STATE ELECTRICITY AUTHORITY
ICELAND

SUMMARY REPORT ON GEOTHERMAL POWER STATION PROJECT AT HVERAGERDI

MERZ and McLELLAN,
Carrier House,
Warwick Row,
LONDON, S.W.1.

FEBRUARY 1964

STATE ELECTRICITY AUTHORITY
ICELAND

SUMMARY REPORT ON GEOTHERMAL POWER STATION PROJECT AT HVERAGERDI

FEBRUARY 1964

MERZ and McLELLAN,
Carrier House,
Warwick Row,
LONDON, S.W.1.

MERZ AND McLELLAN

CONSULTING ENGINEERS

ALAN E. POWELL, M.I.C.E., M.I.Mech. E.
ARTHUR HOWELL, M.I.Mech. E., M.I.E.E.
E. LEWIS E. WHEATCROFT, M.I.Mech. E., M.I.E.E.
HAROLD J. BEARD, M.I.E.E.
WILLIAM H. DIXON, A.M.I.C.E., M.I.Mech. E., M.I.E.E.
WILSON W. CAMPBELL, M.I.Mech. E., M.I.E.E.
ARTHUR W. PEDDER, M.I.Mech. E., M.I.E.E.
THOMAS W. WILCOX, M.I.E.E.
HAROLD B. JOHNSON, M.I.E.E.

CONSULTANTS
CHARLES L. BLACKBURN, M.I.E.E.
T. GRAEME N. HALDANE, M.I.C.E., M.I.E.E.
FREDERICK C. WINFIELD, M.I.E.E.
SIR JOHN HACKING, M.I.E.E.
DR. ALBERT PARKER, C.B.E., F.R.I.C., M.I.Chem. E., M.I.Gas. E.

ALSO
CARRIER HOUSE · WARWICK ROW · LONDON, S.W.1
AND
CARLIOL HOUSE, NEWCASTLE UPON TYNE 1

TELEX: 53224 (ALL OFFICES)

MILBURN,
ESHER,
SURREY

TELEGRAMS: AMBERKRAFT ESHER
TELEPHONE: ESHER 62345

YOUR REFERENCE ....
OUR REFERENCE ELEW

14th February, 1964

THE DIRECTOR-GENERAL,
The State Electricity Authority,
Reykjavik,
Iceland.

Dear Sir,

GEOTHERMAL POWER STATION PROJECT
AT HVERAGERDI

We have pleasure in submitting herewith our report on the proposed development of power from geothermal steam at Hveragerdi, prepared in accordance with your letter dated 18th July, 1963 (Ref. JG/SSE/sg).

The attached report deals with the design of a power station with an initial installation of a single 16 MW condensing turbo-alternator set. The net electrical output will be somewhat in excess of 15 MW in winter but may fall below 15 MW in summer depending on seasonal variation in condenser vacuum. Tenders for the 16 MW turbo-alternator have been received, also estimates have been prepared by the Authority's civil engineers for the particular layout adopted. The report has been compiled mainly from two earlier reports dated March 1961 and April 1963 which we prepared for you, the contents of which have been revised where necessary to include any recent experience. The method of presenting the cost estimates has been altered to suit the proposed administrative arrangement in which the State would develop and own the steam supply system and Sogsvirkjunin (the authority responsible for the Sog hydro-electric development) would own and operate the power station.

Our main findings and conclusions may be summarized as follows:

1. The total power potential of the steam already proven at Hveragerdi is at least 29 MW. We have proposed that the proven live steam should be approximately double that required to meet full normal output of the station. The additional potential of the hot water associated with the steam is of the order of 11 MW. We recommend that use of the hot water for producing flash steam should not be included in the initial development, but deferred for a possible second stage.

2. While the evidence of rather rapid fouling of some of the wells by calcium carbonate deposits is a complication not encountered in such serious degree in any of the other fields so far developed for power, we think that the difficulty is not insuperable since deposits within the well bores can be dealt with by periodic drilling out. We see no reason to expect build up of deposits elsewhere sufficient to interfere seriously with operation. Hence we consider you are adequately

covered against falling off of yield by the provision of roughly a 100 per cent proportion of reserve wells and by the allocation of expenditure on drilling tackle and drilling team almost continuously occupied in cleaning out wells or drilling new ones.

3. We estimate the total project investment of the first stage comprising an installed capacity of 16 MW to be £1,581,000 (£99 per kilowatt installed). Expenditure on the steam supply is £488,000 and on the power station £1,093,000. (We have used a conversion rate of Kr 120.6 = £1) We think it reasonable from experience elsewhere to assume a 20 year life for the plant and pipe-work. For the wells a 10 year life has been used which allows for possible falling off in yield not correctable by cleaning out. On this basis at 7 per cent interest rate we assess the cost of generation at 0.54 pence per kilowatt-hour for an annual generation of 120 gigawatt-hours. The cost of steam at the power station is assessed at 22.62 pence per long ton based on an annual sale of about one million tons. The above costs include appropriate allowances for import duty and State taxes, contingencies, engineering charges and interest during construction.

4. On the basis of deliveries now being quoted by British firms for home and overseas contracts and the programme of the preferred tenderer for the

turbo-alternator, we expect that the first stage could be in service within two and a half years of placing a contract for the turbo-alternator. This assumes that the civil engineering industry in Iceland can achieve the productivity required to fit in with the plant programme.

Yours faithfully,

MERZ and McLELLAN

CONTENTS

TABLES

PLATES (at end of Report)

PLATES (continued)

SECTION 1

ELECTRICITY SUPPLY IN SOUTH WEST ICELAND

Existing situation

The total population of the southwestern region of Iceland was about 130,000 at the end of 1962 or 71 per cent of the whole population of the country. The region which includes Reykjavík, the capital, Kópavogur, Hafnarfjördur, Keflavík, Akranes, Vestmanna Islands and several smaller places shown on the map on Plate 1, receives its electrical supply from an interconnected high voltage network fed by several power stations. (Some outer areas with local smaller power stations are as yet not interconnected). The total installed plant capacity of the region is 93 MW as shown in Table 1. It is planned to extend the transmission network over the whole region within a few years to that shown on Plate 2. The backbone of this network will be the existing Sog system which supplies about 97 per cent of the population in the south west, deriving most of its power from three stations on the Sog River.

These stations, namely Ljósafoss, Írafoss and Steingrímsstöd, together with the two transmission lines to Ellidaár, are owned jointly by the State and the Municipality of Reykjavík. The whole available 76.5 metre head of this river is now harnessed. The installation of a further 15.5 MW machine at Írafoss is now proceeding and with this addition the total installed capacity of the Sog stations will reach 87.5 MW and the system 108.5 MW. This unit is expected to be ready for service at the beginning of 1964. Nearly the whole of the water will then be used and therefore practically no additional energy can be generated. However, provided the deficit of energy were made up from another source, somewhat greater output in kilowatts could still be obtained from the Sog by reduction of load factor entailing rebuilding or installation of additional machines. The Sog derives much of its flow from underground sources and is stabilized by Lake Thingvalla which covers an area of 83 km^2. However storage is at present limited by the permissible level variation of 2 metres implying some 400 hours use of the mean flow of 112 m^3/sec which is sufficient to even out variations over some months and to build up a useful reserve for winter but not to cover deficiency in a dry year.

The power from the Sog stations is transmitted about 50 km into Reykjavík at 138 kV by a single circuit steel tower transmission line completed in 1953 following a route (indicated in Plate 1) which passes near Hveragerdi. The line has a nominal thermal rating of 96 MW and it will be nearly fully utilized when the final set goes in at Írafoss. There is also a single circuit 66 kV wood pole line, some 25 years old, taking another route further north. Operation of the two lines in parallel is not practical, but the output of the Ljósafoss plant may be transmitted separately over the old line, if necessary. This mode of operation is, however, not very desirable as the 66 kV line is subject to outages arising from salt deposits on insulators where the route is near the coast and from ice formation on conductors inland. The load supplied from Sog to the eastern part of the network and not requiring transmission to Reykjavík is at present 5 to 6 MW. This part of the network is operated at 11 and 33 kV. The south west power system is not interconnected with other parts of the island.

There is a run-of-river plant with an installed capacity of 3.16 MW on the Ellidaár River on the outskirts of Reykjavík. Nearby are the receiving end substation of the 138 kV Sog line and a 7.5 MW steam station. The steam station is at present being extended by the installation of a 11.5 MW unit which is expected to be ready for operation early in 1965, bringing the total capacity of the steam plant to 19 MW and the system to 120 MW. The steam plant is intended as a reserve, running in emergency to (partially) cover outages, and as a peaking plant. During the years 1949 to 1953 it ran for longer periods to make up deficiency of energy, but this has not been necessary since the Írafoss station came into service in 1953.

A 3.52 MW storage hydro plant located at the Andakíll River near the west coast is also connected to the Sog system via a 22 and a 66 kV line to the Ellidaár substation. This plant supplies the town of Akranes and some rural networks in the vicinity. During recent years, the demand in this area has exceeded the capacity of the Andakíll plant and the deficiency has been met by the Sog system over the interconnection.

In the Vestmanna Islands, which are linked to the Sog system via a submarine cable, there is a diesel power plant with an installed capacity of 3.93 MW.

There are other generating sets, viz a 7.5 MW diesel plant (60 cycles) at the NATO base at Keflavík International Airport, and a 1000 hp diesel-alternator at the Reykjavík Hot Water Supply pumping station at Reykir, near Reykjavík, but these are regarded as private emergency plants and unavailable for public supply. The 60 cycles plant is connected to the Sog system, via a 5.6 MW 60/50 cycles frequency converter.

Growth of maximum demand

The growth of the electrical supply system in the south west, where the installed capacity in 1952 was approximately 30 MW, is attributable to an annual increase in power consumption for general load, comprising domestic consumers, light industry and commercial premises, supplemented by the introduction of two major industries, comprising an artificial fertilizer factory near Reykjavík in 1953 and a cement factory at Akranes in 1958, and recently by power sales to the Keflavík NATO base. The relative magnitudes of the maximum non-coincident power requirements for the respective loads during 1962 on the interconnected system were as follows:-

General load	-	66.3 MW
Fertilizer factory	-	19.2 MW
Cement factory	-	4 MW
NATO base	-	5.6 MW

Although the fertilizer factory takes about 19 MW at full load only 3.1 MW is firm power to which figure the load can be reduced at any time at short notice to enable the general load to be met. The loads of the cement factory and the NATO base are both much smaller and load shedding is not applied to them. This arrangement has allowed the supply system to be operated without the usual margin of spare plant and to run at an extremely high load factor of the order of 66 per cent. The plant and the 138 kV transmission line have proved very reliable.

The forecast of maximum demand from 1963 to 1970, shown on Plate 3, is based on the forecast of energy requirements, shown on Plate 4 and discussed later, by application of estimated load and diversity factors for the various types of load. Also shown on Plate 3 is the installed system capacity including the frequency converter at the NATO base (through which power from the diesel plant can be delivered to the system). The system capacity allowing for outage of the largest generating unit (15.5 MW in the Írafoss plant) is also shown. An additional 8.5 MW unit for peak load duty will probably be installed at the Ljósafoss station in due course to bring the Sog plants to an ultimate capacity of 96 MW, but a final decision on when the installation will be made has not been taken.

Energy requirements

Plate 4 shows the energy generated in GWh (Gigawatthour = 1 million kilowatthours) per annum in the south western region for the years 1952 to 1962 and the Authority's estimated requirements up to 1970. The estimate has been based on the general load plus the cement factory load, the expected growth of power sales to the NATO base, and certain uncommitted extensions of the fertilizer factory. The possible introduction of new power-consuming industries has not been allowed for.

In the years 1952 and 1953 significant energy had to be produced from fuel to meet requirements beyond what the Sog and other hydro stations generated with the then installed plant. Since the Írafoss plant came into service in late 1953 base-load operation of thermal plant has not been necessary, but the supply of off-peak energy to the fertilizer factory has varied somewhat from year to year. The energy forecast allows for practically all the energy requirements of the factory to be met in the future, i.e. load shedding will not be resorted to except in an emergency.

It is estimated that the flow available in the Sog River under average hydrological conditions will permit the annual generation of 595 GWh and some 25 GWh can be obtained from other hydro stations. Under such conditions however spillage of water will be inevitable for some years to come due to seasonal and daily fluctuations of load. Once the reservoirs have been filled, water will have to be spilled during the periods when electrical demand is less than sufficient to require all the flow. Thus hydro-electric generation might be limited to 550 to 570 GWh for the next few years.

In a dry year, probably occurring once every twenty years on average, the output of the Sog will drop to 480 GWh and other hydro stations to 20 GWh. Practically the whole of this energy will be utilizable after a few years.

Need for additional generating capacity

The coming into service of the third 15.5 MW unit at Írafoss and the 11.5 MW unit at Ellidaár will allow the expected maximum demand to be met up to 1966 but in 1967 the margin of installed capacity over expected demand is very small and it would therefore be prudent to plan for an extension to generating capacity to be available for the winter of 1966/67. It is also apparent from consideration of energy requirements that the new plant should preferably be suited to base-load operation. This is because after about 1966 the energy requirements exceed the available hydro output in a normal year. Fuel-fired plant, whilst meeting the kilowatt demand at a moderate price, would be uneconomic for base-load duty. Both the requirements could be met by a geothermal plant of 15 MW minimum nett output coming into service in late 1966. This plant running on base load (8000 h per annum) is assumed to be capable of producing about 120 GWh sent out annually which enables energy requirements to be met up to 1967 in a dry year and up to 1970 in a normal year.

Although there is still a very large untapped hydro-electric potential in Iceland, any new hydraulic station will be somewhat more remote from Reykjavík than Sog. A new transmission line must also be provided. Such development is best undertaken on a large scale to keep down the cost per kilowatt. The initial expenditure is therefore high. A geothermal plant offers a prima facie case for consideration to meet the temporary need until the time comes to develop a large block of hydro power. It can be built on a small scale and entails lower transmission costs than an alternative hydraulic station. This proposal will now be studied in detail.

TABLE 1

PLANT INSTALLED ON SOUTH WEST ICELAND INTERCONNECTED NETWORK

Plant	Type	Date of installation	Units	Total rating, MW
Ljósafoss	Hydro	1937-44	3	14.6 +
Írafoss	Hydro	1953	2	31.0 +
Steingrímsstöd	Hydro	1929-60	2	26.4 +
Ellidaár	Hydro	1921-33	4	3.16
Ellidaár	Steam	1948	1	7.5
Andakíll	Hydro	1947	2	3.52
Vestmanna Islands	Diesel	1949-61	4	3.93
*Ólafsvík	Diesel	1960-62	2	1.20
*Rjúkandi	Hydro	1954	1	0.84
*Stykkishólmur	Diesel	1946-62	3	0.68
Vík í Mýrdal	Diesel	1960-61	2	0.17
				93.00
Scheduled extensions:				
Írafoss	Hydro	End of 1963	1	15.5+
Ellidaár	Steam	Early 1965	1	11.5
				120.0
Ljósafoss	Hydro	Undecided	1	8.5+
				128.5
+ Load transmitted over Sog line, allowing 6 MW local load				90

* Not yet connected into the main system.

SECTION 2

GEOTHERMAL POWER POSSIBILITIES

Status of geothermal power development elsewhere

The feasibility of making use of natural steam for power production has already been demonstrated in various parts of the world. The following power stations are in operation or in development:-

Plant	Country	MW installed	Commissioning date
Larderello (several stations)	Italy	335	Pre 1939 and 1949-1959
Wairakei 'A'	New Zealand	102	1958-1962
Wairakei 'B'	New Zealand	90	1962-1963
"The Geysers"	California	12.5 12.5	1960 1963
Casa Diablo	California	15.0	Scheduled 1964

USSR developments are not included above although it has been reported that a 5 MW experimental plant is being built in the Pauzhetka River valley in Kamchatka and a similar station is planned in the northern Caucasus.

Larderello is clearly a very profitable investment and in New Zealand geothermal power is a success. Geothermal power there appears competitive in cost with that of hydraulic power though there is some difficulty about applying normal economic comparisons to an asset (the steamfield) whose life is not readily ascertainable. Minor turbine troubles have occurred at Wairakei but these are not related to geothermal steam but to basic turbine design.

In Iceland natural hot water obtained by drilling has been transmitted some 15 km and used for heating about half of the buildings in Reykjavík since 1943. Extensions to the heating scheme are now in hand using hot water from wells recently drilled in Reykjavík but no geothermal power has yet been developed. This has not been of interest hitherto because it has been more convenient to utilize the abundant hydraulic power.

In all of the regions mentioned there were originally natural emanations in the form of hot springs, steam vents or geysers. Steam for power has been obtained by the drilling of wells employing the same type of tackle and technique as for oil well drilling. It appears that the steam or hot water is confined by some sort of quasi-impervious barrier somewhat analogous to a cap formation. The steam conditions in the different countries vary - Larderello has slightly superheated steam in most of the field. The pressure there is of the order of 7 kg/cm^2 gauge at the well giving a working pressure at the station of about 4 kg/cm^2 gauge. At "The Geysers" the pressures are somewhat higher, the steam being also superheated. Wairakei on the other hand has much higher pressure, e.g. 14 kg/cm^2 gauge in deep wells but the steam is very wet with a ratio of water to steam of the order of 6 to 1 down to 3 to 1. At Wairakei the water is separated from the steam at the wellhead and initially only the separated steam was fed to the turbines, the boiling water being discarded. Extensions of the plant now rely partly on lower pressure steam produced by flashing of the hot water.

The Iceland conditions seem to resemble those of Wairakei in that the steam is associated with several times its weight of boiling water but the pressure is lower. The pressure in a field depends mainly on the artesian head and the depth of the yielding stratum. The yield is probably dependent on the 'openness' of this formation in which water circulates and is raised to boiling point by some means not yet thoroughly understood.

