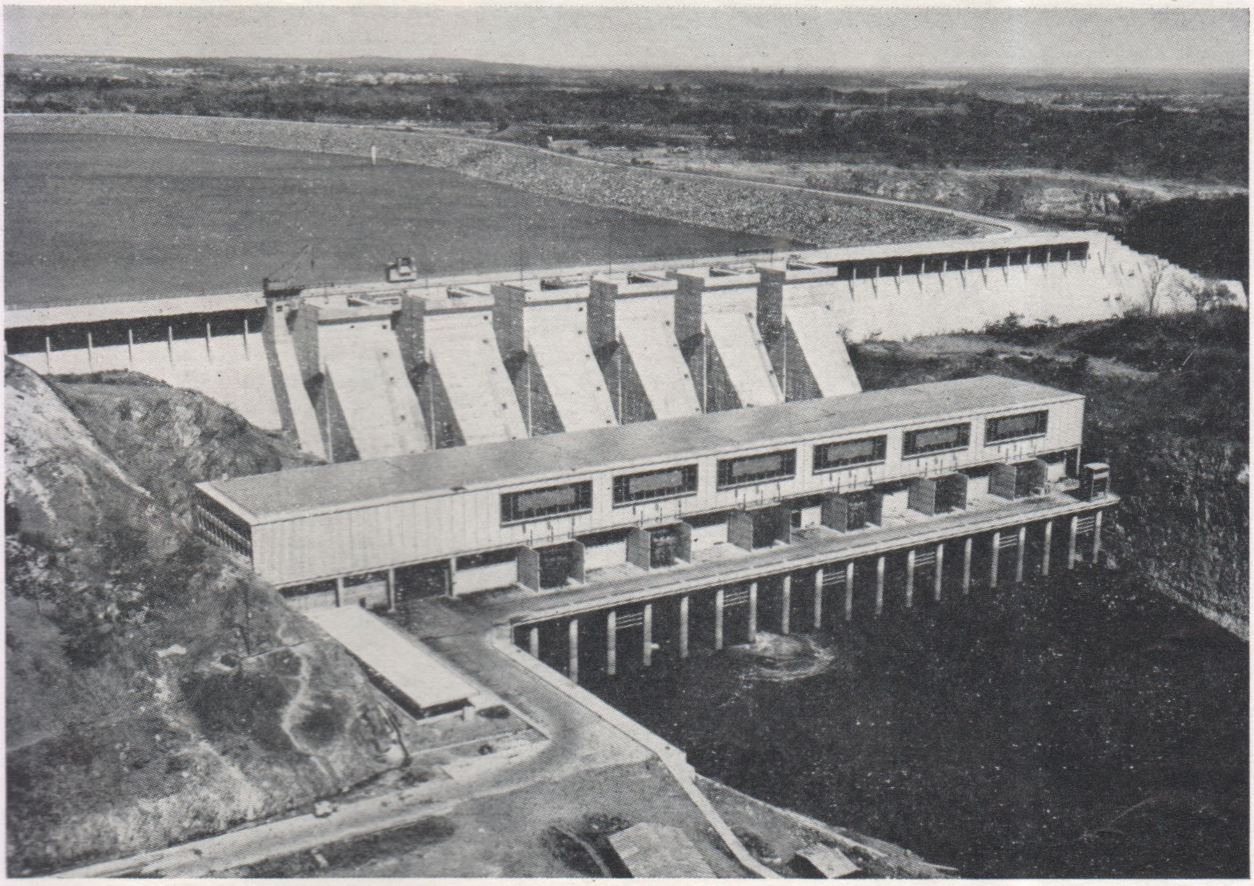

Fig. 1. Macagua No. 1 dam and station seen from downstream

The River Caroní Project

Macagua No. 1, a 370-MW station which forms the first stage in the development of the River Caroní in Venezuela, is now completed. This river constitutes one of the largest hydro-electric reserves in the world

IN our December 1954 issue we gave a brief preliminary outline of a project for a 150-MW development on the River Caroní in Venezuela, which was to form the first of a series of four stages having a total capacity of 8,000 MW. Since that article was published the installed capacity of this stage—known as Macagua No. 1—has been increased to 370 MW and construction is now completed.

In presenting this description of Macagua No. 1 it will be relevant to begin with a short account of the motive for the scheme, which has been to provide power for iron-ore smelting. The existence of extensive iron-ore deposits in Cerro Bolivar in the Venezuelan Guayana had been suspected for many years, but it was only since the last war, during which steel reserves were running low, that surveys were put in hand. As a result of these surveys, a rich deposit covering an area of roughly 7 km^2 was found and since estimated to contain some 2,000 million tons of high-grade ore. In 1952 construction was begun at the confluence of the Caroní and Orinoco rivers on the new town and harbour, Puerto Ordaz, the 146-km long railway from the mine to the Port, and on the dredging of the seaway down the Orinoco. Ore is now loaded at the mine and hauled to Puerto Ordaz where it is crushed and loaded at a rate of 12,000 tons/hour on to ocean-going ore ships of up to 70,000 tons which ply between there and the United States.

The Caroní River, a tributary of the Orinoco, is one of the great water-power rivers of the world, and the Venezuelan Government, realising this, decided to harness some of the vast potential with a view to supplying cheap power to a proposed national iron and steel works for handling the Cerro Bolivar iron ore. Thus in 1948 "La Comisión de Estudios para la Electrificación del Caroní" (C.E.E.C.) was formed to report upon the practicability of such a development. After several years of study, during which Sir William Halcrow & Partners, London, were appointed Consultants to the Commission, a scheme, the first stage of which is known as Macagua No. 1,

