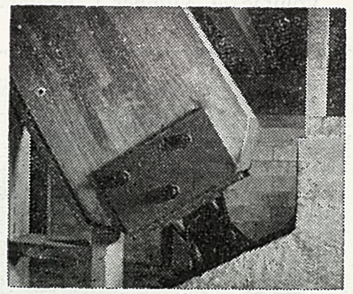
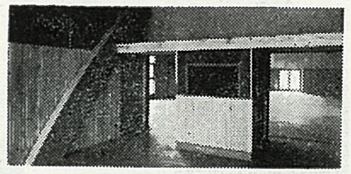
CURVED, CLEAR SWEEPING COST CONSCIOUS ARCHES ENGINEERED WITH PINEX PINE . . .

Situated as it is, in the heart of the timber country, the Tokoroa Youth Club could well be expected to set an example in timber engineering. It does just that. It has given Tokoroa a magnificent auditorium, with the beauty evocative of the imaginative use of timber.

Pinex pine was used throughout, No. 1 framing Grade in the interior and sub-floor, Merchantable grade for sarking the annexe, and Dressing Grade in a ship-lap pattern in lining the foyer, service rooms, and up to 6' 6'' in the hall interior.





PLANNING. The auditorium was required to cater for all the indoor sporting and cultural activities of a fast-growing town of 12,000 people. Maximum clear floor space was required.

DESIGN. The designers specified circular 3-pinned glue-laminated arches. These were fabricated entirely on site. Each arch was made up of twelve 8'' x 2'' 's. These were first kiln dried to a moisture content of 12%. then dressed, cut to length, and stored.

FABRICATION. The required number of 8'' x 2'' 's were taken from storage and passed through a specially developed casein glue spreader to the jigs. Here they were butt-jointed and clamped under 80 lbs. sq./in. pressure for 24 hours, all under closely controlled temperature and humidity conditions

Eighteen half-trusses were fabricated, each half-arch taking about fifty minutes to assemble. Dressing and sanding with portable machines gave a finished section 22'' x 7¾''.

CONSTRUCTION. Concrete foundations, abutments and pre-cut purlins completed, the laminated beams were drilled and made ready to be lifted into position by mobile crane. Lifting and securing the beams occupied two working days. Bitumen-coated corrugated iron roofing and asbestos sheathing completed the exterior.

NEAR PERFECT ACOUSTICS. The auditorium has near-perfect acoustics due to the experienced use of Pinex Wallboards. Above the Pinex Pine dado the auditorium was lined with Pinex Planks, Panels and Acoustic Tiles. These were pre-finished in Decotex and plain white finishes.

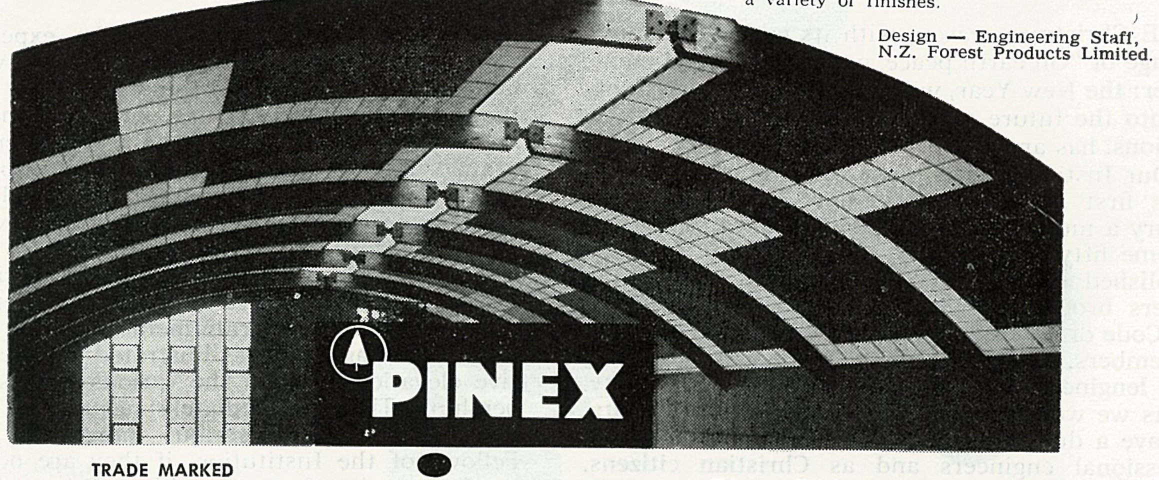
Elsewhere linings are Vitroglaze, Hammerglaze, Leatherboard, leather patterned Pegboard and Hardboard.

FACILITIES ARE COMPLETE. The clear floor area of the auditorium is 105ft. by 85ft. 8ins. A rifle range and weight-lifting area are planned for the space beneath the stage and this clear expanse of 95ft. x 18ft. with 10ft. stud is supported by 14'' x 8'' laminated beams on 6'' x 6'' laminated columns. The stage itself will accommodate the largest theatrical productions. Dressing rooms are in the wings and there is provision for changing rooms, a kitchen and canteen, a manager's office and other service rooms.

WIDESPREAD INTEREST IN LAMINATED TIMBER. Not without reason is glue-laminated timber arousing interest throughout New Zealand.

For this type of construction, using readily available New Zealand grown material, has many distinct advantages. Laminated members are relatively light for developed strength, and therefore well suited for large spans. Graceful curves may be achieved with a minimum of skilled work on the site. Laminated beams are fire resistant. They can be fully exposed to interior view with advantage. They are durable, require minimum maintenance and may be treated with a variety of finishes.

Design — Engineering Staff,
N.Z. Forest Products Limited.



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This auditorium illustrates the immensely attractive result that can be achieved by utilising the beauty of natural wood. Many outstanding examples of modern church architecture feature this method of construction and glue-laminated timbers are also found in many fine auditoria and schools. In addition to these structures, which may be regarded as "show pieces", glue-laminated construction is also widely used in New Zealand mercantile, industrial and storage buildings where utility and economy are prime factors. All things considered, timber framing is New Zealand's best buy. And Pinex pine is New Zealand's best timber.

For further information on any products advertised see second-to-last page

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Main Generating and Electrical Equipment of Benmore Power Station

H. C. HITCHCOCK*
B.E.(HONS.), A.M.I.E.E., (MEMBER)

This paper describes the position of the 540 MW Benmore power station in the development of the Waitaki River basin power potential, and discusses some features and limitations of its operation in conjunction with other stations on the river and with the 220 kV a.c. and 500 kV d.c. transmission systems. It records the basis of the choice of station rating and size of unit, then describes briefly the main generating plant and electrical equipment purchased and installed by the N.Z. Electricity Department, including 125,000 hp turbines, 112,500 kVA generators, 16 kV, 9,000 A isolated phase busbars, 16 kV 3,200 MVA switchgear, and 200,000 kVA transformers.

1. INTRODUCTION

BENMORE is the third station to be built on the Waitaki River system, and is one of the seven which may utimately provide a total output from the catchment area of more than 1,600 MW.

Figure 1 shows diagrammatically the position of Benmore in the chain of storage lakes and power stations. The new 540 MW Benmore station, together with the existing 105 MW Waitaki station and the 220 MW Aviemore station at present under construction, will form an easily managed group with a total capacity of 865 MW—exactly equal to the total of the hydro stations at present on the Waikato River. They will be nearly matched in full-load flow and will be backed not only by the three major storage lakes but also by the lake formed by the Benmore dam, where the 20 ft working range contains more than half as much water and one third as many kilowatt-hours as Lake Taupo's 5 ft.