All geothermal steam contains an admixture of gases of which the two preponderant ones are carbon dioxide and hydrogen sulphide, both of which are potentially corrosive to common metals such as iron and copper. The gas content results in the condenser gas extraction equipment being much larger in geothermal stations than in orthodox plants using pure steam. At Larderello there is also hydroboric acid which is not found elsewhere. Originally it was the boric products which were the reason for the development and as a consequence the earlier power plants work on the so-called 'indirect' system whereby the raw steam is caused to condense in heat exchangers by evaporating off fairly pure steam from the condensate. The gases are blown off to atmosphere and the boric acid recovered from the enriched blowdown. For power production the 'indirect' process is no longer of interest unless the gas content is extremely high because of the sacrifice in output entailed in heat exchange and the high cost of the exchangers. Moreover though the corrosion problem in the turbines is avoided (where it is no longer however regarded as insuperable) it is transferred to the heat exchangers.

A necessary stage in development of geothermal power is the accumulation of sufficient knowledge of prospecting, drilling and measuring techniques to suit the local conditions. In Iceland because of general interest in geothermal possibilities geothermal areas have already been explored and heat flow measurements made over many years. Also drilling has been going on for some considerable time with the result that the technique is established. Thus the initial phases in familiarization and in prospecting may be shortened by virtue of experience already acquired.

Proposed method of utilizing steam in Iceland

The bores so far drilled in Iceland have yielded either hot water or a mixture of boiling water and steam. A yielding bore is generally referred to as a 'well'. The steam no doubt originates from flashing of the water as it comes up the pipe implying that the source is hot water at depth. Accordingly the same techniques as have proved successful in New Zealand can be applied. At each well the discharge will be put through a separator designed on cyclone principles. The steam separated will be reasonably dry (possibly 0.5 per cent water or less) and this steam will be piped to the station and used in condensing turbines. Initially it is proposed to reject the boiling water though at a later date, if the station is extended, the water might also be piped to the station to be flashed in flash tanks so as to produce additional steam at about atmospheric pressure. This steam could be used in separate low pressure condensing turbines but the most convenient arrangement will probably consist of dual pressure "pass-in" turbines operating partly on live steam and partly on flash steam, as has been done at Wairakei 'B' station.

Any wells showing too low a pressure for operating in parallel at live steam pressure could at this later stage also be coupled in on a pipe system operating at about atmospheric pressure if this were found economically worth while. The techniques to be relied on at the initial stage are already well established, some of the plant at Wairakei having already been in service for over 5 years. Experience from New Zealand confirms that from Larderello and shows that mild steel in casings and pipes is satisfactory for use in geothermal steam and does not show severe corrosion. Mild steel separators can also be regarded as having an excellent record, no corrosion trouble having been encountered. Erosion by rock particles can occur in some wells during initial stages but is avoidable by suitable techniques. Certain precautions have to be taken in selecting the types of valves and the metals used in valve trim and in such equipment as traps used for draining the transmission pipes at intervals. At the station the steam will be put through a second separator to remove most of any remaining water, both the bore water which passed the wellhead separator and any additional condensation resulting from heat loss from the pipes. The dilution of the bore water with condensate is advantageous as lowering the chemical content of any residual water remaining after the second stage of separation. Even a very small percentage of water entering with the steam could produce sufficient deposits to interfere with turbine operation in a matter of months because of the very high throughput of steam.

Analyses of the steam and water have shown these to contain the usual chemicals but in lower concentration than elsewhere. Deposit and corrosion aspects are dealt with more fully in Appendix 1 on page A1.

Potentialities of the Hveragerdi region

Exploratory drilling has been conducted by the State Electricity Authority at two sites, namely Krysuvik some 30 km SSW of Reykjavík, and near Hveragerdi some 45 km ESE. Three steam wells were drilled at Krysuvik to depths of 350 to 1274 metres in 1960 but none showed a satisfactory yield. It was then decided to concentrate on Hveragerdi. This is an active geothermal area forming the southern fringe of a large geothermal region known as the Hengill area some 50 km^2 in extent. It reaches into high inaccessible ground further to the north. The heat yield from the whole region has been assessed by Gunnar Bödvarsson as within the limits of 25,000 to 125,000 kcal/sec. This is equivalent to a heat release of the order of 100 to 500 MW.

The area where the drilling has taken place is on a fairly level terrace bounded by geothermal altered rising ground with many natural steam vents immediately to the north and a geyser a little to the south. Lower down in the village of Hveragerdi there are many shallow steam wells drilled for dwelling house and glasshouse heating.

The bores so far drilled for power purposes are located as shown on Plate 5. Depths vary between 295 and 1200 metres as shown in Table 2. Maximum temperatures of 216°C have been encountered at about 400 metres in No. 3 and 226°C in No. 7 at a similar depth. Yielding horizons lie at various depths down to 640 metres for No. 6. All of the bores have an inner casing of 9⅝ inch nominal (outside) diameter and are continued into the rock at 8¾ inch diameter. The underlying ground below a sedimentary surface layer consists of tuffs and lavas and in view of their solid nature it is not necessary to case to great depth.

Table 2 also shows the yield of six of the wells (No. 5 is regarded as a reference bore to be used for monitoring temperature in the steam field and No. 1 is not included as it had to be abandoned). The satisfactory yielders are wells 2,3,6,7 and 8 and their characteristics are shown in Plate 6. The yields are of very wet steam with a ratio of steam to water in the region of 1 to 4 by weight. The closed valve pressures are in the range 8 to 12.5 kg/cm^2 gauge. The likely working pressure is probably about 5.5 kg/cm^2 gauge at the wellhead. Analysis of the characteristics shows that if only the steam fraction is utilized, the power output is a maximum at the lowest working pressure (somewhat below 4 kg/cm^2 gauge) but a higher wellhead pressure in the region of 5 to 6 kg/cm^2 gauge yields the maximum output if the heat in the boiling water is assumed to be utilized by production of flash steam at atmospheric pressure. The five wells 2,3,6,7 and 8 together at full flow yield a potential output from condensing turbines of 29 MW using steam alone or about

40 MW if both steam and water are used. No. 4 which is a poor yielder for power purposes is being used to supply steam and hot water to local farms and would not be included in a power scheme.

Thus the intended output of 16 MW is already covered and one other well of the class of No. 3 would bring the proven steam quantity to more than twice the theoretical requirements. Some such margin, set arbitrarily, is considered necessary to allow for such eventualities as wells being out of service for maintenance or falling yields from wells.

TABLE 2

LIST OF WELLS

(all with inner casing of $9\frac{5}{8}$ inch outside diameter and drilled $8\frac{3}{4}$ inch diameter in uncased length)

Bore No.	2	3	4	5	6	7	8
Date completed	Oct. 1958	Oct. 1958			Nov. 1960	Jan. 1961	Jan. 1961
Ground level, metres above sea	62	67	69	65			
Drilled depth, m	400	652	687	1200	661	830	295
Casing depth, m	196	196	196	196			
Maximum temperature, °C	188	216		200		226	213
Yield, steam kg/sec	8.7	16.7	2.0		8.5	7.7	23
water kg/sec	90	66	43		54	46	78
Wellhead pressure, kg/cm2 gauge	5.5	5.5	4.5		5.5	5.5	5.5
Closed valve pressure, kg/cm2 gauge	8	12	5.5		10	8	12.5

Total steam proven	64.6 kg/sec (No. 4 excluded)
Equivalent power yield	29 MW
Power required	16 MW
Steam required to provide safe margin	72 kg/sec
Additional steam to be proven (say)	7.4 kg/sec

SECTION 3

DESIGN OF POWER STATION

Site selected

The site provisionally selected for the power station lies about 2 km north north west of Hveragerdi which is a village of about 600 population forming the centre of a recently developed horticultural industry based on geothermally heated glasshouses. Access is by road, there being no railways in Iceland. The region is subject to earthquakes, the probable maximum intensity of which is defined by magnitude 7 of the Modified Mercalli Scale (this corresponds to accelerations of 80 cm/sec^2). The land is not agricultural and is owned by the State. The location is shown on Plate 5.

According to a geological report prepared by Jón Jónsson, the site is on the youngest lava flow in the valley, the thickness of which is 3 to 5 metres. It is a rather fine grained basalt lava with few and small phenocrysts of plagioclase resting on a bed of gravel of unknown thickness but which is 3 to 4 metres where it crops out farther south at the River Varmá. It is thought to be thinner than this at the site. The gravel bed rests on another lava flow which is basalt, very rich in phenocrysts of plagioclase and with some olivine. This flow seems to be some 4 to 6 metres thick or possibly greater and very likely rests on a third flow of basalt lava.

It is stated that the strata will form an extremely stable foundation for the proposed power station.

The general nature of the sub-strata is known from holes drilled on the site and well borings nearby. Trials have not been made to determine the load bearing characteristics but no difficulty is expected to arise. The load imposed on the foundation area by the power station building, if regarded as uniformly distributed over the main slab, will be of the order of $\frac{3}{4}$ ton/ft^2 (8 ton/m^2). The main slab will be a minimum of $\frac{1}{3}$ metre thick with local deeper excavations for the main columns and foundation block which may be contiguous.

The site lies about 400 m west of the Varmá River, a small stream subject to considerable variation of flow and not offering sufficient advantage to be worth making use of for cooling water. The area between the site and the river is suitable for a spray pond which can be constructed by bulldozing off top soil and loose lava to a suitable depth. The ground contours provide natural elevation of the power station building over the spray pond with desirable saving in height of building for a scheme employing the orthodox type of jet condenser positioned immediately beneath the turbine.

It is centrally situated with respect to the latest wells drilled, 6, 7 and 8, and to the steamfield generally.

Accordingly we have based our estimates on the assumption that development will proceed on the site selected and we have made provision for the possibility of having to transmit steam some hundreds of metres from possible future wells somewhat to the north.

Cooling water supplies

A steam turbine using saturated steam at about 4 kg/cm^2 gauge inlet pressure with 0.07 kg/cm^2 abs back pressure (2 inch Hg) will reject to the exhaust approximately 1.07 kcal per kW second. Thus a station containing 16 MW of plant will reject about 17,000 kcal/sec and will require in rough terms $1\frac{1}{2}$ ton/sec of cooling water with 12°C rise.

The choice of cooling lies between natural draught cooling towers, mechanical draught cooling towers, or sprays. In the present case sprays seem to be the most suitable. The pumping loss for sprays would be no higher than with cooling towers and no fan power is required. Moreover the estimated project investment at about £82,000 for the pond, sprays, pipework and make-up supply compares with say £87,000 for a mechanical draught cooling tower with ancillary equipment or £106,000 for a natural draught cooling tower. The reduction in cost together with the saving in fan power (capitalized value about £20,000) is sufficient to outweigh the defect that the performance of a spray pond, being somewhat variable and dependent on the direction and strength of the wind, is not as calculable or as consistent as that of a cooling tower. Sprays have additional advantages in simplicity of construction, the small amount of equipment to be purchased abroad, and in freedom from freezing difficulties. The system would be self-draining and could be brought into service immediately by starting the booster pump without risk of being frozen up. The main spray pipes might be of concrete and the smaller ones of asbestos cement, to save freight on cast iron, and would be supported on precast concrete posts. The equipment is virtually immune from damage or outage through ice building whereas cooling towers would require exercise of special care and precautions in a cold climate.

A preliminary survey of the site area carried out by Sigurdar Thoroddsen has revealed that a shallow basin can be formed by bulldozing away 1 to 2 metres of top soil and loose lava. Sealing of the bottom and sides can be effected with clay available in the vicinity. The depth is unimportant but about 1 to 1½ metres would be reasonable. Water to be circulated is 20,000 Imperial gal/min = 1520 litre/sec. A pond some 15,000 m^2 in area will be needed for the initial installation of one 16 MW set (possible extension to 25,000 m^2 is kept in mind in case of installation of a second 16 MW set).

Seepage from the pond should be kept reasonably low as the loss from the spray system arising from evaporation and drift loss might average about 2½ per cent of the water quantity in circulation. This loss, amounting to 38 litre/sec, is almost made up by the exhaust steam condensed, which at full load is 36 litre/sec including an allowance for steam jet ejectors. The deficiency can be made up by diverting a supply from the Reykjadalsá River. This involves building a small intake dam at a point west of Well No. 8 and laying about a 6 inch bore pipe over a distance of about 500 metres to the pond. The pipe capacity would be about 30 litre/sec which is amply sufficient to cover high drift losses under prolonged abnormal wind conditions. Freezing of the spray pond is not a problem as the temperature will be well above 0°C at normal load. In emergency caused by freezing of the make-up supply, water might be pumped from the Varmá by fire pumps.

Layout

Plate 7 shows a site plan and Plate 8 a preliminary layout of the power station on the site discussed above. The initial installation is a single 16 MW turbo-alternator set. Further development on the same general lines is allowed for except that the extension is envisaged as employing a pass-in machine to make use of the flash steam produced from hot water yielded by the wells. The flash plant would probably be located out-of-doors near the station.

An in-situ reinforced concrete structure is proposed in the power station building design prepared by the civil consulting engineer, Sigurdar Thoroddsen of Reykjavik. With the exception of perhaps a few weeks in mid winter, construction work can generally be carried on at the site throughout the year. Lengthy delays in the building programme due to adverse weather conditions are unlikely to occur and therefore in this respect precast construction has no special merit. The building would be monolithic with the basement slab as well as the machine foundation and the design would take into account horizontal forces arising from seismic accelerations up to 0.1g. Prestressed concrete panels are proposed for the roof and heat insulation is by precast lightweight pumice concrete slabs.

The station is placed on a flat rock shelf to take advantage of the natural elevation above the spray pond, the precise location chosen being a compromise to suit the lie of the ground, in particular the average gradient between the station and the pond, and general access.

The main axis of the station is shown in an approximate north/south direction with future expansion taking place to the north. Basement level is at 78.5 metres, the present general level of the ground in the area, and the operating floor is 11.2 metres above basement at 89.7 metres. This height of operating floor is necessary as mentioned later in order to provide sufficient height for the barometric leg of the condenser above the level of the spray pond which we have taken to be 74.5 metres. The machine, which is 14.2 metres in overall length, is placed longitudinally in the turbine house with the turbine end towards the loading bay. The generator is adjacent to the generator transformer and 138 kV switchgear compound at the south end of the station. The 10.5 kV connections would go straight out from the generator circuit breaker, housed in the turbine foundation block at basement level, to the generator transformer.

Access for heavy loads is through the workshop. This has the advantage that plant can be transferred from the turbine room to the workshop without passing out-of-doors. During the early stages of the construction period, equipment awaiting erection can be stored in the workshop as workshop facilities will not then be required. We visualize that, later on, field equipment such as drill rods, valves, pumps and even vehicles can normally be stored under cover in the space allocated for loading bay and workshop, though it will of course be necessary to move such equipment out of the way when carrying out a turbine overhaul, since a clear loading bay will be required for setting down major turbine components.

The control room is at operating floor level with a glass division wall so that the control room staff, while insulated from the turbine house noise, will have an over-sight of the machine. Space for a cable chamber is provided below the control room. The main entrance to the power station building is on the west side adjacent to the workshop.

The space in the turbine room below operating floor is used for housing 400 V switchgear, carbon dioxide fire-fighting equipment, station battery, offices and stores. Office accommodation and store rooms are provided at two levels and space is allocated for a mess room and other welfare facilities.

Turbine inlet pressure

The turbine inlet pressure is arrived at by compromise between several factors of which the most important are on the one hand the characteristics of the wells, and the pressure drop to be allowed in transmission to the station, and on the other the variation of turbine steam rate with pressure as illustrated in Plate 9. As mentioned earlier the wells show a maximum power output on live steam alone at a pressure somewhat below 4 kg/cm^2 gauge at the wellhead. If, however, flash steam is to be made use of, the wellhead pressure for maximum output rises to 5-6 kg/cm^2. We are of the opinion that no great reliance is to be placed on extrapolation of the measurements below say 4 kg/cm^2. Hence we disregard the apparent advantage of lower pressure. A pressure about 5.5 kg/cm^2 at the wellhead will allow for say 4-4.5 kg/cm^2 at the station and this is a convenient range for the turbine design. A higher pressure would entail too high a wetness at the exhaust and a lower one is inconvenient for use of steam jet ejectors. Hence we propose that the station should be designed for a turbine inlet pressure of 4 kg/cm^2 gauge and that initially provision should be made for using only the steam fraction of the well discharges. We consider that a design based on this concept will enable the station to be commissioned within the required time whereas the use of flash steam would introduce delay and some measure of uncertainty in performance. Hence we recommend that development of power from the water phase be deferred to a possible future extension of plant, by which time substantial operational experience on pilot flash steam plant at Wairakei 'B' will be available and proven techniques could be designed into the plant for Hveragerdi.

The steam rate expected for the inlet conditions of 4 kg/cm^2 gauge 151.5°C with 1% moisture present and a back pressure of 0.07 kg/cm^2 abs is 7.8 kg/kWh. This does not include the steam required for jet ejectors which we put at about 1 kg/sec.

Design of turbine

For the size selected of 16 MW and an inlet pressure of 4 kg/cm^2 single cylinder double flow machines are preferred as avoiding a gland at the inlet and providing internal steam thrust balance. An overload valve is not required, rated output being the normal running condition. Control to lower loads is by throttling.

The area of exhaust assumed is approximately 2 x 1.8 m^2. The calculated exhaust wetness at a back pressure of 0.07 kg/cm^2 abs is 14 per cent which is about the recommended limit. This assumes that the steam contains 1 per cent moisture at turbine inlet and follows convention in making no allowance for removal of water at any interstage drains provided in the cylinder casing. The efficacy of such arrangements is difficult to assess but we think in fact the exhaust wetness will be less than the calculated 14 per cent, possibly by as much as 2 points. The maximum blade tip speed has been specified not to exceed 900 ft/sec (273 m/sec). At least one tender has been received complying with requirements. The limit on tip speed is partly to avoid erosion and partly to ensure that the machine should be designed for a low stress level. The materials of construction are quite ordinary, viz rotor of low alloy steel (1 per cent nickel 0.7 per cent chrome), casings of cast iron and blading of 12 to 14 per cent chrome stainless iron in the fully annealed condition. A drum rotor with reaction construction is preferred (other things being equal) as utilizing rather low stresses and exposing less surface of rotor to corrosive action of the steam. Certain precautions such as avoidance of brazing and of martensitic steel and omission of erosion shields on the blades have to be taken but otherwise the turbines follow orthodox techniques. Evidence elsewhere has shown that this procedure is sound and no large amounts of corrosion resistant steel need be employed. Some erosion of blades and other parts has to be accepted but is considered less dangerous than the risk of cracking which provision of erosion shields or blade hardening would entail. Erosion has not been found to be excessive in other plants. Further important precautions are the exclusion of steam from standing plant and the rapid drying out by circulation of hot air after shut-down. If these precautions are not taken serious standby corrosion is liable to occur through presence of hydrogen sulphide in company with oxygen.

