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EXPLOITATION OF EL TATIO GEOTHERMAL FIELD, NORTHERN CHILE

Feasibility Report

ELC-Electroconsult, Milano, Italia
March 1975 GCI-D-3489/e

INDEX

LIST OF DRAWINGS

1 INTRODUCTION

1.1 Terms of Reference

ELC was commissioned by the United Nations (UNDP) to carry out a Feasibility Study for the El Tatio geothermal project in Chile under the Contract No. 79/74 of June 15th, 1974.

ELC was requested to evaluate the technical, economical and financial feasibility of generating electrical power by using the thermal fluid produced from some of the El Tatio wells and was also asked to consider the possibility of coordinating power generation with the production of potable water, process steam and mineral extraction from the geothermal brines.

The Feasibility Study consisted of the following parts:

a. Reservoir and Production Wells Assessment

b. Electricity Production

c. Potable Water Production

d. Steam for Processing

e. Effluent Disposal

f. Preliminary Investigation of Extraction of Minerals of Marketable Value

g. Environmental Impact of the Project

1.2 General Remarks

The Feasibility Study had to be obviously adjusted to the results obtained from the production drilling program at El Tatio, barely completed by the time the study was start ed and only half way when the terms of reference for the study were prepared.

The fact that only two wells out of the seven drilled proved to be commercial producers, made it impossible to answer the critical questions on the reservoir and production assessment such as:

a. Size of the reservoir;

b. The probable reservoir drawdown at production rates of 1 000 and 5 000 tons per hour over a period of 25 years;

c. Estimate of the minimum spacing for development wells.

The present total mass output from the field is only 480 t/h. It should be also pointed out that an attempt of even making a very rough estimate of the size of the field is hampered by the fact that the seven wells are concentrated in an area of less than 1 km^2.

For the same reasons, it was impossible to construct a mathematical model of the reservoir, which is still a difficult task even in well developed and long exploited geothermal fields.

The present limited availability of geothermal fluid also reduced the manoeuvrability in dealing with the evaluation of the possible exploitation other than power, for example, the production of fresh water.

On the other hand, the solutions suggested and the choices made in the study apply to the present situation and refer only to the known small part of the El Tatio geothermal field.

If the field exploitation is extended in the future, such solutions could be modified according to the new situation.

1.3 Previous Studies

Under the UNDP project, a study was started in 1968 and lasted until 1974; a considerable amount of work was carried out in the El Tatio Area, listed as follows:

a. Geoscientific Surveys

Geology The geology in the selected project areas was undertaken and reported on by Sanchez (1963), Healy (1964; 1967; 1968; Feb., March, 1969; 1970, El Tatio, Puchuldiza; 1971; 1972; 1973 and 1974), Lahsen (1969; 1970 and 1971), Trujillo (1969; 1970; 1971 and 1972).

Geological surveys at El Tatio included mapping a large area extending west to Toconce and Caspana, and a detailed survey around El Tatio. Six exploration wells were drilled, through which surface and subsurface geologies were correlated.

The hydrology of the El Tatio basin was reported by Healy (1971), Mahon (1970) and Navarro (1972).

Geophysics Geophysical survey, consisting mainly of resistivity surveys, was undertaken and reported by Hochstein (1968; 1971, El Tatio and Puchuldiza; and 1972), Risk (1970, El Tatio and Puchuldiza), and Macdonald (Jan. and March, 1969; 1973 and 1974).

Geochemistry Field sampling and laboratory analyses were carried out by Ellis (1968; 1969, Jan. and June; 1970) and Mahon (Feb. Dec., 1970; Jan. Aug. 1971; 1972 and 1974).

b. Drilling Operations

Monitor Wells Between 1969 and 1971, six monitor wells were drilled to a nominal depth of 600 m, cased with 4" dia, with 3 1/2" dia. slotted liner over the lower 300 metres.

Production Wells Seven production wells were drilled between 1972 and 1974, with depth ranging from 863 to 1 821 m.

The cost of the whole activity was covered by the UNDP and the Government of Chile whose contributions amounted respectively to $ 1 917 701 and E° 710 799 960. These amounts were not included in the economical evaluation of the Project, being considered as sunk funds.

1.4 Existing Documents

A complete list of documents examined is given in Appendix No. 1.

1.5 Activities of ELC

At the end of July 1974 a team of experts from ELC arrived at Santiago and visited the El Tatio geothermal area to collect and examine the available documents and field data and to discuss all the aspects of the project with U.N. personnel and the CORFO Technical Staff.

During August and September, a testing program on wells 7 and 11 was carried out by ELC specialists.

In September, the ELC Chief Electrical Engineer paid a two week visit to Chile, calling in Santiago, Antofagasta and in El Tatio, in order to collect the relevant information about the production, transmission and electrical energy consumption in the Antofagasta province.

From September 1974, a study of all the aspects of the project required to be examined by the terms of reference, was carried out. In December 1974, the ELC Chief Geologist visited CORFO Offices in Santiago to collect the latest available data. An account of findings, a study of the data, the solution proposed for the preliminary design of exploitation of available commercial fluids and the relevant recommendations are the subject of the present report.

1.6 Acknowledgements

ELC are pleased to acknowledge the valuable assistance of UNDP Project Team, and of CORFO personnel, as well as that of all Governmental Agencies and Private Companies met by ELC personnel during their missions in Chile.

2 CONCLUSIONS AND RECOMMENDATIONS

2.1 Conclusions

The present study has been developed on the basis of the investigations performed at El Tatio geothermal field and of all existing data related to the electric power generation and water supply of the Antofagasta province.

2.1.1 The Geothermal Field The United Nations project explored the El Tatio geothermal field by geoscientific investigations followed by drilling 6 monitoring wells to a nominal depth of 600 m and 7 production wells to a nominal depth of 1 800 m. ELC experts carried out production tests in the wells.

Two production wells (N° 7 and 11) are now yielding 485 t/h of geothermal fluid at a well head pressure of 17.5 kg/cm^2 with an enthalpy of 270 kCal/kg.

The geological investigations indicate that the surface manifestations of hot water, geysers and steaming ground are concentrated in a depression of the tributaries of the Rio Salado Valley; the heat discharge is estimated at approx 30 000 kCal/sec.

The size of the geothermal area as defined by a geoelectrical survey is of the order of 30 km^2. Within this area, the most promising section seems to be the El Tatio Sur (about 6 km^2) where the production wells are situated.

The lack of basic data on the reservoir geometry, variations impermeability, recharge system, and relationship with cold acquifers do not permit an assessment of the energy potential of the field.

Nevertheless, if it is assumed that the most interesting sector has the same potential as that proved by the production wells, it can be estimated that there is a total energy potential of 100 MW.

2.1.2 The Geothermal Plant Possible utilization schemes for energy production can be based on the data of the characteristics of the available thermal fluid and tests that were carried out. The optimum scheme envisages an operating pressure of 17.5 kg/cm2 for wells 7 and 11, with two stage flashes at 5 and 1 kg/cm2 pressure for separating steam (with a condenser vacuum of 0.07 kg/cm2 abs), a turbine directly coupled to a generator and capable of producing 15.5 MW net electrical power.

The net potential at the outlet of the turbine generator set is 15 500 kW and can be produced for 8 000 hours/year.

This energy can be delivered to Chuquicamata through a 110 kV line, 95 km long, resulting at the 15 kV bus-bar of the Chuquicamata substation a net power of 15 000 kW or an available electrical energy of 120 GWh/year.

The total cost of investment for the El Tatio project (geothermal plant and transmission line) is evaluated at 12.1 million US$.

The cost of the energy delivered to Chuquicamata will be 16 mills/kWh.

2.1.3 Economics of the El Tatio Project In order to carry out the economic feasibility of the project, an anlysis of the characteristics of the present generating system of Antofagasta province was made for comparison purposes.

The generating system of the Antofagasta province consists of steam and diesel plants scattered at the consumption centers. The major part of the present potential (2 300 MW) is installed in Tocopilla; lines of 110 kV capacity with a length of 150 km deliver the energy to the mines of Chuquicamata, which consume 80% of the energy generated by the system.

The present average production cost of the power is approx 0.8 cents/kWh.

Owing to the future energy demand and the necessity of replacing obsolete and inefficient units, it will be necessary to install some additional potential of 100 MW divided in one or two steam plants, possibly in Tocopilla.

The effective production cost of the energy generated by the geothermal system and delivered to the substation at Chuquicamata was compared with that obtained from a conventional 115 MW thermoelectric plant installed at Tocopilla and 110 kV line for delivery to Chuquicamata.

In the first case (geothermal plant) the energy cost is 16 mills $/kWh and for the second case (conventional plant) it is 37.4 mills $/kWh.

The difference in cost is 21.4 mills/kWh in favour of geothermal power. With this value the benefit cost ratio and internal rate of return were calculated showing that the economic advantage of the project is maintained for interest rates up to 16-18%.

2.1.4 Potable Water Supply The water of the Cordilleran rivers are used for the potable water supply of Antofagasta province and the waters are delivered to the consumption centers by means of lengthy pipelines.

The present system can supply the demand up to 1980, except for a small deficit. In 1985 the deficit will rise to 500 l/s (15 million m^3/year) and will be concentrated mostly in the department of Antofagasta.

The study has analyzed various alternatives for partially or totally covering the foreseeable deficit.

One solution would be installing a conventional multiflash plant of 300 m^3/h capacity for desalinating the residual water from the geothermal plant; the cost of water treated in this way and supplied to the Toconce water mains will amount to a figure in the order of 1 US$/$m^3$ excluding transport costs to Antofagasta.

Another solution would be to install a conventional desalination plant in Antofagasta for treating sea-water with a capacity of 1 500 m^3/h and the cost of treated and delivered water could be approx 0.6 US$/$m^3$.

Finally, the Cordilleran rivers such as Rio Grande (San Pedro de Atacama) can be utilized to supply the above mentioned volumes with tubing similar to that of the existing network at a cost of 0.4 US$/$m^3$.

From the above, it can be concluded that desalinisation of residual water from the geothermal plant presents no advantages.

Furthermore, it should be noted, that the discharge of this residual geothermal water in the Rio Salado presents no ecological impact and the water can be used downstream by the Chuquicamata mines.

2.1.5 Mineral Extraction The extraction of minerals from the geothermal brines does not appear econimically feasible for the following reasons:

- the markets for elements such as caesium and rubidium are limited and local, and could only absorb about 20% of the amount extracted from the geothermal brines of El Tatio;
- it is easier to extract lithium from minerals, as the concentrations are higher;
- the metal extraction presupposes desalination of the residual water, an operation which was not considered economically feasible.

2.1.6 Corrosion Problems Possible causes of corrosion in materials of construction, valves and machinery of the geothermal plant were studied leading to the conclusion that it would be possible to prevent corrosion whithin a wide margin of safety using special materials or treating the materials used in an adequate manner.

2.1.7 Effluent Disposal The simplest solution will be to discharge the waters into the Rio Salado, when it can be considered that the same waters can also be used by the Chuquicamata mine.

2.1.8 Environmental Impact If the ecological conditions of the El Tatio area are considered, taking into account the limited size of the geothermal project, it is foreseen that they will not be affected appreciably.

2.2 Recommendations

Complete the long term testing programme started in August 1974 until data on reservoir pressure decline and wells interaction are completely satisfactory. Check in particular the following points:

- reservoir pressure decline with time
- variations of the pressure recovery time by means of shut in recovery tests
- interaction between the producing wells

If the results at the end of the recommended testing period (6 months is considered to be the minimum) will prove to be favourable:

Proceed with the preparation of the Project Contract of the geothermal plant and transmission line as soon as possible;

Try to enhance production of wells 10, 12 and 13 by means of injection of cold water so that the permeability is increased due to fracturing of the rocks by contraction;

Carry out additional investigations, mainly geo-electric, in the zone east of the El Tatio South to verify the extension of the productive zone, and then, on the basis of data obtained, drill new production wells;

Execute a hydrogeological study of the Andean region of the Antofagasta province to evaluate the water resources available for supplying the various centers of the Province.

3 THE LOCAL ELECTRICAL SYSTEM

3.1 Present Systems of Power Generation and Transmission

The area where the proposed geothermal plant is located is the First Geographic region of the Endesa System, which extends from Arica to Chañaral.

This region is characterized by a highly developed mining industry, a low population density, scarce water resources and by the concentration of consumption in isolated centres formed by the towns of Arica, Iquique, Antofagasta, by the installations of the Gran Mineria and by rural centres.

These characteristics have contributed to the development of isolated generation systems made up entirely of power plants with steam and diesel units.

The systems which are important with regard to the geothermal project are the ones of Cochuqui and Antofagasta.

3.1.1 The Cochuqui System The Cochuqui system (the Copper Company of Cochuqui), belongs to the mining company and feeds the whole group of mines of Chuquicamata and Exótica and the towns of Calama and Tocopilla.

The total installed capacity is 233 MW supplied by two plants.

The Tocopilla Plant is equipped with various groups of different ages starting from 1927 and having the following power capacities:

1.	7 MW	5.	9 MW
2.	5 MW	6.	18 MW
3.	8 MW	7.	18 MW
4.	18 MW	8.	8 MW

(The mean specific consumption of these groups is 0.46 kg Bunker C/kWh). Furthermore:

9. 45 MW

10. 38 MW

11. 38 MW

(With a mean specific consumption of 0.307 kg Bunker C/kWh).

The Chuquicamata plant which uses the furnace gases and is equipped with 3 groups of 7 000 kW, only two of which work simultaneously.

The maximum demand of the system, constituted basically by the mines of Chuquicamata and Exotica and the towns of Calama and Tocopilla, is at present 160 MW approximately.

The power is sold to the municipality of Calama at 40 Esc/kWh (exchange ~ 1 000 Esc/US) and the municipality sells it to the user at 27.5 Esc/kWh (average).

The official sale prices of power in Calama and Tocopilla are the following:

Regular Tariffs (Rates)

Use of Power	1 682.2 Esc/kWh
Energy up to 4 000 kWh	22.7 Esc/kWh
Energy up to 26 000 kWh	19.8 Esc/kWh
Energy up to 170 000 kWh	16.6 Esc/kWh
Energy above 200 000 kWh	13.4 Esc/kWh

Rates within 17 and 22 Hours

Energy up to 4 000 kWh	22.4 Esc/kWh
Energy up to 26 000 kWh	16.0 Esc/kWh
Energy above 30 000 kWh	11.0 Esc/kWh

The production costs of electric power are very high, because the Tocopilla plant is equipped with out-of-date groups and has a rather large staff; the average cost is approx 0.8 cts. US$/kWh.