In addition, Fig. 1 shows the manner in which Benmore is connected to feed into the North Island system via the 500 kV d.c. inter-island transmission system and also into the South Island system via the 400 MVA of interconnecting transformers.

The operation of this group of stations is a little unusual. Power for the North Island is drawn by the converter equipment directly at generator voltage, and the amount sent to the North Island is kept at any chosen value by the power regulator of the converters. The turbine governors in all three stations will be adjusted manually to give the required total generation from the group, and this total will normally be allocated to give approximately equal water flow in all three stations.

For the control of voltages, the converter control devices can adjust automatically the setting of the voltage regulators on the Benmore generators to suit the operation of the converters. To avoid such changes affecting the South Island system, on-load-tap-changing equipment on the interconnecting transformers automatically maintains any desired voltage on the Benmore 220 kV bus or by suitable adjustment of the reactive compensation device a degree of automatic control of MVAr flow can be obtained. Voltage control at Waitaki and Aviemore will be by the usual manual adjustment of the automatic voltage regulators to maintain the allocated MVAr loading or bus voltage as may be required.

Figure 2 illustrates the operating flexibility of the Middle Waitaki group of stations: Fig. 2a shows the three stations generating 865 MW with 600 MW, the maximum possible, being sent to the North Island, leaving 265 MW for the South Island; Fig. 2b shows the same station output but with 725 MW, the maximum possible, into the South Island, leaving 140 MW for the North Island.

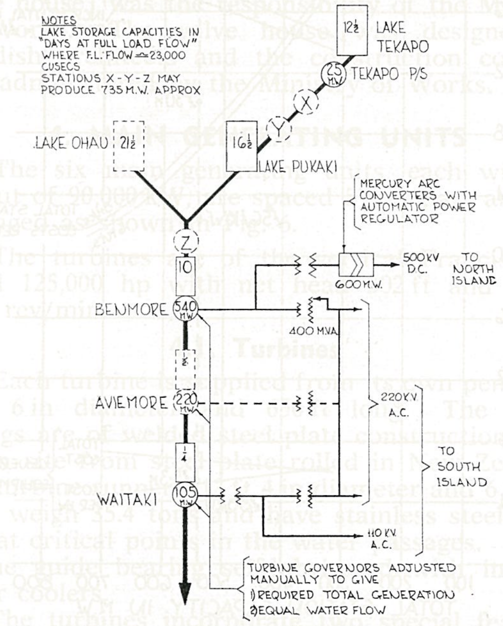

Fig. 1: Diagram of Middle Waitaki power stations.

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*Design engineer, power stations design section, N.Z. Electricity Department, Wellington.

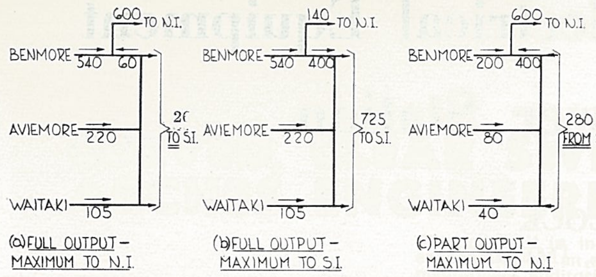

Fig. 2: Power flows from Middle Waitaki stations.

Although only three-quarters of the kilowatt capacity of Benmore is available to the South Island, a very much higher proportion of the kilowatt-hour output could be so directed if ever operating conditions require it. It is this range of load despatch that will make the inter-island transmission helpful in planning power station construction, because a large station can be built in one island and by adjustment to the inter-island transmission, it can be made to assist in meeting the load growth in the other island as well.

A further benefit accrues to the South Island alone: even though a large portion of the output of these stations may be going to the North Island, all the generating sets in the group respond to small frequency changes in the South Island system by increasing or decreasing their output to the South Island just as though they were generating solely for the South Island. In other words, while the North Island gets some of the power, the South Island gets all the stabilising effect of all the governors in reducing minor frequency variations.

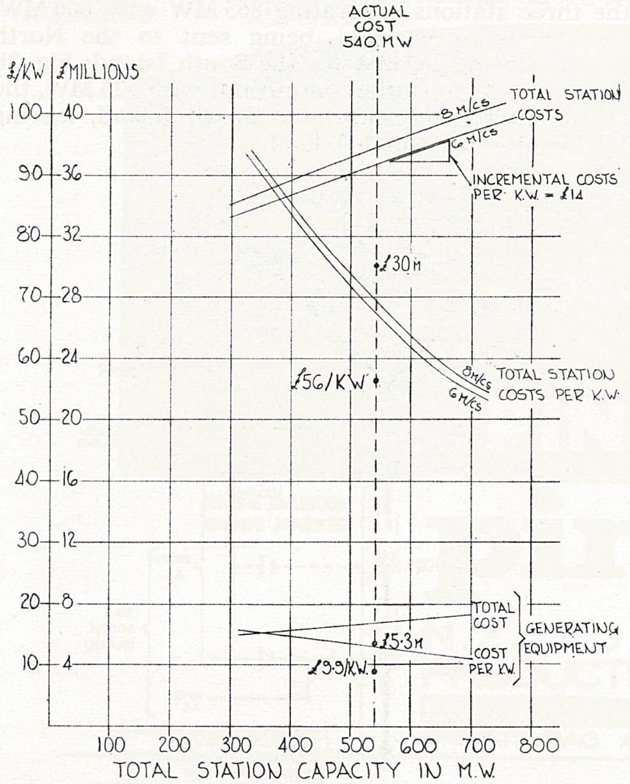

Fig. 3: Benmore power station: cost v. installed capacity.

Figure 2c illustrates a load flow that may occur when Manapouri is linked to the system and it is desired to conserve water in the Waitaki basin while maintaining maximum transmission to the North Island. The station outputs shown are the minimum possible while (a) maintaining full transmission 600 MW to the North Island, (b) equalising the water flow, and (c) not overloading the interconnecting transformers, 400 MVA, at Benmore.

2. SELECTION OF STATION RATING

The gross head made available by the dam was 305 ft and the long-term mean flow of the Waitaki River at Benmore was 12,300 ft³/s. Assuming 90% of the flow to be utilised for power generation with an overall station efficiency of 85% the mean power available was just over 240 MW. Taking the normal value of 50% for the plant factor (ratio of mean output to rated output), the preliminary figure of 480 MW was obtained for the station rating. This corresponds to an output of 2,100 million kWh per year, but later studies indicated that beter utilisation was probable and an output of 2,200 million kWh per year was adopted for planning purposes.

It was evident, however, that with the largest artificial lake in the country above it and the second largest below it Benmore provided an opportunity for installing extra plant for peak loads, particularly as the curves of total station cost versus plant capacity (Fig. 3) show the low incremental cost of £14/kW for such capacity.

An obvious use for this extra capacity was to allow a reduction in the capacity of plant installed in future stations in the Upper Waitaki, in particular the two stations proposed to take water from the existing Tekapo station. These would inevitably have long and expensive water channels and tunnels, and would show considerable savings in capital cost if designed for a higher plant factor than normal.

On this basis it was decided to increase the Benmore plant rating from 480 MW to 540 MW. It was considered that there were too many uncertainties to justify any larger increase in rating.