Arrangement of condenser

For geothermal plants only the jet condenser need be considered since it has the advantages of cheapness, freedom from fouling, and much lower corrosion risk than the surface condenser which is used in plants equipped with boilers primarily because the condensate must be recovered. Jet condensers are built in two forms, namely the high level type with barometric seal and the low level type with extraction pumps. The high level barometric type requires the turbine to be set above the cooling water level by something like 15 metres and hence entails a more expensive turbine foundation and power station building. On the other hand the low level condenser requires extraction pumps to handle the full circulating water quantity against full vacuum. The pumps would require to be set some 9 metres below the condenser in order to limit risk of cavitation. They would also be subject in the present instance to risk of corrosion because the condensate would contain corrosive gases. Because of this and the reputation that low level condensers have of being temperamental even in the smaller sizes where they are used, we have decided against that type.

A further possibility was considered, namely the use of outdoor barometric condensers as at "The Geysers" geothermal station in California and Lago Station at Larderello. That layout allows of setting the turbine about 5 metres lower than when the condensers are placed immediately under the turbine as in previous geothermal stations at Larderello and Wairakei. Some saving on building cost is thereby achieved which may be attractive in the Californian plant which operates with rather high back pressure and is not subject to freezing. In Icelandic conditions we consider an outdoor arrangement less desirable because of the risk of corrosion in the long exhaust duct and of ice building up within the vapour extraction pipes especially in light load conditions. It is supposed that the reason why it is possible to use geothermal steam without incurring severe corrosion of mild steel is that the film of FeS is ordinarily adherent and protective. Below a temperature of about 30°C however it seems that a different corrosion product is formed and this is not protective. Hence low outdoor and vacuum temperatures entail added risk of corrosion. Also we consider that internal corrosion might be serious in the long exhaust duct due to the presence of air with H_2S in the exhaust steam. (Small quantities of air will almost inevitably leak through the subatmospheric joints of a turbine). Thus the use of special steels or other expensive protection against corrosion becomes necessary. The exhaust duct for "The Geysers" plant is made of Type 304 stainless steel (18 per cent chromium 8 per cent nickel class).

One further objection to the outdoor arrangement is that water precipitated from the exhaust steam must be removed and this requires the use of an extraction pump or ejector which constitutes a small additional complication better avoided in the plant.

In "The Geysers" plant advantage is also claimed for the use of a contra-flow condenser. We have looked into this but while there is a theoretical advantage, it does not in practice seem to amount to anything very significant and is insufficient to offset the disadvantage of the longer exhaust duct entailed.

Manufacturers were invited to tender for turbo-alternator plant with conventional or outdoor jet condensers and the bid received from the preferred tenderer showed that the extra cost of the outdoor arrangement, with an exhaust duct of mild steel, would be about £20,000 FOB. The corresponding net extra project investment for the plant would be approximately £38,000. The saving on building costs for the turbine house is estimated to be only £22,000. Moreover additional annexe space would have to be provided to house some of the equipment located in the turbine house in the orthodox scheme which would further increase the cost differential in favour of the orthodox scheme.

Thus after full consideration of the alternatives we have come down strongly in favour of the orthodox arrangement with the jet condenser immediately below the turbine. Because advantage can be taken of the favourable lie of the ground the power station basement is not unduly high and a reasonably high basement has advantages in facilitating accommodation of pipes and equipment and obtaining flexibility in pipe layout.

Selection of design back pressure

The appropriate back pressure has to be arrived at by compromise between several factors. In the first place it is clear that the inlet circulating water temperature and the rise allowed (which is dictated by the quantity circulated) fix the lowest vacuum temperature. In practice there is also to be allowed a 'depression' between the vacuum temperature and the circulating water outlet temperature. This is dependent on the amount of gas and on the design of the condenser.

If the vacuum temperature can be lowered the turbine can generate more power with a given quantity of steam, but against this must be offset the extra power taken by the circulating water pumps (if the gain is obtained by circulating more water) and there must also be a deduction for the extra power taken by the gas ejectors. Until the gas content of the steam is established with greater certainty the effect of gas extraction power cannot be properly settled. The gas contents so far measured are low but other wells could produce different values and gas content may increase with time.

It should also be mentioned that for a given potential gain in output by lowering of vacuum temperature, the real gain may be significantly reduced by leaving and hood loss and if the leaving loss is to be kept down, a larger last row annulus must be adopted. This will not only result in an increase of turbine price but will also most probably involve a higher tip speed bringing with it higher blade stressing and greater proneness to erosion and fatigue trouble. As mentioned earlier we put an arbitrary limit on tip speed of 900 ft/sec (273 m/sec) but an even lower value might well be advantageous for the sake of ensuring greater reliability.

In view of these many variables and some uncertainties it is thought that it is unwise to strive for too low a back pressure and better to compromise on a moderate figure of the order of 2 inch Hg (0.07 kg/cm^2) abs such as will apply with recooled water under average conditions and this will lead to a cheaper and more robust turbine and in the output being less sensitive to cooling water inlet temperature.

<u>Gas extractors</u>

Gas content of the steam as so far measured is about 0.1 per cent by weight. This is very low compared with geothermal steam elsewhere, the average figure at Wairakei being some 5 times higher and at Larderello 50 times higher. However, it is necessary to pump out of the condensers not only the gas but also the air which comes in dissolved in the circulating water, air which leaks into the turbine, and also some amount of associated water vapour. Some gas, mainly CO_2, is dissolved in the outlet water. Hence the total quantity of incondensables has to be fixed somewhat arbitrarily. The total quantity is still likely to be vastly higher than that in normal condensing steam turbine plant and hence it is more important than usual to consider means of reducing the power taken by the gas exhausters.

Several methods are available differing in cost, efficiency, and reliability. Of these qualities we attach most importance to reliability. The most efficient method is the mechanical compressor but this is also the dearest amd most liable to give trouble and we do not consider the saving in power in the present instance to be enough to justify risk of outage and high maintenance expenditure. Hence we have restricted the choice to the water jet and steam jet ejectors. In principle the water jet is slightly more efficient and in suitable cases the least complicated. However it is not as familiar to some manufacturers as the steam jet ejector. The water jet ejector consumes electric power to drive its pump and this power has to be generated. This power costs more than the equivalent amount of steam and according to preliminary estimates the installation costs of water ejectors are higher than for the steam alternative.

On the other hand the steam jet ejector has certain drawbacks: at the proposed steam pressure at the power station of 4 kg/cm^2 it is operating near to the minimum pressure for two stages. Hence the steam jet is rather vulnerable to possible fall in steam pressure of the wells which cannot be ruled out until there is more experience of the field. A three stage ejector could be used but with additional complication and cost.

The inter-condensers would be of the spray type with separate barometric pipe. There is a corrosion problem in all such parts where air and gas occur together but this is not to be regarded as desperately acute. An after-condenser is not essential if it can be accepted that the gases together with something like 2 tons of steam per hour can be blown to atmosphere. If this quantity of steam is regarded as objectionable then it must be condensed in some form of after-condenser, and because of the corrosion risk it would probably be best to make the exhaust pipe in non-metallic composition such as glass fibre and construct a rough spray chamber over the cooling water outlet channel to act as an after-condenser.

The best combination may well be a steam jet first stage followed by a water jet second stage. All difficulty about disposing of the corrosive gases is thus avoided. The second stage would be housed in the circulating water pump-house. The only drawback is a rather lengthy intermediate vacuum pipe.

There is also a possibility of using the available boiling water to actuate the ejectors but this idea is still in the development stage requiring some additional trials before it could be utilized.

It is worth mentioning that consideration has been given to utilizing the heat in the ejector exhausts for space heating in the station. Unfortunately this is not practicable because of the highly corrosive mixture of H_2S,

CO_2, air and steam which has to be disposed of. Live steam is therefore a better proposition - or hot water which is abundant.

Circulating water system

The main circulating water pump and booster pump are accommodated in a detached unattended pumphouse at the spray pond. The pumphouse is 6½ m x 14 m by 6 m high and a loading bay is provided at the south end. A 5-ton runway will handle equipment during installation and maintenance. The pumps proposed are of the horizontal spindle type and priming of both is effected by the main ejectors sucking through the condenser and circulating water delivery pipe (and use of a balance snifter connection). Duplicate pumps are not considered necessary. Neither non-return nor isolating valves are required at the initial stage but provision is made for inserting an isolating valve in the CW delivery pipe if and when a second stage is proceeded with. Interconnection of the two CW delivery pipes would then enable either condenser to be supplied separately from either CW pump. Simple rack screens at the CW pump inlet will suffice to prevent any trash from entering the system. Self-cleaning screens are not justified in the absence of leaves and vegetable matter with jet condensers having sizeable nozzles. Trouble with growth of vegetation is thought unlikely. A fine strainer is provided for each auxiliary cooling water service, such as the oil coolers and the alternator air coolers, where tubular heat exchangers are used.

The circulating water pump will deliver 20,000

Imperial gal/min (1520 litre/sec) against a net head of 46 ft (14 metres). The motor rating will be about 260 kW assuming an overall efficiency of 80 per cent for pump and motor.

Circulating water will be delivered to the turbine room in a single steel pipe, about 90 cm in diameter laid approximately at ground level, except in vicinity of the turbine house where it is elevated so as not to restrict access in the area reserved for steam pipes. Semi-flexible joints will be used.

Water sprayed through jets into the condenser will descend the barometric tube into the sump and return along the channel to the booster pump suction bay which is connected to the pond by an overflow pipe to control the level in the channel. Gases released from the water in the sump and culvert will be prevented from entering the turbine room by a water seal where the barometric tube passes through the floor. The gases will be vented from the sump along the culvert, which will be sealed in the vicinity of the building, and emerge clear of the station. All water drains in the turbine room will be piped to the sump. The object of these measures is to prevent risk to personnel or corrosive attack of components in the turbine room which might occur if local concentrations of H_2S were allowed to build up.

The booster pump will deliver 20,000 Imperial gal/min against a net head of 41 ft (12.5 m). The motor rating will be 235 kW. The pump draws warm water from the forebay and delivers to the sprays. The two pumps might well be identical and could be driven by a single 500 kW motor.

Wells

The present wells drilled primarily for prospecting are all provided with an inner casing of $9\frac{5}{8}$ inch outside diameter. It is usual to fit a master valve on top of the wellhead and the bore of this is the same as that of the casing though it might with advantage be larger. Immediately above the master valve a full bore tee off is necessary. This allows of quenching a well by pumping in cold water or of discharging steam clear of the rig when for instance it is necessary to service a well subsequent to drilling.

Discharge characteristics of the wells have so far been obtained by throttling at the master valve and measuring the discharges of water and steam separately at atmospheric pressure. The yield of flash steam is deduced from that of boiling water and subtracted from the total steam yield to give the yield at wellhead pressure. The characteristics obtained by this indirect method seem to indicate that at least two wells, Nos. 3 and 8, when running at the lowest pressure end of their characteristics (where the power output is the maximum) must be discharging at a velocity approaching sonic velocity in the wet mixture. This does not seem to be advisable as it implies very high pressure drops involving local high stresses and possible risk of erosion. It also seems to indicate that the discharge of the well is being limited by the outlet conditions and hence a larger output could apparently be obtained if the diameter in the upper 20 metres or so were enlarged. Hence for any future production wells it would seem worth while to adopt a larger diameter of inner casing for say the first 20 metres even though the well is continued with $9\frac{5}{8}$ inch casing to normal depth and with $8\frac{3}{4}$ inch in the rock as before. The expectation is that this will result in an augmented discharge for the same wellhead pressure and at little increased cost for the well. Alternatively on the same discharge the velocity will be reduced in the critical part. This seems worth while even though it entails a departure from the standard diameters adopted and hence interferes with interchangeability of valves, pipes, etc.

On the existing wells it would be possible to limit the effects of sonic velocity by fitting a divergent adapter between the master valve and the separator so that the velocity within the separator would be reduced to the order of 150 ft/sec (45.7 m/sec) at which we have satisfactory test data. However, in order to keep the size and weight of separator manageable, and for the purpose of interchangeability, it seems that the inlet branch diameter should not exceed 12 inch. Hence for Nos. 3 and 8 wells two such separators might be required in parallel entailing a bifurcation in the pipe.

The steam yields of the five wells at present available for power production are given below.

STEAM YIELD AT 5.5 kg/cm^2 gauge

Well No.		kg/sec
2		8.7
3		16.7
6		8.5
7		7.7
8		23.0
	Total	64.6

Steam required for 16 MW	36 kg/sec
Total steam required to provide safe margin	72 kg/sec

Well 2 is approximately 1500 metres from the proposed station site, roughly twice the distance of any other well. Transmitting the steam from this well would be relatively costly hence we ignore it in anticipation of further successful drilling nearer the station. The four remaining wells yield about 56 kg/sec. The nominal steam requirement for 16 MW gross electrical output is 36 kg/sec, including 1 kg/sec for ejectors. Hence to cover the nominal requirement by 100 per cent margin an additional 16 kg/sec of steam must be proven. One further well drilled up the valley might reasonably be expected to suffice in the light of the success attained in the drilling of No. 8.

A total of five operational wells is the minimum on which full output could be guaranteed. This will allow the best well, at present No. 8, to be shut down for maintenance, and the four remaining wells with a combined yield of say 49 kg/sec will cover the station output. There would normally be sufficient margin to permit either Well 6 or Well 7 to be off for maintenance at the same time as Well 8, or alternatively on standby duty. Calciting encountered earlier on Well 2 is reported as not serious on Wells 3,6,7 and 8. They were blown at 3 to 5 kg/cm^2 gauge for about four months during 1961 and for a further period of six months from November 1962 to May 1963. A fall off of 0.5 to 1 kg/cm^2 occurred on Wells 6 and 7 during the first week but thereafter no significant change in pressure was detected. Well No. 8 is particularly free of calciting.

It is to be noted that the small number of wells (possibly four) required to supply the power station will result in necessity for some throttling of yield at times to enable the output of the wells to fit the turbine demand. Only in this way will it be possible to avoid blowing off large quantities of excess steam at the station, the range of variation of yield by making use of the natural characteristics of the wells, that is by throttling at the station, being limited to about 10 per cent. Some additional range of control is also available by varying the vacuum.

In order to keep down the cost of pipes and also roads to wells, and to ensure a high proportion of good yielders it seems very desirable to drill duplicate wells close to existing ones. In general these will not be utilized at full output simultaneously, one of each pair being normally held in reserve or undergoing cleaning out.

Separators

The first full-scale wellhead separator to be used in Iceland has recently been tried out at Hveragerdi. Hitherto the indirect method of measuring the well characteristics has avoided their use. It is desirable that this separator working at wellhead pressure should be experimented with since this will clear up a number of uncertainties and provide further important experience. Some development work is advisable on this in advance of the power station project since it is necessary to be certain that in extrapolating experience from New Zealand the expected separator efficiency is still achieved. Desirable experience will also be obtained in dealing with the flashing hot water.

The yields of the wells vary considerably and if one standard size separator is to be used then it is probable that the high yielding wells, such as 3 and 8, will require two separators in parallel, each of the other wells having only one. If the total discharge of Well 8 were passed through the experimental separator (12 inch inlet) built by the Authority the wetness at outlet might be as high as 5 per cent, whereas $\frac{1}{2}$ per cent or less might be achieved with two in parallel, each with a steam throughput of about 11 kg/sec. It is true that most of the water carried over will be removed in a second stage of separation at the station, but one disadvantage of a high carryover is that the water reaching the station will have a high dissolved solids content. The desired dilution by condensate from heat loss, of the bore water carried into the transmission pipe, is lessened with higher carryover and there is consequently greater risk of deposits forming on the blading. A high separating efficiency at the wellhead is therefore desirable and the performance of the prototype separator is accordingly of considerable interest.

We visualize that a second stage of water separation will be carried out at the station in a vessel on the lines of that indicated in Plate 8. This also serves as a steam receiver. At the wellhead some 99 per cent of the water is to be removed but at the station 70 per cent or 80 per cent removal will be sufficient and we expect 85 may well be achieved.

Steam pipes

The site is fairly centrally situated with respect to the wells, apart from No. 2 which we have suggested should be omitted from the scheme. We propose that three transmission pipes should be used initially: one from Well 3, another from Wells 6 and 7 combined, and a third from Well 8 coupled with the additional well which has yet to be drilled. We refer to this as Well 9 and assume that it is drilled close to Well 8. There would clearly be financial and other advantages to be gained from standardizing on pipe size for the three lines. This would enable pipe supports, lagging and valves to be universal. If 18 inch bore tube is adopted throughout the velocity will be about 30 m/sec for Well 3, resulting in an acceptable pressure drop. In the line from Wells 8/9 the velocity would be 45 m/sec for a throughput of 23 kg/sec giving a correspondingly higher but still acceptable pressure drop. Nevertheless we have assumed 22 inch bore for this line for the purpose of estimating though ideas cannot be finalized until sufficient wells have been drilled. A compromise of 20 inch diameter all round is also possible.

From point of view of pipe flexibility a radial system has advantages even though two pipes may follow the same route. For a given steam quantity to be transmitted at a given pressure drop, one large pipe costs much less than two smaller pipes. However, a single large pipe would be so stiff that it would require special compensators to provide flexibility whereas it is suggested that these could be largely avoided with the smaller pipes by suitable technique. This entails selection of an indirect route and introduction of deliberate offsets to obtain flexibility. It is also to be mentioned that about 20 inch diameter is the upper limit for solid drawn tube and above that it is necessary to use lap welded tube which is of a slightly lower standard though costing about the same price per ton.