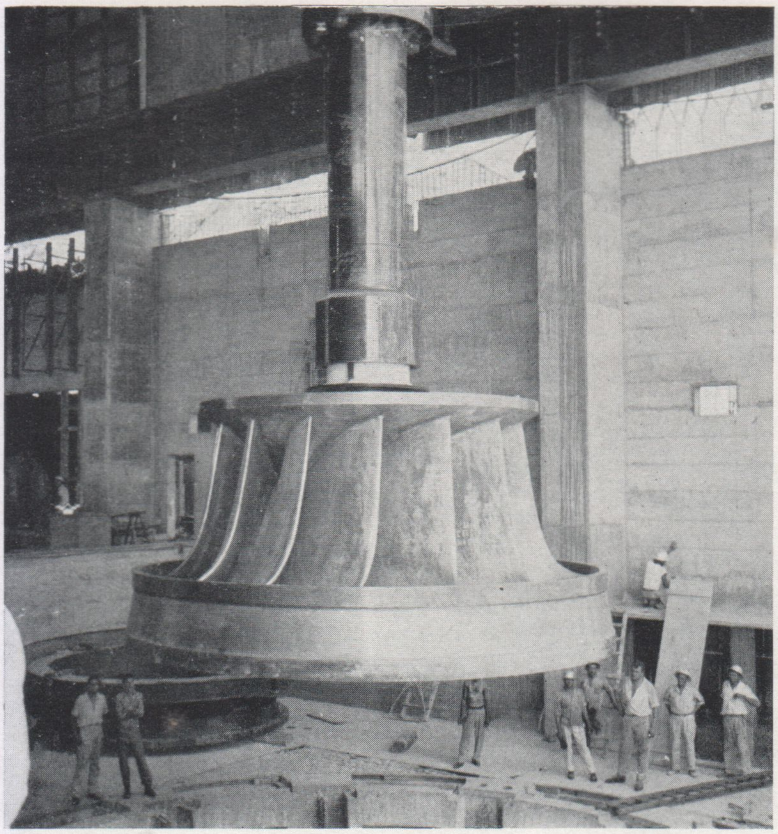

Fig. 2. Runner of one of the Voith turbines in the station

was finally adopted, and construction work commenced in 1954.

The installed capacity of the first stage is 370 MW and preliminary schemes have been prepared to increase the output by stages up to the maximum potential of the river. A report on the future hydroelectric development of the Lower Caroní River, prepared by Sir William Halcrow & Partners, showed that this river is one of the world's largest hydroelectric reserves with a power potential of about 10,000 MW.

Meantime, planning work had been going on for the industrialisation of the Guayana region of Eastern Venezuela, and in particular for the steelworks employing the Cerro Bolivar iron ore. After exhaustive studies with the aid of foreign experts, a target figure of 700,000 tons annually of refined steel from electric reduction furnaces was aimed at with an ultimate annual capacity of 1,200,000 tons. Construction work on this refinery commenced in 1955, and it is now in production, using the power generated at Macagua No. 1.

Outline of the Scheme

Macagua No. 1 is a run-of-river scheme located some 8 km upstream from the confluence of the Rivers Caroní and Orinoco, designed for an average flow of 5,300 m^3/sec, an annual maximum of about 17,000 m^3/sec, and an estimated catastrophic flood of 40,000 m^3/sec. The headpoint is formed partly by a concrete buttress-type intake dam having a maximum height of 40 m and partly by an earth dam built across the erstwhile spectacular Lower Falls some 8 km upstream from the confluence of the Caroní and the Orinoco. The intake dam is flanked on both sides by concrete abutments, the south one running into high ground and the north one connecting with the earth dam 1,930 m long. In order to increase the pondage, plans have been prepared for the prolongation on the north side by a spillweir about 1·5 km in length which would form part of the future development.

The power station houses six 62·5-MW vertical Francis sets.

Construction Programme

It was late in 1954 when it was decided to go ahead with the development. In an attempt to complete the scheme in little more than three years the initial work was divided up into separate contracts which were carried out while the tenders were being prepared for the main work. The first contract, for access roads to the site, was placed in 1954, followed by one for the cofferdams; in all about 3 km of cofferdam up to 20 m high were constructed, costing about £500,000. Soon after this, a contract was awarded for the bulk excavation for the power house and intake, not only to speed progress on the main works but also to provide rock for the cofferdams, and later for the aggregate, for the crushing of which yet another preliminary contract was let.

On account of the late decision to proceed with the cofferdams, the main cofferdam reached the deepest channel at the start of the wet season (April 1955) when the flow in the river started to rise from about 3,000 m^3/sec up to about 15,000 m^3/sec in August. The size of the rock being tipped into the channel was gradually increased until boulders weighing up to 20 tons were used. In addition, 30 railway wagons filled with rock, kept in by welded sheet pile, were pushed into the breach. Even some of these were washed away, but the channel was crossed a few days before a sudden rise in flow, heralding the commencement of the rainy season.

A start was immediately made on the bulk excavation for the power house, which in some places reached a depth of 40 m. Power shovels, dumpers and 15-cu-yard carriers were all employed on this work.

Meantime, tenders for the main civil-engineering works and also for the electrical and mechanical equipment were called for on an international basis. The following were the principal awards:—

Intake and Power House (Civil):
Campenon Bernard de Venezuela.

Turbines and Ancillaries:
J. M. Voith, GmbH, Germany.

Alternators and Ancillaries:
AEG, Germany.

Transformers and Ancillaries:
Oerlikon Engineering Company, Switzerland.

