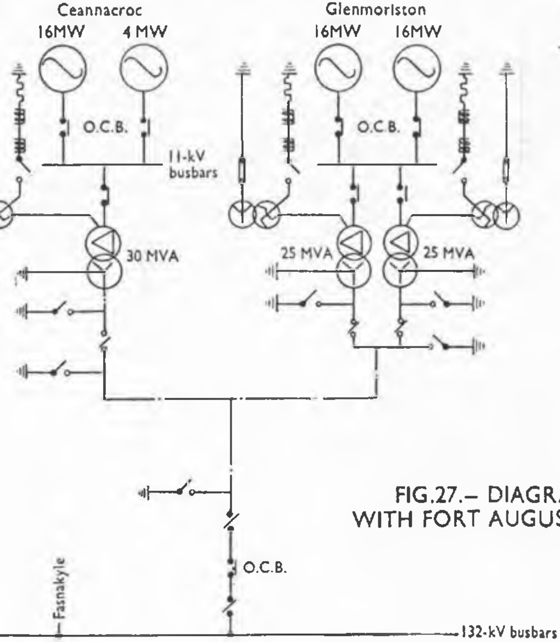


FIG.27.– DIAGRAM OF MAIN CONNECTIONS
WITH FORT AUGUSTUS GROUP CONTROL CENTRE