It is proposed to suspend the pipes from concrete posts with hangers so that they are at least one metre clear of the ground and thus out of the way of normal snow and flood water where appropriate. Where convenient two pipes can be suspended from one post with a double cantilever. For a single pipe two posts strapped together to form an A support will ordinarily be used. The pipe hangers will allow a fair amount of flexibility, the only firm restraints being at each wellhead and at the station. Some amount of lagging is desirable in view of the wet and windy climate and to guard against burning of animals or human beings by contact.

Proprietary precast lagging 2 inches thick of, say, calcium silicate covered with aluminium foil will cost very roughly £0.5 per metre per inch of pipe diameter. This includes fixing. Thinner insulation such as would suffice would not cost a great deal less. It should be possible to manage with something cheaper than this, for instance foamed concrete made with pumice dust in precast sections, also covered with aluminium foil, but it would be necessary to interest some local concern and possibly carry out a little development. It is improbable that pumice dust concrete moulded in situ round the pipe would work out economical, because of high labour costs in the field.

Design pressures for pipes and equipment

The highest wellhead pressure so far measured is about 12.5 kg/cm^2 gauge with closed valve. The pressure subsides to much lower values after a well has been closed in for some time. Master valves need therefore to be of at least 250 lb/in^2 (17.6 kg/cm^2) class (steel steam valves). Even a higher class may be chosen according to the maker. The maximum pressure on the wellhead gear and on the pipes in service does not need to be as high as this as it can be limited by two forms of protection. Under normal conditions the pressure at the station would not be allowed to rise above about 5.5 kg/cm^2 at which relief valves installed on the steam receiver/separator or associated pipework would be set. These valves are primarily to protect the turbine. They can be 'exercised' from time to time by the station staff to make sure they are free. Relief valves in the field are undesirable and it is proposed therefore to rely on bursting discs installed as emergency protection at each wellhead. This protection is required only against an operating mistake such as shutting the valve at the station before the master valve at the wellhead. Such a mistake could readily be prevented by simple interlocks requiring the key with which the station valve is to be unlocked before closing, to be retrieved from the wellhead valve only when this is in the closed position. If bursting discs are used they may be set to some nominal pressure of the order of $8\frac{1}{2}$ kg/cm^2. This allows all valves except the master valve at the wellheads to be of 150 lb/in^2 (10.6 kg/cm^2) class, this being the lowest design pressure usually adopted for steel steam valves such as are intended.

The pipes and separators would also be designed for 150 lb/in^2 pressure. The hydraulic test pressure to be applied to completed components, viz pipes, separators and valves, would be at least $1\frac{1}{2}$ x design pressure in accordance with relevant design standards. Because of corrosion allowance, and difficulty in making pipes and vessels of thin plates, the wall thickness will be more than what is called for by stress considerations. This allowance is taken account of in assessing the hydraulic test pressure to be applied and on separators, for example, the pressure will be of the order of 2 x design pressure. Because of this high initial factor of safety, separators designed for normal service will also be suitable for testing well characteristics. In such a test, which is not classed as commercial operating service, it will be permissible to exceed the design pressure.

Electrical features

The proposed diagram of electrical connections is as shown in Plate 10. Generator voltage is 10.5 kV. The output of the station will be stepped up to 138 kV for connecting into the existing 138 kV single circuit transmission line, which passes within 2½ km of the station. This line, nominal capacity 120 MVA (96 MW at 0.8 power factor), runs from the Sog River switching station at Ljósafoss to the Ellidaár switching station and will be required to carry about 15 MW output from the geothermal power station. The line will be able to transmit this additional power also allowing for the third 15.5 MW machine at Írafoss scheduled to come into service at the end of 1963 (see Table 1). The load transmitted to Ellidaar will then be about 81.5 MW. (About 6 MW will be tapped off for local supplies between the Sog switching station and Hveragerdi village.) When the geothermal station comes into service the transmitted load will rise to about 97 MW. The 11.5 MW steam turbo-alternator set on order for the Ellidaár reserve station has been designed so that the alternator can be uncoupled from the turbine and run as a synchronous condenser of 16 MVA rating. Thus from early 1965 with the synchronous condenser in operation the nominal transmission capacity of the 138 kV line will be about 103 MW.

The rupturing capacity assumed for the 138 kV circuit breaker is 1500 MVA. This is well above what the system can require even in the remote future but it is unlikely that any maker will quote a breaker of lower rating at this voltage. The 138 kV breaker and 19 MVA generator transformer are placed in a fenced enclosure on the same side of the road as the power station and at the south end. The 10.5 kV connections from the generator circuit-breaker are brought out through the end wall of the turbine room directly onto the transformer which is assumed to be provided with on-load tap change. Space is allocated for extending the switchyard to the east. The 3-winding 10.5/11/0.4 kV auxiliary transformer serves as a combined station/unit transformer, the third winding giving an alternative feed to the local 11 kV distribution system. It is housed in an annexe to the turbine room at the south end of the station.

Fault duty on switchgear

The calculated fault duty on the 10.5 kV switchgear, for 20 MVA installed generating capacity and including all other system extensions at present visualized, is a little under 350 MVA and can be held at this level if the station capacity is doubled at a later date. Accordingly in our estimates we have allowed for switchgear rated at 350 MVA.

A duplicate arrangement of electrical connections would be adopted for a possible future second generator and generator transformer as shown dotted in Plate 10. A second auxiliary transformer would be required and the two 400 V auxiliary boards could be coupled together and fed from either transformer in emergency.

Supply of auxiliaries

In a geothermal station steam is always available and can be regarded as a more reliable source of power than any alternative. It might appear therefore attractive to drive the auxiliaries by steam in a way analogous with practice in hydraulic stations. It is of course necessary to start auxiliaries such as a circulating water pump so as to raise vacuum before putting the main machine on load. Such auxiliaries must accordingly be driven by non-condensing turbines. On the other hand, since much of the power at the low steam pressure available is developed in the sub-atmospheric stages, it is clear that the auxiliaries should, for economy, be driven by condensing turbines which would require separate jet condensers. Because of these contradictory requirements steam-driven auxiliaries have to be dismissed as too complicated for the size and speeds in question.

We accordingly revert to the usual course of driving auxiliaries by electric motors. The auxiliaries are simple compared with those in a normal fuel-fired station, since there are no boiler feed pumps, extraction pumps or boiler fans. They comprise circulating water and booster pumps, gas removal equipment, lubricating oil pumps and various minor station auxiliaries, i.e. those not associated with the generating unit.

The principal auxiliaries are the circulating water pump and the booster pump rated at about 260 kW and 235 kW respectively. As mentioned previously they might be combined on a single shaft and driven by one motor.

Even this arrangement would not necessitate a higher voltage than 400 V. It may also be decided to use a water jet ejector in which case this will require a booster pump with motor drive.

Other electrical auxiliaries with much smaller ratings include the stand-by motor driven lubricating oil pump, a motor driven oil purifier with heater and a blower with heater for drying out the turbine after a shut down. Small supplies are required for station lighting, cooking, turbine room crane and the workshop. We propose that the auxiliary power requirements totalling about 680 kW should be supplied by a 2 MVA-400 V winding of the above-mentioned 3-winding transformer. The rating selected is sufficient to meet in emergency the auxiliary power requirements of two 16 MW sets. The third winding is also rated 2 MVA and will supply load to the local 11 kV distribution system. Maximum load on both outputs is not expected simultaneously. Hence the primary winding is rated 3 MVA.

When the station is shut down the 400 V supply will be available as a back feed from the 138 kV system or the 11 kV existing supply. It may be mentioned that for starting up the station, in the remote event of a supply for auxiliaries being unavailable, resort could be had to running up the main machine with atmospheric exhaust since steam will always be available.

SECTION 4

ESTIMATE OF COSTS

Capital expenditure

We understand that the steam supply system would be developed and owned by the State and the power station owned and operated by Sogsvirkjunin (the authority responsible for the Sog hydro-electric development). The capital estimate given in Table 3 is compiled in two sections, one for the steam supply system and one for the power station. The former includes all work and equipment associated with the winning of steam and transmitting it to the station, the terminal point (or point of sale) being at the power station building where the main steam supply pipe passes through the wall. A proportion of civil costs for the construction camp, roads, bridges and houses for operators, has been allocated to steam supply.

The estimate is for a station having one 16 MW condensing turbo-alternator with the condenser placed in the orthodox position underneath the turbine. The net output of the station will ordinarily be about 15.4 MW and will vary seasonally within small limits according to the vacuum, the highest output being available in winter. The nominal sent out output has been put at 15 MW.

The estimates, in so far as they relate to imported material, are based primarily on price data collected in Great Britain, the price level being that ruling in 1963, and on tenders received in October 1962 for turbo-alternator plant. No escalation has been allowed for, since we do not know whether prices will rise or by how much in Iceland or in the country of supply.

The estimate for civil works, comprising the power station buildings and foundations, circulating water pump-house, switchyard, spray pond, circulating water make-up pipeline, houses for station operators, roads and bridges, and construction camp on site, was prepared by the Authority's Civil Consulting Engineer (Sigurdar Thoroddsen). It is based on prices ruling in November 1963. The building sizes are based on the turbo-alternator plant dimensions supplied by preferred tenderer.

A sum of £45,000 has been included for cooling the water discarded at the wells and its subsequent disposal to the Varma River. (The disposal of hot water is discussed in Appendix 2.)

The allowance for engineering and supervision is shown at 8%, in accordance with the Authority's practice, and expenditure of £66,000 incurred up to the present is included separately. Contingency allowances have been put at 5-15% depending on the item and the expected accuracy of estimating. A provisional sum of £83,000 is intended to cover unforeseen costs. Interest during construction is shown as 10%, a token figure only since the amount will depend on the terms of payment to be fixed for the various contracts.

The amount of import duty for each item is shown separately and is assessed in accordance with rates at present operating.

TABLE 3

ESTIMATE OF CAPITAL COST
(£ sterling)

Item		POWER STATION			STEAM SUPPLY			TOTAL	
		FOB price + freight & insurance + erection	Import duty	Total	FOB price + freight & insurance + erection	Import duty	Total	Duty free basis	Including import duty
1. Power station building, pumphouse		81,000	11,000	92,000				81,000	92,000
2. Cooling pond and make-up pipeline		29,000	4,000	33,000				29,000	33,000
3. Houses, roads and bridges		43,000	6,000	49,000	9,000	2,000	11,000	52,000	60,000
4. Camp site		18,000	2,000	20,000	5,000	1,000	6,000	23,000	26,000
5. Turbo-alternator and spare steam rotor		225,000	87,000	312,000				225,000	312,000
6. Steam transmission system		5,000	2,000	7,000	98,000	25,000	123,000	103,000	130,000
7. Electrical equipment including substation and 138 kV transmission line spur		122,000	48,000	170,000				122,000	170,000
8. Cooling water system and spray pond equipment		55,000	13,000	68,000				55,000	68,000
9. Cranes		13,000	4,000	17,000				13,000	17,000
10. Drilling rig (well cleaning)					14,000	6,000	20,000	14,000	20,000
11. Additional wells					30,000	2,000	32,000	30,000	32,000
12. Collection and cooling of rejected well water					35,000	10,000	45,000	35,000	45,000
SUBTOTAL DIRECT COST		591,000	177,000	768,000	191,000	46,000	237,000	782,000	1,005,000
Contingencies on Items 1-4 and 11	10%	17,000	2,000	19,000	4,000	1,000	5,000	21,000	24,000
Contingencies on Items 5-10	5%	21,000	8,000	29,000	6,000	1,000	7,000	27,000	36,000
Contingencies on Item 12	15%				5,000	2,000	7,000	5,000	7,000
TOTAL DIRECT COST		629,000	187,000	816,000	206,000	50,000	256,000	835,000	1,072,000
Engineering and supervision, including Authority's engineering costs	8%	50,000		50,000	16,000		16,000	66,000	66,000
Expenditure to date		66,000		66,000	150,000		150,000	216,000	216,000
Provisional sum		61,000		61,000	22,000		22,000	83,000	83,000
CONSTRUCTION COST		806,000	187,000	993,000	394,000	50,000	444,000	1,200,000	1,437,000
Interest during construction	10%	81,000	19,000	100,000	39,000	5,000	44,000	120,000	144,000
PROJECT INVESTMENT		887,000	206,000	1,093,000	433,000	55,000	488,000	1,320,000	1,581,000

TOTAL PROJECT INVESTMENT PER KILOWATT INSTALLED: £99

Cost of steam at power station

The cost of steam at the power station has been computed for annual interest rates of 5, 7 and 9 per cent and is shown in Table 4. The sinking fund is assumed to earn interest at the same rate as that payable on the capital.

The total project investment for the steam supply is £488,000, the cost of the wells and drilling rig amounting to £232,000 and other work £256,000. For the wells a 10 year life has been assumed in calculating financial charges. This means that we allow for wells to be replaced at 10 year intervals and even if it were necessary to drill more remotely in order to continue to provide steam over the life of the station we would not regard this as seriously affecting the calculations. We see no reason to distinguish between the lives of other assets except for the small drilling rig used for cleaning out the bores. In particular the pipework, on which we allow 20 years, according to our experience will not show any shorter life than for instance the turbines.

Under maintenance, materials and stores for cleaning out the wells is included at £5000 and a further £3000 is allowed for wellhead equipments and steam transmission system. Local taxes and reserve fund, future prospecting and testing, and provision for royalties payable on the steam field are together shown as 20 per cent, and 15 per cent is included for risk. Steam utilized per annum is expected to be about one million tons, i.e. approximately 36 kg/sec for 8000 hours.

TABLE 4

COST OF STEAM AT POWER STATION

Interest rate, %	5	7	9
Sinking fund rate, %			
(a) 10 year life	7.95	7.24	6.58
(b) 20 year life	3.02	2.44	1.95
	ANNUAL CHARGES (£ Sterling)		
Financial charges			
(a) Wells and drilling rig Basis 10 year life Project investment £232,000	30,000	33,000	36,000
(b) Other works Basis 20 year life Project investment £256,000	21,000	24,000	28,000
Maintenance			
(a) Materials and stores for wells	5,000	5,000	5,000
(b) Outside labour and materials for other equipment	3,000	3,000	3,000
Wages of maintenance personnel	4,000	4,000	4,000
Administration and supervision	2,000	2,000	2,000
	65,000	71,000	78,000
Taxes and reserve fund, future prospecting and testing, provision for royalties on steam field, 20%	13,000	14,000	16,000
	78,000	85,000	94,000
Provision for risk, 15%	12,000	13,000	14,000
TOTAL ANNUAL CHARGES	90,000	98,000	108,000
COST OF STEAM, PENCE/TON (Based on annual sale of 1.04×10^6 tons)	20.77	22.62	24.92

Cost of generation

The cost of generation is computed in Table 5. Financial charges have been calculated on the basis of a 20 year life for all assets and annual generation is taken as 120 GWh nett, which corresponds to 8000 hours use of 15 MW maximum demand.

A life of 25 years is frequently used for thermal plant but in this case we have preferred 20 years in view of the high load factor assumed. The normal history of orthodox thermal plant is that it operates at high load factor during the first few years and thereafter its utilization falls; it is seldom called on for more than 40 per cent load factor over 25 years life. Geothermal plant may be in a different category but there is no experience of 20 years operation as yet (the early Larderello plants use 'indirect' steam), so we cannot cite load factors actually obtained over life of plant or even be categorical about likely availability. It is however relevant to note that during 1961 the total output of eleven Larderello stations with a total installed capacity of 335 MW was 2290 GWh, i.e. an average annual load factor of 78 per cent for a maximum demand of 335 MW. Larderello No. 3 station (four 26 MW sets), which uses natural steam, went into service in December 1949 and has operated consistently at high load factor with an average availability for all units of 98 per cent*. High availability is intended to be assured by provision of a spare steam rotor. This is the most vulnerable item and the spare can be inserted within 24 hours in case of trouble.

* 'Latest trends in the design of geothermal plants', by F. Villa, UN Conference on New Sources of Energy, 1961.

TABLE 5

COST OF GENERATION

Interest rate, %	5	7	9
Sinking fund rate, % (Basis 20 year life)	3.02	2.44	1.95
Total financial charges, %	8.02	9.44	10.95
	ANNUAL CHARGES (£ Sterling)		
Financial charges on capital excluding import duty Project investment £887,000	71,100	83,700	97,100
Steam	90,000	98,000	108,000
Maintenance including outside labour and materials	30,000	30,000	30,000
Administration, supervision and operation	20,000	20,000	20,000
	211,100	231,700	255,100
Local tax and reserve fund, 7.5%	15,800	17,400	19,100
Total annual charges, duty-free basis	226,900	249,100	274,200
Financial charges on import duty Project investment £206,000	16,500	19,400	22,600
Total operating cost	243,400	268,500	296,800

COST OF GENERATION AT THE SOG LINE (For an annual generation of 8000 hours at 15 MW = 120 GWh)		pence/kWh	
(a) Duty-free basis	0.45	0.50	0.55
(b) Including import duty	0.49	0.54	0.59

Possible extension to Stage II

The extension of the station to 30 MW by a second stage consisting of a similar machine (except that it might make use in part of pass-in flash steam from the hot water) is estimated to cost about £73 per kilowatt. The completed station would then cost £86 per kilowatt installed. The estimates are not shown in detail because the parts which would differ markedly from the first stage, namely the transmission pipes for hot water, depend on the locations of supplementary steam wells. These and the flash plant can only be given token prices at the present stage. The spray pond would be extended by roughly 10,000 m^2 to provide the required cooling capacity. No allocation has been made for any additional transmission line or for electrical extensions at the receiving end since this will depend on the timing of the further extension in relation to general system development.

The operating costs would be roughly 15 per cent lower on the doubled output primarily because of the lower financial charges but also because the staff would need little augmentation. Experience by that time may well show that a smaller ratio of spare wells will suffice on the greater number.