3.1.2 The Antofagasta System The town of Antofagasta has, at present, an installed power capacity of 22.6 MW, produced by Diesel groups; the installation of a new Diesel group of 9 400 kW is expected by 1975.

The local market demand in 1971 was 15.4 MW power capacity and 58 GWh of electrical energy.

The production costs of power are between 7 and 12 cts. US$/kWh.

3.2 Foreseen Increase of Power Demand

3.2.1 Cochuqui System Once the present enlargements of the Chuquicamata-Exótica complex, now in progress, are completed, the production of refined copper will increase from 300 000 to 500 000 tons, so that the demand for electrical energy in 1980 will be a minimum of 232 MW to deliver 1 625 GWh/year.

According to unofficial information given by the Copper Company of Chuquicamata, it seems that a complete restructuring and modernizing of the whole metallurgical and mining complex is planned, which will increase the power demand up to 380 MW by 1990 with a total generation of 2 700 GWh/year.

The forecast for electric consumption for the towns of Calama and Tocopilla have been prepared by ENDESA and correspond to the following:

Years		1975	1980	1985
Tocopilla	(MW)	4.6	5.8	7.5
	(GWh/year)	17.0	29.0	27.0
Calama	(MW)	5.8	7.0	10.8
	(GWh/year)	19.0	24.0	32.0

3.2.2 Antofagasta System ENDESA also made a forecast of electrical power consumption for Antofagasta and surroundings, considering each sector of consumptions separately (domestic, commercial, industrial, mining services, etc.). The forecast was made by taking into account the growth of population, the increase of specific consumptions and known development plans.

The total demand was calculated by adding up the peak demands of various categories of consumers, occurring normally in winter, from 7.00 to 10.00 p.m.

The global forecast for the Antofagasta system is the following:

Years	1975	1980	1985
Power demand (MW)	23.0	34.0	46.0
Generated power (GWh/year)	95.0	132.0	210.0

A provision is made for a link up with the Cochuqui system. In order to meet the increased demand expected in the year 1980, in the inter-connected Cochuqui-Antofa gasta system and also to replace some of the older and in efficient existing groups, the installation of two 50 MW steam units in Tocopilla is planned.

4 EL TATIO GEOTHERMAL FIELD

4.1 Location

The area under consideration, which covers about 100 km^2, is located on the easternmost part of the Antofagasta province, near the Bolivian border, about 230 km from the sea and 90 km east of the major copper mine of Chuquicamata (See Plan GCI-1001).

The nearest harbour is Antofagasta (about 400 km by road) and the nearest airport, connected by regular flights to Antofagasta, is at Calama.

From Calama, the El Tatio area can be reached by a good road (195 km) through San Pedro de Atacama. Alternative roads from Calama are the road of the aqueduct of Toconce to Linzor through the village of Caspana, and the international road to Bolivia via the Calama sulphur mine and the town of Linzor.

4.2 Physiography

The El Tatio geothermal area is a fairly flat depression on the Andean Cordillera, situated at an average altitude of 4 300 m. The surrounding slopes and mountains have rounded forms, which are the result of frost action of Quaternary glacial erosion and of the covering by morenic deposits. (See Plan GCI-1002)

This depression corresponds to the drainage basin of Rio Salado that collects the flow of several small streams and of numerous thermal springs. The springs of cold fresh water are rare and have low discharge.

Climatically, the El Tatio area is in the region corresponding to the "high-Andean climatic plain" (also known as microthermal plain). This part is above the 4 200 m level with a yearly average temperature of approx 0° C (minimum -20° C and maximum +20° C) with low precipitation (less than 150 mm/yearly concentrated in the period of December/ /March) and high evaporation (approx 2 000 mm/yearly).

4.3 Geology

4.3.1 General The El Tatio and surrounding area were studied in detail by Healy, Lahsen and Trujillo and the results were presented in a number of reports.
A synthesis of these data and of the subsurface information is found in the Final Report by Healy, 1974.

For the regional geological picture, reference can be made to the papers by Cecioni, Frutos and others (See References).

From the available information, the essential elements of the El Tatio Geothermal field can be summarized as follows.

4.3.2 Stratigraphy The stratigraphic sequence consists of volcanics (ignimbrites, breccias, tuffs and lava flows) of Miocene to Quaternary age, resting on Cretaceous marls (Quebrada Justo Formation) and partially marine Jurassic sediments. The thickness of the volcanic sequence in the wells is in excess of 1 800 m (in well 9 the Cretaceous was not reached).

4.3.3 Structure The El Tatio area is part of large graben (÷8 km wide) bound on the west by the N/S trending (Serrania de Tucle horst with outcrops of Cretaceous marls) and on the east by the Bolivian plateau, where Cretaceous shales also outcrop. The exact position of the eastern limit, probably running along the eastern side of the Tocorpuri-Deslinde volcanic belt, is not well defined. In the producing area of El Tatio the downthrow of the graben is in excess of 2 000 m and surface geophysical information suggest that the geothermal area is divided into blocks by faults with trends NNE-SSW, N-S and ESE-WNW. Some of these fractures are proven to act as hydrogeological barriers (See Plan GCI-1003).

4.4 Hydrogeology

In the geothermal area, an upper aquifer is found in Tucla dacite, resting on the impervious Tucla tuffs (perched aquifer).

Below this aquiclude the geothermal acquifer is encountered in the Puripicar-Salado ignimbrites and in the upper Peñaliri breccia. The remaining section of the Peña liri Formation is impermeable or poorly permeable, but the main aquiclude is the Cretaceous shaley unit lying at unknown depth. The permeability is always related to fisures and joints.

The recharge of the geothermal aquifer takes place in the Bolivian plateau and in the eastern slope of the Andean Cordillera. Groundwater flows westwards towards Serrania de Tucle horst, whose Cretaceous core acts as a barrier that forces water to emerge in the El Tatio area, in the form of hot springs and geysers (See Plan GCI-1004).

Both spring and borehole water appear to have the same origin, hot water with principal constituent NaCl. Isotopic analyses also confirm a common origin for spring and well waters and points to a recharge area in the east.

Heating of water infiltrated in the Bolivian territory probably takes place in the volcanic belt of the Andean Cordillera where a good permeability and an easy penetration of water at depth can be expected.

During the underground migration these waters change their chemical and physical properties due to different mixing processes with cold waters, heat loss or gain through conductivity, ebullition or interchange with the reservoir rocks etc., but never they totally conceal their common origin as it is indicated by some molar relations Cl/B, Rb/Cs, Na/Li and by the value of certain elements: Cl.B.Cs.

4.5 Characteristics of the Geothermal Field

4.5.1 Surface Manifestations consisting of hot springs, geysers and fumaroles, are concentrated in an L-shaped depressed area, in the valleys of the tributaries of Rio Salado. Estimated natural heat discharge is about 30 000 kCal/sec.

The size of the geothermal area was defined by geoelectrical surveys, including the dipole. The area with resistivity lower than 5 Ohm/m, (corresponding to probing depths of 1 000 to + 2 000 m) is about 30 km^2. It is fairly well defined except to the SE and NE, where assumed upflow areas lie (See Plans GCI-1005/1 and GCI-1005/2).

4.5.2 Wells Drilled Apart from six exploratory slim holes, seven production wells have been drilled in the geothermal field.

These wells were concentrated in the El Tatio South area, which from surface and subsurface information appeared to be the most promising.

Well 7: good commercial producer. The production zone was located at 795 m, near the bottom of the Salado ignimbrites.

Well 8: non producing, due to lack of permeability in the interval of interest. The section of maximum temperature (Puripicar) has been cased off.

Well 9: non producing apparently due to poor permeability. The section of maximum temperature was cased off. The well discharged about 500 t of fluid together with large amounts of materials during 4 hours, until the hole became blocked. After being cleared the well again discharged, but with lesser intensity, and was blocked again up to the casing shoe (599 m). According to Healy the well discharged drilling fluid flashing in the Peñaliri Formation.

Well 10: mediocre producer because of reduced permeability probabily due to hydrothermal alteration. The well initially discharged about 400 t/h, and progressively decreased to about 70 t/h total fluid.

Well 11: good commercial producer. The production zone could not be located because, due to a casing failure at 572 m, it was impossible to take measurements below that level.

Well 12: non commercial producer, as output insufficient for power. Wellhead pressure declines to about 0.7 kg/cm2 in about an hour of vertical discharge. Circulation losses (40 t/h) from 814 m to 999 m suggest moderate permeability in the lower part of Salado and the upper Peñaliri where maximum temperature is found (226° at 816 m).

Well 13: non commercial producer, similar in behaviour to well No. 12.

4.5.3 Synthesis of the Data In Plans GCI-1006 and 1007, the stratigraphic correlations and the temperatures of the different wells are given. In Plan GCI-1008 are given the geometry of the more important geological formations obtained from the stratigraphy of the wells.

Only two out of the seven wells drilled proved to have a steady and commercially exploitable output and were considered for the feasibility study of the power plant. Well 10 though not of negligible output, did not guarantee a steady regime and was therefore excluded from this first power scheme.

Erratic permeability seems to be, therefore, the critical factor in the El Tatio field. Despite the occurence in the reservoir rocks of a diffused network of fractures and joints (as shown by the drill cores), these appear to have been progressively sealed up by the precipitation of silica and calcite from the geothermal water circulating towards zones of lower pressure and temperature.

This fact suggests, indirectly, that better permeability may be encountered closer to the assumed upflow areas in the south east of the field, where higher temperatures may be expected.

The distribution and position of maximum temperatures in the geothermal reservoir (See Plan GCI-1009) indicate in fact a temperature increase towards the SE, accompanied by a progressive lowering of the maximum temperature level. The temperature profiles of each well (Plan GCI-1006) and their correlation (See Plan GCI-1007) clearly point to a general hot water flow towards the NW.

It should also be observed that only wells 8, 9 and 10, situated on the western side of the area drilled, show a marked temperature inversion below the zone of maximum temperature. The fact that a similar temperature inversion is not observed towards the east also suggests the proximity of the area of upflow.

4.6 Production Tests- Discussion of Results

4.6.1 Tests on Well No. 7 The internal dimensions of this well are shown in Plan GCI-1010, to enable flow calculations to be made for conditions prevailing within the rising fluids. From the point of view of electric power, the most important test result is shown in Fig. 4/1, where the total flow is given at various well head pressures. The enthalpy was found to be constant over the whole range of pressures measured and was determined with the flow by means of lip pressure and water discharge rates over a rectangular weir at the mobile silencer outlet. Actual temperatures of the water phase entering the hole were measured (See Fig. 4/2) and they were found to be a little higher at 262.4° C than the comparable temperature taken from the enthalpy as determined above. However, the lower value is taken for all calculations of quantities and electric energy.

A pressure and temperature profile was measured by weighted instruments lowered down the hole at the greatest possible flow of 245 t/h and it was found that flashing took place right at the hole bottom. This is shown in Fig. 4/2 by the fact that the temperature was increasing even at the lowest level although very close to the all-water condition obtained at a temperature of 262.4° C.

With a pressure instrument set at 800 m, the well discharge was progressively reduced in stages and the rise in pressure was registered on the 3 hour clock of the instrument. The results are plotted in Fig. 4/3 and show that over most of the range, the "draw-down" is proportional to flow to the 1.85 power. This result could agree with the hypothesis of a flow through cracks but it could also indicate that flow into a well is dominated by a turbulent flow regime. Assuming the hypothesis of a flow through cracks, to find the exact location of the crack supplying the well, the region was narrowed down to about 30 m. Temperature measurements were taken at one meter interval over this range for conditions of minimum sustained flow at MDP (Maximum Discharge Pressure). The results in Fig. 4/4 show the crack to be located at about 795 m below the CHF.

Also plotted was flow versus the total vertical pressure drop in the well from a depth of 800 m to the wellhead pressure location. This is given in Fig. 4/5 and when the curve is extrapolated to the maximum flow of 275 t/h, the bottom hole pressure can be estimated and hence the drawn-down. This value is transferred to Fig. 4/3 where it is shown as a dotted extension, indicating that the whole curve on log-log paper is of the "S" type.

Calculations confirm that the pressure at the bottom of the well near the crack falls to below 28 kg/cm2 abs and hence well below the saturated vapour pressure of water at 262.4° C which is 48.5 kg/cm2. In fact, the high velocity at which the water travels along the crack towards the well (calculations have determined that it reaches about 100 ft/sec when entering the hole) prevents the nucleation of steam bubbles and then the formation of steam. Hence, there appears to be no threat of mineral deposition in the crack, which would progressively choke off the flow.

4.6.2 Tests on Well N° 11 The internal dimensions of well N° 11 are shown in Plan GCI-1011 and are similar to those of well N° 7.

The output test of Fig 4/6 shows that the maximum discharge is about 9% less than that of well N° 7 while the MDP is identical at 25 kg/cm2 abs.

It was not possible to measure below a depth of 572m because of a suspected casing break or other damage at that depth. Therefore Fig. 4/7 only shows pressures and temperatures down to 500 m and hence we were unable to measure reservoir pressures and temperatures.