2.1. Selection of Unit Rating

The plant cost curves, Fig. 3, showed clearly that fewer machines of larger output gave lower capital costs. An even number of machines was necessary to fit in with the possible conversion plant, and consideration was given to four, six, or eight machines.

Four machines at 135 MW each would have presented difficulties in release for maintenance or in the event of breakdown. The turbine runners would have exceeded some firms' manufacturing capacity and would have presented considerable transport difficulties. The penstocks at about 21 ft in diameter would have been too large a step forward for the then state of the technique of precast prestressed penstock construction.

None of these difficulties applied in the case of six machines at 90 MW each, so this rating was adopted, although the prestressed concrete penstocks even at 17 ft 6 in diameter were a major advance.

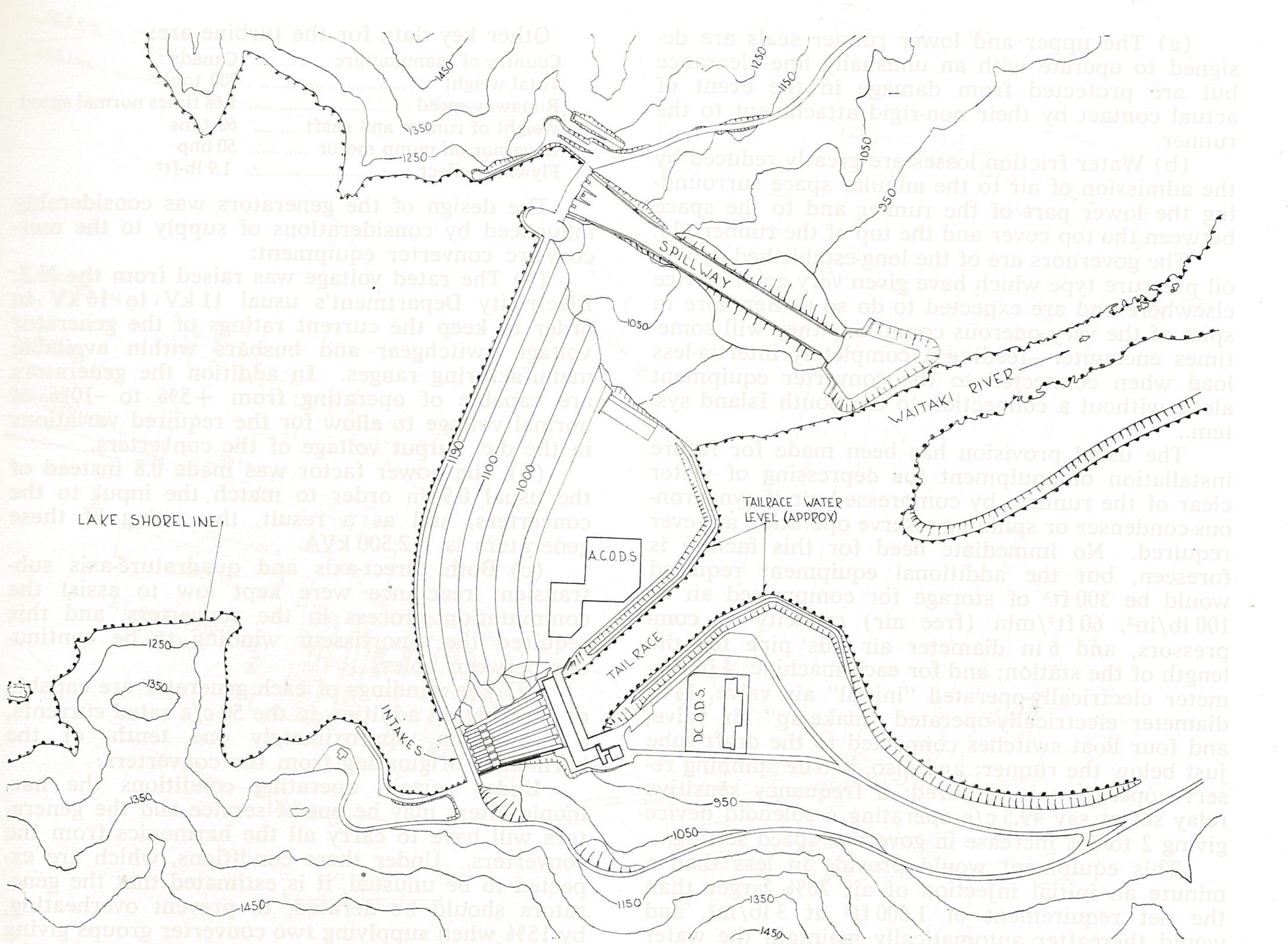

Fig. 4: Layout of site.

3. GENERAL LAYOUT

Figure 4 shows the earth dam spanning between natural prominences on the sides of the valley, the one on the left bank accommodating the spillway and that on the right, the intakes and penstocks. In Fig. 5 can be seen the tailrace, 420 ft wide at the top and 63 ft deep, with the 220 kV outdoor switching station on its left bank and on its right the 500 kV d.c. outdoor switching station containing the 370 ft long and 100 ft wide valve house for the mercury arc converter plant.

The main powerhouse building is 480 ft long, 67 ft wide and 58 ft high.

On the downstream side of the main building the main transformer banks are supported by a platform from which all drainage passes through an interceptor tank capable of preventing the entire 7,300 gal in the largest transformer from polluting the river.

Adjoining the main building are three connected blocks containing the workshops, offices, and control room. Distinctive architectural features of these buildings are the extensive use of Oamaru stone in the walls and the use of copper cladding on the roof.

The design and construction of all civil engineering work including all buildings (except the valve house) was the responsibility of the Ministry of Works. The valve house was designed by Swedish architects and the construction contract was administered by the Ministry of Works.

4. MAIN GENERATING UNITS

The six main generating units, each with an output of 90,000 kW, are spaced 57 ft apart and are arranged as shown in Fig. 6.

The turbines are of the vertical Francis type rated 125,000 hp with net head 302 ft and speed 166.7 rev/min.

4.1. Turbines

Each turbine is supplied from its own penstock, 17 ft 6 in diameter and 650 ft long. The spiral casings are of welded steel plate construction built up on site from steel plate rolled in New Zealand. The turbine runners, 13 ft 4 in in diameter and 6 ft 8 in high, weigh 35.4 tons and have stainless steel overlays at critical points in the water passages. There is one guide bearing self-lubricated with integral water coolers.

The turbines incorporate two special features by which losses are reduced:

(a) The upper and lower runner seals are designed to operate with an unusually fine clearance but are protected from damage in the event of actual contact by their non-rigid attachment to the runner.

(b) Water friction losses are greatly reduced by the admission of air to the annular space surrounding the lower part of the runner and to the space between the top cover and the top of the runner (1).

The governors are of the long-established flyball-oil pressure type which have given very good service elsewhere and are expected to do so at Benmore in spite of the very onerous conditions they will sometimes encounter—feeding a completely intertia-less load when connected to the converter equipment alone without a connection to the South Island system.

The usual provision has been made for future installation of equipment for depressing of water clear of the runners by compressed air if synchronous-condenser or spinning-reserve operation are ever required. No immediate need for this facility is foreseen, but the additional equipment required would be 300 ft^3 of storage for compressed air at 100 lb/in^2, 60 ft^3/min (free air) capacity of compressors, and 6 in diameter air bus pipe for the length of the station; and for each machine: 4 in diameter electrically-operated "initial" air valve, 1½ in diameter electrically-operated "make-up" air valve, and four float switches connected to the draft tube just below the runner; and also, if true spinning reserve operation is required: a frequency sensitive relay set at say 49.5 c/s operating a solenoid device giving 2 to 3% increase in governor speed setting.