Staffing

The operating staff required for a geothermal station may be taken as about the same as that in a hydraulic station containing the same number of generators. Hydraulic stations are a better guide in this respect than fuel-fired steam stations in which the staff is largely occupied on the boilers and their associated coal handling and ash disposal plant, which do not arise in this case. In line with the State Electricity Authority's practice we visualize that the operating staff will consist of the following:

Station superintendent

Shift staff, 3 shifts each consisting of shift charge engineer and assistant charge engineer

Electrician

In addition there will be a day staff consisting of maintenance crew, including drillers, mechanics and general labourer: Total 16 men

The drilling crew of five men will normally be engaged on the redrilling of wells every other week, doing maintenance work on the wellhead and other equipment when they are not engaged on drilling. It is difficult to visualize exactly how much work the wells will entail, but since a crew capable of using the drill must be kept together they should preferably be capable of this dual function of drilling and routine maintenance to keep down operating costs.

There will not ordinarily be sufficient work to keep workshop staff occupied in this station, and it will be found more economical to form a central overhaul and breakdown group available to all stations, hydraulic and steam, provided of course that staff is sufficiently adaptable to work on both types of plant. We do not think that this should create difficulty unless it is contrary to trade union practices.

We have not seriously considered remote control since we consider the technology is not yet sufficiently established for the plant to be left unsupervised nor are the possible contingencies readily visualized.

We consider that the circulating water pumphouse should not be attended since the pumps will be started from the station and there will be no valves to operate. There will of course have to be a routine daily visit to inspect the level in the pond, condition of the intake screens and to check over the gland and bearing temperatures and lubrication of the pumps. Once a year each pump will have to be overhauled and for any major work we consider they would be removed to the workshop.

As there will ordinarily be no high voltage switching to be done at Hveragerdi we think that the whole control including 138 kV gear can be done by the shift charge engineer or his assistant who will be in telephone communication with the switching stations at Ljósafoss and Ellidaár.

The wellhead equipment and pipelines require no constant attention but periodic inspections once per week are to be recommended when wellhead gauges and other instruments are to be read and logged. Less frequently all valves need to be operated to avoid seizure. Instrumentation both in the field and in the station can advantageously be kept to a minimum. The most important pressure is that of the steam received and this can be read on a mercury manometer. Vacuum pressure would be indicated by an absolute mercury gauge. Temperatures are within the range of mercury thermometers. Thus basic instruments of the simplest kind are adequate.

Time of construction

In a tentative construction programme shown in Plate 11 we have scheduled Stage 1 to be in commercial service in thirty months from placing the order for the turbo-alternator. This could be done immediately a decision was taken to proceed with the scheme as the turbo-alternator bids have been received and adjudication has been completed. The preferred tenderer has stated that the machine could be erected on site within twenty-eight months of an order being received, allowing approximately twenty-one months for manufacture, two months for shipment and five months for erection. We have adopted thirty months as prudent for planning purposes. The manufacturing periods allowed for plant and equipment, other than the turbo-alternator, are representative of deliveries now being quoted by British firms for home and overseas contracts.

APPENDIX 1

CORROSION AND DEPOSITS

Provisional analyses of the impurities in the steam and of the water delivered by Well No. 3 are given in Table 6. The main contaminants in the steam are the gases carbon dioxide and hydrogen sulphide which are regularly found in geothermal steam in other parts of the world, the contents in the present case being distinctly lower than experienced elsewhere. The water contains common salt and scale-forming substances. This is also usual but the salt concentration is much lower than met with in New Zealand while the calcium carbonate is higher.

All geothermal waters are liable to be saturated with some scale-forming constituents from the rocks. The most important of these are silica and calcium carbonate. Calcium sulphate seems to be less common and hydroboric acid in large concentration is uncommon though it occurs at Larderello.

The gases CO_2 and H_2S are both potentially corrosive in the presence of water which is unavoidable in the plant as resulting from condensation of the steam. Corrosion tests were started at Hveragerdi in October 1960 to obtain data on the suitability of a range of construction materials likely to be used in a power plant. The results of these tests show the same sort of pattern of attack as experienced elsewhere. Some of the specimens show very violent attack in oxygenated steam. However this is normal experience and ample practical evidence obtained elsewhere, confirmed by inspection of equipment used in tests so far in Iceland, shows that general corrosion of common materials of construction such as mild steel and cast iron is not serious either in the turbine or in the pipework so long as there is no oxygen present. It appears to be generally true that geothermal steam does not contain oxygen, presumably because this has been used up in reacting with other substances underground.

The H_2S does initially attack steel even without oxygen, but the reaction product FeS, which is a black scale, is adherent and forms a protective coating. This coating inhibits further attack so long as it is not disturbed. Continued attack therefore is concentrated where the scale is removed by water erosion, e.g. on the turbine stator, and precautions have to be taken to protect, or make renewable, any areas so affected. Injection of amines intended to counteract H_2S has been tried but found undesirable as it removed the protective FeS film.

There is a more violent corrosion environment in the exhaust duct and gas extraction parts of the condenser where oxygen is present, through having leaked in or been released from the circulating water. However this affects mainly parts which are static, not very expensive and also can be protected by coatings.

Experience confirmed by tests shows that various films such as graphite (Apexior No. 1) and oil offer some protection even in the presence of oxygen and make possible the exposure of bright parts, such as valve spindles, without serious attack at least for several months before renewal of protection is necessary. Both austenitic stainless steel of 18/8 chromium nickel type (and its variants) and in lesser degree ferritic 12 per cent chromium iron are reasonably resistant to H_2S. They also acquire a black film of FeS. However 12 per cent chromium steel in martensitic state and probably all hardened steels are subject to stress corrosion cracking. Hence it is inadvisable to employ any such alloy in hardened state since this is likely to contain martensite and its behaviour will be unreliable.

As H_2S also attacks copper violently and some of its alloys, it is advisable to exclude brazing compounds which consist largely of copper. Nickel is also attacked.

The selection of materials is somewhat complicated by the possible presence of chlorides in the form of sodium chloride. Very little can be carried in the steam phase but large amounts in the water. It is not practicable entirely to eliminate water by separators and this will bring some salt with it. Unfortunately some of the best materials for resisting H_2S are prone to chloride attack. This is so both with 12 per cent chromium and austenitics such as 18/8/3 chromium nickel molybdenum. However practical experience with 12 per cent chrome iron at Wairakei so far shows that this is not a serious problem when using live steam. It is unlikely to prove any more serious using flash steam, as steam scrubbers are used to reduce the chloride content of any bore water carried over in the steam from the flashing process. The scrubbed steam is passed through demisting meshes of stainless steel (nylon is also being tried) where most of the diluted water droplets are removed. The Hveragerdi bore water is not very high in salt content, hence the problem would be slightly alleviated.

Scaling

The scale-forming substances silica and calcium carbonate (commonly described as 'calcite' though more properly aragonite) are liable to occur in saturation or even supersaturation in the bore water. Saturation concentration of silica (quartz) at a temperature of 200°C is quoted as about 250 ppm and of calcium carbonate (in the presence of CO_2) the order of 2000 ppm. The presence of one substance may affect the solubility of another. Silica can also be carried in steam in very small concentration, possibly 0.05 ppm, and as a colloid in excess of saturation in the water. Silica tends to be thrown down by drop in temperature of water but because of the colloidal state shows a time lag. Calcite on the other hand is not soluble in steam and hence is mainly thrown down by evaporation or by release of CO_2 from solution (e.g. by flashing of steam) when it then occurs in excess of saturation in the remaining water. Deposition then seems to occur without time lag. Hence silica deposits can be expected to form deep down in the bores where the pressure is lowered in relation to the lithostatic pressure at which the silica was initially in equilibrium. They may possibly occur also in the passages in the rock feeding the bores. In either case a slow falling off in yield will take place. In the first case the well can be restored to its initial output by putting the drill down at intervals. In the second case no remedy is known but it is not certain that the trouble occurs.

With calcite the deposits occur about where the steam flashes, i.e. generally high up in the bore, and can be of much greater magnitude. Hence falling off of output is much more rapid. No. 2 well at Hveragerdi showed significant falling off in a period of two months continuous operation and this was ascertained to be caused by calcite. The output was restored by putting the drill down and this may be required every few months in bad cases.

It appears that calcite is not likely to cause deposits beyond the wellhead since in service flashing will cease there and the reverse process of slight condensation will occur. However all droplets may be expected to contain saturation concentration of calcite and hence a very small percentage of carryover of water could in a matter of months represent a sufficient weight of scale to be troublesome if it deposits within the turbine. Silica and calcium sulphate can also cause trouble in the turbines but may be expected to be in lesser quantity. The process of reducing the effects of carryover is helped by the formation of condensate in the steam transmission pipe due to heat loss from the pipe surface. This condensate will reduce the salt concentration in the bore water carried over from the wellhead separator and some of the mixture will be discharged through traps in the pipelines. We propose installing a water separator at the station and it is even possible that demister screens, to catch any small droplets, may have to be installed behind this. In this way the salt concentration of droplets carried into the turbine, and also the total quantity of salts associated with the steam, will be considerably reduced. The evidence so far obtained is insufficient to enable a final decision to be reached as to the seriousness of the problem, however it is possible that the high pH (9.5) of the water indicates that it contains dissolved salts such as sodium carbonate which may be beneficial as counteracting the acid gases.

Corrosion of concrete and cement

In geothermal regions the content of sulphates in the ground water is often sufficient to cause rapid deterioration of concrete made with ordinary Portland cement. This is now recognized to be caused by reaction between the sulphates and the tricalcium-aluminate which is a constituent of most Portland cement. The reaction involves a conversion to calcium sulphate which is accompanied by a considerable increase in volume. This causes disruption of the concrete and ultimately complete loss of strength. Remedies consist in selection of the raw materials to produce a cement having a low content of tricalcium-aluminate or alternatively volcanic trass may be incorporated in the concrete mix. It is possible that the cement made in Iceland using some volcanic materials may be naturally resistant. Tests have been suggested to establish whether this is so.

Asbestos cement goods for use in geothermal waters must also be made of sulphate resisting cement, otherwise their decay is likely to be rather rapid.

General corrosion from atmosphere

The H_2S content of the air in and around the power station and bores is unlikely to be high enough to require any special precautions against corrosion other than of the parts mentioned above. Copper in electrical conductors and the like exposed to rain or condensation may be expected to form a purple or green patina after which the speed of attack is reduced. A bright appearance can be preserved by lacquering or greasing. In the case of very thin wires of copper alloys such as constantan (especially if not carrying current) the surface to volume ratio may be so high that attack will reduce the cross section seriously within a short time so the resistance is not constant and the wires ultimately disappear. This trouble is known in higher contaminated industrial atmospheres and the remedy is to use nickel chrome wires which are more resistant to attack. Pure aluminium is not significantly attacked.

Bore water contains some fluoride and if it is allowed to concentrate on glass by evaporation, the surface may show roughening and loss of transparency. The calcium carbonate, silica and other soluble salts may also be left as deposits when geothermal water evaporates and, though these do not corrode, they may cause inconvenience in that they will have to be cleaned off.

Corrosion in circulating water

The circulating water will be the condensed geothermal steam containing some carbon dioxide, hydrogen sulphide and oxygen in solution. The dissolved solids content in the condensate will be negligible, however some solids will be introduced into the pond via the make-up line from the Reykjadalsá stream. The analysis of the water from this stream is likely to vary considerably throughout the year, possibly from mainly geothermal water to rain water. To safeguard against possible corrosive properties of very pure circulating water it is advisable that stainless steel should be employed for the impellers, shafts and seals of circulating water and booster pumps. Aluminium or stainless steel can be used for the tubular materials in the heat exchangers. The quantities involved are small and the cost is not seriously higher than that of cuprous material. Mild steel protected with bituminous compound is likely to be satisfactory for pipes where erosion is not severe. Cast iron in pump casings is considered to be thick enough to resist corrosion for a normal life. If erosion-corrosion occurs stimulated by the very pure water the affected areas can be built up with stainless steel by arc deposition or by metal spray. Brasses which are subject to dezincification in very pure water should be excluded from seals, valve trim, etc.

Analysis of the Reykjadalsá water should be made at regular intervals forthwith to provide a basis for the final choice of materials.

TABLE 6

GAS CONTENT OF WELL 3 STEAM
(measured at atmospheric pressure)

	parts per million by weight
Carbon dioxide (CO_2)	590 - 790
Hydrogen sulphide (H_2S)	76 - 106
Hydrogen	1 - 2
Balance, mostly nitrogen (N_2)	25 - 25
Total	692 - 923

ANALYSIS OF WELL 3 WATER

Hardness (as $CaCO_3$)	9.5
Phenolphthalein alkalinity (as $CaCO_3$)	87.5
Methyl orange alkalinity (as $CaCO_3$)	155.5
Silicic acid (as SiO2)	341.2
Chloride (Cl^-)	167
Sulphate (SO_4^{--})	61.2
Fluoride (F^-)	2.3
Calcium (Ca^{++})	1.5
Sodium (Na^+)	174
Potassium (K^+)	30
Total minerals	904

pH 9.56

APPENDIX 2

DISPOSAL OF HOT WATER

We have recommended that in the initial development of geothermal power at Hveragerdi the hot water produced by the wells in association with steam should be discarded. The water is potentially an asset, particularly in a cold country, though if it cannot be usefully disposed of it becomes an embarrassment.

The quantities yielded at present at a wellhead pressure of 5.5 kg/cm^2 gauge are as follows:

Well No.		Water yield kg/sec
2		88
3		66
6		54
7		46
8		75
	Total	329

The additional well or wells yet to be drilled would increase the total yield above the figure shown in the table but as it is proposed to exclude Well 2 from the power scheme the total water yield for the 16 MW station will be about 320-350 kg/sec. As all the wells will not be in use at the same time the water to be disposed of will ordinarily be about 260 kg/sec. The temperature of the water discharged at the wellhead will be approximately 160°C and the available heat above 30°C will be about 120 Gcal/h. Flash steam produced from this water may at some future stage of development be used for power generation. This would reduce the quantity of hot water to be disposed of to about 230 kg/sec and the heat above 30°C would be roughly halved.

Disposal to river

The simplest course would be to let the hot water go into the Varmá River after flashing at atmospheric pressure. This would be tolerable under high river flow conditions (5 m^3/sec is attained for about 10 per cent of the time) but at the low flow it would be lethal to the fish since 230 l/sec at 100°C would result in a rise of about 40°C at minimum river flow of 250 l/sec. The cost of compensating the fishing interests and any other riparian owners downstream sets an upper limit on the amount to be spent on provision of any alternative cooling arrangement designed to recool the water to a low temperature before its discharge to the river. If fishing interest were disregarded the cooling of the boiling water to a temperature unobjectionable to cattle or human beings is relatively simple since the heat in excess of 100°C can be flashed to atmosphere while a small cascade will readily cool the water to the order of 50°C. The further stage of cooling down to 25°C requires much more expenditure. The simplest way of reducing the temperature of the water is to discharge the flashing mixture from the wellhead separator across an area of open ground some distance from the station and allow the water to drain back into the river. This might be done on either side of the river according to convenience. There are some defects in such a scheme and the first is that the cooling cannot be calculated with any certainty. It might also lead to ground erosion and in winter ice build-up would bring problems. Silica deposition might kill vegetation but, on the other hand, the heat released might be expected to improve the general climate in the vicinity and so promote growth of vegetation outside the range of silica or excess heat. Vapour carry-over and noise are both problems, though we think they could be dealt with by suitable directing of the jet. Complaint due to carryover of scale-forming substances onto distant greenhouses such as has occurred with vertical discharge is not likely. A period of trial would in any case be essential before devising any remedial measures.

Cooling towers

It is apparent that any more elaborate alternative to such a simple scheme must involve higher costs. The ultimate development is to use cooling towers, though not of conventional design. Boiling water can be cooled very rapidly. We visualise a contraflow tower taking boiling water under sufficient pressure to cause it to discharge up into a tower without pumping. The air would be heated sufficiently to produce a strong draught without the use of an unduly high chimney. An unusually deep contraflow fill is required. Normal evaporative cooling to a reasonable approach to air temperature would take place in the lower part. A fill of material able to withstand the high temperature would be required and this might be plain or reinforced glass on concrete bearers or possibly concrete or asbestos cement. A scaling problem can be foreseen but no solution can be offered until practical experience is obtained. There could be a tower at each wellhead, one tower to two wells, or a central tower serving a number of wells. The cooling equipment will clearly cost less if it is concentrated into one unit but this entails piping the hot water from the various wells to a central point.

Recommended scheme

If disposal to the river with only preliminary cooling by flashing and a small cascade is unacceptable then we recommend a scheme in which Well 8 and the additional well or wells to be drilled are piped to a single cooler of the type discussed above and centrally located with respect to the wells to minimize expenditure on pipework; Wells 3,6 and 7, which are in close proximity to each other, will be similarly served by a single cooler. There are several possible variations but we conclude that something on the lines proposed is feasible. A certain amount of trial and development will be required since such high temperatures are not usual in existing cooling tower technology. However we foresee no serious design difficulties as the size of tower required is modest. In our opinion it will be possible at reasonable cost to keep the temperature of the Varmá River to say 25°C except possibly in a combination of very unfavourable circumstances such as high atmospheric temperature, high natural river temperature and low river flow. A sum of £45,000, plus £7000 for contingencies, has been allowed in the estimate (Table 3).

Alternative methods of disposal

Several schemes for making use of the hot water have been considered including transmission to Reykjavik to supplement the district heating scheme, the heating of Hveragerdi village and salt production.

Transmission of the hot water to Reykjavik would involve an expenditure of the order of £2 million and would not show to advantage compared with drilling for hot water in Reykjavik, which has recently been done with success.