However, because of the similarities of flows and

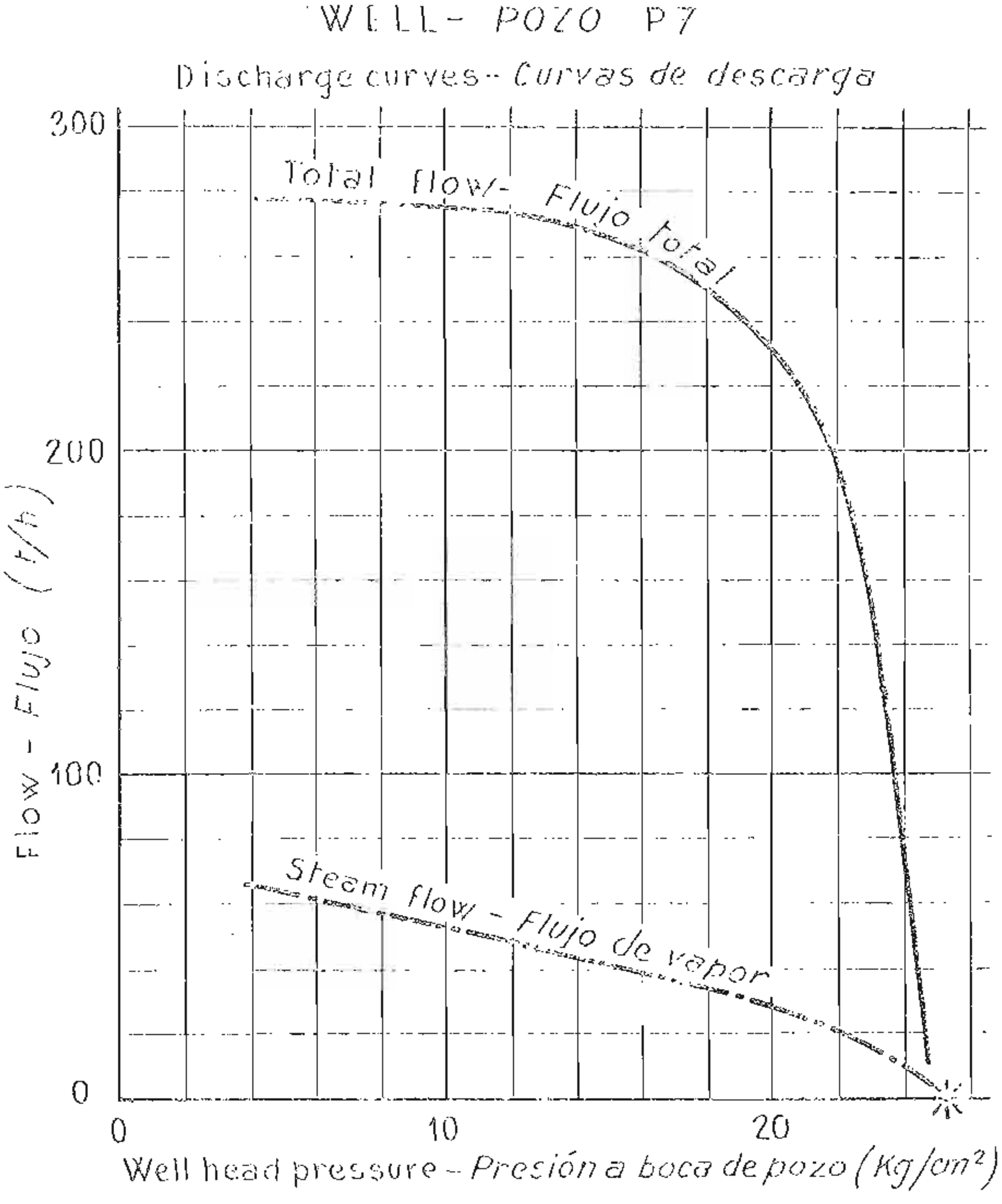

WELL- POZO P7
Discharge curves - Curvas de descarga
300
200
100
0
Flow - Flujo (t/h)
Total flow - Flujo total
Steam flow - Flujo de vapor
0
10
20
Well head pressure - Presión a boca de pozo (Kg/cm²)

FIG. 4/1

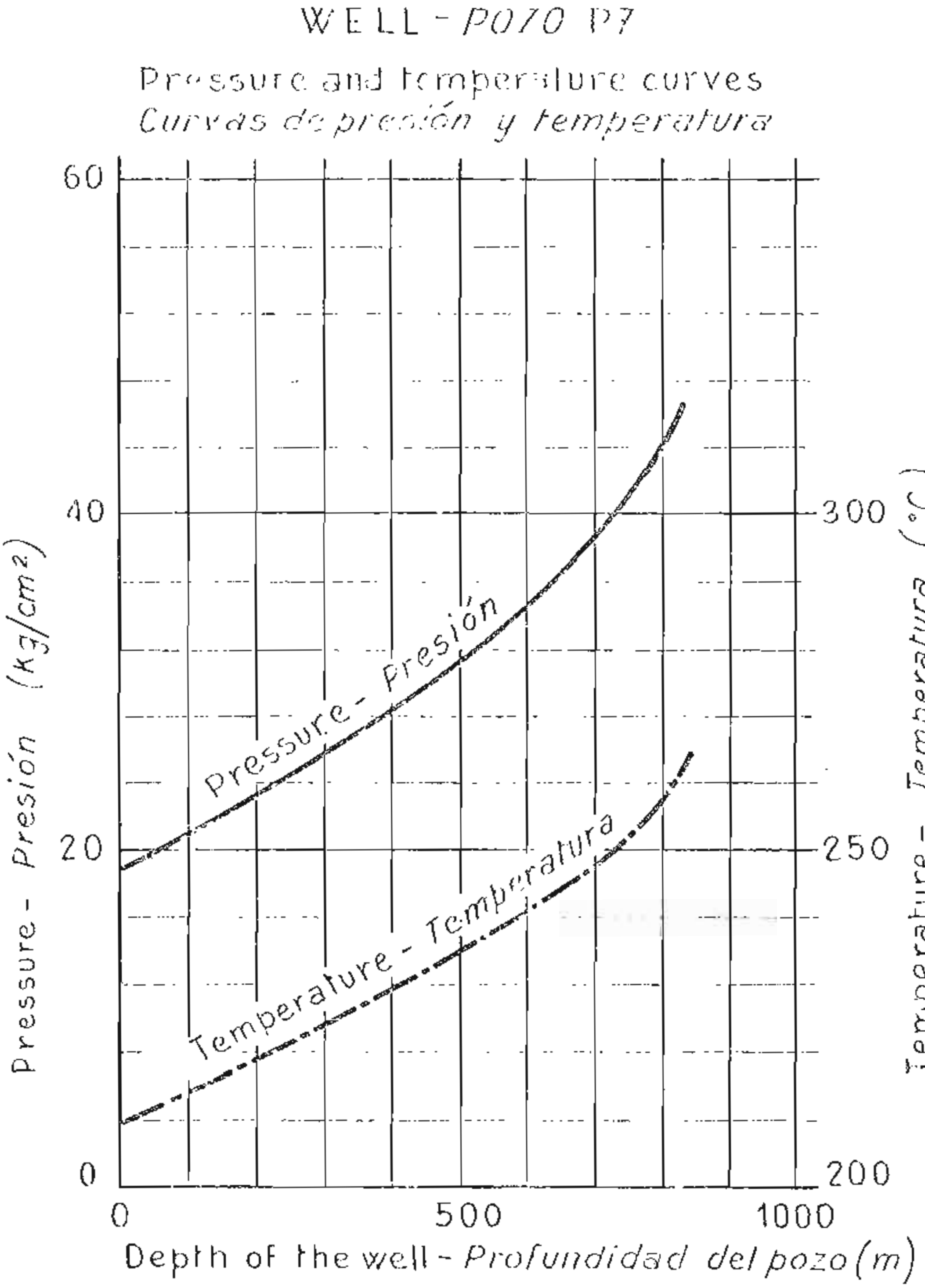

WELL - POZO P7
Pressure and temperature curves
Curvas de presión y temperatura
60
40
20
0
300
250
200
0
500
1000
Pressure - Presión (kg/cm²)
Temperature - Temperatura (°C)
Pressure - Presión
Temperature - Temperatura
Depth of the well - Profundidad del pozo (m)

FIG. 4/2

enthalpy with that of well No. 7, it is believed that both wells derive their hot water from the same source. The geo chemistry results support this viewpoint. Also a comparison between the pressure and temperature curves of Fig. 4/2 and 4/7 for identical flows is reassuring. It should be noted, too, that the same mobile separator-silencer was used to determine the outputs and enthalpies of both wells and the same lip pressure pipes and gauges were similarly employed.

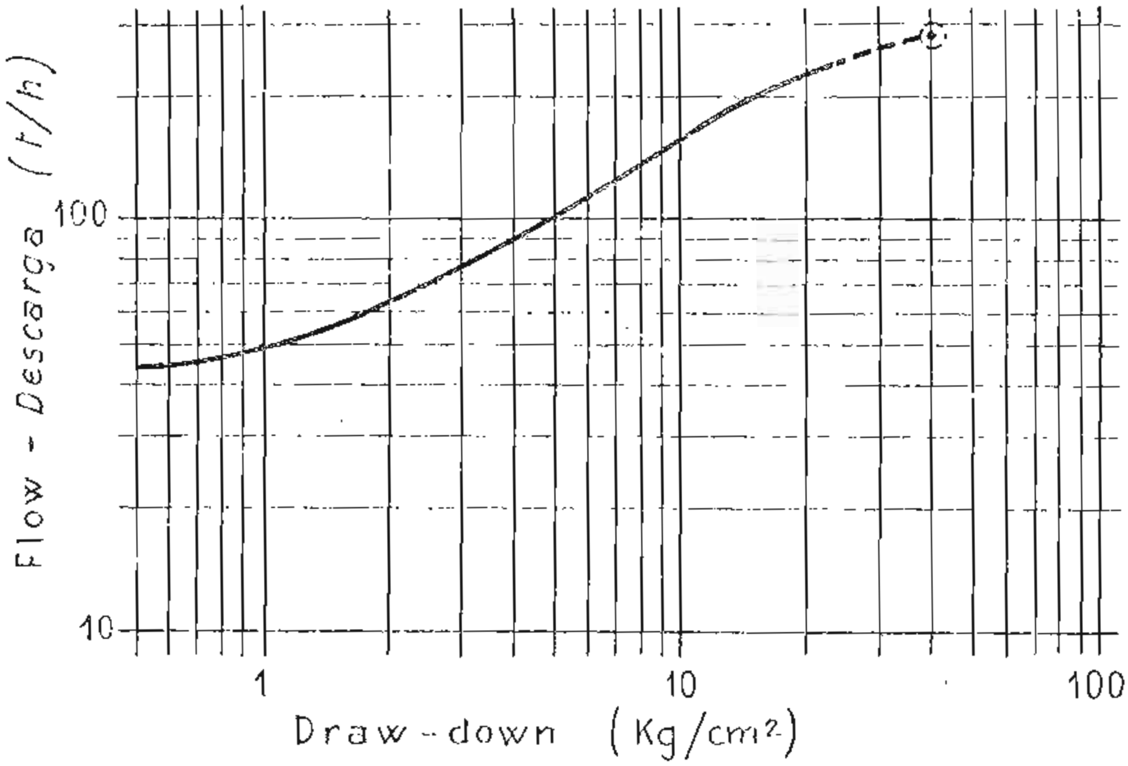
4.6.3 Interaction Tests Between Well No. 7 and No. 11 Well No. 7 was opened up vertically under conditions of maximum discharge and left discharging for one day in order to stabilize. Once the lip pressure and well head pressure were steady, well No. 11 was similarly discharged vertically without causing any significant change measurable on the gauges of well No. 7. Also, the gauge readings on well No. 11 were the same as those taken when that well had discharged previously with no others open. Hence, it is accepted that no interaction occurs between these wells. It should be noted that both wells would be throttled to an operating wellhead pressure of 17.5 kg/cm2 abs under production conditions which means that their bottom hole pressure would normally be at about 42 kg/cm2 abs; this can be compared with a bottom hole pressure of less than 28 kg/cm2 when the wells are discharging at a maximum vertically. Hence, if there is no detectable interaction found under maximum flow conditions, there is certain to be no effect under normal operating conditions.

4.6.4 Reservoir Changes under Draw-Off Measurements taken in May 1973, soon after Well No. 7 had been drilled, show that the static reservoir pressure at that time - and before any significant discharge had taken place - was 68 kg/cm2 abs. Estimates have been made as to the amount of fluid removed from the reservoir since that time and also during the present series of tests. These amounts are plotted against recent measurements which show that an initial pressure decline is tending to level-out; at the same time, there is no apparent change in the reservoir temperature (See Fig. 4/8).

4.7 Power Potential of the Geothermal Field

As indicated in paragraph 4.5, the area of geothermal interest defined by the geoelectricity is approximately 30 km2.

Flow-rate plotted against draw-down at 800 m depth.
Draw-down en función de la descarga a 800 m de profundidad.