This equipment would provide in less than a minute an initial injection of air 20% larger than the net requirement of 1,500 ft^3 at 3 lb/in^2, and would thereafter automatically maintain the water level below the bottom of the runner. The compressors would recharge the storage tanks in approximately half an hour.

Facilities are provided in the penstocks of No. 2 and No. 5 machines for installing flow-measuring equipment for turbine efficiency tests. For these tests an arm will be mounted diametrically in the penstock and will be capable of rotating about the penstock axis 60° each side of vertical. This will carry 15 Ottmeter-Texas Mark V propeller-type current meters each of which sends impulses proportional to water flow to recording equipment.

The current meters have been calibrated up to 20 ft/s at the D.S.I.R. Hydraulics Research Station, Wallingford, England and plaster casts are held by the N.Z. Electricity Department for checking the accuracy of their profiles. The automatic digital recording equipment, developed by the fluid mechanics division of the National Engineering Laboratory, East Kilbride, Scotland, counts the impulses from each flow meter for an accurately-determined period and photographs the readings for permanent record.

The time measurement is crystal-controlled with an error of less than 2 ms in a 100 s run; the counters are accurate to counting speeds equivalent to velocities greater than 35 ft/s. The current meters register correctly with oblique water flow up to 15°.

Other key data for the turbine are:

Country of manufacture	Canada
Total weight	300 tons
Runaway speed	1.68 times normal speed
Weight of runner and shaft	60 tons
Governor oil pump motor	50 bhp
Flywheel effect	1.9 lb-ft^2

The design of the generators was considerably influenced by considerations of supply to the mercury-arc converter equipment:

(a) The rated voltage was raised from the N.Z. Electricity Department's usual 11 kV to 16 kV in order to keep the current ratings of the generator voltage switchgear and busbars within available manufacturing ranges. In addition the generators are capable of operating from +5% to -10% of normal voltage to allow for the required variations in the d.c. output voltage of the converters.

(b) The power factor was made 0.8 instead of the usual 0.9 in order to match the input to the converters, and as a result, the rating of these generators is 112,500 kVA.

(c) Both direct-axis and quadrature-axis subtransient reactance were kept low to assist the commutation process in the converters, and this required the amortisseur winding to be continuous between poles.

(d) The windings of each generator are capable of carrying, in addition to the 50 c/s rated currents, a proportion, approximately one tenth, of the harmonics originating from the converters.

Under certain operating conditions the harmonic filters may be out of service and the generators will have to carry all the harmonics from the converters. Under these conditions, which are expected to be unusual, it is estimated that the generators should be derated, to prevent overheating, by 15% when supplying two converter groups giving so-called "12 pulse" operating conditions, and by 40% when supplying a single converter group giving "6 pulse" conditions.

Special thermocouples have been installed in No. 6 machine to allow direct measurement of copper temperature under these unusual conditions.

The stator winding is connected in two halves, which permits split-phase protection. The 36 poles of the rotor are secured to a rim built up on the site from steel plates. The 25 ft 6 in diameter rotor weighs 214 tons and is the heaviest lift in the assembly of the machines.

A combined thrust and guide bearing located below the rotor is of a self-pumping type with integral water-cooling tubes and is designed for a maximum load of 510 tons. A direct-coupled main exciter and a permanent magnet-governor generator are mounted above the rotor, and the fast-acting voltage regulator employs a separate motor-driven amplidyne set.

Up to 5% of the circulating air can be bled off for station heating; replacement air enters via an air filter. This makes available the equivalent of approximately 100 kW per machine.

Half a ton of CO_2 is released into the generator in the event of fire and a further half ton is available for delayed release, if required, while water sprinkler rings are available as a last resort.

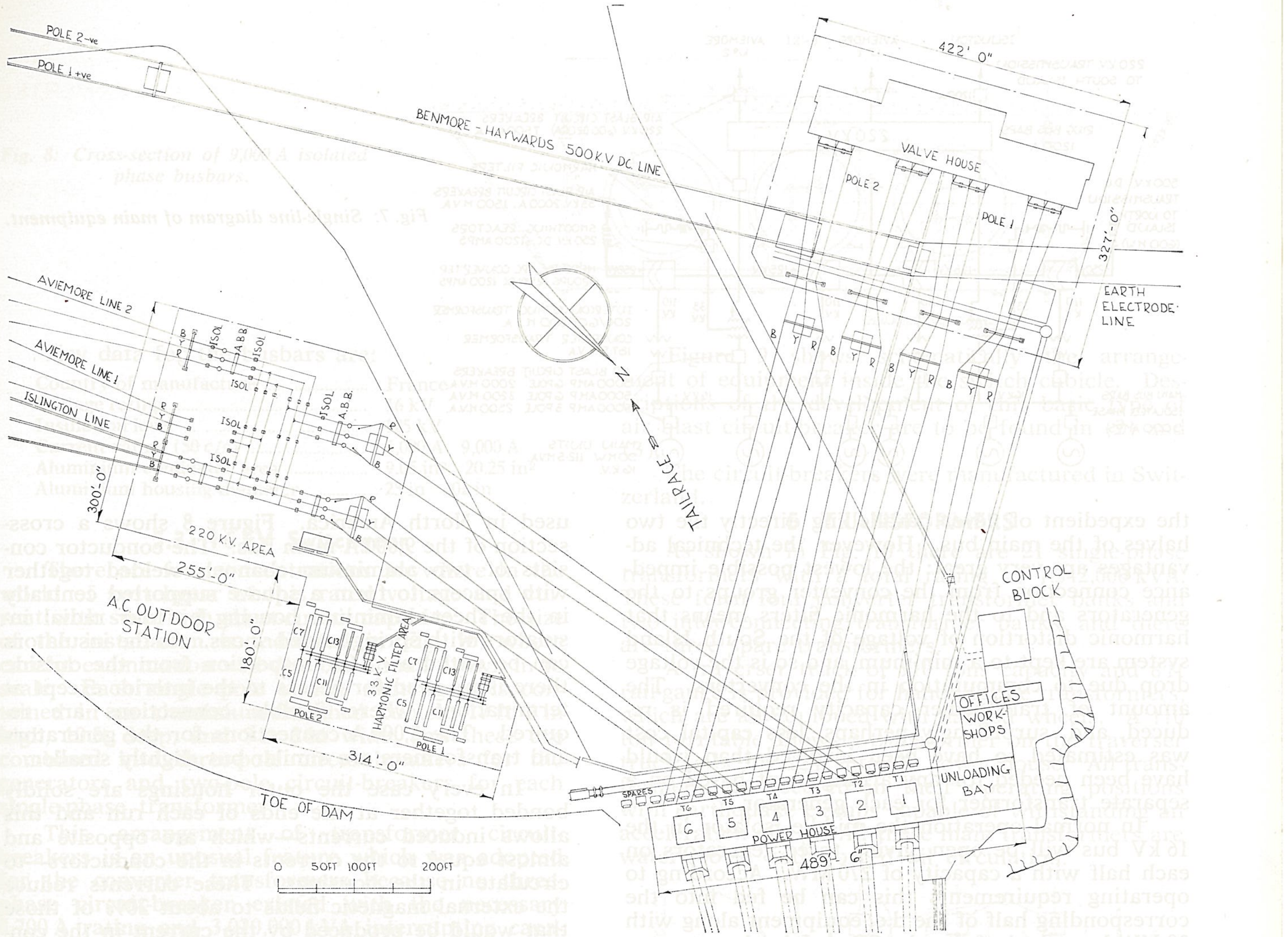

Fig. 5: Layout of powerhouse and outdoor stations.