The present maximum demand for heat in Hveragerdi is about 10 Gcal/h and it is adequately supplied by wells put down in the village. The heating system is similar to that used in Reykjavik, the well water being rejected to the sewers after passing through the radiators. The heat demand is small compared with the amount of heat to be discarded (less than 10 per cent at present) hence there would be no significant lowering of the water temperature and the problem of cooling the water before disposal to a river remains. The possibility of pumping hot water back into the ground has often been suggested though it has not been tried, so far as we are aware, in a geothermal region. (Oil companies regularly pump water into depleted fields to maintain the pressure that forces oil to the surface after natural pressure begins to subside.) The sinking of wells for this purpose south of Hveragerdi village has been considered, the chosen location probably being sufficiently remote from the steam field to avoid interference with hydro-thermal systems. However, the effects would require long-term observation in experiments designed to determine the feasibility and consequences of such a scheme. The technical uncertainties and the absence of a substantial demand for the hot water in Hveragerdi village make the scheme unattractive.

The only potential use we have thought of for the large quantities of hot water at 100°C is in salt production by evaporation of sea water. A scheme was put forward in a preliminary way by which sea water could be evaporated in ponds heated by passage of hot water through tubes or under sheets of polythene. We suggested that a pilot pond on these lines should be constructed for preliminary testing.

The 230 kg/sec of boiling water mentioned above as having to be discarded by the power station would be sufficient to produce about 15,000 tons of salt a year. It would involve converting a flat area of some 8 hectares into polders so that sea water could readily be pumped into them. The bottom would have to be made impervious by use of puddled clay unless the site were already on clay. The flat region to the south of Hveragerdi appears to be quite well suited though it is unfortunate that the water in the estuary of the nearby Olfusa River will be too diluted with fresh water to be economic as a source of salt water. A pipeline would have to be constructed to convey full strength sea water from some suitable point on the coast. The distance of 14 km is not intolerable. On the other hand the cost of the hot water pipe delivering by gravity over a distance of say 5 km might amount to some £100,000 and therefore though the hot water is free at the source above Hveragerdi it may not prove cheaper at point of use than hot water available elsewhere, e.g. at Krysuvik which is within 7 km of the sea.

APPENDIX 3

CIVIL ENGINEERING WORKS

The estimates for civil engineering work have been prepared by Sigurdar Thoroddsen of Reykjavik, the Authority's consulting civil engineer on the Hveragerdi project. Several aspects of civil engineering design are briefly mentioned in Section 3 and a breakdown of cost is given in Table 3 on p.51. This appendix is a summary of Sigurdar Thoroddsen's report (dated November 1963) to the Authority.

Site surveying and geological investigation

In 1962 the thickness of the earth layer on the proposed power station site was examined with a rod and the bottom contour of the layer was recorded. The earth layer averaged about 1 metre in depth. Holes were later made with an excavator and it was found that under the earth layer was a 1 metre thick layer of scoria (volcanic ashes) on top of the basalt lava. In the latter part of 1963 two holes were dug with an excavator and eight holes were drilled to measure the depth of rock layer.

Sand and gravel

In 1962 it was thought that most of the sand and gravel required for construction was obtainable from a quarry just west of Hveragerdi. According to recent information supplied by Atvinnudeild Háskóla Islands

(Research Institute of the University of Iceland) this quarry is almost exhausted and accordingly before tenders are invited it will be necessary to examine other areas around Hveragerdi where sand and gravel are available.

Clay and fill

It is expected that clay for sealing the cooling pond will be obtained locally from a site north of the river Varmá.

Material for filling up dams and protecting the clay will be taken partly from local loessian deposits and partly from loose rock deposits on Mount Ingólfsfjall about 6 km east of Hveragerdi. Examination of this material was in hand at the end of 1963.

Cooling pond

The lava bottom of the pond will be made water-tight by a compacted layer of clay about 0.3 m thick, on top of which will be protecting layers of sand and gravel, also underneath where necessary. For estimating purposes it was assumed that the permeability coefficient of the clay would not exceed 10^{-7} m/sec. (The Authority have since measured the permeability which is about 10^{-9} m/sec.) Dikes with a core of clay will be built around the pond, the crest of the dikes being about 1 m above the water surface and the width about 4 m.

Make-up water supply

Both Hengladalsá and Reykjadalsá were examined as to suitability for providing make-up water for the cooling pond. Both rivers carry much silt. Reykjadalsá is preferred as it is better suited for the construction of a small dam. A small concrete gravity dam with an intake basin is proposed and a site has been surveyed. A 6 in bore pipe will be laid over a distance of 500 m to the power station and will have a capacity of about 30 l/sec under the gravity head available.

Houses for operators

It has been assumed that houses will be built in Hveragerdi village for the station superintendent and three operators.

Roads and bridges

A road will be built from Hveragerdi to the station. A spur road will be built across a bridge over the Varmá to Wells 6 and 7 and from there across a bridge over Graendalsá to Well 8. A road to the east of Graendalsá will be built up to Well 1. The road along the Graendalsá river which carries much gravel must be capable of protecting the wells from the river at times of high flow, hence it is assumed to be at least 1 m high and protected by rock facing on the river side. The same also applies to the road alongside the Varmá in the region of the confluence with Graendalsá.

Bridges over the Varmá and Graendalsá will be about 25 m long and 3.6 m in width. For the purpose of estimating they are assumed to be built of steel beams carried on concrete columns, with floors of wood.

Estimate of cost

A Bill of Quantities for the principal items has been prepared and a summary of the cost estimate is given below. Conversion from Icelandic kronur has been made at 120.6 Kr = £1 sterling.

	£ sterling
Power station building	78,000
Foundation and rails under transformer and fence around same	4,200
Pumphouse	10,000
Water supply	5,700
CW pipe foundations	400
Cooling pond	26,700
Houses for station staff	39,200
Roads and bridges	20,500
Construction camp	25,700
Direct cost	210,400
Contingencies, 15%	31,600
	242,000
Supervision, 8%	19,400
	261,400
Interest during construction, 10%	26,100
Total project investment	287,500

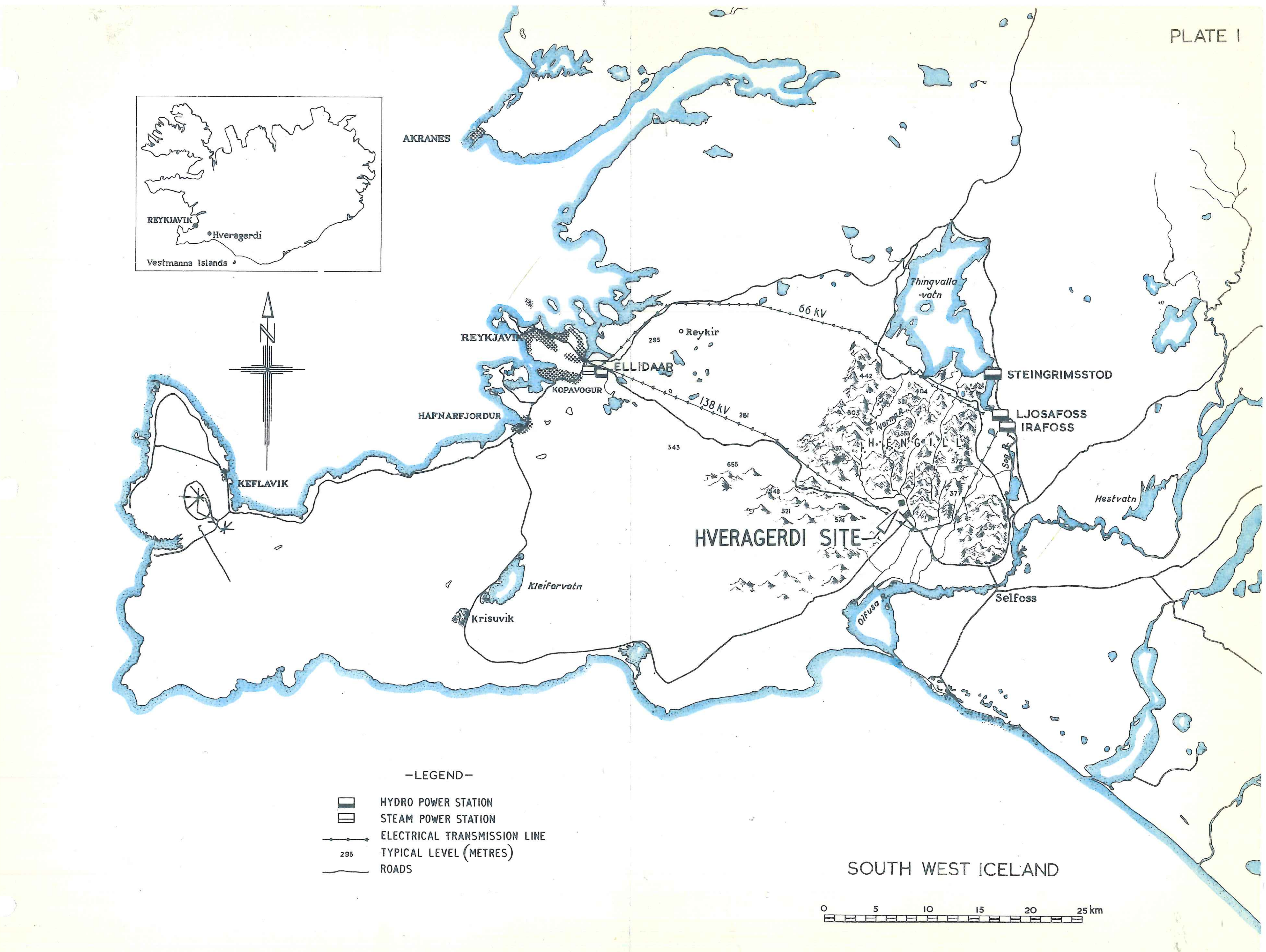
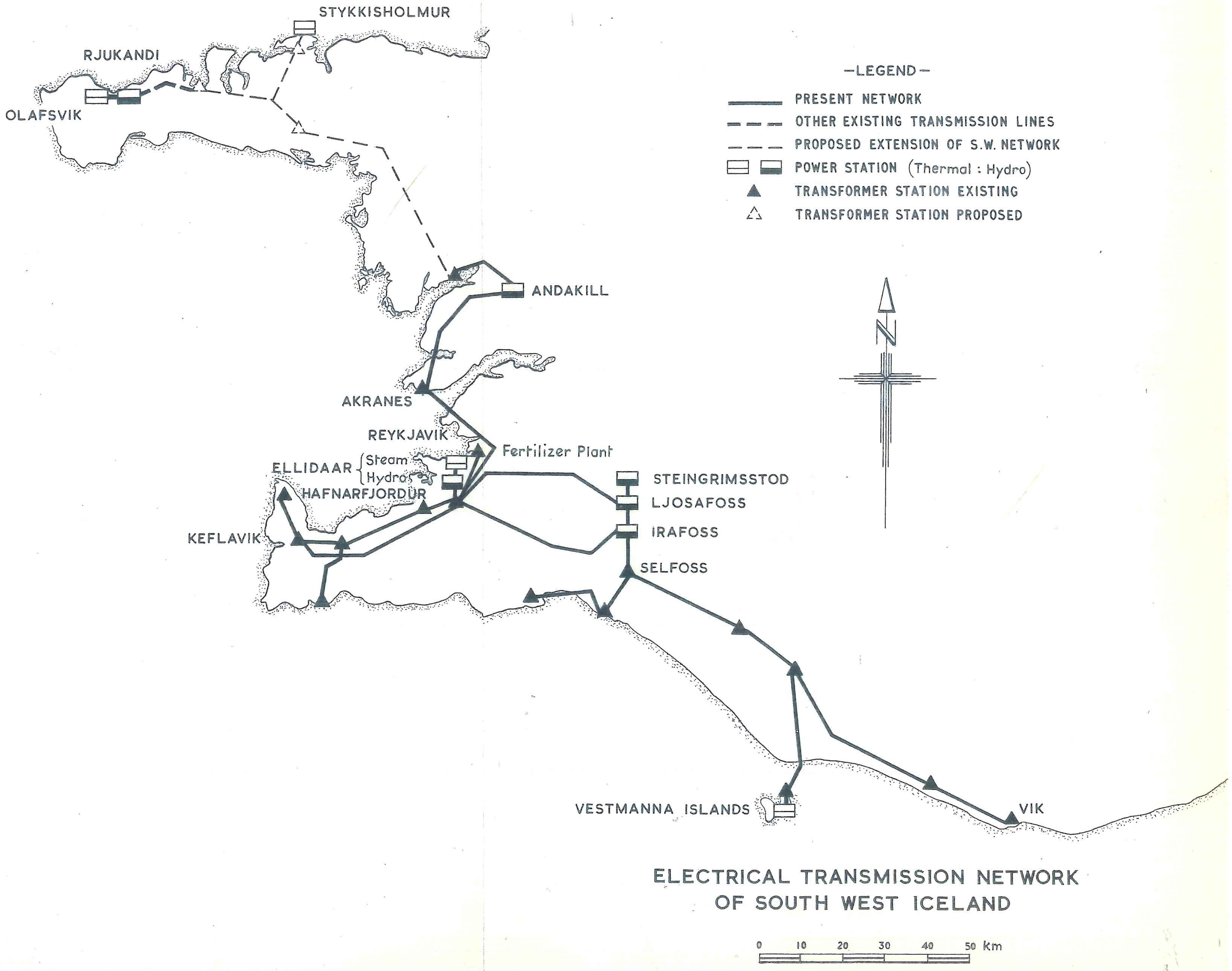
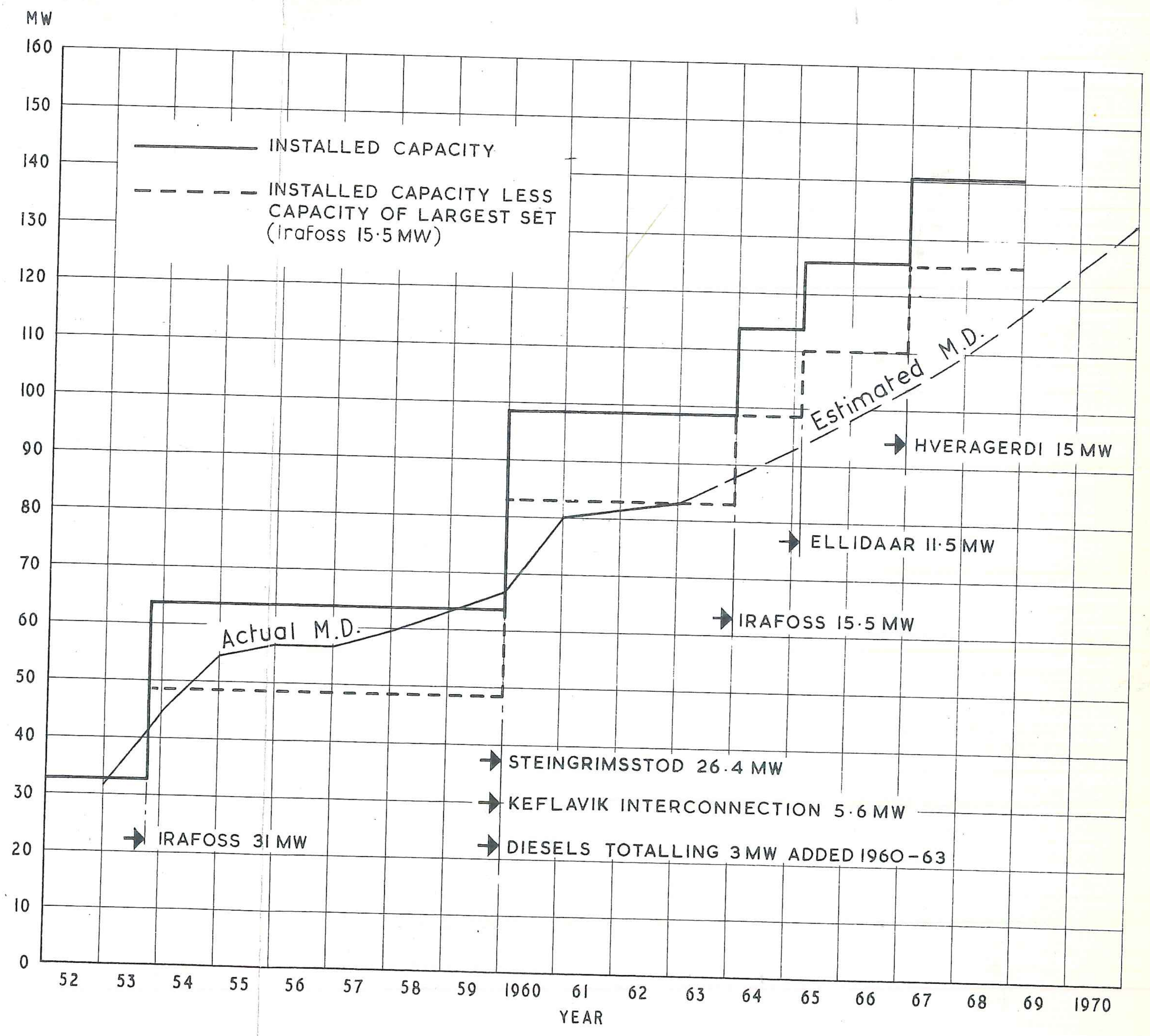