Note:

Draw-down = $\Delta P = (P_o - P_B)$

P_o = Reservoir pressure - *Presión del reservorio*

P_B = Bottom hole pressure - *Presión de fondo pozo*

⊙ Calculated for max. flow - *Calculado para la descarga máxima*

FIG. 4/3

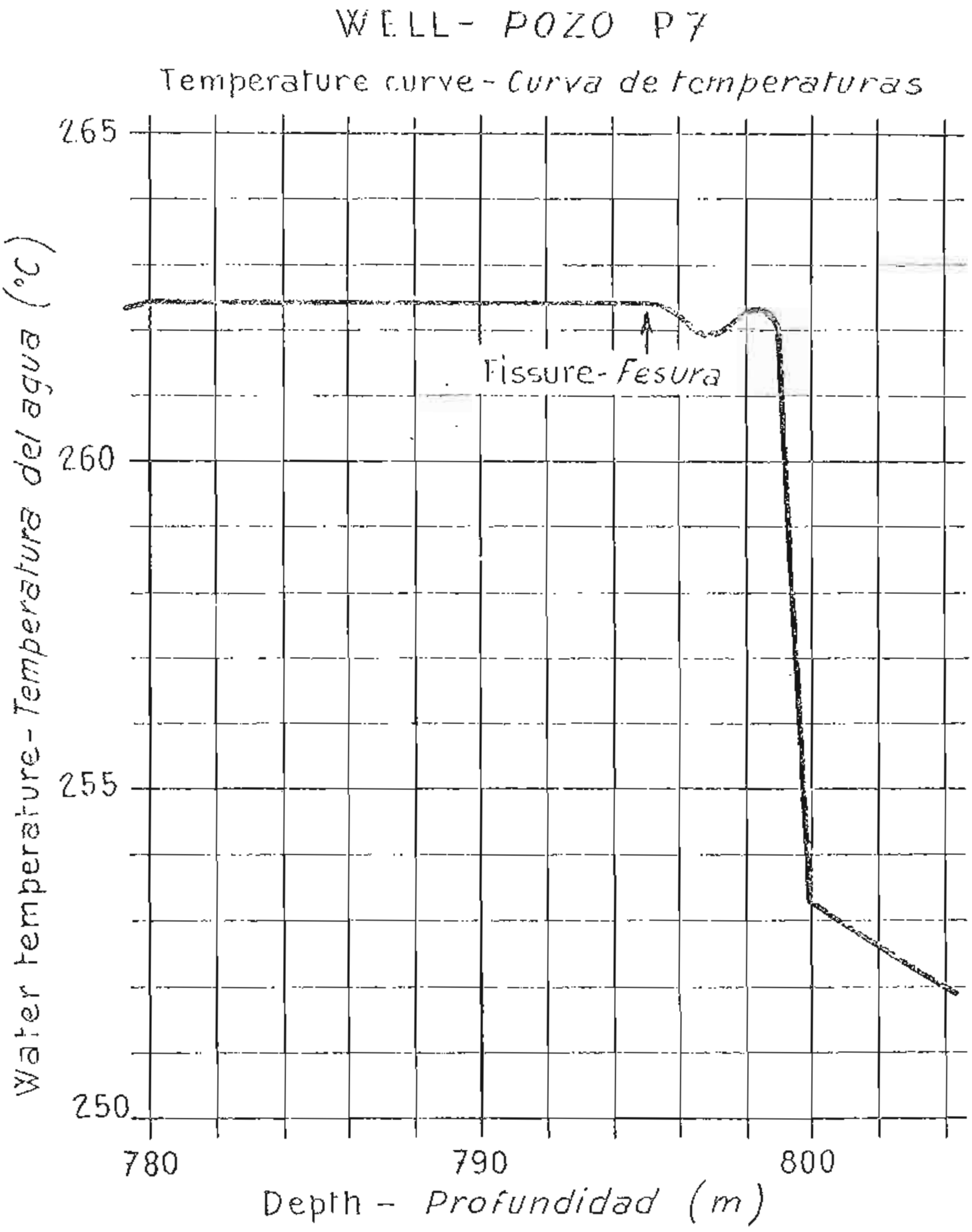

WELL- POZO P7
Temperature curve - Curva de temperaturas
265
260
255
250
Water temperature - Temperatura del agua (°C)
Fissure - Fesura
780
790
800
Depth - Profundidad (m)

FIG. 4/4

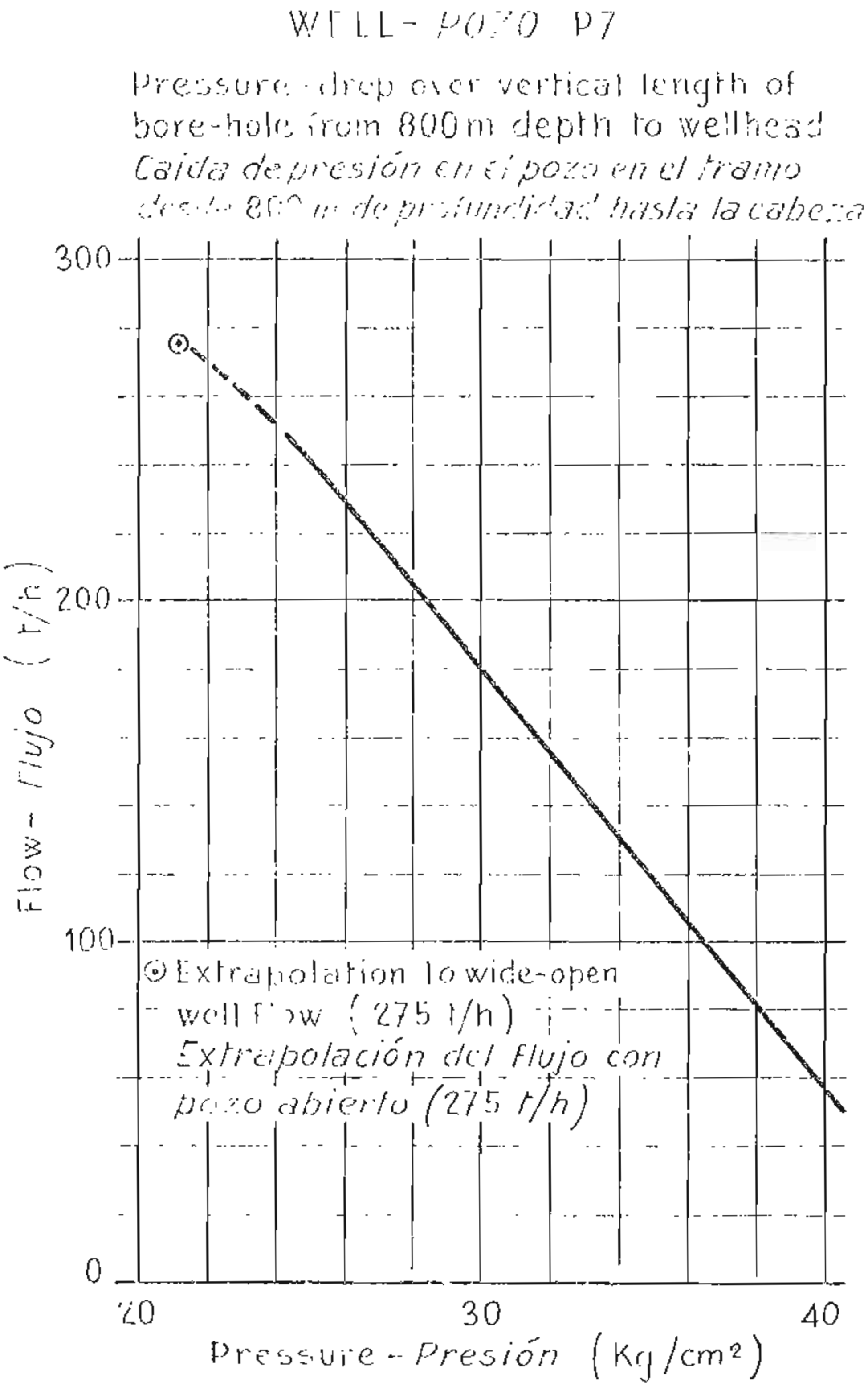

WELL- POZO P7
Pressure-drop over vertical length of bore-hole from 800m depth to wellhead
Caida de presión en el pozo en el tramo desde 800 m de profundidad hasta la cabeza
300
200
100
0
20
30
40
Flow - Flujo (t/h)
Pressure - Presión (Kg/cm²)
⊙ Extrapolation to wide-open well flow (275 t/h)
Extrapolación del flujo con pozo abierto (275 t/h)

FIG. 4/5

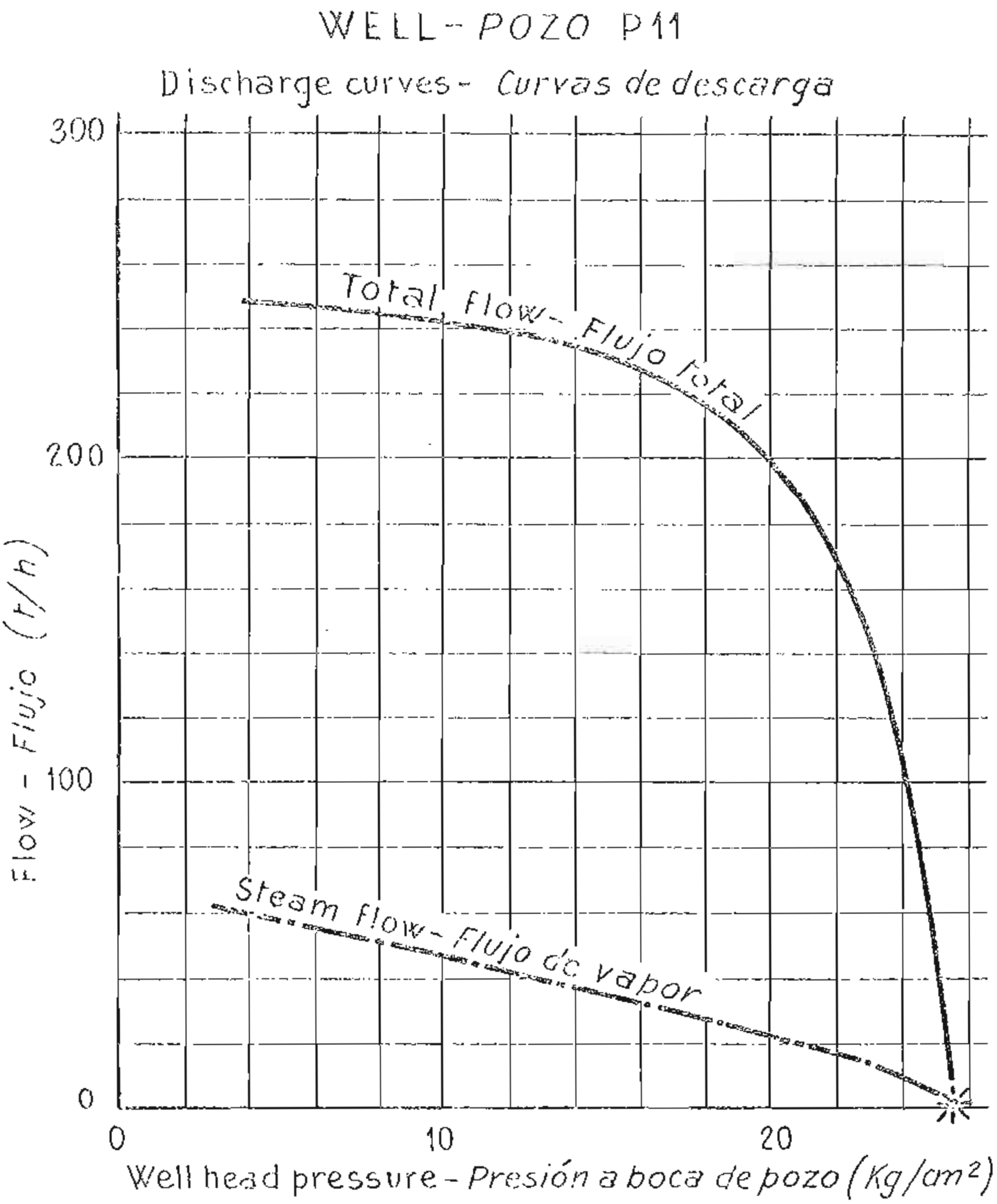

WELL - POZO P11
Discharge curves - Curvas de descarga
300
200
100
0
Flow - Flujo (t/h)
Total flow - Flujo total
Steam flow - Flujo de vapor
0
10
20
Well head pressure - Presión a boca de pozo (Kg/cm²)

FIG. 4/6

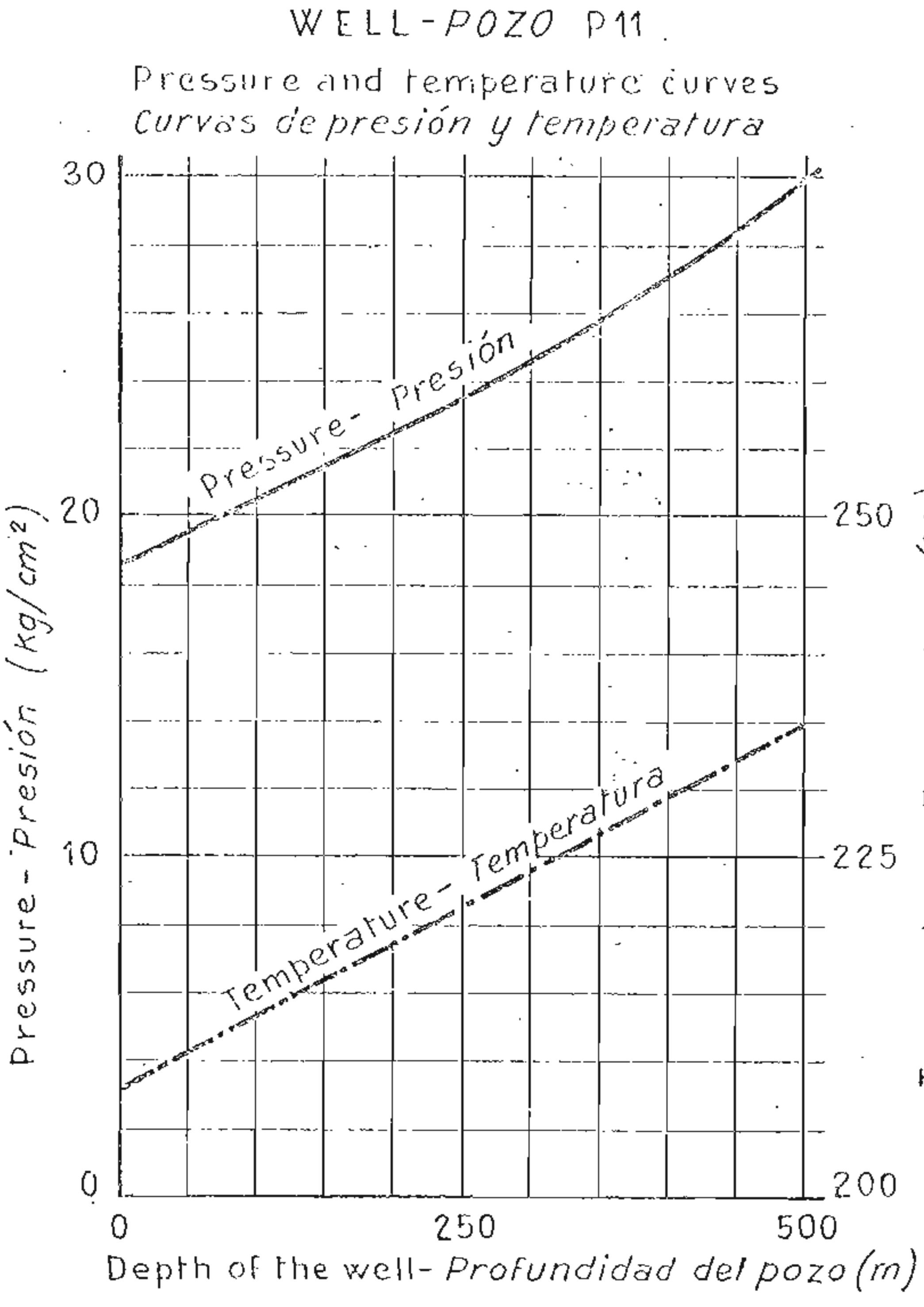

WELL-POZO P11
Pressure and temperature curves
Curvas de presión y temperatura
30
20
10
0
250
225
200
Pressure- Presión
Temperature- Temperatura
Pressure - Presión (kg/cm²)
Temperature- Temperatura (°C)
0
250
500
Depth of the well- Profundidad del pozo (m)