Other data for the generators are:

Country of manufacture	Canada
Total weight	482 tons
Weight of wound stator	158 tons
Weight of the complete rotor and exciter	241 tons
Weight of heaviest lift	214 tons
Flywheel effect	46.17 × 10^6 lb-ft^2
Stator inside diameter	25 ft 7 in
Stator core length	6 ft 2 in
Design overspeed ratio	1.68
Transient reactance	26.4%
Subtransient reactance:	
Direct axis	17.4%
Quadrature	19%
Synchronous reactance	114%
Stator temperature rise	60 degC

5. 16 kV CONNECTIONS AND SWITCHGEAR

5.1. General

The single-line diagram of Fig. 7 shows the connections of the main equipment and illustrates a further unusual feature of the station—the generator voltage busbars. These give rise to the disadvantages that can be expected—large amounts of heavy current equipment and a very high short-circuit level of 3,020 MVA (three-phase) in spite of

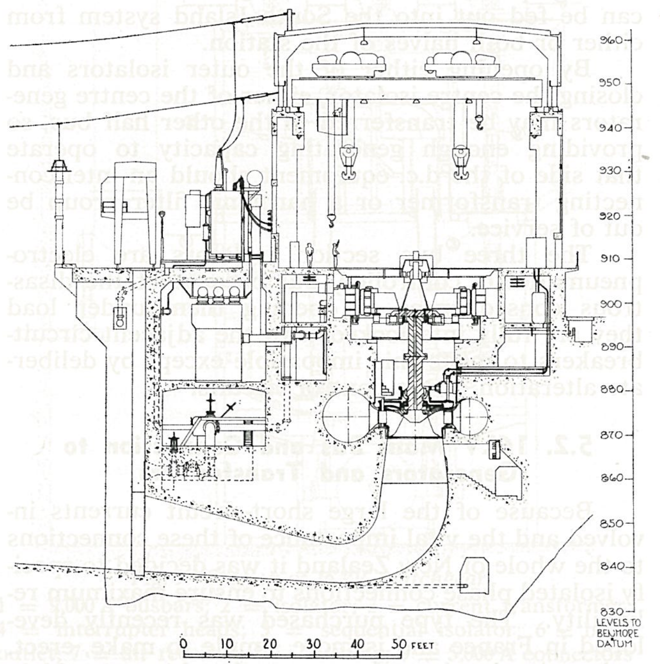

Fig. 6: Cross-section of powerhouse and main units.

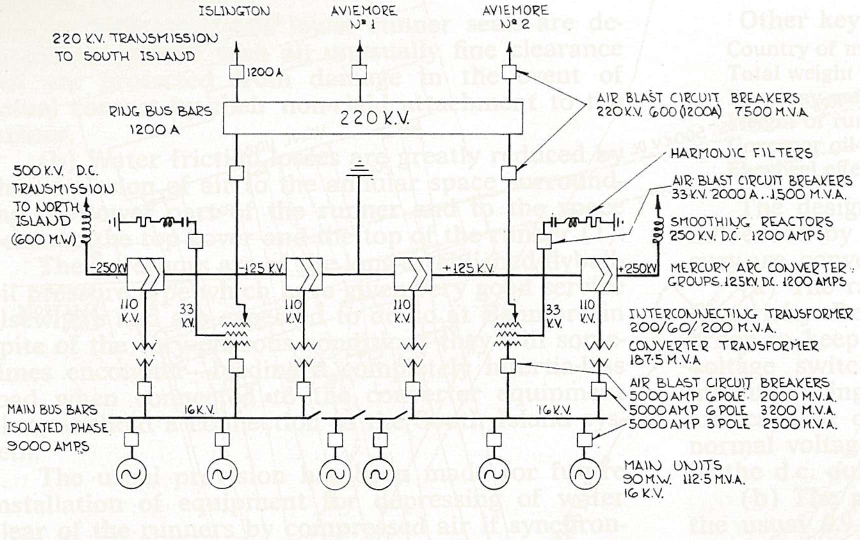

Fig. 7: Single-line diagram of main equipment.

the expedient of never parallelling directly the two halves of the main bus. However, the technical advantages are very great: the lowest possible impedance connection from the converter groups to the generators and to the harmonic filters means that harmonic distortion of voltage of the South Island system are kept to a minimum, and so is the voltage drop due to commutation in the converters. The amount of transformer capacity required is reduced, and, surprisingly perhaps, less capital cost was estimated to have been involved than would have been needed for any arrangement based on a separate transformer for each generator.

In normal operation the middle isolator in the 16 kV bus will be open, giving three generators on each half with a capacity of 270 MW. According to operating requirements this can be fed into the corresponding half of the d.c. equipment along with 30 MW brought in from the South Island system, so making up the rated 300 MW, or as much as 200 MW can be fed out into the South Island system from either or both halves of the station.

By opening either of the outer isolators and closing the centre isolator, either of the centre generators may be transferred to the other half bus, so providing enough generating capacity to operate that side of the d.c. equipment should an inter-connecting transformer or a harmonic filter group be out of service.

The three bus section isolators are electro-pneumatically controlled, but because of the disastrous consequences of opening them under load they are fully interlocked with the adjacent circuit-breakers to make this impossible except by deliberate alteration of the control circuits.

5.2. 16kV Main Bus and Connection to Generators and Transformers

Because of the large short-circuit currents involved and the vital importance of these connections to the whole of New Zealand it was decided to specify isolated phase connections to ensure maximum reliability. The type purchased was recently developed in France and is more simple to make, erect, and maintain than the conventional types widely used in North America. Figure 8 shows a cross-section of the 9,000 A main bus. The conductor consists of two aluminium channels welded together with spacers to form a square supported centrally in the sheet-aluminium housing by four radial insulators with spring-loaded shoes. As the insulators can be withdrawn for inspection from the outside there is no need for access to the interior except at terminations where flexible connections are required. The 5,000 A connections for the generators and transformers are similar but slightly smaller.

In every case the outer housings are solidly bonded together at the ends of each run and this allows induced currents—which are opposite and almost equal to the currents in the conductors—to circulate in the housings. These currents reduce the external magnetic fields to about 20% of those that would be produced by the current in the conductors alone. This feature has two most important effects:

(a) Short-circuit forces between conductors are so substantially reduced that support points can be as much as 20 ft apart for the busbar conductor and 33 ft for the housings.

(b) The risk of damage to reinforced concrete by the magnetic field from the busbars is very greatly reduced.

The main busbars are close to the under side of the 3 ft thick transformer platform, and p.v.c. sleeves were fitted at every point in the bottom layer of reinforcing where one steel bar crossed another in a 16 ft wide zone above the whole length of busbars. This eliminates continuous metallic loops in which magnetic flux from the busbars could induce circulating currents.

When the first section of transformer platform was constructed the design of the busbars was not complete and it was considered prudent to place heavy copper rings on the transverse reinforcing bars to guard against magnetic heating; however, the decision to adopt solid bonding of the enclosures with the consequent magnetic shielding made the copper rings unnecessary, and they were not installed in later sections.