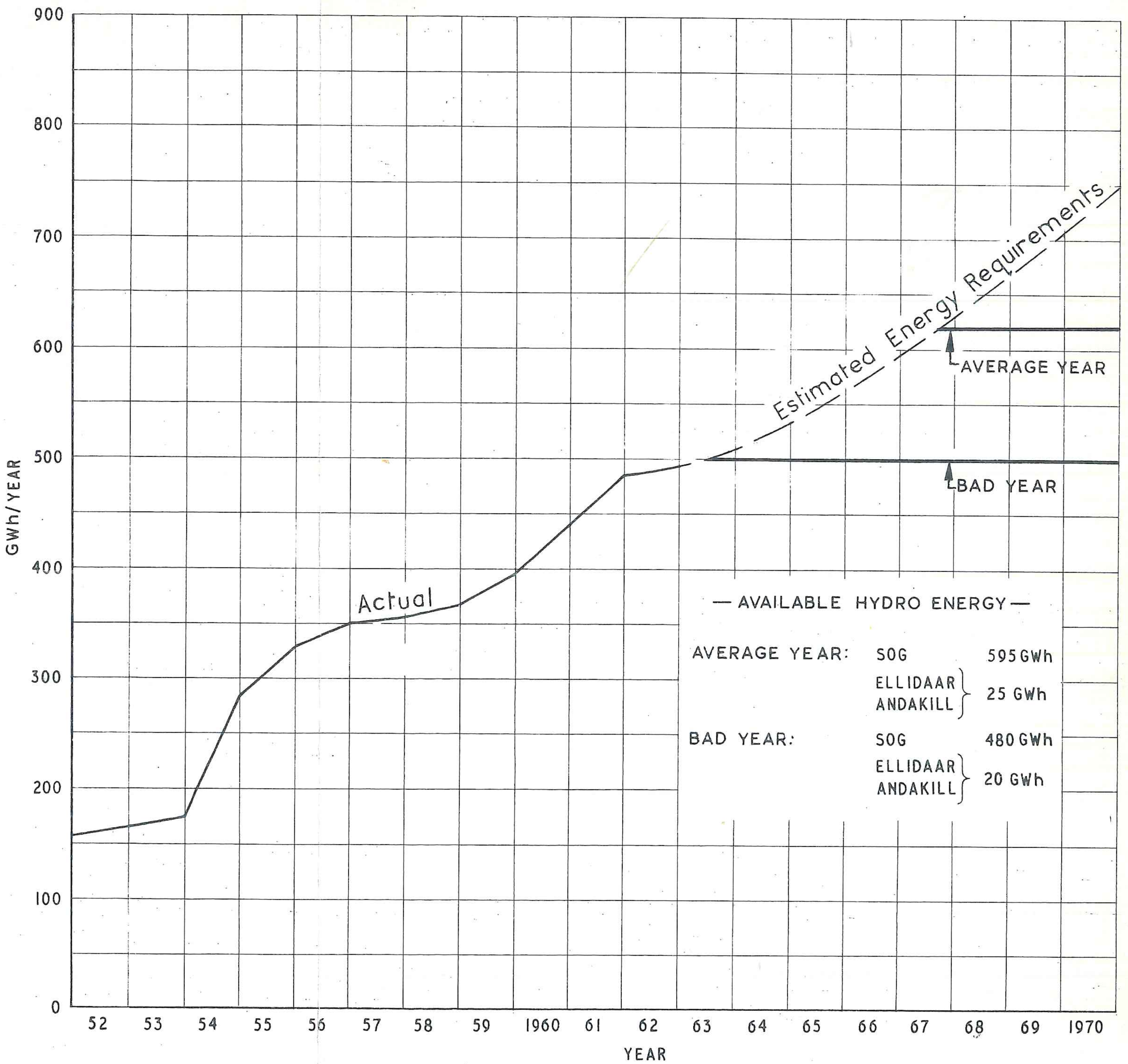
PLATE I
REYKJAVIK
Hveragerdi
Vestmanna Islands
N
AKRANES
REYKJAVIK
ELLIDAAR
KOPAVOGUR
HAFNARFJORDUR
KEFLAVIK
Reykir
66 kV
138 kV
Thingvalla-vatn
STEINGRIMSSTOD
LJOSAFOSS
IRAFOSS
HENGILL
Sog R.
Hestvatn
HVERAGERDI SITE
Kleifarvatn
Krisuvik
Selfoss
Olfusa R.
-LEGEND-
HYDRO POWER STATION
STEAM POWER STATION
ELECTRICAL TRANSMISSION LINE
295 TYPICAL LEVEL (METRES)
ROADS
SOUTH WEST ICELAND
0 5 10 15 20 25 km