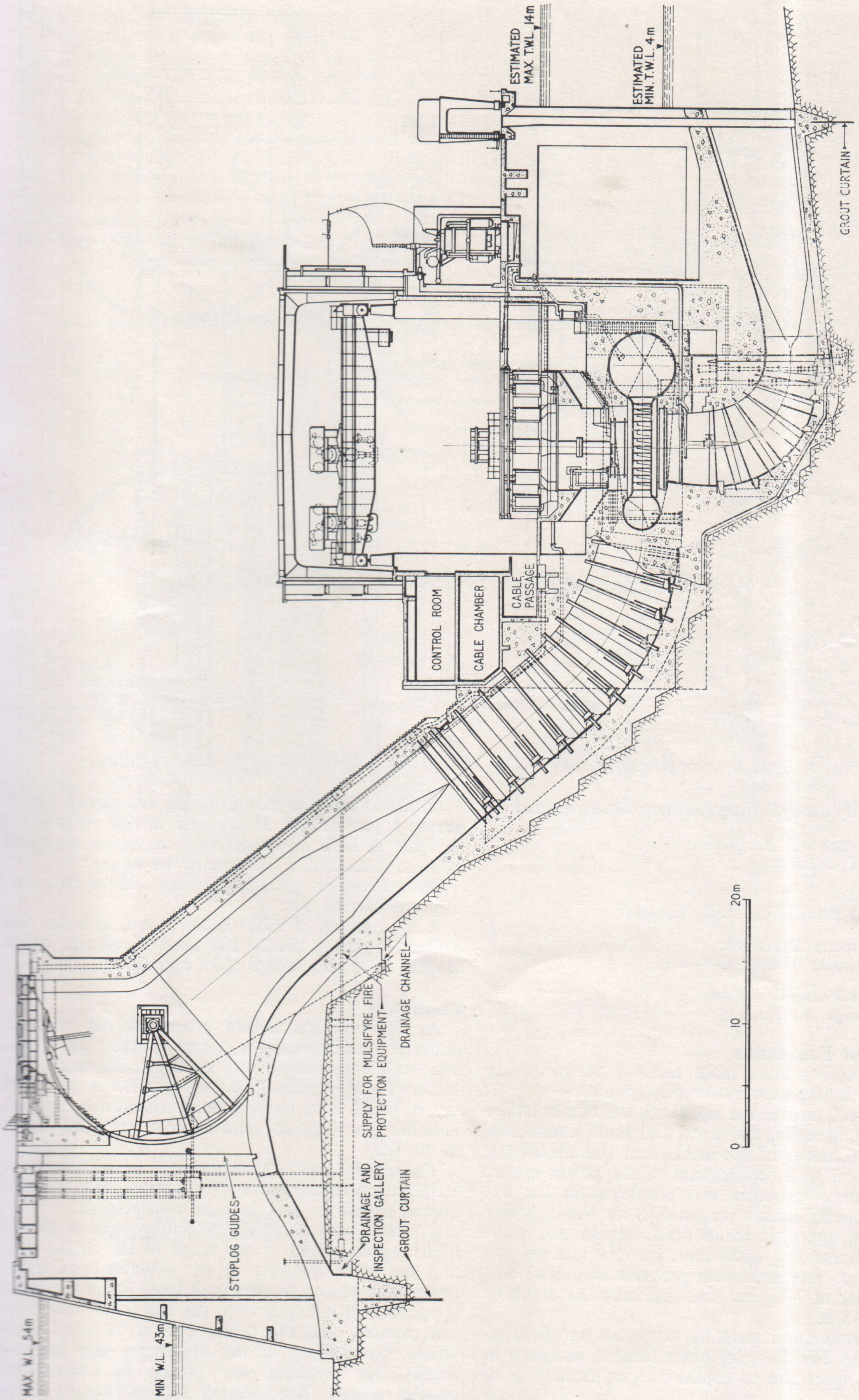

Fig. 3. Section through Macagua No. 1 dam and power station

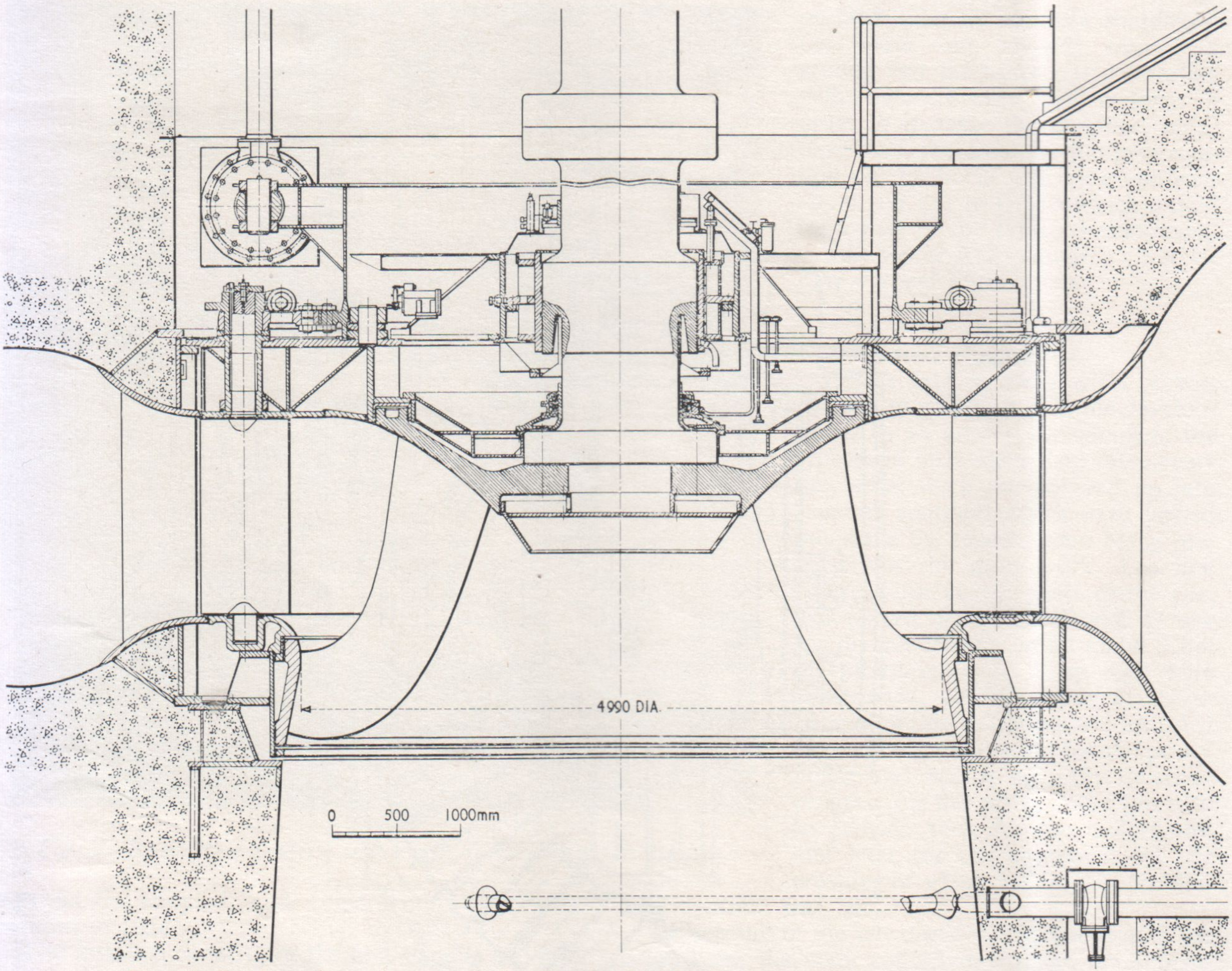

Fig. 4. Section through one of the Voith 86,000 h.p. 116 r.p.m. 40 m head turbines

Subsequently the following contracts were awarded:—

Intake Gates and Ancillaries:
VOEST, Austria.

Switchgear:
English Electric Co. Ltd., England.

Superstructure Steelwork:
Dortmunder Union, Germany.

Overhead Travelling Cranes:
Applevage, France.