FIG. 4/7

WELL POZO P7

Reservoir pressure decline
Declinación de la presión del reservorio

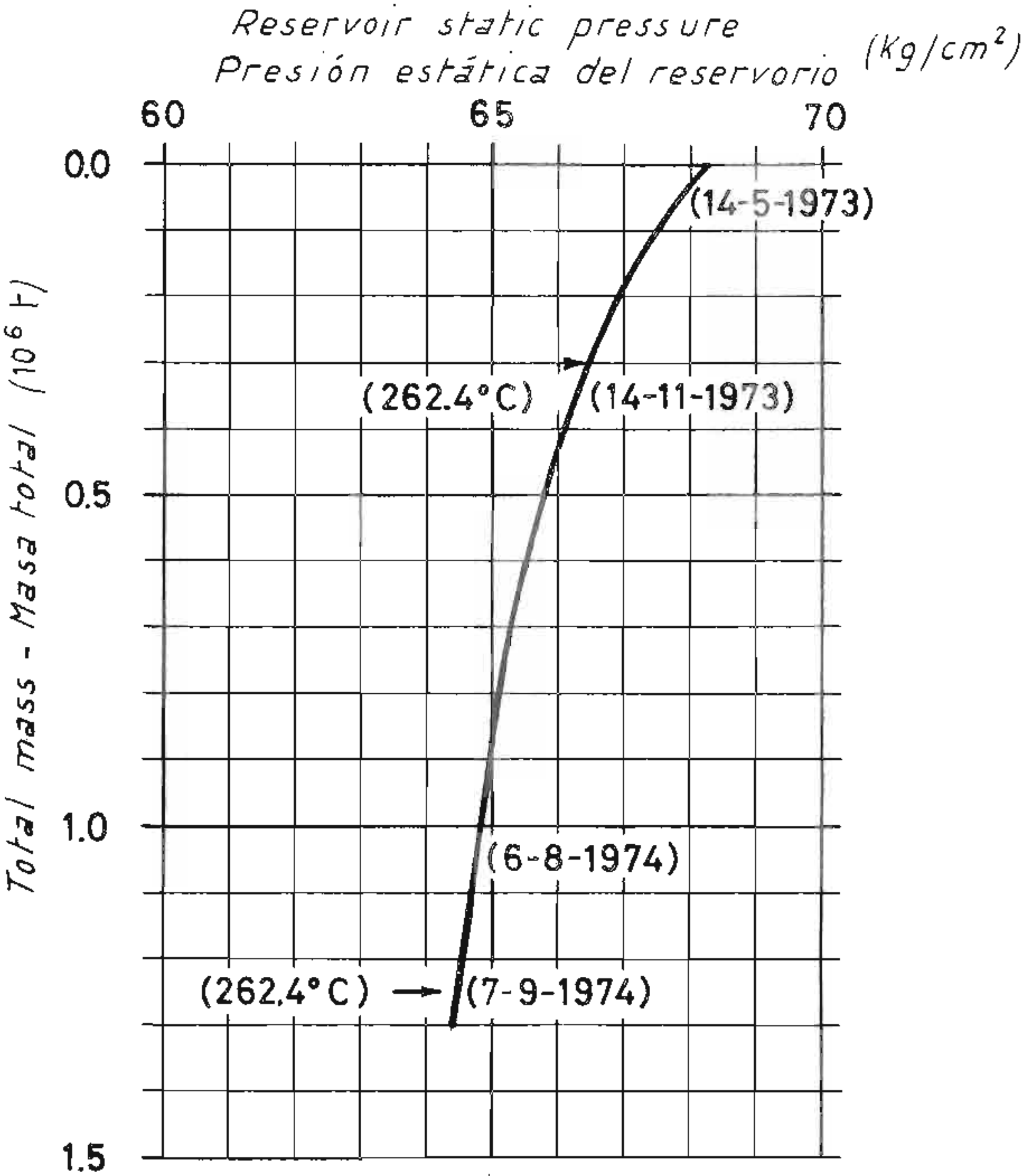


FIG 4/8

The most interesting section of this area is El Tatio South, from the productive wells, well 6 included, to the southeast, where the upflow of the hot fluids is supposed to occur.

This section has an approximate area of 6 km2.

The lack of basic data, such as the geometry of the reservoir, the permeability variations, the recharging cycle and the relationship between the diffent aquifers does not allow an estimate of power capacity of the reservoir.

If it is assumed that the above area has proportionally the same potential as the area of the productive wells, a minimum energy potential of 100 MW can be estimated for the El Tatio field. However, this study had to be necessarily limited to the available production, given by wells 7 and 11, which, as it will be discussed in the following chapter, have a gross potential of 17 MW.

5 GEOTHERMAL POWER PRODUCTION

5.1 Introduction

From the results of the studies carried out in the area of El Tatio, the characteristics of a plant which makes use of the geothermal fluids to produce electrical energy, can be defined. This plant will be connected to the generating system of the province of Antofagasta at Chuquicamata, where the demand for electrical energy is the greatest.

In the following pages the possible generating schemes are analized and compared, and the technical and economical parameters of the most convenient geothermal alternatives are defined.

It should be pointed out that the cost and other economic factors are valid only for the time this report was prepared, and the unstable situation of the world markets must be taken into account.

5.2 Characteristics of the Geothermal Fluids

The characteristics of the geothermal fluid produced by well No. 7 and well No. 11 of El Tatio were used as basic data for designing the geothermal power plant.

The wells produce a mixture of saline water, steam, and a small quantity of gas.

The fluid output under the recommended production pressure of 17.5 kg/cm^2 are 261 t/h for well No. 7 and 224 t/h for well No. 11 giving a total available flow of 485 t/h.

The calculated mean enthalpy of the fluid is 272.7 kcal/kg.

The non-condensable gas content in the steam separated at 5 kg/cm^2 abs is 0.3% by weight and consists mainly of CO_2 and H_2S.

The concentration of salts in the residual geothermal water at atmospheric pressure is 16 000 ppm, mainly constituted by sodium chloride. The water also contains silica in supersaturated conditions.

The actual production pressure of 17.5 kg/cm^2 at the well head is considered rather high compared with the possible utilization pressure at the turbine. Therefore a pressure reduction is necessary and this can be obtained by means of a control orifice placed at the outlet of the wells.

If a production pressure decline occurs in time, as normally expected in geothermal fields, the size of the control orifice will have to be progressively enlarged to maintain a constant energy output.

To optimize the exploitation of the field, the lowest possible turbine inlet pressure is utilized, taking into account however the following two fundament relationships:

a. The plant efficiency is a function of the turbine inlet pressure;

b. The plant capital cost increases with decreasing inlet pressure.

It has been also assumed that the total geothermal fluid production and the enthalpy of the mixture will remain practically constant during the period of utilization, though a small increase in the steam percentage of the total fluid may be expected.

Therefore, the size of the geothermal plant has been designed on the present flow rates, but in such a way that it combines a high efficiency for flow fluctuations within the range of 60% to 120% of the present steam flow resulting from the first flash, and within 0 to 150% of the steam flows from the 2nd flash.

The plant has been planned also with the provision that it can be expanded with an additional unit of a capacity up to 140% of the present one. If the geothermal field develops beyond the present known potential, an additional geothermal plant will need to be planned.

5.3 Local Conditions and Services

The geothermal wells are located at 4 300 m above sea level. The site has roads which can be used by heavy vehicles with loads up to 50 tons, after minor adjustments (see Plan GCI-1016).

The site where the geothermal plant is to be built is almost flat with a slight inclination, and it has good load bearing characteristics.

The average atmospheric pressure is approximately 0.6 kg/cm^2 abs. The atmosphere is very dry with average humidity of about 50%. There is practically no rainfall. The temperature varies from -20° to +20°C with an average temperature little above 0°C.

The available drinking water is sufficient only for the domestic uses of the staff. There is no fresh water for other needs.

The data of the on local environmental conditions (wind, earthquakes, etc.), on the topography, and on detailed geology for foundations are not complete.

However, the information at hand is sufficient for a provisional siting of the plant which can be used for feasibility studies and cost estimates. The complete data will have to be provided for the detailed working project. Also consideration will have to be given to the locations of future wells as the plant must be sited as near the centre of the producing field as possible.

5.4 Alternative Schemes

Electrical power can be produced for the geothermal fluid by utilizing the steam fraction which can be separated after one or several stages of flashing. The following schemes are considered for this purpose:

Scheme a: once flashed steam with back pressure turbine which discharge directly into the atmosphere;

Scheme b: once flashed steam with a turbine and condenser set with cooling towers;

Scheme c: two successive steam flashings with a turbine with two steam entries, condenser and cooling towers.

The schemes with three or more stages of flashing are not considered, as the increase of power would be modest against high additional costs.

The power obtainable from the three schemes and their relative costs are notably different.

The following figure illustrates the curves of the net power obtainable at the exit of the plant by each steam with varying first flash pressures making use of the fluid produced by the two present wells.

Net Power against the First Flash Pressure

Potencia neta en función de la presión del primer flash.

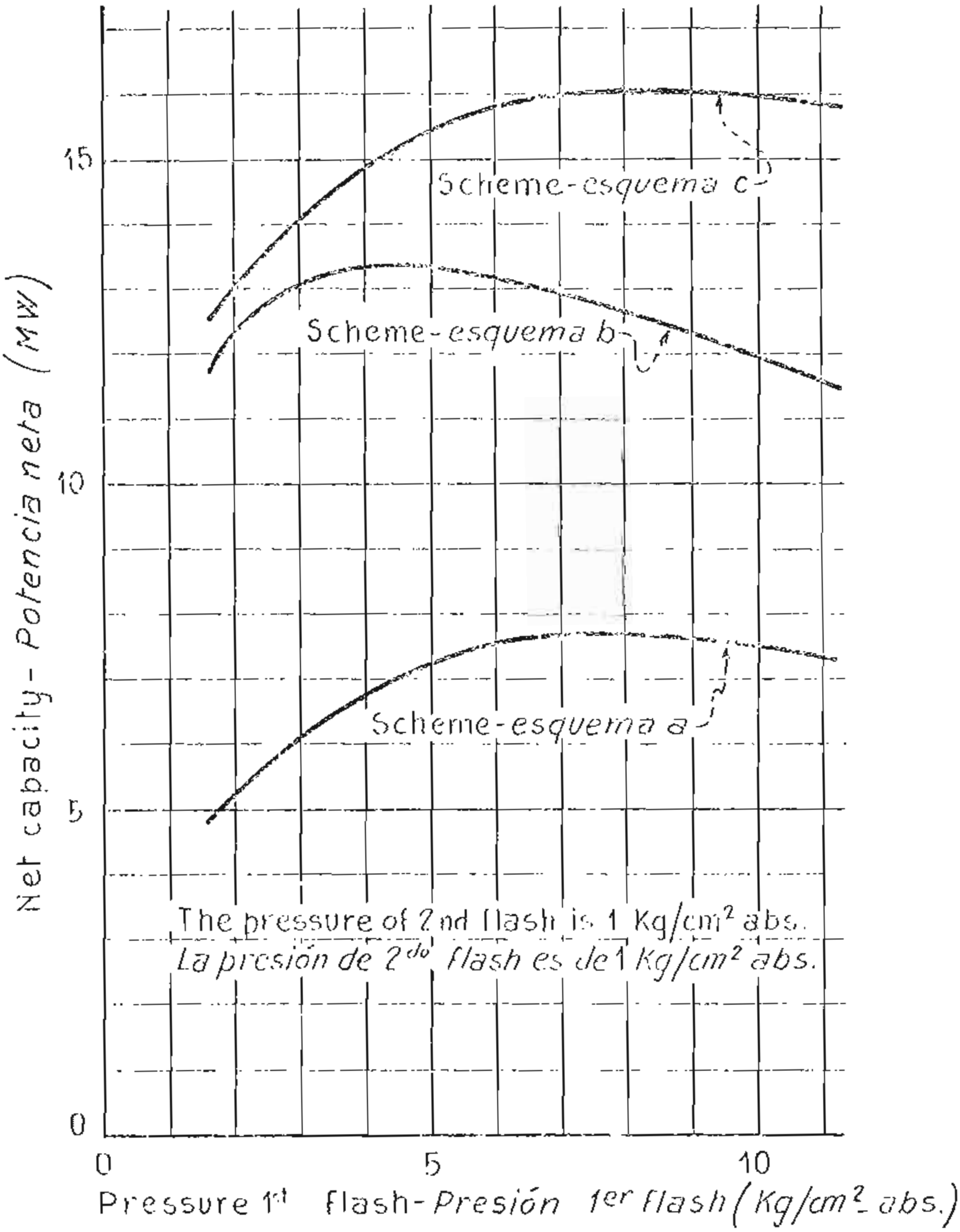


FIG. 5/1

It will be noted that the best output is within the following range of pressure:

Scheme a: 1st flash pressure 3 to 7 kg/cm^2 abs

Scheme b: 1st flash pressure 2 to 6 kg/cm^2 abs

Scheme c: 1st flash pressure 3 to 7 kg/cm^2 abs

The 2nd flash takes place at a pressure of 1 kg/cm^2 abs and maintains a range of good efficiency between pressures of 0.6 to 1.4 kg/cm^2 abs.

We therefore consider the following flash pressures as the best suited to the respective schemes:

Scheme a: 1st flash pressure 5 kg/cm^2 abs

Scheme b: 1st flash pressure 4 kg/cm^2 abs

Scheme c: 1st flash pressure 5 kg/cm^2 abs
2nd flash pressure 1 kg/cm^2 abs

If the steam flow rate changes, the above chosen pressures allow a very good output in the nominal capacity of 0.6 to 1.2 making the turbine function with completely open valves and with steam pressure variable according to the power output. The chosen pressures are rather low, yet they yield the best output in the whole working range without resulting in appreciable increase in cost.