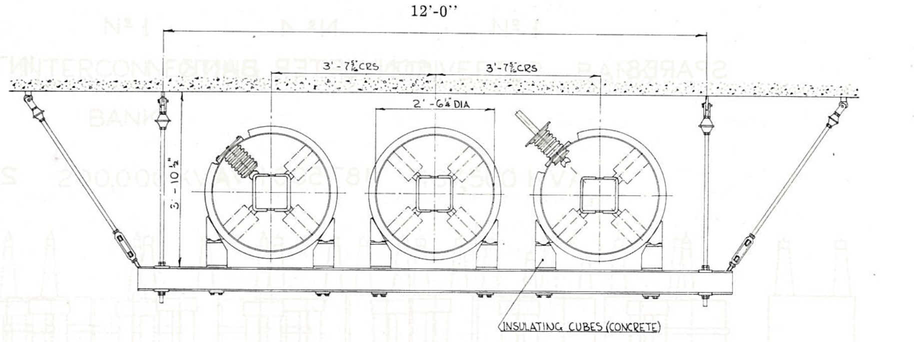

Fig. 8: Cross-section of 9,000 A isolated phase busbars.

Key data for the busbars are:

Country of manufacture	France	
Voltage rating	16 kV	
Insulation level	125 kV	
Current rating (50 c/s)	5,000 A	9,000 A
Aluminium conductor area	9.05 in²	20.25 in²
Aluminium housing diameter	25 in	30¼ in

5.3. 16 kV Switchgear

There are few concentrations anywhere in the world of switchgear of this rated voltage and current with such high short-circuit capacity. The size of the installation is indicated in Fig. 10, where careful examination will disclose a man drawn in to scale. Each single pole of this switchgear is contained in an aluminium-sheathed cubicle 17 ft 6 in high, 10 ft deep, and 3 ft 3 in wide, and these are combined into three-pole circuit-breakers for the generators and two-pole circuit-breakers for each single-phase transformer.

This arrangement of transformer circuit-breakers is an unusual feature which was adopted for the converter transformers because no three-phase circuit-breaker existed with the necessary 8,700 A rating and 3,020,000 kVA interrupting capacity. The three two-pole circuit-breakers of each converter bank are each rated 5,000 A, 1,600,000 kVA and are operated simultaneously as a six-pole breaker by a single control switch. Because a delta connection is required, the two-pole breaker per single phase transformer requires much simpler connection to the transformer banks than a three-pole breaker, and it was adopted for the interconnecting banks even though the short-circuit duty was not so high—only 2,000,000 kVA. It also allowed the use of 5,000 A instead of 8,700 A circuit-breakers and connections.

All three types of circuit-breaker, together with their associated isolators are operated by compressed air at 220 lb/in² which has been dried by expansion from 335 lb/in². The 335 lb/in² storage receivers are charged by two twin-compressor sets.

The circuit-breakers for the generator, converters, and interconnectors are capable of interrupting symmetrical fault currents of 90,000 A, 100,000 A and 62,500 A respectively in 0.06 s.

Although the r.m.s. value of the normal current including its harmonics is in each case, approximately 4,000 A, each breaker is designed to carry continuously 5,000 A. (sine wave form) 50 cycles to allow adequate margin for the extra heating due to skin effect.

Figure 9 shows schematically the arrangement of equipment inside the switch cubicle. Descriptions of the development of this basic type of air blast circuit-breaker are to be found in (2) and (3).

The circuit-breakers were manufactured in Switzerland.

6. TRANSFORMERS

As shown in Fig. 10 there are 21 single-phase transformers with a total rating of 1,342,000 kVA. These form four converter transformer banks and two inter-connecting transformer banks, and there are three spare transformers.

A traverser truck of 110 tons capacity and 8 ft rail-gauge is provided for handling the transformers, which are all equipped with flanged wheels. A 110 ton turntable allows a transformer on the traverser truck to be brought into the power house. All transformers are secured in their operating positions with earthquake clamps capable of withstanding an acceleration of ¼ g. All these main transformers are water-cooled with forced oil circulation.

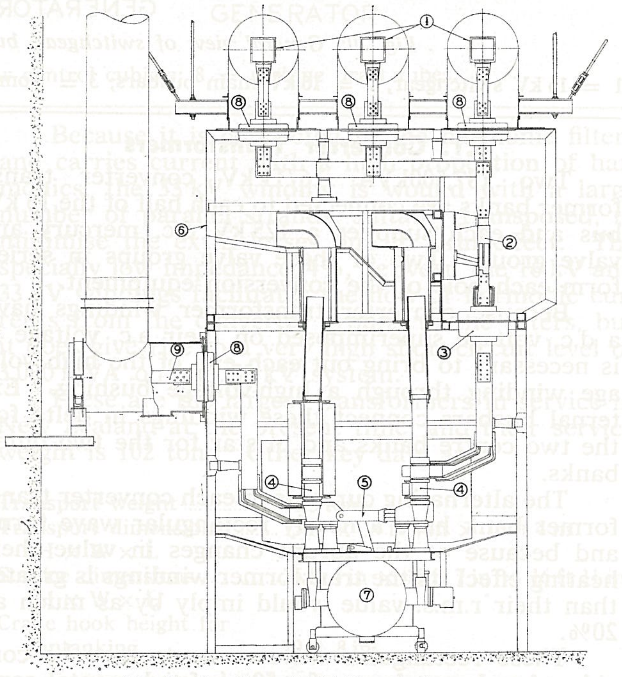

Fig. 9: Section of 16 kV switchgear.

1 = 9,000 A busbars; 2 = isolator; 3 = current transformer; 4 = interrupter heads; 5 = sequential isolator; 6 = blast outlet; 7 = air receiver; 8 = bushing; 9 = 5,000 A connectors to transformers.

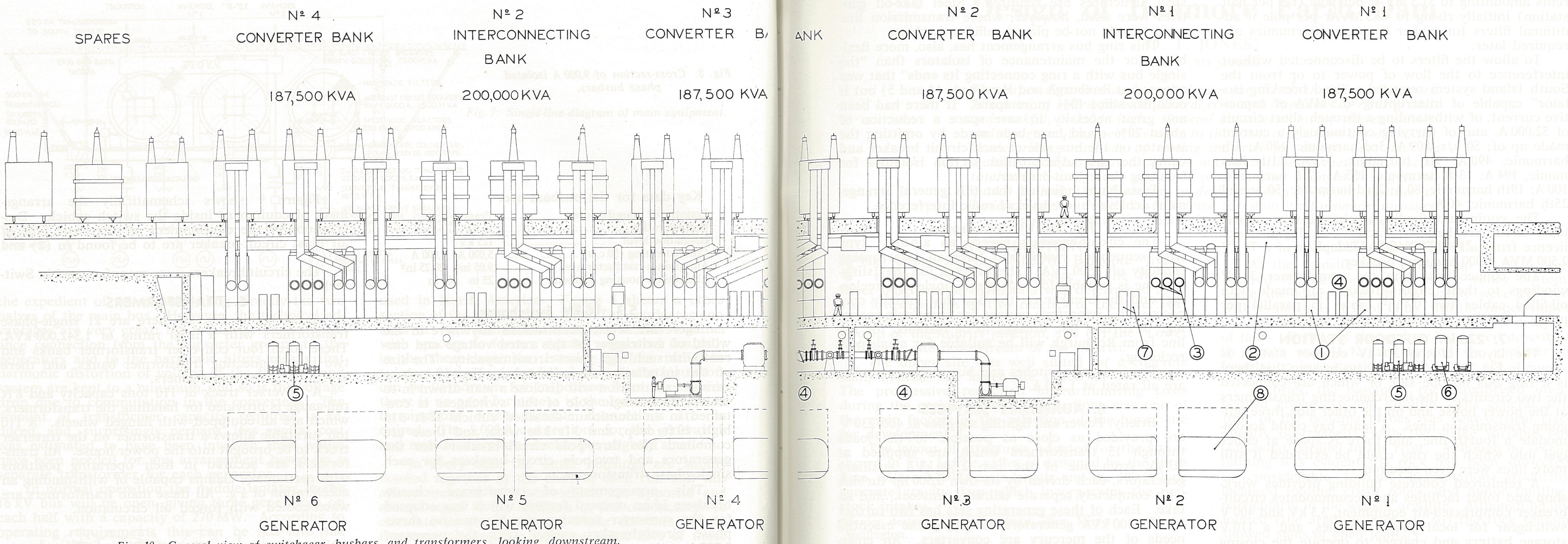

Fig. 10: General view of switchgear, busbars, and transformers, looking downstream.