Grouting of Foundation

The following three main sections of the power house and intake were extensively grouted:—

(a) Cut-off wall at the upstream toe of the intake dam, including the north and south abutments.
(b) Foundations of the intake and the abutments.
(c) Cut-off wall downstream of the power house.

(a) Curtain grouting was employed in the excavated cut-offs using a wagon drill on 2-in-diameter holes, 2 m apart, at inclinations, depths and pressures, all depending upon the rock stratification and composition. The maximum pressure employed was of the order of 7 kg/cm^2 and generally the depth of hole was 13 m.

(b) Consolidation grouting was used on all foundations, the 2-in-diameter holes being 2 m apart, in lines 5 m apart and to depths ranging from 5 m to 8 m.

(c) Concrete-rock joint grouting was carried out to ensure a perfect seal. Holes were drilled vertically 3 m apart in both directions to a maximum depth of 10 m at a maximum pressure of 4·2 kg/cm^2.

In addition, fan grouting at both ends of both cut-offs was carried out.

A total length of 9,200 linear metres of holes was drilled, requiring nearly 200 tons of cement, which works out at an average of 22 kg/m.

Concreting

As the bulk excavation proceeded the resultant material was crushed for coarse concrete aggregate. The rock encountered was mainly sound and satisfactory for aggregates with the exception of the upper layers, which were badly weathered and decomposed. Suitable sand deposits were found conveniently close to the site.

The cement used was ordinary portland cement of Venezuelan manufacture (Pertigalete) and was delivered to site in bulk in road transporters.

Concrete was mixed in a batching plant of 28 m^3/hour capacity sited to the south of the intake dam and the main quantity of the concrete was transported and placed by means of three aerial ropeways supported on luffing towers, the two outer ones of 8-ton capacity and the centre one of 12 tons. Elsewhere, particularly in the abutments and buttress blocks, the concrete was placed by Lima 2000 crawler cranes. Air-operated bottom-opening skips of 1-m³ and 2-m³ capacity were used.

In general, steel shuttering designed for standard lifts of 1·5 m was used, supplied by Acrow, Great Britain. Special steelclad timber shutters for draft tubes, transitions, etc., were fabricated on site.

Much thought was given during the early stages to the necessity of reducing the temperature of the concrete placed under tropical conditions. Although it was never considered necessary to install a cooling system within the massive structure, provision was made to use iced water and to hose down aggregates. However, observations and readings from thermo-

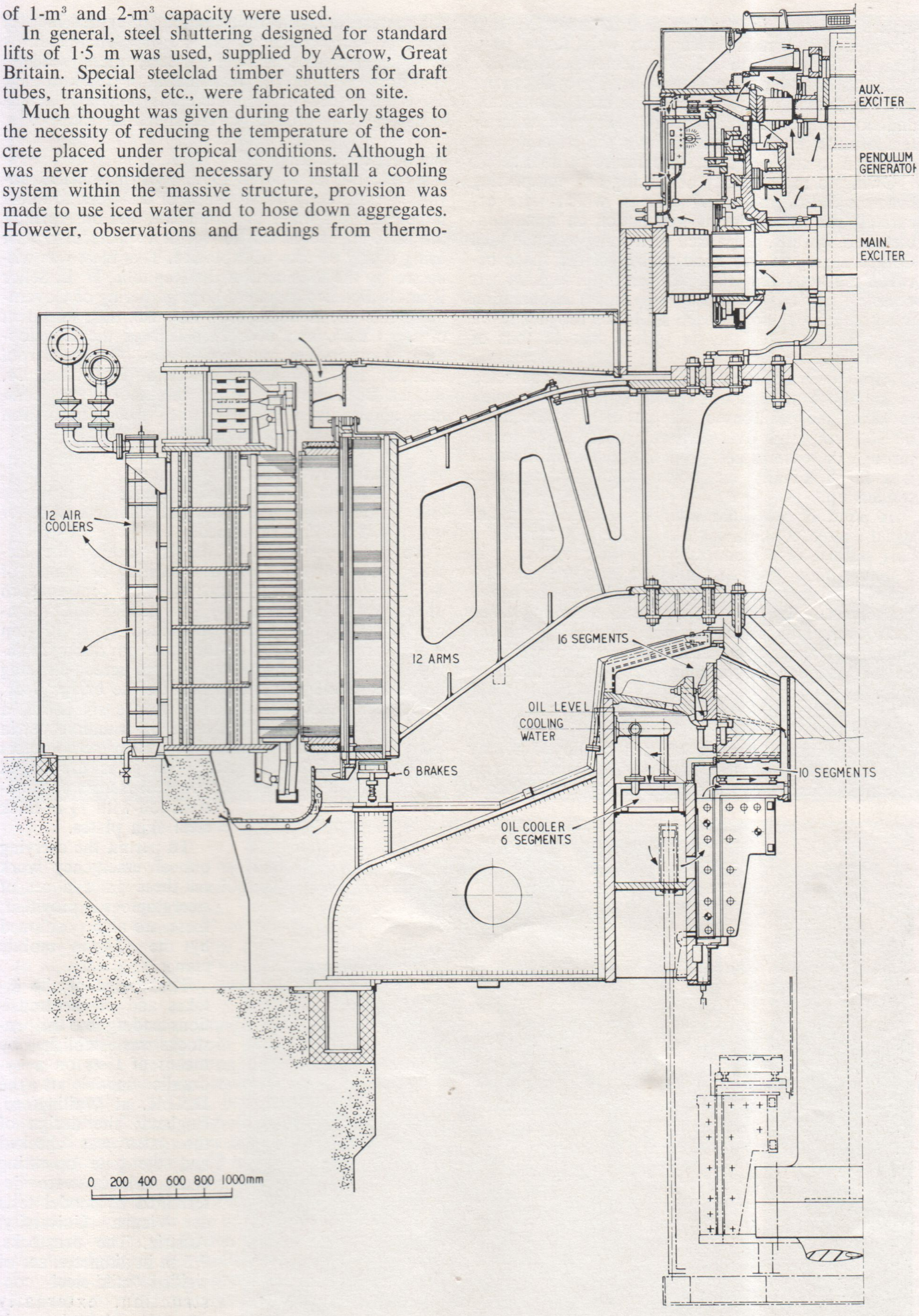

Fig. 5. Section through one of the AEG 70 MVA 13·5 kV 0·88 p.f. 116 r.p.m. generators

meters installed in the initial lifts indicated that provided the normal precautions were taken (e.g., limiting lift height to 1·5 m), the temperature differentials would not be dangerous. Type II cement and Plastiment, as a retarder, were used throughout, and no trouble occurred through excessive concrete temperature, even though at times the concrete was delivered to the pits at a temperature of 80°F.