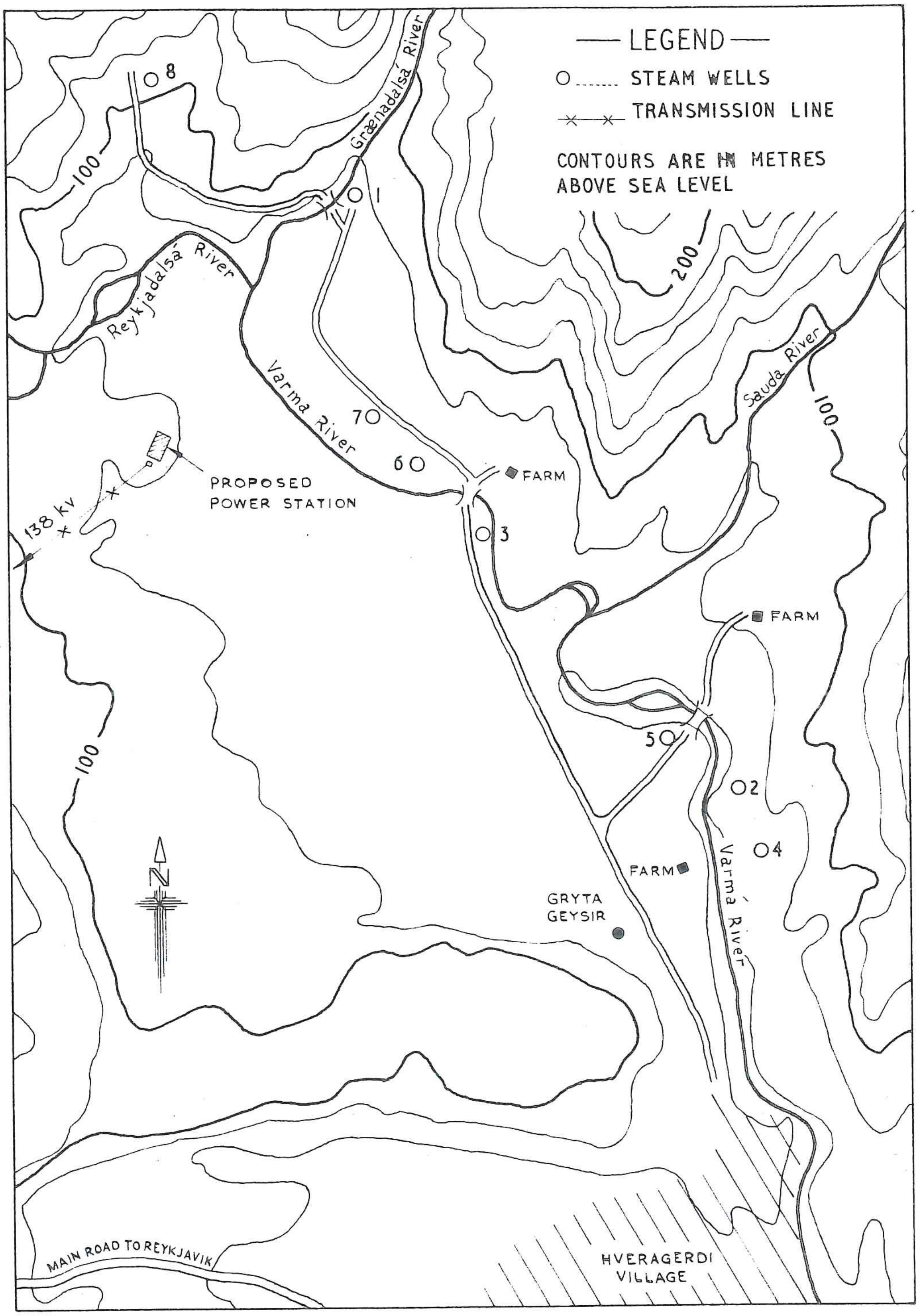
ELECTRICAL TRANSMISSION NETWORK OF SOUTH WEST ICELAND



PLANT INSTALLATION PROGRAMME
AND COINCIDENT MAXIMUM DEMAND (½ HOUR)
IN SOUTH WEST REGION

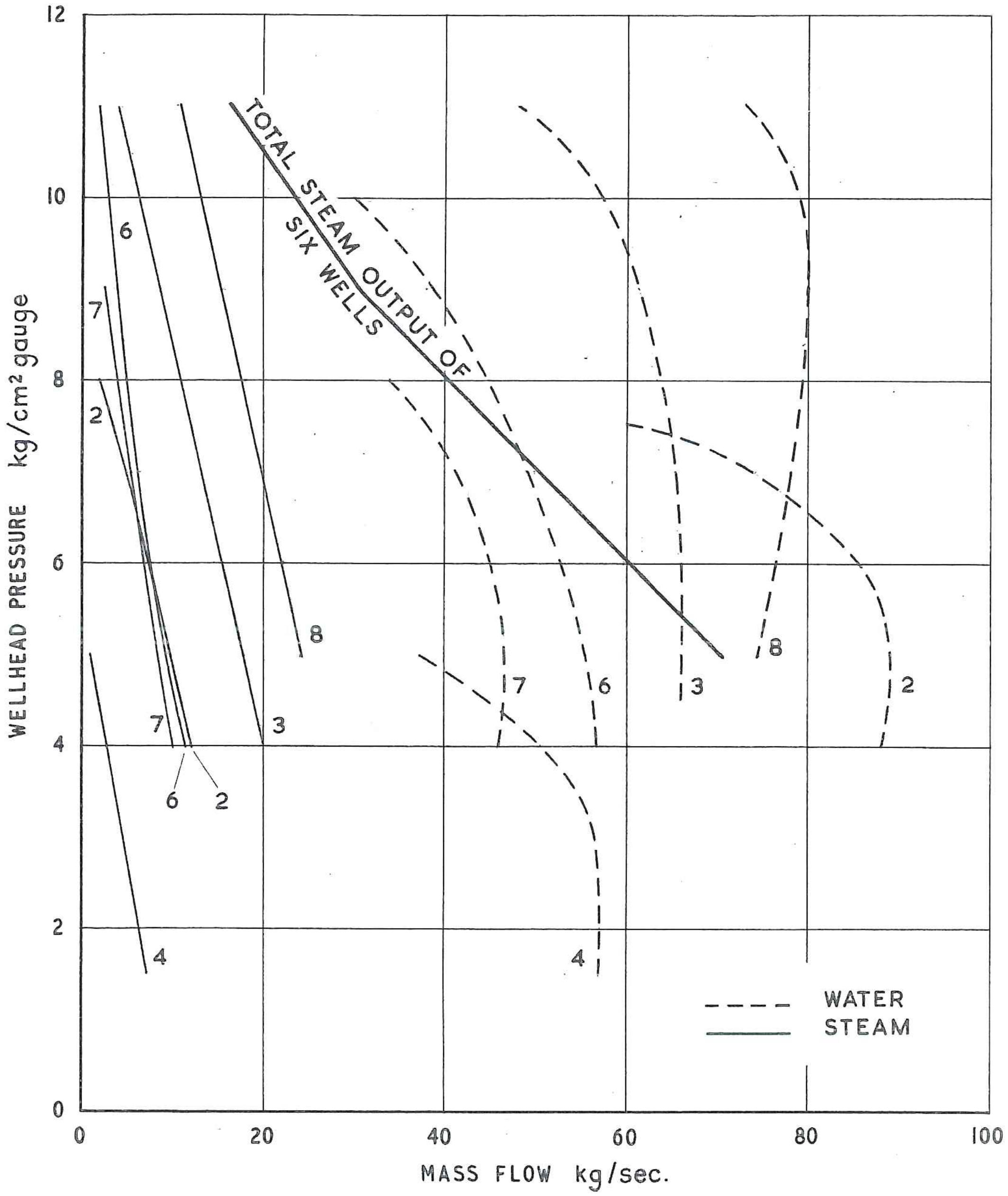


ANNUAL ENERGY REQUIREMENTS IN SOUTH WEST REGION

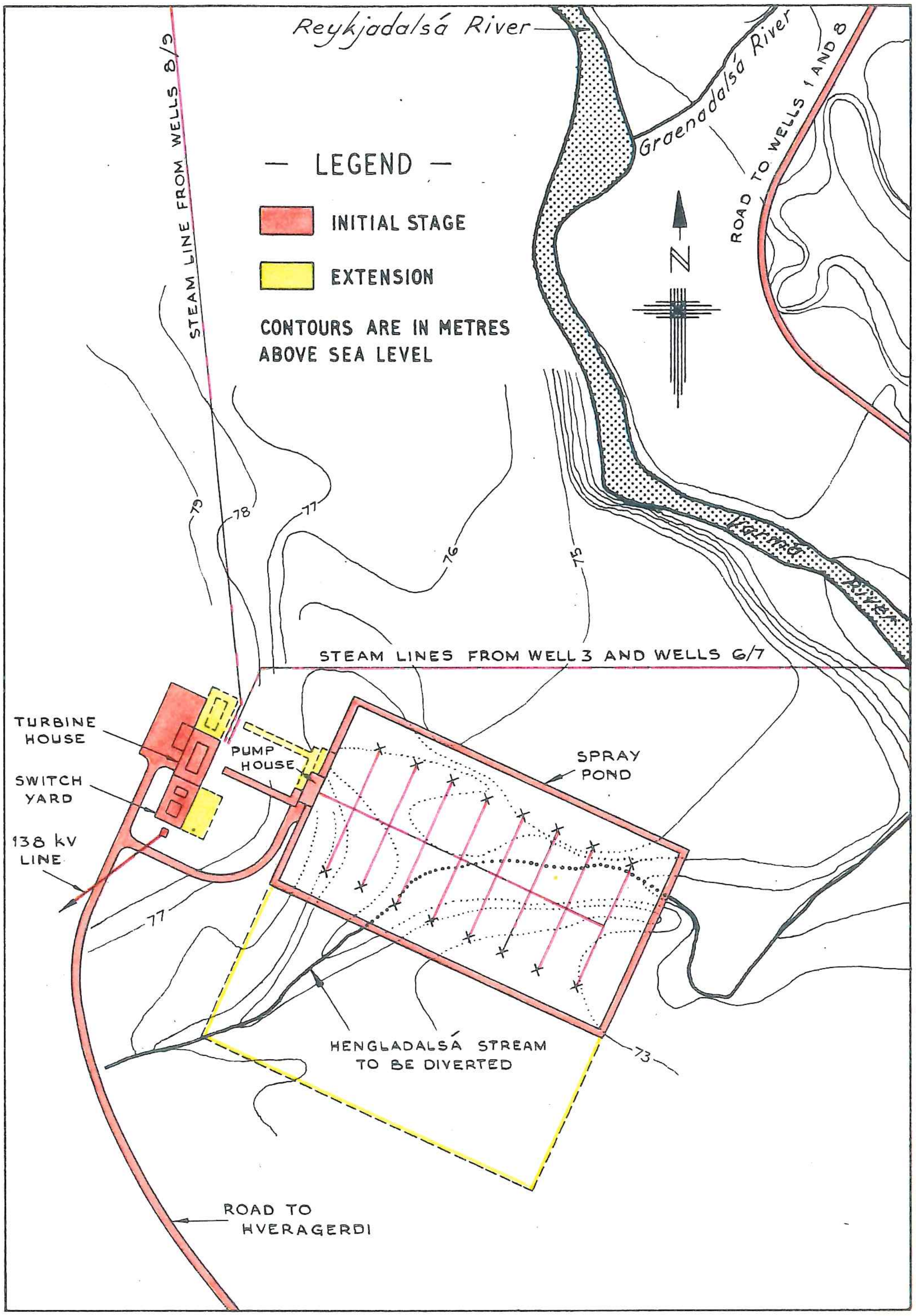


HVERAGERDI STEAMFIELD

0 100 200 300 400 500 m



CHARACTERISTICS OF WELLS



SITE PLAN OF PROPOSED POWER STATION

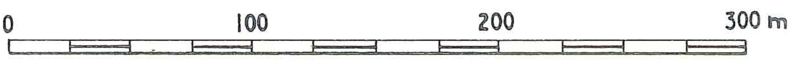
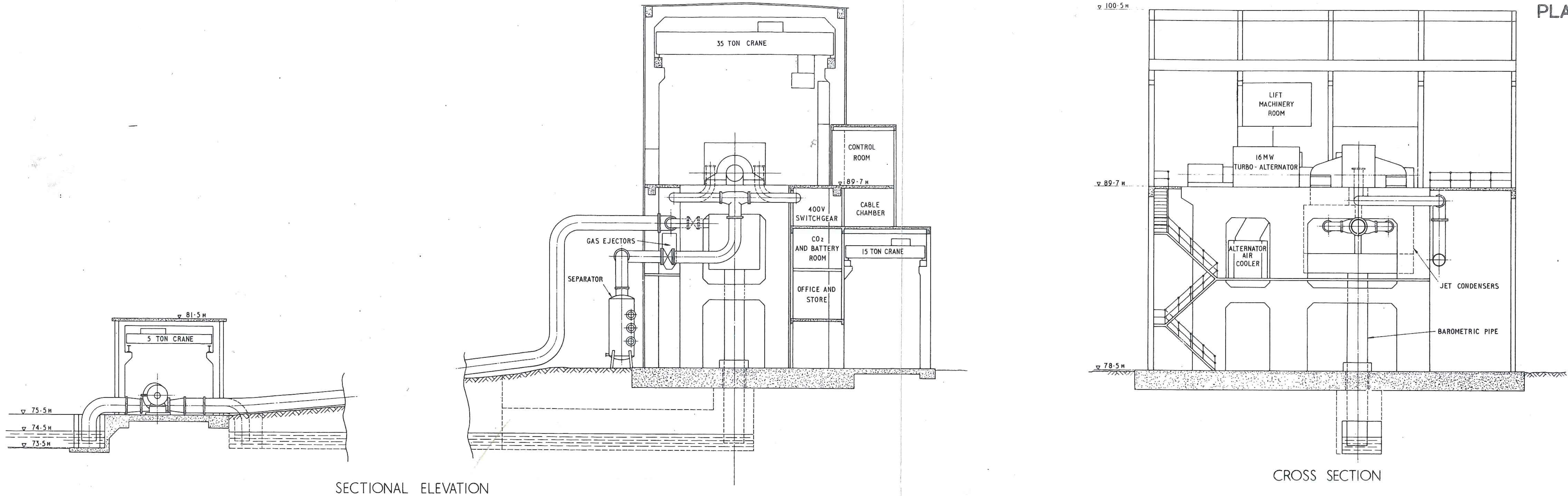
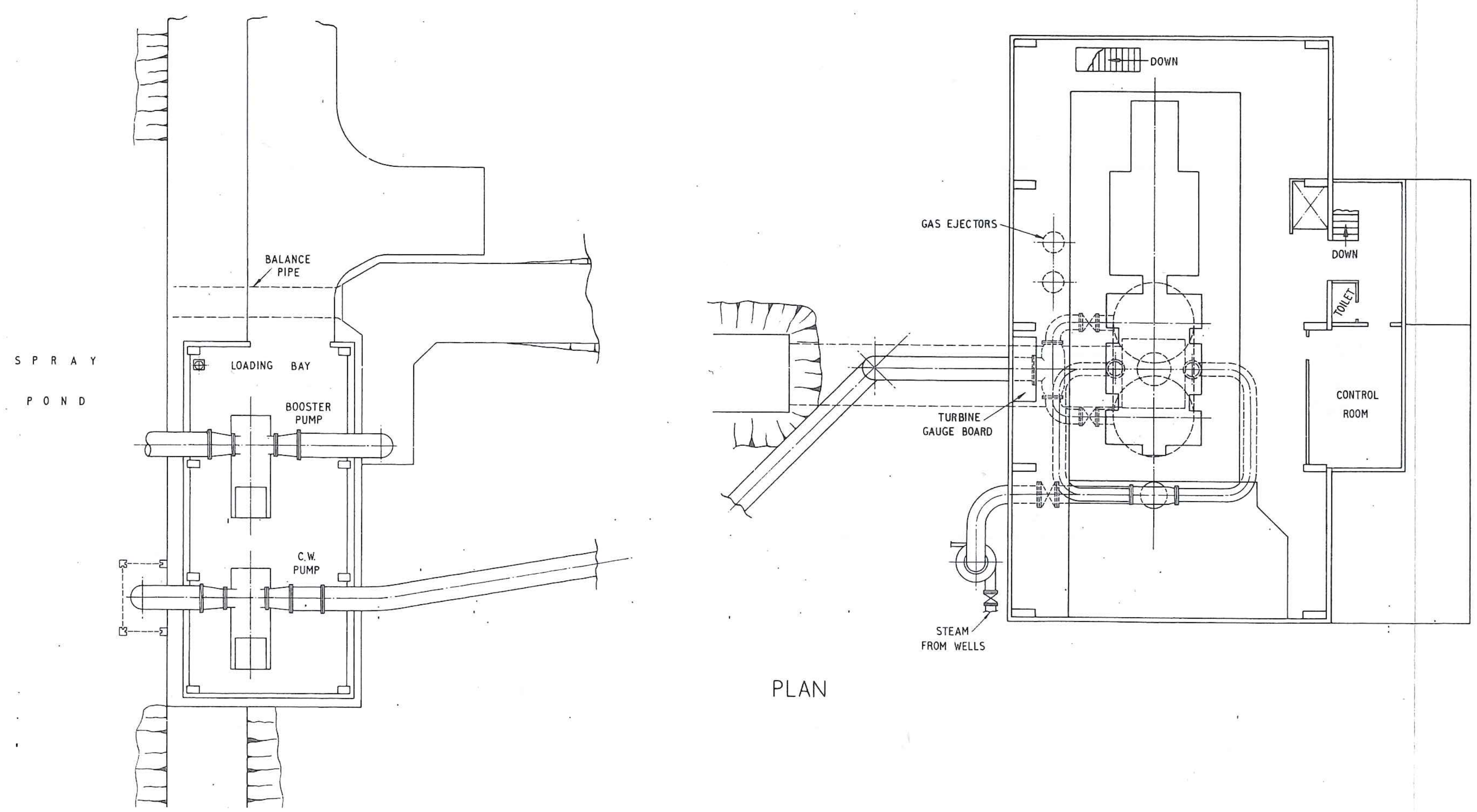
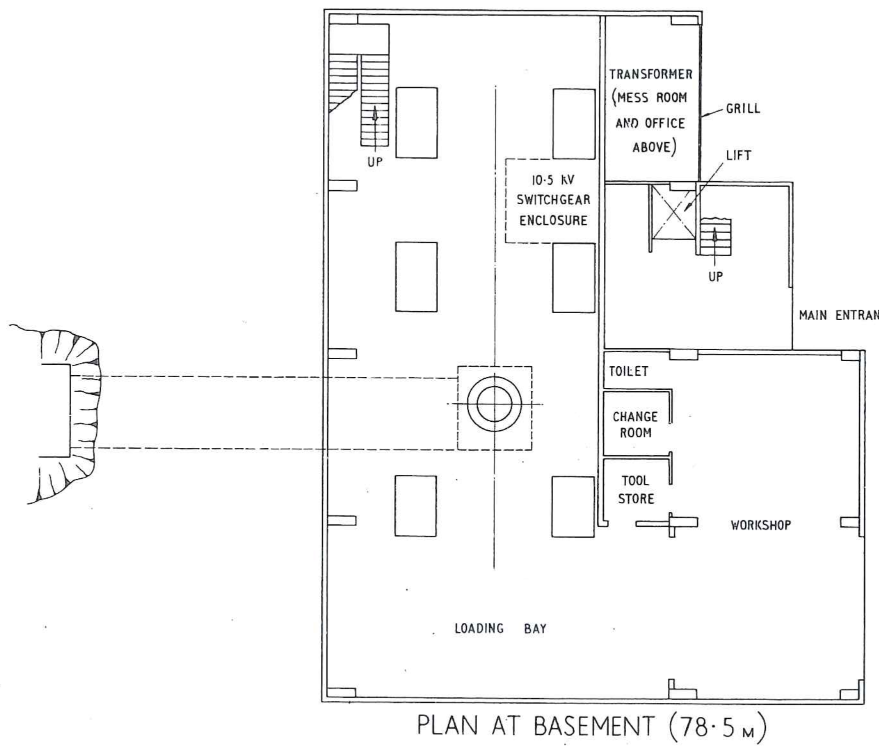


PLATE 8

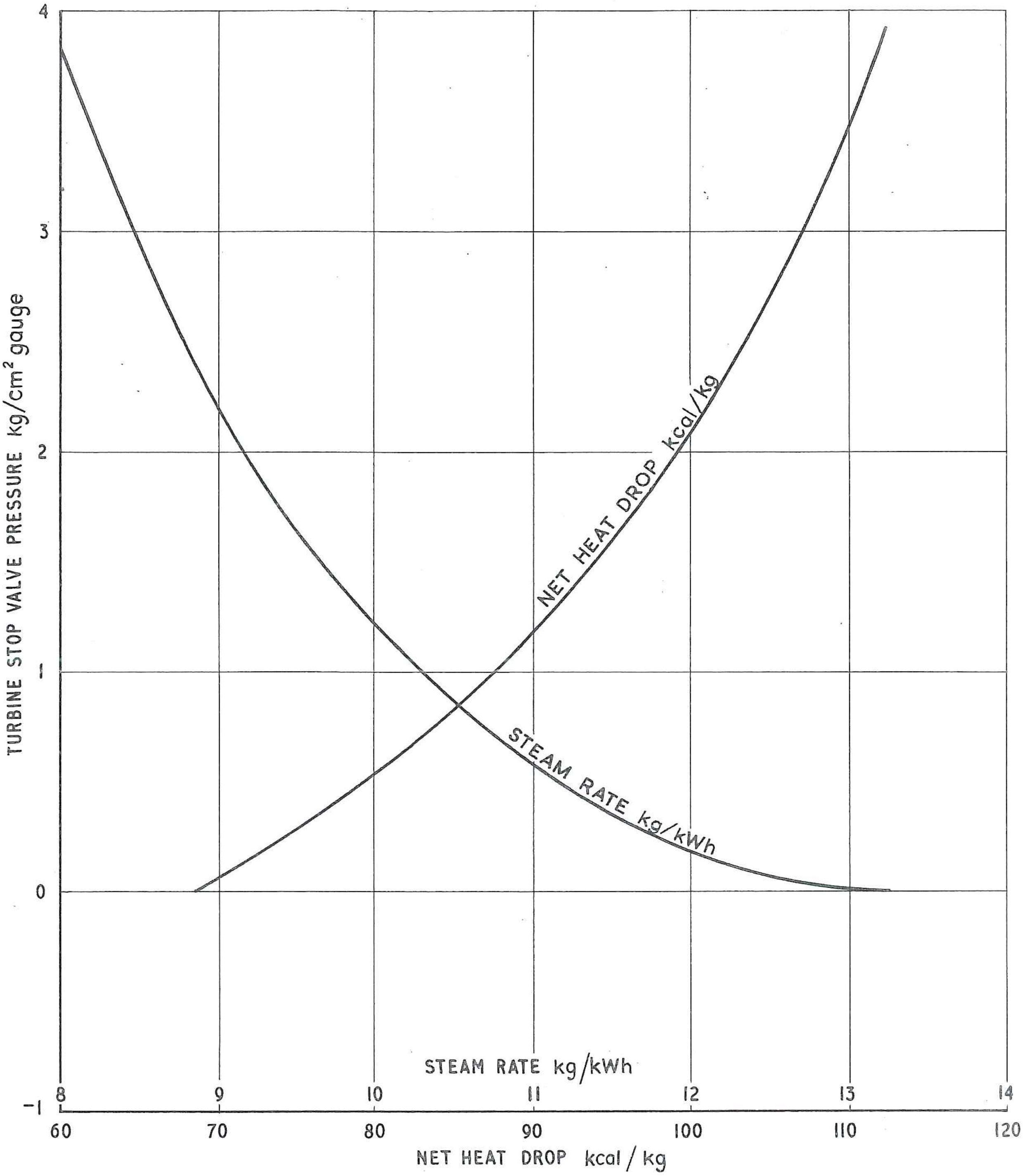






LAYOUT OF 16 MW GEOTHERMAL POWER STATION

5 4 3 2 1 0 5 10 15 20 METRES



HEAT DROP AND STEAM RATE WITH EXPANSION OF SATURATED STEAM

ASSUMPTIONS:

(a) BACK PRESSURE 0·069 atm. abs (2 in Hg)
(b) 5% PRESSURE DROP IN THROTTLE VALVE
(c) STEAM 1% WET AT TURBINE INLET
(d) LEAVING LOSS OF 5·55 kcal/kg
(e) POLYTROPIC EFFICIENCY 0·85
(f) BAUMANN WETNESS CORRECTION APPLIED

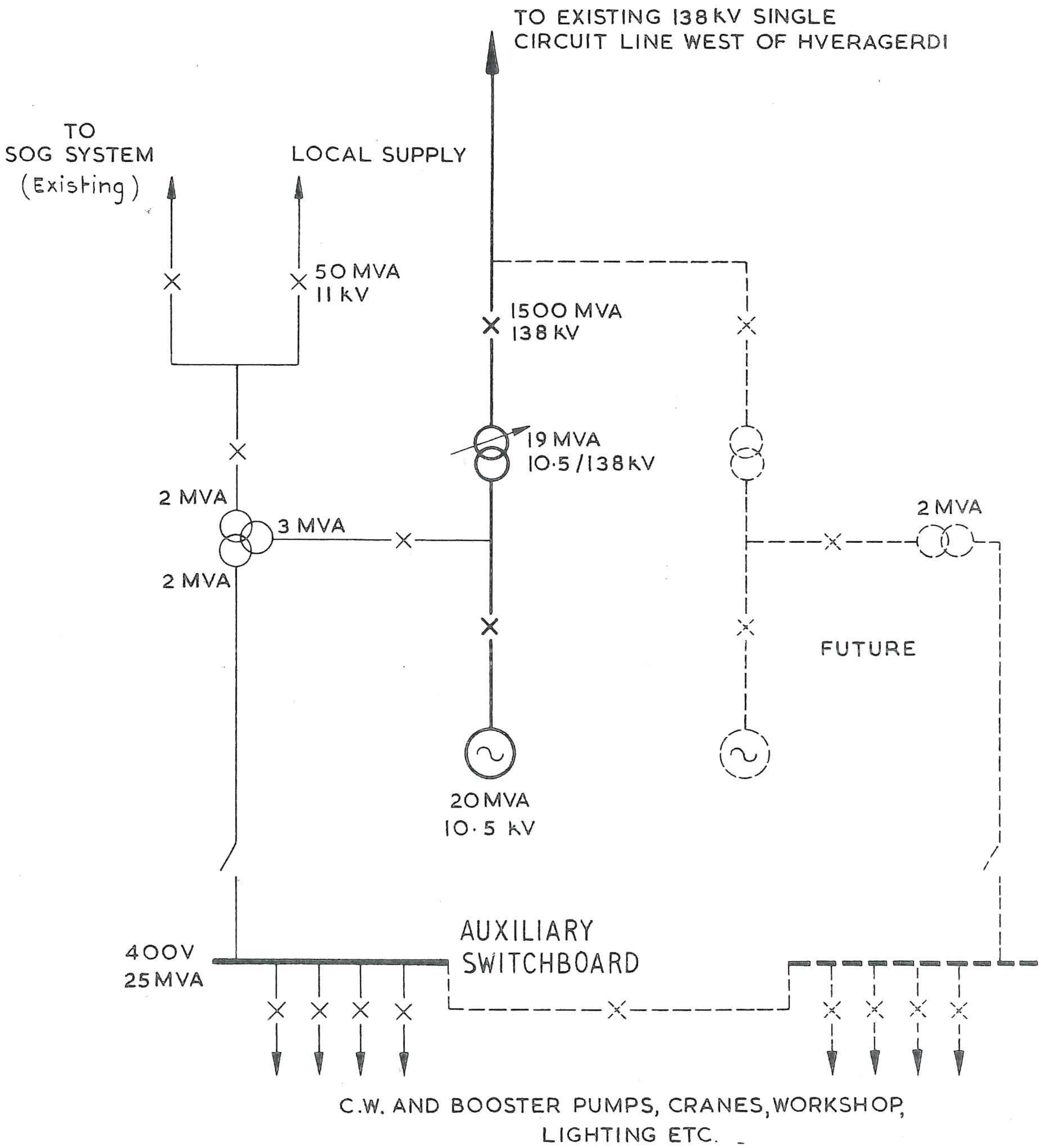
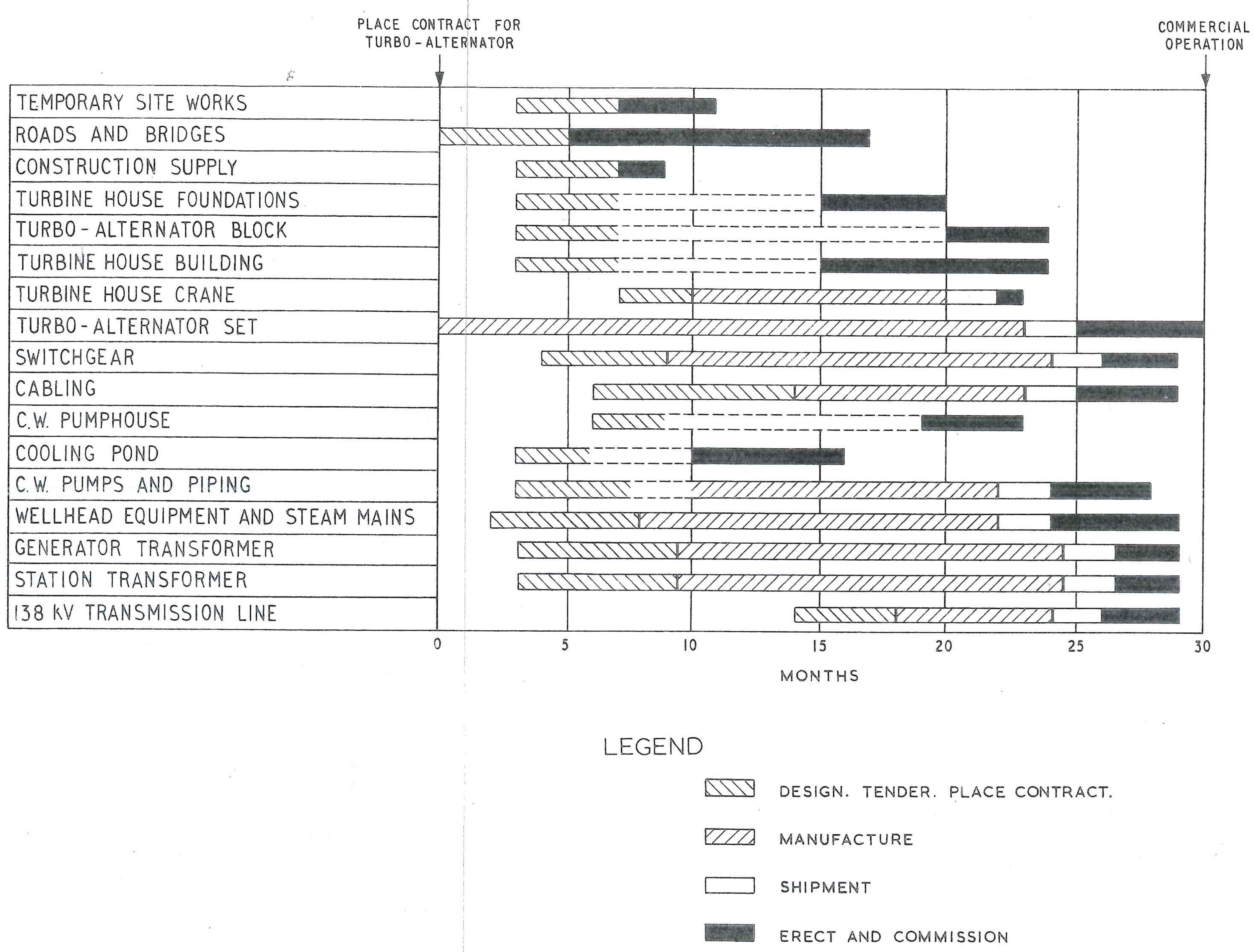


DIAGRAM OF ELECTRICAL CONNECTIONS

PLATE II



TENTATIVE CONSTRUCTION PROGRAMME
FOR STAGE I - 16MW