1 = 16 kV switchgear; 2 = 16 kV main busbars; 3 = connections to generators; 4 = cooling water pumps; 5 = switchgear air compressors; 6 = workshops air compressors; 7 = switch-gear control cubicle; 8 = turbine draft tubes.

6.1. Converter Transformers

Two 187,500kVA, 16/11 kV converter transformer banks are connected to each half of the 16 kV bus and each supplies a 125 kV d.c. mercury arc valve group. Two of these valve groups in series form each pole of the conversion equipment.

Because converter transformer windings have a d.c. voltage superimposed on their a.c. voltage it is necessary to bring out each end of the high voltage winding through a high-voltage bushing. External busbars connect these windings in delta for the two centre banks and in star for the two outer banks.

The alternating currents in each converter transformer bank have a nearly rectangular wave form, and because of the abrupt changes in value their heating effect on the transformer windings is greater than their r.m.s. value would imply by as much as 20%.

These rectangular wave currents may be considered to be made up of a 50 c/s fundamental component and a series of harmonics (the odd numbers which are not multiples of 3). If precautions are not taken these harmonics will spread back into the a.c. system and may cause overheating of equipment or interference with communications or ripple-control systems. However, by making one of the transformer banks for each pole delta-delta and the other delta-star the 5th, 7th, 17th, and 19th harmonics virtually cancel out by passing along the busbars between the two banks, leaving only the 11th, 13th, 23rd and 25th to enter the a.c. system. Even with this reduction in harmonics it is still necessary to provide a substantial installation of harmonic filters.

Each converter transformer bank is equipped with a surge-diverter on each phase to protect it against surges originating in the conversion equipment. In addition, a surge-diverter is connected to the star point of each star-connected bank.

Transport limits originally specified gave a maximum transport height of 13 ft, but the manufacturers of the converter transformers advised that an increase in transport height to 15 ft would allow the contract price to be reduced considerably. Re-examination of the route showed that the limiting obstructions could be raised for a very much less amount.

These transformers were made in Sweden and other data are:

Connections	delta-delta	delta-star
Insulation level	125/775 kV	125/1,050 kV
Transport weight	52 tons	62 tons
Service weight	71.5 tons	88 tons
Transport dimensions H × W × L	15 ft × 11 ft 6 in × 9 ft 3½ in	15 ft × 13 ft × 10 ft 4 in
Service dimensions H × W × L	22 ft 6 in × 11 ft 6 in × 12 ft 3 in	25 ft × 13 ft × 13 ft 5 in
Crane hook height for untanking	33 ft 9 in	34 ft 5 in

6.2. Interconnecting Transformers

The two interconnecting transformer banks which link the respective halves of the 16 kV bus to the 220 kV bus, each have three windings rated 16/33/220 kV and 200/60/200 MVA respectively. The corresponding insulation levels are 125/200/900 kV. No surge-diverters are fitted on the 16 kV or 33 kV windings, but the standard 38 in rod gap is provided on the 220 kV bushings. The 220 kV windings have on-load tap changers of a high-speed resistance transfer type giving a range of +16.7% to −13.3% in $1\frac{2}{3}\%$ steps .

Because it is connected to the harmonic filters and carries current with a high proportion of harmonics, the 33 kV winding is wound with a large number of parallel strands, suitably transposed, to minimise the extra losses due to skin effect. The specially low impedance, 4%, between the 16 kV and 33 kV windings facilitates the flow of harmonic currents from the converter groups to the filters, but it does give rise to a very high short-circuit level of 3,000 MVA on the 33 kV system.

These are the largest transformers in service in New Zealand at the present time, and their service weight is 102 tons. Other key data are:

Transport weight	68.5 tons
Transport dimensions H × W × L	15 ft × 14 ft 4 in × 10 ft 4 in
Service dimensions H × W × L	25 ft 4 in × 15 ft 7 in × 16 ft 11 in
Crane hook height for untanking	29 ft 8 in

6.3. 33 kV Connection to Harmonic Filters

The harmonic filters consist of groups of circuits tuned to absorb currents at harmonic frequencies. They carry, also, substantial 50 c/s capacitive currents amounting to 31.5 MVAr per pole (i.e. per half station) initially rising to 42.5 MVAr per pole if additional filters for higher frequency harmonics are required later.

To allow the filters to be disconnected without interference to the flow of power to or from the South Island system required a "load breaking isolator" capable of interrupting 42.5 MVA of capacitive current, of withstanding a through short circuit of 52,000 A, and of carrying continuously a current made up of: 50 c/s, 809 A; 3rd harmonic, 100 A; 5th harmonic, 490 A; 7th harmonic, 338 A; 11th harmonic, 194 A; 13th harmonic, 155 A; 17th harmonic, 100 A; 19th harmonic, 80 A; 23rd harmonic, 50 A; and 25th harmonic, 40 A.

The equipment finally purchased was an air-blast circuit-breaker manufactured in Japan under licence from a French firm, an adaption of a 70 kV 2,500 MVA 2,000 A circuit-breaker.

The connections from the transformer 33 kV windings to these circuit-breakers are made with oil-filled cables two 0.4 in^2 cables in parallel per phase. These were manufactured in England.

7. 220 kV OUTDOOR STATION

The layout of the 220 kV outdoor station is shown in Fig. 5 from which it can be seen that there is a ring bus on one side of which are connected the two circuits to the interconnecting transformers at the power house and on the other side three outgoing transmission lines. A spare bay could accommodate a fourth line, and there is space at either end into which the ring could be extended if still more lines were ever required.

A reinforced concrete building provides workshop and toilet facilities and accommodates circuit-breaker compressed-air equipment, 3.3 kV and 400 V switchgear for local power supplies, and a 110 V storage battery and charger to operate the closing and tripping coils of the air-blast circuit-breakers.

7.1. 220 kV Ring Busbars

The 3 in diameter copper conductors of the ring bus are supported 17 ft above the ground by insulator stacks mounted on concrete posts, and the connections from the bus to the switchgear for transformers or transmission lines are rigid copper tubes (Fig. 11).

This arrangement achieves a saving in cost, as no overhead tensioned conductors or supporting steel structures are required. Steel take-off gantries were used, however, where transmission line towers could not be placed sufficiently close.

This ring bus arrangement has, also, more flexibility for the maintenance of isolators than "the single bus with a ring connecting its ends" that was adopted at Roxburgh and Haywards (4 and 5) but it occupies some 10% more space. If there had been any great necessity to save space a reduction of about 20% could have been made by omitting the isolator on the bus side of each circuit breaker and using the two adjacent bus section isolators for isolating the circuit-breaker.