Owing to the difficulty of placing and compacting concrete below the spiral casings, which were accurately positioned during installation on small concrete radial walls, prepacked concreting was adopted. Coarse aggregate was hand-packed in the space between the walls and grout pumped in through 24 sets of holes, 1·8 m apart, in each stayring. The operation was continuous and for each set lasted roughly seven hours. For each of the six spirals over 15 tons of cement were used.

After seven days the area of each spiral concreted in the above manner was tested by hammer tapping to locate the positions of any cavities. Where areas of 900 cm^2 and over existed, holes were drilled through the casings and grout injected until the area was filled. Finally the holes in the casing were welded up.

A point of particular interest, calling for an unusual degree of skill, was the handling of the 58-ton cast stainless-steel runners which were offloaded in a tank landing craft and dragged ashore. Each runner was taken on a special road trailer to the power house, where the 260-ton overhead travelling crane took over. This procedure was adopted for all six runners. The main generator transformers weighing 65 tons stripped for shipping were handled the same way.

Labour

The maximum number of men employed at any one time was about 400. The unskilled workers were recruited locally with nearly all European nationalities represented. A certain amount of skilled labour, however, was brought to the site by particular firms as specialists, such as steel erectors, fitters, welders, etc. For example, the installation of the turbines, alternators, transformers, etc., was done by technicians expressly brought to the site from Europe.

Completion of Stage 1

By the end of March, 1959, construction had advanced sufficiently on all stages of the work to allow impounding of water to commence, and on April 21 the main cofferdam was blown in a spectacular blast using nearly 80 tons of explosive. This blast was witnessed by the President of the Republic, H. E. Señor Romulo Betancourt, and a large gathering of Government officials, including Col. Alfonzo, then President of the CEEL and now President of the Development Corporation, the originator of the Caroní scheme, and his chief engineer at that time, Dr. Rafael De Leon A. Testing on the first set commenced shortly afterwards, since when installation of the remaining sets has continued.

Intake and Power House

Fig. 3 shows a general arrangement of the intake and power house, the principal characteristics of which will now be described.

To prevent river-borne debris reaching the turbines, screens are provided consisting of panels of 1-in by 6-in steel flats spaced at 10-cm centres, each panel being 4·44 m wide by 2·44 m high and weighing 1,600 kg. They are positioned by a 12½-ton mobile crane travelling on the upstream deck. Cleaning is by means of a Waagner-Biró screen-cleaning machine running on tracks laid on the bridge deck.

At each intake, of which there are six in all, a tainter gate is provided mounted on trunnions set in each buttress and operated by twin servomotors hydraulically interconnected. The gates are 10 m wide by 11 m high, and are of steel framework construction with 1¼-in-thick steel skin plates.

To permit the carrying out of emergency work on these gates a set of steel stoplogs is provided; these are also positioned by the 12½-ton mobile crane.

The design of the intakes and of the transitions leading into the penstocks was established by means of tests on a hydraulic model at the D.S.I.R. at Wallingford, England; the design of the gates was checked and the gate operating characteristics were determined by model tests at Vienna University, Austria. The penstocks, 7·5 m in diameter, are of welded mild-steel construction, externally strengthened at intervals with lattice stiffeners; they are coated on the outside

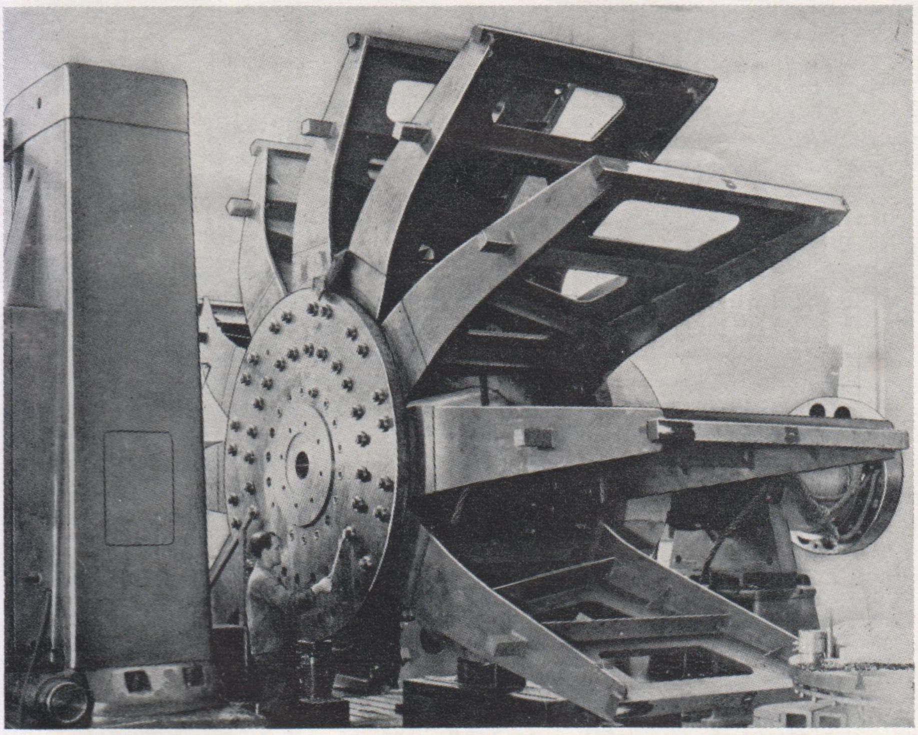

Fig. 6. Spider of one of the generator rotors in the AEG works

Fig. 7. Macagua No. 1 machine hall after the installation of all six machines

with an elastic coating to allow expansion without stressing the concrete casing, and on the interior with a bituminous compound.

The power house, 137 m long by 20 m wide, with a maximum height above draft-tube foundations of 46 m, contains the six Francis vertical turbo-alternators and their ancillary equipment described later in this article.

The substructure, founded on rock, is concreted up to the operating floor at the 13·9-m level, and above this is the building, consisting of reinforced-concrete columns and concrete walls to the crane-girder level at 26·0 m, on which are mounted the steel portal frames supporting the aluminium deck roof. Between the power house and the rock face is a two-storey building 102 m long by 8·5 m wide with the ground floor on the 17·0 m level and the first floor containing the control room at the 25·0 m level. On the downstream side of the power-house building is a platform at the 17·0-m level, 8 m wide, on which the transformers are positioned, each flanked by its firewalls. Along this platform operates a 15-ton Goliath travelling rail crane which handles the draft-tube stoplogs.