The gross power obtained at the alternator terminals net power output of the plant in each scheme are as follows:

	Gross Power (kW)	Net Power (kW)
Scheme a:	7 500	7 200
Scheme b:	14 200	13 250
Scheme c:	17 000	15 500

5.5 Economic Evaluation of the Schemes

The choice of the layout and consequently of the power capacity of the geothermal plant is made according to the least capital cost of the installed kW and of the corresponding energy produced. The choice of the scheme also takes into account other factors such as the fluid characteristics, the functioning flexibility and the characteristics of the electrical system served.

The estimated construction costs of the geothermal plants for each of the above stated schemes are shown in the following table. These estimates takes into account the local market conditions for the materials at hand in the project area and for equipment and machinery imported from the North American and European markets for the end of 1974.

Table 5/1

CONSTRUCTION COSTS OF GEOTHERMAL PLANTS (US$ x 10^3)

	PLANS	a	b	c
1.	Infrastructures and miscellaneous	300	300	300
2.	Civil works	300	1 000	1 250
3.	Pipeworks and separators	550	600	600
4.	Turbine and condenser	700	2 200	3 100
5.	Electrical installations	350	500	600
6.	Cooling tower and pumps	-	500	600
7.	Auxiliary equipment	150	200	250
8.	Contingencies (~ 7%)	150	350	400
	Sub-total	2 500	5 650	7 100
9.	Indirect costs (~ 30%)	750	1 700	2 100
	CONSTRUCTION COST	3 250	7 350	9 200
	Capital cost of kW installed ($/kW)	430	510	540
	Capital cost of kWh (cent $/kWh) (for 8 000 hours/year)	5.9	6.9	7.3

According to schemes a and b the power plant generates less power, but the turbine is of lighter and more economical construction. In fact, in scheme b the pipeline and relative accessories are not needed for the 2nd flash and the turbine has only one steam inlet. In scheme a, the cooling towers, the condenser and their accessories are also eliminated. The power house can be reduced in height and the turbine can be set on the ground with an upward discharge.

In order to facilitate an automatic start off, without any need for external energy, the power plants in schemes b and c need an auxiliary back pressure group (of the kind considered by scheme a) with a power capacity of approx 800 kW.

As regards the economics of the different schemes, it will be noted that the installed capital cost is smaller for schemes a and b , at unit costs of US$ 430 and US$ 510 respectively, in comparison to scheme c with a unit cost of US$ 540. The capital generation costs of schemes a and b are, therefore, 20% and 6% less than that of scheme c. Limited to these considerations, scheme a would appear to be the most economic. However, in order to choose the most convenient scheme, the following aspects must also be considered.

The three schemes indicate possible energy outputs of 55, 100 and 120 millions of kWh/year respectively with the capital costs as shown in Table 5/1. These outputs are destined to be fed into the Chuquicamata network, and for this reason the capital cost of the transmission system must be added to the capital cost of the plants, the transmission system comprising a line carrying 115 kW for a distance of 95 km.

For the assessment of the schemes, the line requires a total investment of 3 million US$. The respective production capital costs for schemes a, b and c, are therefore 5.4, 3.0 and 2.5 cents $/kWh. As a result of this, the capital cost of the geothermal electrical energy available at the inlet of the Chuquicamata substation for the different schemes is as follows:

Scheme a:	11.3 cents $/kW
Scheme b:	9.9 cents $/kW
Scheme c:	9.8 cents $/kW

It is interesting to note that, providing some annual operation costs (staff, administration, line maintenance) are the same for each of the three schemes, the real production cost tends to modify the difference between the aforementioned costs in such a way that the scheme which will produce the largest quantity of energy becomes the most favourable.

The scheme c utilizes the maximum potential of the wells by permitting the generation of maximum possible energy (120 GWh/annum against 100 and 55 GWh/annum capacities of the schemes b and a respectively).

As the cost of geothermal power generation is highly competitive compared with the power generation costs of conventional thermo-generation systems, the cheap cost of the greatest possible energy production justifies, without the other considerations, the choice of scheme c.

5.6 Description of Power Plant Scheme

Since the wells No. 7 and No. 11 are approximately 300 m apart and well No. 13 is between them, it seems logical to place the two cyclone separators at well No. 13 (See Plan GCI-1012). The steam from these separators will pass through their respective pipelines to the turbine house.

The water rejected from the low pressure cyclone is discharged through a control orifice into a concrete walled ent chamber and from there it passes through a culvert to the stream which is between wells No. 11 and No. 13.

A description of the arrangement is as follows: the steam-water mixture coming from each of the two production wells passes through a control orifice which restricts the well-head pressure to 17.5 kg/cm² abs while the pressure just downstream of the orifice is approximately 6 kg/cm² abs. Then the mixture from each well enters into a High Pressure (HP) cyclone at 5 kg/cm² abs. The water separated at the HP cyclone is flashed through a control orifice into the Low Pressure (LP) cyclone with a pressure of 1 kg/cm² abs. The steam fraction separated at each cyclone is then transmitted through separate pipes to the turbine. Along the pipelines extraction pots are placed to collect the condensed water, in order to reduce corrosion from the salts dissolved in the geothermal water. If necessary, a moisture separator is also installed for the same reason.

The turbine is connected to a barometric condenser with a vacuum less than 0.07 kg/cm² abs. This vacuum is considered suitable because of the dryness of the atmosphere at El Tatio, and the generally low temperature.

A multi-stage centrifugal gas exhauster will remove the small amount of non-condensable gases which are 0.3% by weight of the steam at 5 kg/cm² abs.

It will be noted that a pressure of 6 kg/cm² abs is all that is required at the well head while we have 17.5 kg/cm² abs available. This allows for a steady decline in reservoir (and hence well head) pressure during the life of the field.

5.7 Plant Outline

The following description refers to the scheme c., that is a power station with a turbine with two steam entries for two successive flashes of different pressures, including a condenser and cooling towers (see Plans GCI-1014 and 1015).

The structure of the power plant consists of a steel frame construction with the condenser outside the power house. This design requires few permanent buildings and facilitates the structures to be dismantled and set up in another place should the wells be used up.

The turbine has two separate entries each being equipped with filters, and blocking and regulating valves.

The nominal capacity of the turbine-generator set is 17 000 kW - 21 500 kVA.

All the parts of the turbine and the condenser which are in contact with the geothermal fluid, are either made from or lined with stainless steeel or some other corrosion resisting material. The same applies to the pumps and water cooling pipes.

The turbine is equipped with efficient draining devices.

The condenser into which the steam is discharged from the turbine is of the barometric type and can reach a rather high vacuum (less than 0.07 kg/cm² abs).

The extraction of the incondensable gases from the condenser is achieved by means of vacuum pumps.

The water-cooling circuit of the condenser is made up of:

. Circulating water pumps to towers with intake level control by means of automatic recirculation;

. Cooling towers with ventilators and adjustable exhauster to control the water temperature;

. Filters & circulating water pumps to the condenser.

The turbine and the generator oil can be cooled by the same geothermal water through an auxiliary cooling system or by air through an open circuit.

Considering the environmental conditions, it is necessary to take the following precautions to prevent the water from freezing:

. Make use of geothermal steam heating and defrosting systems;

. Provide an automatic relief device on the pipeline for the water in case of blockage in the circuit;

. Regulate the water temperature at its exit from the towers.

The power house crane is capable of lifting approx 40 tons, the weight of the stator of the generator.

The automatic fire prevention equipment provides protection for the transformers, the turbine oil boxes and the generator.

The power house is fitted out with a main transformer of 21 250 kVA, service transformers and a substation. The switch control room and some offices are situated at the first floor of the auxiliary building and space for panels, battery room and a small workshop is provided on the ground floor.

5.8 Transmission Line

The geothermal plant of El Tatio will be connected to the existing electrical system of the substation at Chuquicamata (110 kV - MT) by a three-cable transmission line of nominal tension of 110 kV. Its length will be about 95 km from east to west (See Plan GCI-1016) at levels varying between 4 300 and 2 700 m above the sea level.

Considering the environmental conditions, the main characteristics of the line are (See Plan GCI-1017):

Nominal tension	110 kV
Maximum tension	191 kV
Degree of impulse isolation	
for height less than 3 500 m a.s.l.	900 kV
for height more than 3 500 m a.s.l.	1 000 kV
Cables set out in delta configuration 3 ACSR 395.5 MCM (26+7)	IBIS
Ground cable of galvanized steel	Ø 9 mm
Electrical resistance	0.146 Ω/km
Reactance	0.482 Ω/km
Steel towers of truncated pyramid type with bases of separate concrete foundations	

Power losses by "crown effect" (according to W.S. Peterson) are estimated to be about 3 kW/km corresponding to about 300 kW along the whole of the three-cable line:

Power Transmitted MW	Losses kW	Potential Drop cosfi= 0.85
15	120	6%
30	475	12%
45	1 075	18%

The substation of Chuquicamata will be expanded so that the 110 kV new line coming from El Tatio can be connected to it and the energy can be transformed.

The following works have also been taken into account:

- Expansion of the line, complete with high and low tension equipment;

. Transformer 110/10-15 kV of 20 MVA with automatic tension converter;

. Intermediate tension equipment;

. Low tension equipment, control panels;

. Protection and telecommunications El Tatio-Chuquicamata;

. Related civil works.

5.9 Cost Estimate

5.9.1 Capital Cost The cost is estimated in US dollars with the conventional exchange rate of 1 000 escudos per dollar.

The cost of civil works and that of other various works of the plant are estimated according to a preliminary metric calculation and by using current prices for machinery, materials and local labour.

The equipment and electro-mechanical installations are considered as imported materials. The relative estimate takes into account the cost of transportation and assembling (which is in an average 35% of the factory cost).

The total direct cost carries an allowance of 10% for contingencies.

The indirect costs consist of the following:

. Engineering expenses which include the detail design, specs, construction & bidding assistance;

. Administration costs of the local organization which will supervise the work;

. Interests during construction calculated at an annual rate of 10%.

The following table shows the approximate total value of the investment estimated as 12.1 million US$.

Table 5/2

GEOTHERMAL PROJECT COST ESTIMATE (US$ x 10^3)

1.	DIRECT COSTS		
1.1	Various works		
	Site preperation	80	
	Road conditioning	120	
	Camps	100	
			300
1.2	Civil Works		
	Excavations	50	
	Foundations	150	
	Supersubstructures	200	
	Steel structures	500	
	Completions	250	
	Drainage	100	
			1 250
1.3	Transmission pipeline and control equipment	800	
1.4	Turbine, condenser, filters and accessories	3 100	
1.5	Electrical equipment for middle and high tension (incl. trans.)	600	
1.6	Pumps	200	
1.7	Auxiliary equipment (cranes, firefighting equipment and auxiliary set)	250	
1.8	110 kV line (cables, towers, insulators, incl. assembly)	1 750	
1.9	Chuquicamata substation	500	
1.10	Contingencies (~ 7%)	600	
			7 800
	TOTAL DIRECT COSTS		9 350
2.	INDIRECT COSTS		
2.1	Engineering (12%)	1 130	
2.2	Administration and expenses (5%)	470	
2.3	Interests during construction (10% per annum for 2 years)	1 150	
	TOTAL INDIRECT COSTS		2 750
3.	ESTIMATED TOTAL		12 100

5.9.2 Operating Expenses It is reasonable to expect that the plant has to be controlled and supervised. In fact, the climatic conditions in the El Tatio area make it necessary to keep a careful and continuous control and supervision over the equipment and machinery of the power plant.

An estimate of the yearly operating expenses of the plant is as follows:

a. Staff The operation of the plant and of the transmission line is to be conducted by 20 people at a yearly cost of 190 000 US$:

Management	2 persons	40 000	US$/annum
Shifts	10 persons	100 000	US$/annum
Maintenance	5 persons	40 000	US$/annum
Services	3 persons	10 000	US$/annum
		190 000	US$/annum

b. Maintenance The annual expenses are calculated at about 1.50% of the direct capital cost, which is US$ 140 000;

c. Administration General and administrative expenses are about 20% of the total of the staff and maintenance costs amounting to a total of 66 000 US$/annum;

d. Insurance and Taxes Annual expenses for insurance against risks and taxes have been estimated at about 1% of the direct costs, amounting to 94 000 US$.

The annual costs of operating the plant and the power transmission line add up to a total of 490 000 US$.

5.9.3 Financing Costs The annual financing costs consist of the interest on the invested capital and the depreciation of the works of the project, as follows:

a. Interest The interest has been calculated on the basis of the required total investment of 12.1 million dollars at a rate of 8% for a period of 25 years giving an annual cost of 960 000 US$;

b. Depreciation Considering the characteristics of the wells, the location and equipment installed, the plant should have an average life span of 25 years; the depreciation cost, therefore, is estimated at 340 000 US$/annum. The average life of the transmission line is considered to be 35 years with a depreciation cost of 110 000 US$/ annum. The total depreciation cost of the project adds up, therefore, to 450 000 US$/annum.

5.9.4 Production Cost The power capacity of the geothermal power plant is less than the demand of the network into which it feeds power. This allows the use of the plant at 100% output.

It is advisable to shut the plant for maintenance at least one month a year. This results in net potential utilization for approximately 8 000 h/annum. The available energy produced amounts to 125 million kWh/annum. Taking in to account the transmission losses at about 5 million kWh/annum the energy which can be sold at the 15 kV bus bar at Chuquicamata is 120 million kWh/annum.

Based on these considerations the actual cost of the energy production by the Geothermal Power Plant at the inlet of the Chuquicamata substation is estimated as shown in Table 5/3.

Table 5/3

ACTUAL COST OF POWER PRODUCTION

Net generation (at Chuquicamata) GWh/annum 120	
Annual expenses (US$ x 10^3)	
. Staff	190
. Maintenance	140
. Administration	66
. Insurance and taxes	94
. Interests	960
. Depreciation	450
TOTAL	1 900
Cost of production and transmission (mills US$/kWh)	16

It will be noted that the interest (at a rate of 8%) constitutes approximately 50% of the total annual costs. For interest rates of 5%, 10% and 15% the cost of production would result 13, 18 and 23 mills US$/kWh respectively.