Tests have indicated that this general arrangement achieves a low level of radio interference.

7.2. 220 kV Switchgear

The circuit-breakers are of an air-blast type with sequential switch and have an interrupting capacity of 7,500 kVA. The breaker for the Islington line is suitable for high-speed single-pole reclosing, and the breaker on the line that initially connects with Livingstone is used for three-pole reclosing. A further line breaker to be installed for the line from Roxburgh will be suitable for single-pole reclosing.

The isolating switches and bus section switches are all rated at 1,200 A.

8. AUXILIARY SERVICES

Briefly: Power and lighting supplies at 400/230 V are provided as close as possible to the loads through 15 transformers which are supplied at 3.3 kV from one of the two 2,500 kVA auxiliary generators, each driven by its own 3,500 hp turbine with completely separate tailrace, penstock, and intake. Each of these generating sets has two further 3.3 kV, 400 kVA generators to supply the essential needs of the mercury arc converters. An emergency supply can be obtained from the Waitaki Power Board.

Cooling water is pumped from the tailrace by one of two 12,000 gal/min 400 hp pumps which are speed-controlled by rotor resistor taps.

9. CONCLUSION

Brief mention must be made of the magnitude of the task faced by the N.Z. Electricity Department's construction forces to install the first half of the station equipment in time to allow five

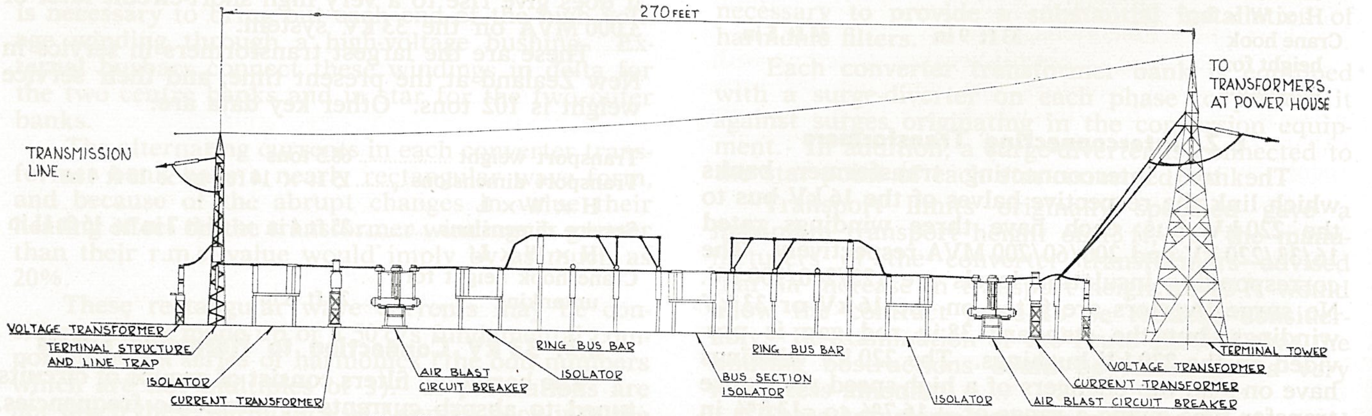

Fig. 11: Cross-section of 220 kV outdoor switching station.

Design of Benmore Earth Dam

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The paper describes aspects of design for the earth dam at Benmore. The dam, of rolled fill with central core and shoulders of river gravels and rockfill, is 360 ft high. General considerations of site conditions and design requirements leading to the form of the dam are discussed. In describing methods of testing material for design data and the stability analysis carried out the author outlines a method of "semi-total-stress" analysis to allow for pore-pressure changes during earthquake loading. Modifications in design arising from construction experience are outlined, installations for dam performance measurements are described, and their results to date are given.

1. INTRODUCTION

THE siting of the 540 MW Benmore hydro-electric station in the gorge of the Waitaki River upstream of Otematata was determined after site investigations of two reaches of the river: (a) Blackjack's Point, or the "Upper Benmore" site upstream of the Ahuriri junction, and (b) the "Lower Benmore" site downstream of the Ahuriri.

The upper site was well suited for a concrete dam, whereas the lower site suited an earth dam. The progressive reduction in earthmoving costs during the period of the investigations was one of the main factors in the selection of the lower site for development.

The layout of structures adopted for the site is shown in Fig. 1. The valley is dammed by the earth dam, with a 2,700 ft crest length, and the 400 ft long concrete gravity dam which incorporates the penstock intakes.

2. SITE CONDITIONS

At the damsite river gravels up to 80 ft deep covered the basement rock in the valley bottom, while the lower sides of the valley were covered with as much as 30 ft of talus. On the upper slopes rock outcropped with localised pockets and layers of talus. Details of the geology have been described by Oborn and McKellar (1) and the engineering foundation investigation by Ballintine (2).

In brief, the basement rock comprised interbedded greywacke and argillite. The general attitude of the bedding planes was near-vertical (frequently overturned), with the strike variable but somewhat parallel to the river. Although no recent faulting was evident the rock had been subjected to considerable tectonic deformation producing localised folding, crush zones, and minor faulting, particularly in the weaker argillite. Although highly jointed (the argillite intensely so) the rock seldom showed signs of open joints.

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Generating and Electrical Equipment—contd.

months' testing of the d.c. equipment before the scheduled commissioning date, April 1, 1965, in spite of a number of adverse circumstances, the most important of which were:

(1) Turbines, generators and transformers were all much larger than any previously installed in New Zealand.

(2) The programme included much unusual equipment—16 kV busbars and switchgear, mercury arc converters with a great variety of associated indoor and outdoor equipment which, even with expert assistance from manufacturers, involved the Department in a great deal of additional work.

(3) The period between the Government's final decision to proceed with d.c. transmission in March 1961 and the commencement of trial operation in November 1964 necessitated quick preparation of specifications and setting early delivery dates. However, the unusual nature of most of the equipment and the fact that much of it required development beyond existing designs led to delays which still further concentrated construction work into the last few months, thus aggravating the already difficult task of assembling and using effectively a workforce sufficiently large and appropriately skilled.

(4) Although the powerhouse site was generally favourable, failure of some exposed rock batters hindered Ministry of Works construction forces in making working area available.

It has been both a privilege and a satisfying experience for the author to have been one of the many persons in this and other countries by whose joint efforts this rather unusual power station has come into being.

The author thanks the members of the power stations section of the N.Z. Electricity Department design office for their very considerable assistance in the preparation of this paper, and the General Manager for permission to present it.

10. REFERENCES

(1) SPROULLE, R. S., and ROELLER, P. (1964): Reduction of Fluid Friction Losses in Rotary Hydraulic Machines. *Trans. Eng. Inst. Canada* (May).

(2) RUCKSTUHL, H. (1954): Metal Clad Outdoor Type Switchgear. *Brown Boveri Review* (October).

(3) MORF, A. (1962): Indoor Air-blast Circuit-breakers. *Brown Boveri Review* (September-October).

(4) FYFE, R. J., and NIXON, C. E. (1955): New Zealand's 220 kV Substations. *N.Z. Engineering, 10* (9) : 279-96.

(5) HITCHCOCK, H. C., and ROTHMANN, S. (1956): The Equipment of Roxburgh Power Station, *N.Z. Engineering, 11* (7) : 214-31.