Two overhead travelling cranes are provided, one with twin crabs having hooks of 130 tons and 25 tons capacity, and a second with single crab of 25 tons capacity operating at higher speed. At the south end there are a workshop and storeroom having a 10-ton overhead travelling crane which also serves the two 400-kVA auxiliary diesels.

With a view to obtaining good ventilation and the maximum amount of light consistent with the elimination of glare, double walls with an intermediate space of 0·8 m have been built above crane-rail level on both the upstream and downstream sides, presenting a pattern texture of louvres. The inner wall is of aluminium framing with aluminium curtain walling. The outer wall consists of precast concrete louvres set in precast vertical frames spaced at 2·2-m centres, and is approximately 10 m in height resting on the concrete structure supporting the crane beams. Between these vertical frames, precast slabs are fixed to form three galleries within the double wall and running the full length of the building to provide access to the crane rails and the main power-cable insulators.

The interior finishes have been selected to present a restful appearance. Floors are of granolithic finish and terrazzo tiling. Walls are painted cream, the roof is unpainted, and the machinery is all grey.

During construction of the station, Bassett-Lowke

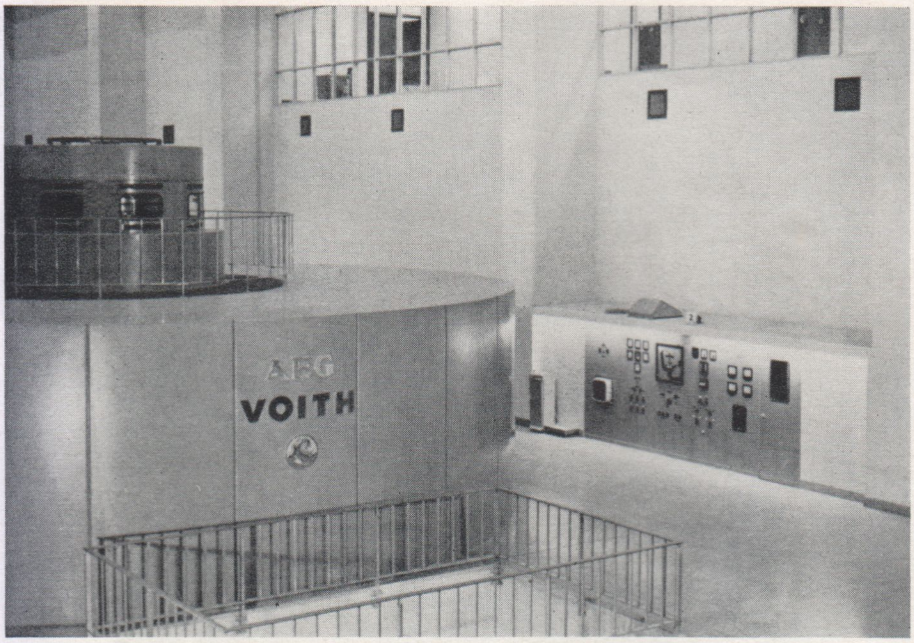

Fig. 8. One of the generating sets and its instrument board

Limited, Northampton, with the aid of detail drawings, built a scale sectional model in scale $^1/_{500}$ of the generating unit. Also, Huntings provided a $^1/_{1000}$ model of the power house and intake dam, containing removable sections showing the foundation details.

Turbines

J. M. Voith GmbH, Heidenheim, supplied all the turbines complete with steel penstocks and draft-tube linings and all auxiliary plant. The turbines are vertical Francis type designed to work under a net head range of 35 to 40 m, the guaranteed output at full gate opening and 40 m net head being 86,000 h.p. A section through one of the turbines is shown in Fig. 4.

The distance between centre lines of machines is 22 m. The stainless-steel runners have a maximum diameter of 5·38 m and a finished weight of 57·5 tons. They were supplied by Bochumer Verein and are believed to be the largest integrally cast stainless-steel runners in existence. The 24 wicket gates, 1·54 m in height, are of cast-steel construction and their operating mechanism incorporates links which are so adjusted as to break if an obstruction greater than 6 mm thickness should prevent any wicket gate closing completely. The gate actuator consists of two servomotors located on the upstream side of the turbine pit, with oil tank, pressure vessel and governor adjacent on the floor at the 10·0 m level. On this level are also accommodated the water-filtration plants for cooling-water supplies, the air-compressor units common to each pair of machines, and the oil-storage and portable oil-filtration plant.

Generators

The six generators, with their instrument panels and ancillary equipment, were supplied by AEG, Germany, each machine being rated at 70 MVA at 0·88 p.f., 60 c.p.s., 13·5 kV, 116 r.p.m., and complying with ASA standards. They are of the umbrella type, having a combined thrust and guide bearing below the rotor and no upper bearing. The main and pilot exciters and the pendulum generator are nested into the top of the machine, and are included in the