5.10 Construction Programme

Table 5/4 illustrates time needed for different phases of the El Tatio Geothermal Power Project, taking into account tender, award of contract and construction periods.

A period of approximately 1 year is foreseen in order to complete the topographical and geological investigations on site, to prepare the tender documents and to select the successful bidder.

As far as the construction is concerned, the longest time is required for the manufacture of the turbine and its accessories, the transportation and installation at the site. For this operation a period of 27 months is foreseen.

It is estimated that the execution of civil works and installation of other equipment, such as the power transmission line will take 24 months.

Six to seven months are allocated for preliminary trial runs and the testing operation of the plant.

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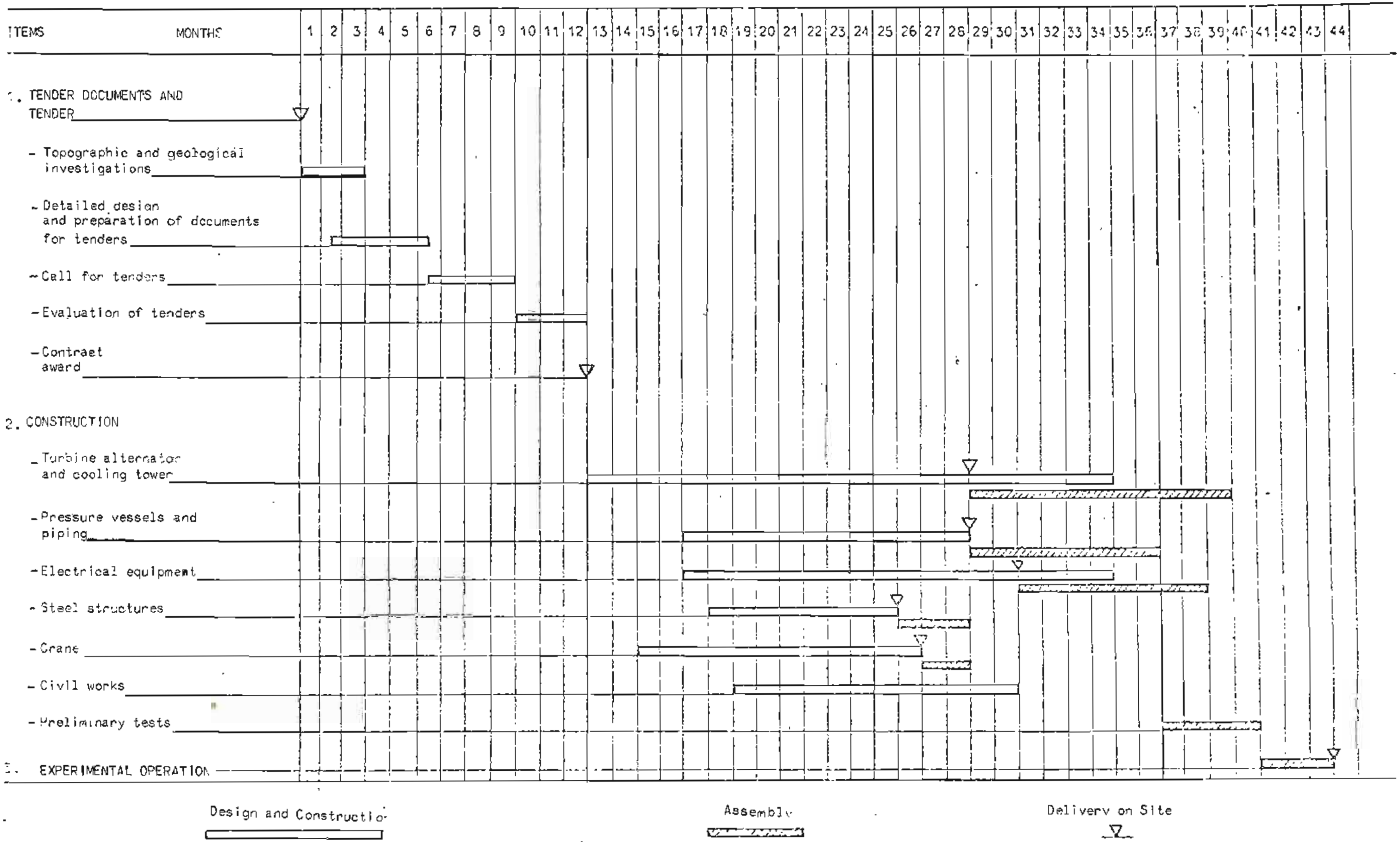
Table 5/4

TIME SCHEDULE



6 ANALYSIS OF ECONOMICS AND FINANCE

6.1 Prospects of Electrical Network Development in the Province of Antofagasta

The development prospects of the power generation systems in the province of Antofagasta exclude the convenience of an important interconnection with the southern regions and particularly with the Central region of Chile where prospects of power generation by hydro-electrical and nuclear plants seems feasible.

For the province of Antofagasta, the following prospects are foreseen (see Plan GCI-1018):

Short time prospects:

within a few years (1978) the interconnection between Cochuqui and Antofagasta power networks should be in operating conditions;

only 120 MW of the 260 MW produced will actually be available within 1975, as approximately 50 MW of the remaining capacity constitutes the reserve system (the largest plant is of 45 MW capacity and is in Tocopilla) and approximately 90 MW belong to various obsolete plants of small and irrecoverable potential.

Long term prospects:

the local network system requires approx 280 MW of effective power within 1980. Of this, 230 MW is to be available to the mines with a utilization factor of 0.8 and the remaining 50 MW is to be available to the urban network (various consumers) with an average utilization factor of approx 0.5 ;

within the following ten years (1980-1990) an increased demand of 380 MW by the mines is foreseen besides an increase of about 5 MW per year to satisfy the demand of the urban and rural centers.

6.2 Alternatives and Bases for Economic Comparison

The present study does not aim to give the most convenient developing programme as this would require, among other things, a technical and economical analysis of a series of possible alternatives. The aim is to justify the economical advantages of introducing the El Tatio geothermal power plant into the developing power network.

The following considerations are made in order to define the widest possible range of alternatives against which the economical advantages of the geothermal plant can be evaluated:

- the geothermal plant can produce 15 MW salable energy for approximately 8 000 h/annum;
- the generating system can be enlarged by installing steam plants of 50 to 100 MW unit capacity and gas plants of 12 to 36 MW unit capacity in combination with the existing plants;
- in any traditional thermo-electrical system the most convenient cost of production corresponds to the optimum utilization costs of the major steam groups.

It is evident from the above that the best evaluation can be achieved by comparing the production cost of the geothermal plant with that of the conventional steam plants of greater capacity, with the provision that the conventional steam plant capacities are increased by an amount equal to the capacity of the geothermal power plant.

6.2.1 Economy of the Thermal Plants The economic parameters of gas and steam plants are described below. These parameters might be relevant to the development of the local alternatives, facilitating a realistic comparison with the geothermal power plant.

The unit prices and following costs and estimates have been obtained from the current market prices in the province of Antofagasta at the end of 1974, information from ENDESA, and from the customary methods used to estimate the specific unit costs.

A conventional exchange rate of 1 000 Esc = 1 US$ has been used.

Investments The cost of construction costs of thermal plants of steam and gas type are shown in the following table.

Table 6/1

INVESTMENTS FOR STEAM AND GAS TYPE THERMAL PLANTS

UNIT CAPACITY MW	IN LOCAL CURRENCY (Escudos $\times 10^6$)	IN FOREIGN CURRENCY (US$ $\times 10^6$)	TOTAL (US$ $\times 10^6$)
A. Steam Plants with Mixed Fuel (Coal + Bunker C)			
50	9 000	22.0	31.0
100	15 800	38.2	54.0
B. Steam Plants with Bunker C Fuel			
50	7 000	15.0	22.0
100	12 500	28.5	41.0
C. Gas Plants			
12	1 000	2.1	3.1
24	2 100	3.5	5.6
36	3 200	4.8	8.0

Fixed Annual Operating Costs The annual operating costs of thermal plants equipped with above mentioned groups consist of expenses related to staff, fixed maintenance (independent of production) and administration, taxes and insurance.

The Table 6/2 outlines the fixed annual costs in US$ x 10^3 (equivalent to 10^6 Esc.).

Table 6/2

FIXED ANNUAL COSTS FOR THERMAL PLANTS

	STEAM PLANTS		GAS PLANTS		
Unit capacity (MW)	50	100	12	14	36
Fixed annual expenses:					
. Staff	450	480	180	200	230
. Maintenance	340	540	60	100	130
. Administration, taxes and insurance	400	500	120	150	180
Total	1 190	1 520	360	450	540

<u>Financing Costs</u> These costs consist of the interests on the invested capital and depreciation. The interest on the invested capital has been calculated at a rate of 8% per annum (with the Straight Line method). The depreciation of the steam plants is estimated over 30 years and that of the gas plants over 25 years.

Total financing costs are shown in Table 6/3 in US$ x 106 (equivalent to 10^9 Esc.).

Table 6/3

FINANCING COSTS FOR THERMAL PLANTS

	STEAM PLANTS				GAS PLANTS		
	Mixed Fuel		Bunker C				
Power capacity (MW)	50	100	50	100	12	24	36
Construction Cost	31.0	54.0	22.0	41.0	3.1	5.6	8.0
Interest during costruction	4.6	8.1	3.3	6.2	0.5	0.8	1.2
Total Capital Cost	35.6	62.1	25.3	47.2	3.6	6.4	9.2
Financing Cost							
. Interest	2.8	4.9	2.1	3.8	0.3	0.5	0.7
. Depreciation	1.2	2.1	0.8	1.6	0.1	0.2	0.4
Total Costs	4.0	7.0	2.9	5.4	0.4	0.7	1.1

6.2.2 Fuels

Coal is the national energy resource for which has been programmed an intensive utilization.

The cost of coal in Bocamina is at present 40 000 Esc/t but an increase is forecast.

Further north (in Guazco) the cost of coal is at present 53 350 Esc/t.

The estimates of the cost of transport to Tocopilla show an increase of approximately 40% on the previous costs.

The specific heat consumption, for a quality of coal of 35% ash content, varies from 2 600 to 2 300 kcal/kWh for plants from 50 to 100 MW capacity respectively. The specific heat consumption for Bocamina (125 MW) is 2 250 kcal/kWh.

Natural Gas available in the region of Magallanes is not enough to assure the production of the country's total electrical energy.

By 1979 liquid gas will be carried by ship from Magallanes to Tocopilla and from Tocopilla to Chuquicamata by a gas pipeline, for use in the metallurgic plants.

The production of gas for 1979 is estimated at 80×10^6 m^3/day equal to 2×10^6 t/annum. The demand in the province of Antofagasta in 1979 is estimated at 10^6 t/annum.

Without referring to the actual prices which do not seem to be very realistic, the price per calory of gas is assumed to be the same as that of Bunker C, the cost of Bunker C at 80 $/t corresponding to 100 $/t cost of the natural gas.

Bunker C is largely imported. Its cost in 1974 was 40 $/t (old purchase) and 55 $/t (new purchase) and an immediate increase up to 80 $/t is foreseen.

The cost of Diesel oil for Diesel plants was 107 $/t when the Bunker C was worth 55 $/t.

6.2.3 Variable Costs The variable costs of the thermal plants depend on the effective production. They include fuel costs, material costs, administration costs and general expenses, always in relation to the effective generation.

For the thermal plant considered, the variable production costs have been estimated and are shown in the following tables.

Table 6/4

VARIABLE COSTS FOR THERMAL STEAM PLANTS

	FUEL Bunker C				FUEL Coal			
Unit capacity (MW)	50		100		50		100	
Utilization (h/annum)	4 000	8 000	4 000	8 000	4 000	8 000	4 000	8 000
Output (GWh/annum)	200	400	400	800	200	400	400	800
Efficiency (kg/kWh)	0.26		0.24		0.50		0.40	
Fuel consumption (t/annum)	52 000	100 000	96 000	198 000	100 000	196 000	160 000	310 000
Fuel cost (US$ x 10^6) (80 $/t for Bunker C and 70 $/t for coal)	4.2	8.0	7.7	15.2	7.0	13.3	11.2	21.7
Variable maintenance and administration costs (mill/kWh)	0.8		0.6		1.5		1.3	
Variable maintenance and administration costs (US$ x 10^6)	0.2	0.3	0.2	0.5	0.3	0.5	0.5	0.9
Total variable costs (US$ x 10^6)	4.4	8.3	7.9	15.7	7.3	13.8	11.7	22.6
(cts $/kWh)	2.2	2.1	2.0	2.0	3.6	3.4	2.9	2.8

Table 6/5

VARIABLE COSTS FOR THERMAL GAS PLANTS

Unit capacity (MW)	12		24		36	
Utilization (h/annum)	2 500	5 000	2 500	5 000	2 500	5 000
Output (GWh/annum)	30	60	60	120	90	180
Efficiency (kg/kWh)	0.40		0.35		0.30	
Fuel consumption (t/annum)	12 000	24 000	21 000	42 000	27 000	54 000
Fuel cost (US$ x 10^6) (unit cost 100 $/t)	1.2	2.4	2.1	4.2	2.7	5.4
Variable maintenance and administration costs (mill/kWh)	1.2		1.0		0.9	
Variable maintenance and administration costs (US$ x 10^6)	0.03	0.07	0.06	0.12	0.08	0.16
Total variable costs (US$ x 10^6)	1.3	2.5	2.2	4.4	2.9	5.7
(cts $/kWh)	4.3	4.2	3.7	3.6	3.2	3.1

6.2.4 Production Costs of the Thermal Plants

The actual cost of production of the thermal plants has been calculated on the basis of production, without considering the contribution of the transmission lines.

The following tables illustrate the actual production costs of thermal plants using different fuels.