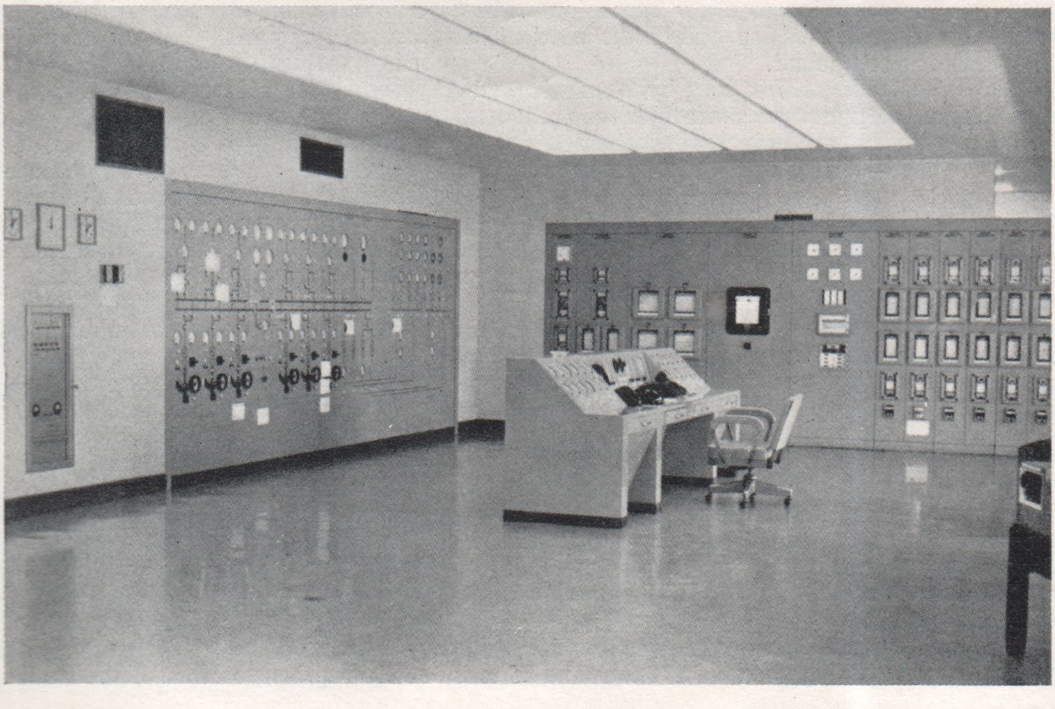

Fig. 9. A view of the control room

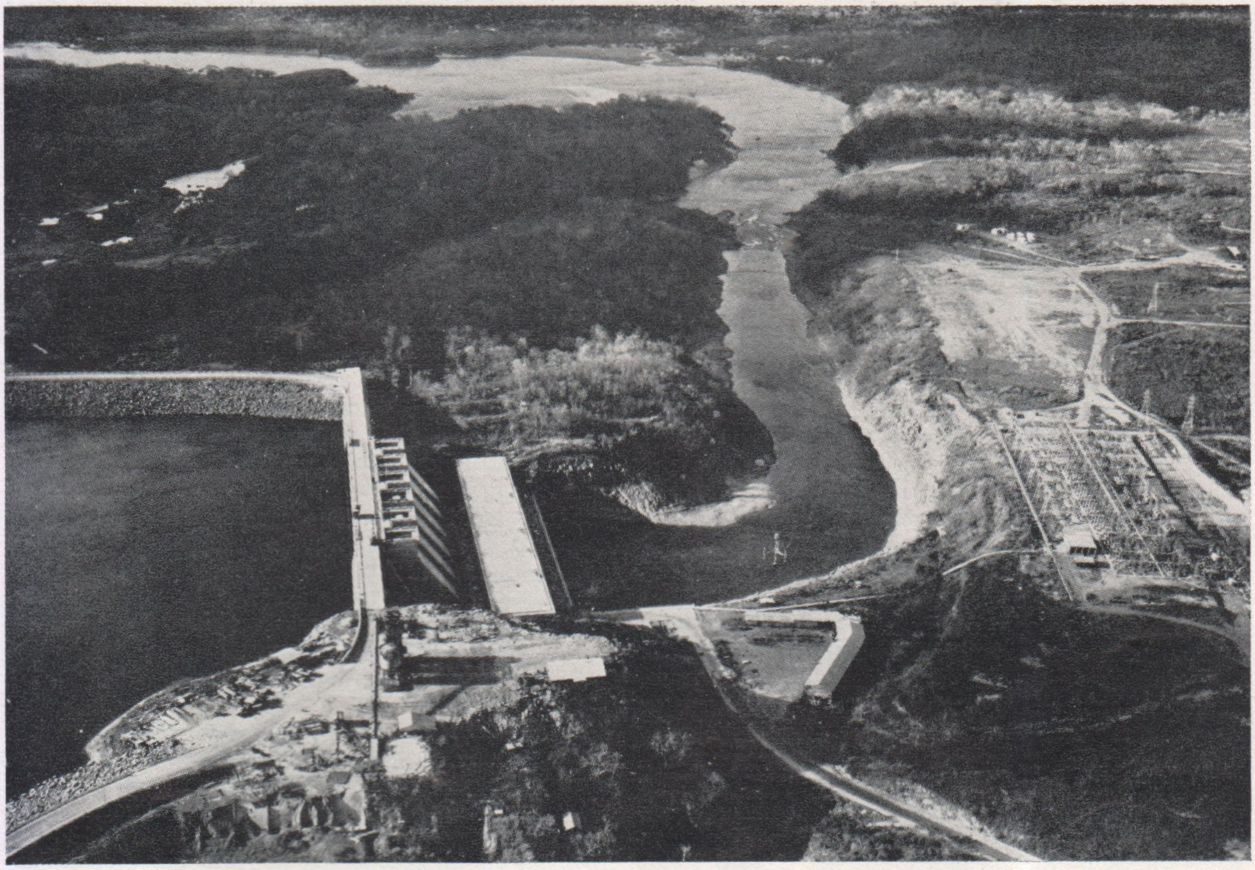

Fig. 10. Aerial view of the dam, power station, and switchyard

closed-circuit ventilation system, but brushes are kept out of it. To keep down the rotor length and to obtain the necessary flywheel effect of 11,300 tons m^2 the stator bore has been made 7,900 mm in diameter and the active iron length is 2,000 mm. The stator bore enables not only the turbine runner but also the turbine cover and the alternator bottom bracket to be lowered through it. A half-section through one of the generators appears in Fig. 5.

The stator was split into four parts for transport. The laminations are 0·5 mm thick and have a loss coefficient of 1·5 W/kg. The stator winding is a two-layer transposed type connected as a winding with two parallel circuits per phase, the bars being insulated with varnished fibreglass and, in the slot portion, encased in shellac micafolium.

The rotor comprises a spider consisting of 12 welded arms surrounded by a rim built up of sheet-steel segments 4 mm thick. Laminations 1·5 mm thick are used for the pole pieces, which are secured to the rim by double-wedged hammerhead keys. Removal of three poles enables stator bars to be replaced without lifting out the rotor.

The thrust bearing is designed to sustain a load of 800 tons being the total of 380 tons static load of all rotating parts with the addition of hydraulic thrust. The thrust-bearing segments are supported on groups of preloaded cup springs, and can be replaced without removing the rotor. Six rams bolted to the lower bracket arms are provided for braking and jacking of the rotor. When the unit decelerates, an automatic braking valve supplies compressed air at 15 atm into the braking piping when 40% of the rated speed is reached. Before the machine is started after a prolonged shut-down, the same rams are connected to a portable oil pump operating at 400 atm for jacking purposes.

Within separate compartments in the generator casing, and also supplied by AEG, are the exciter-field switch and the generator-neutral and line-terminal equipment. The former houses a Clophen-filled (non-flammable Askarel) earthing transformer and the latter contains cast-resin-type voltage transformers, surge diverters and Clophen-filled protective capacitors.

General protective gear includes sensitive stator earth-fault protection derived from measurement of the current in the loaded secondary of the generator-earthing transformer. The load, consisting of iron-hydrogen resistance connected in the manner introduced by Dr. Buetow, offers low resistance when cold and thereby enables a sensitive current relay to respond to low current in the generator neutral.

Busbars carry the generator phases to the generator transformers on the downstream deck. To these busbars an English Electric unit transformer of 150 kVA rating is connected; the transformers, being sited on the 13·9 m level within the power station, have non-inflammable fluid filling (pyrochlor).

Generator fire protection is afforded by automatic operation of CO$_2$ equipment, and the main generator transformers are protected by an automatic Mulsifyre installation.

Instrumentation and Control

On the 13·9-m level in the upstream wall of the power station a gauge panel opposite each unit provides the instrumentation, indications and controls necessary for operating the intake gate and turbine.

The panel is in five separate units and contains the Brown Boveri automatic voltage regulator, the hydraulic indications, a mimic diagram providing automatic indication by appropriately coloured lights of intake-gate position, wicket-gate opening, generator-field and line-switch states, etc., the generator and transformer temperature indications, and finally an alarm panel. This last incorporates an alarm facia and equipment supplied by Standard Telephones and Cables Limited for the indication of a total of 48 alarms divided into equal groups of intake gate, turbine, generator and transformer. Communication with the control room consists of telecommand equipment and a direct-wire telephone.

The gauge panel is of the corridor type, and front and rear doors give access to the auxiliary starter panel, each starter or group of starters for main and standby units being enclosed in individual steel panels. The starters accommodated here provide remote or local control of intake-gate main, standby and leakage-oil pumps, governor-oil pumps, air compressors and transformer-oil pumps.

In the control room on the 20·5-m level the entire equipment was provided by The English Electric Co. Ltd., and comprises a control desk, mimic diagram, miniature control panels for the 115-kV generator and feeder switchgear, the interbus transformer and the 33-kV feeder switches. All miniature control and indicating equipment was provided by Standard Telephones and Cables Limited under sub-contract from The English Electric Co. Ltd. Relay and metering panel suites at the north end of the control room align with panels accommodating a Leeds & Northrup frequency controller and the Voith turbine flow indicators and summator. The control desk has wing panels for each generator, whereby the attendant has full control of excitation and loading, and a central section housing telecommand gear, direct wire and P.A.B.X extension telephone, synchronising selection, switch-closing and repeat alarms, which indicate to the attendant the appearance of an alarm at any one of the four groups on the gauge panel of each machine.

Auxiliary Services

The machine auxiliaries are started from a supply taken from an English Electric Superform switchboard located on the 17·0-m level on the upstream side of the power station. This switchboard is coupled directly to an adjacent 33-kV/440-V, 1,000-kVA house transformer, and once again this is filled with non-inflamamble fluid (pyrochlor). The 33-kV feed is cabled from the 33-kV switchyard.

When generator excitation is increased to bring the terminal voltage up to 90% rated volts, changeover switches in the unit starter panel operate automatically to switch all unit auxiliary supplies to the generator unit transformer. Oscillograph tests have been made on this quick switching system to prove freedom from current and voltage surges.

If there should be a failure of supply to the station 1,000 kVA auxiliary transformer an automatic starting sequence is initiated to bring one of the two Mirrlees 400-kVA diesel generators into service. When the selected machine reaches full voltage it is closed automatically on to the station auxiliary switchboard.

Cables in the switchyard and the power station other than those to machine devices were supplied and installed by British Insulated Callenders Cables Limited. Those between machine devices and the gauge panels were supplied by AEG. Generally cables are PVC insulated steel-wire or tape armoured and PVC sheathed, but paper-insulated cable is in use where length of run proved it to be economical.

115-kV and 33-kV Switchyards

The entire switchyard equipment was supplied and installed by The English Electric Co. Ltd. The 115-kV switchgear is 3,500-MVA symmetrical-breaking capacity air-blast type, the compressed-air plant being housed on the site together with a relay room for protection equipment for busbars and for feeders in both switchyards. The main and reserve busbars provide six outgoing feeder circuits in addition to the supply to the 33-kV switchyard; all isolators, being pneumatically operated, can be controlled from the mimic-diagram panels in the power station control room. A 12-MVA interbus transformer fitted with on-load tap-change gear provides the first-stage supply to the single 33-kV busbar. Initially this busbar was commissioned with three feeders, the switchgear being 350-MVA symmetrical breaking capacity with three single-phase switch tanks.

Test Water Load

As it was known that there would not be sufficient system load for proving the first machines or for ascertaining their efficiency, a water rheostat was designed to accept the full output of one machine. As the resistivity of the water was too high for a 13·8 kV rheostat the unprecedented step was taken of designing the rheostat to operate at 115 kV and connecting it to the generator overhead connections spanning the tailrace. The electrodes were insulated from a three-armed structure freely supported on a vertical post installed in the tailrace prior to flooding, the required immersion of electrodes being obtained by a d.c. motor-driven hoist with radio or direct wire control. Initial difficulty due to flashover at the surface of the water was completely overcome by a system of floating stress rings evolved in practical experiment. In frequent usage the rheostat has since proved capable of maintaining a balanced three-phase load up to 75 MW at 115 kV for long periods, and suitable for carrying out efficiency tests, which confirmed model test results.

Acknowledgments

Permission to publish this article has been kindly given by the President of the Corporacion Venezolana de Guayana, Colonel Rafael Alfonzo R., and we have also been indebted to the good offices of Dr. Rodolfo Telleria, who is in charge of the installation. The collaboration of the main consultants, Sir William Halcrow & Partners, and of the mechanical and electrical consultants, Messrs. Kennedy & Donkin, is also gratefully acknowledged. The photographs are by courtesy of the main civil-engineering contractors, Campenon Bernard de Venezuela, Caracas, by J. M. Voith, GmbH, and by AEG.

The Hydraulic Equivalent Principle Adaptable to Critical Flow. Mr. Francis S. Y. Lee, who contributed this article to our June 1962 issue, p. 236, wishes to point out that Equation (4) should read $V_{cr}=E_v\ \sqrt{D}$ and that Line 3 in Fig. 2 should intersect the D line exactly at $D=2$.