Table 6/6

ACTUAL PRODUCTION COST FOR THERMAL STEAM PLANTS (BUNKER C FUEL)

Unit Capacity (MW)	50		100	
Utilization (h/annum)	4 000	8 000	4 000	8 000
Effective output (GWh/annum)	180	370	380	760
Annual expenses (US$ x 10^3)				
. Fixed operating costs	1 190	1 190	1 520	1 520
. Financial costs	2 900	2 900	5 400	5 400
. Variable costs	4 400	8 300	7 900	15 700
Total	8 490	12 390	14 820	22 620
Actual Production Cost (mill $/kWh)	47.1	33.5	39.0	29.8

Table 6/7

ACTUAL PRODUCTION COSTS FOR THERMAL STEAM PLANTS UTILIZING COAL

Unit Capacity (MW)	50		100	
Utilization (h/annum)	4 000	8 000	4 000	8 000
Effective output (GWh/annum)	180	370	380	760
Annual costs (US$ x 10^3)				
. Fixed operation costs	1 190	1 190	1 520	1 520
. Financing costs	4 000	4 000	7 000	7 000
. Variable costs	7 300	13 800	11 700	22 600
Total	12 490	18 990	20 220	31 120
Actual Production Cost (mill $/kWh)	69.2	51.2	53.1	41.0

Table 6/8

ACTUAL PRODUCTION COSTS FOR THERMAL PLANTS UTILIZING GAS

Unit Capacity (MW)	12		24		36	
Utilization (h/annum)	2 500	5 000	2 500	5 000	2 500	5 000
Effective output (GWh/annum)	28	57	57	112	84	168
Annual costs (US$ x 10^3)						
. Fixed operation costs	360	360	450	450	540	540
. Financing costs	400	400	700	700	1 100	1 100
. Variable costs	1 300	2 500	2 200	4 400	2 900	5 700
Total	2 060	3 260	3 350	5 550	4 540	7 340
Actual Production Cost (mill $/kWh)	74	57	58	50	53	44

6.3 Comparison of Economics

The geothermal plant has many things in common with the conventional thermal plants, such as the equipment, the construction time and amount of civil works and use of electromechanical equipment. The methods commonly used to compare different development alternatives is of little use in the present case, because they are only based on estimates of the present annual costs of construction and operation at various interest rates. The degree of suitability of the geothermal power system is determined by its power capacity (15.5 MW) in proportion to the system dimensions.

Making use of the economic estimates given in the preceding paragraphs as regards the plants which might be utilized in the future development of the power generation network, a direct comparison of the total production costs of these plants is made with that of the geothermal power plant. This comparison takes into account the hours of annual utilization rate and is based on the relevant criteria and assumptions.

Figure 6/1 illustrates the comparative effective production costs. The advantage of geothermal power production in comparison with that from other thermal plants is quite evident.

The production cost of the El Tatio plant of a utilization rate of about 8 000 h/annum is 40% less than that of the steam plant of 100 MW capacity. The cost difference becomes less at reduced utilization rates, but always main-

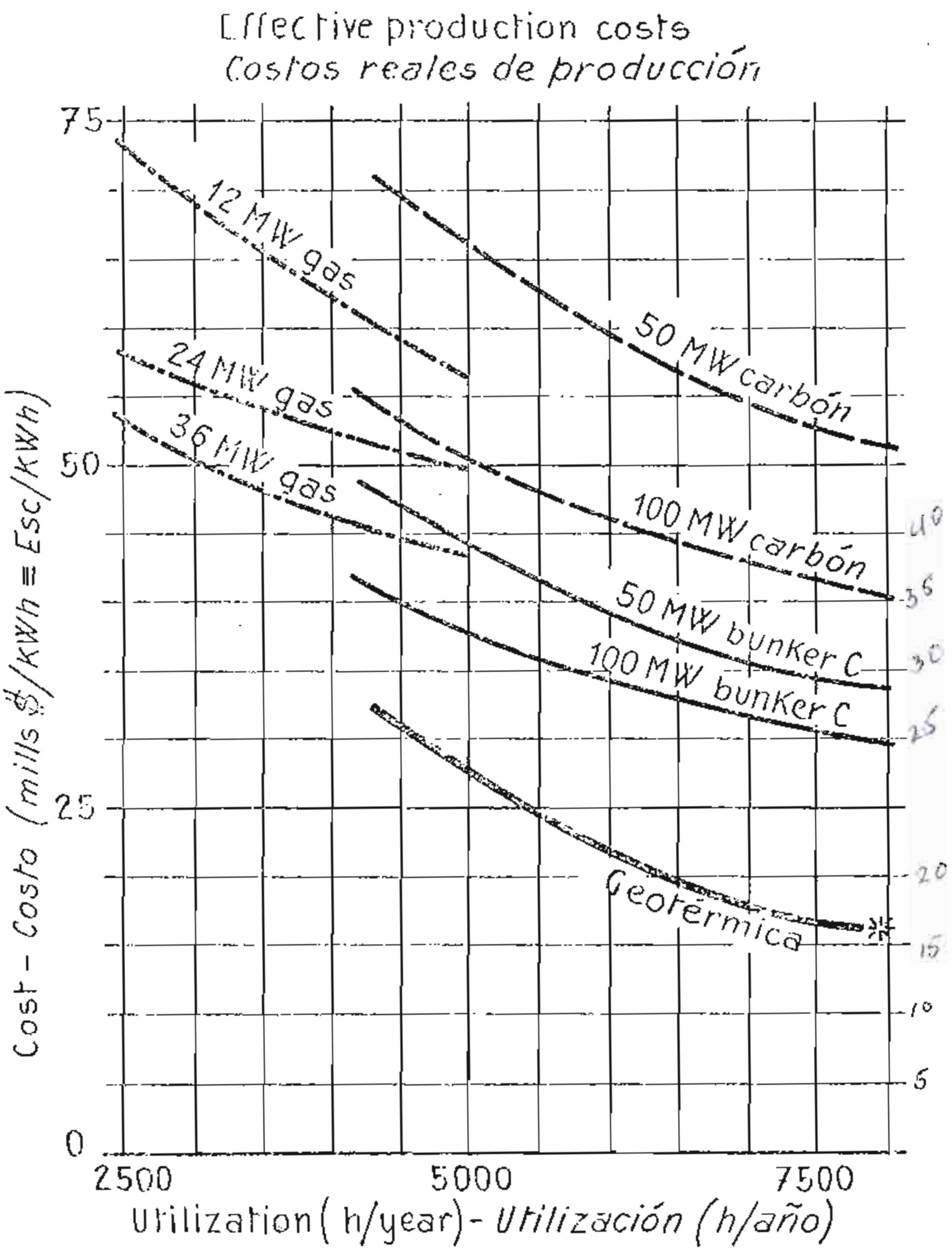

Effective production costs
Costos reales de producción
75
50
25
0
2500
5000
7500
12 MW gas
24 MW gas
36 MW gas
50 MW carbón
100 MW carbón
50 MW bunker C
100 MW bunker C
Geotérmica
Cost - Costo (mills $/kWh = Esc/kWh)
Utilization (h/year) - Utilización (h/año)
40
35
30
25
20
15
10
5

FIG. 6/1

tains a competitive value in favour of the geothermal power plant.

Figure 6/2 shows the variable generation costs of the conventional thermal plants against those of the geothermal power plant. The geothermal power generation is always more economical than the conventional thermal generation within the limits of rate of utilization as indicated in the diagram.

In the economic evaluation of the cost for generating geothermal energy, not taken into account are the sums of money already spent in exploration activities (geoscientific investigations, monitor and production wells), which amount to 1.9 million US$ and 710 million Esc., as these are considered as "sunk funds". However, for any future increments of power, the costs of the associated production wells should be taken into consideration.

6.4 Benefit-Cost Relationship of the Project

The two parameters of the assessment of economics are the"benefit-cost ratio" and the "internal rate of return" calculated by making use of the effective values of the benefits derived from the plant and the costs of the project at different rates of interest.

In order to evaluate the benefits derived from the geothermal power generation, the same criterion is applied, and the benefits against the effective production cost of the project are compared with those of the equivalent conventional plants. In this sense a more restrictive comparison basis can be achieved by considering a power capacity of 15 MW in addition to a steam plant of 100 MW capacity and then refer the consequent difference in the production cost to the production cost of the 100 MW plant.

With this in mind, consideration is given to the production cost of the additional 15 MW capacity to the conventional thermal plant of 100 MW capacity installed at Tocopilla providing energy for Chuquicamata. The resulting cost is 20.0 + 8.8 + 8.6 = 37.4 mills $/kWh, constituted by three cost factors. The first of these factors represents the variable costs of the 100 MW capacity steam group, the second one accounts for the capital costs necessary to be added to the operation costs for the 15 MW power increment and the third factor accounts for the cost of energy transmission to Chuquicamata.

For a utilization rate of 8 000 h/ annum, the assumed benefits result in the following difference between the unit costs: 37.4 - 16.0 = 21.4 mills $/kWh and the total difference for the energy available at Chuquicamata is: 21.4 mills $/kWh x 120 GWh/annum = 2 560 x 10^3 US $/annum.

Variable generation costs for conventional thermal plants.
Gastos variables de generación para plantas térmicas convencionales.

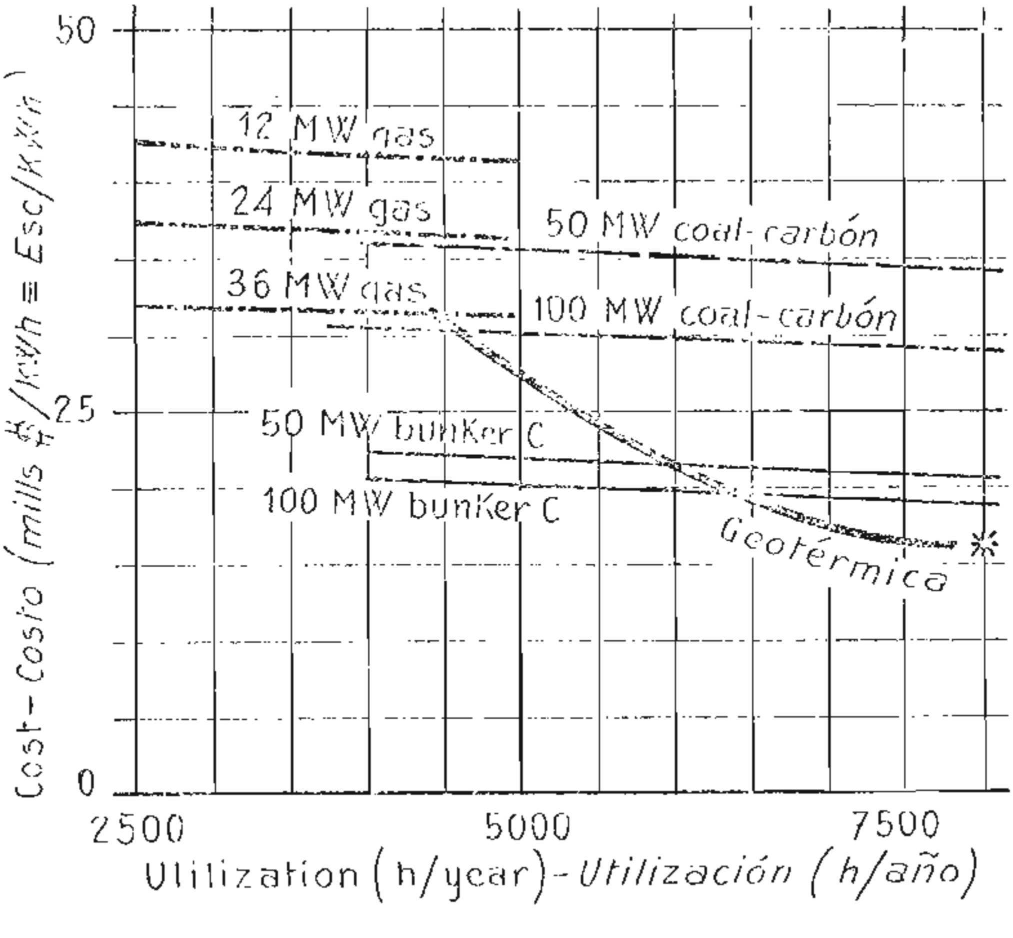


FIG. 6/2

In fact, it should be noted that the real benefits derived from the geothermal power plant will be greater than those based on the average production cost of the local generating system which will be higher for a new steam plant of 100 MW. The production cost of this steam plant would be over 60 mills $/kWh and the benefits accruing from the geothermal plant would rise to 40 to 45 mills $/kWh.

Table 6/9 illustrates the basis for calculations for defining the parameters of the economic assessment.

The project costs are made up of annual expenditures resulting from the construction of the works and include engineering, administration and operation expenses. The benefits of the project are calculated at a value of 2 560 x 10^3 US$.

These values are valid from the first year of construction for a plant life of 25 years, at the following different rates of interest: 5%, 10%, 15% and 20%.

Table 6/9

PRESENT VALUES OF COSTS AND BENEFITS OF THE GEOTHERMAL PROJECT (US$ x 10^3)

YEAR		1	2	3	4-25	TOTAL
COSTS						
. Construction		3 000	4 000	3 950	--	10 950
. Operation		--	--	490	490	--
Total		3 000	4 000	4 440	490	
BENEFITS		--	--	2 000	2 560	--
RATES OF DEPRECIATION	5%	1 000	0.952	0.864	0.823x13.16	--
	10%	1 000	0.909	0.826	0.751x8.77	--
	15%	1 000	0.870	0.756	0.657x6.36	--
	20%	1 000	0.833	0.694	0.578x4.91	--
EFFECTIVE COSTS	5%	3 000	3 830	3 830	5 300	15 960
	10%	3 000	3 680	3 650	3 210	13 540
	15%	3 000	3 490	3 350	2 040	11 880
	20%	3 000	3 330	3 080	1 380	10 790
EFFECTIVE BENEFITS	5%	--	--	1 730	27 800	29 530
	10%	--	--	1 650	16 900	18 550
	15%	--	--	1 510	10 750	12 260
	20%	--	--	1 400	7 400	8 800

6.4.1 Benefit-Cost Ratio Effective values of the annual Benefits and Costs of the project at different rates of interest are as follows:

Interest Rate	5%	10%	15%	20%
Effective benefits	29 530	18 550	12 260	8 800
Effective costs	15 960	13 540	11 880	10 790
Ratio	1.86	1.34	1.04	0.81

6.4.2 Internal Rate of Return The internal rate of return of the project corresponds to a rate of interest at which the effective gains and effective costs of the project are equal. Figure 6/3 shows the relationship between the effective costs and benefits at different rates of interest, indicating that the internal rate of return is 16%.

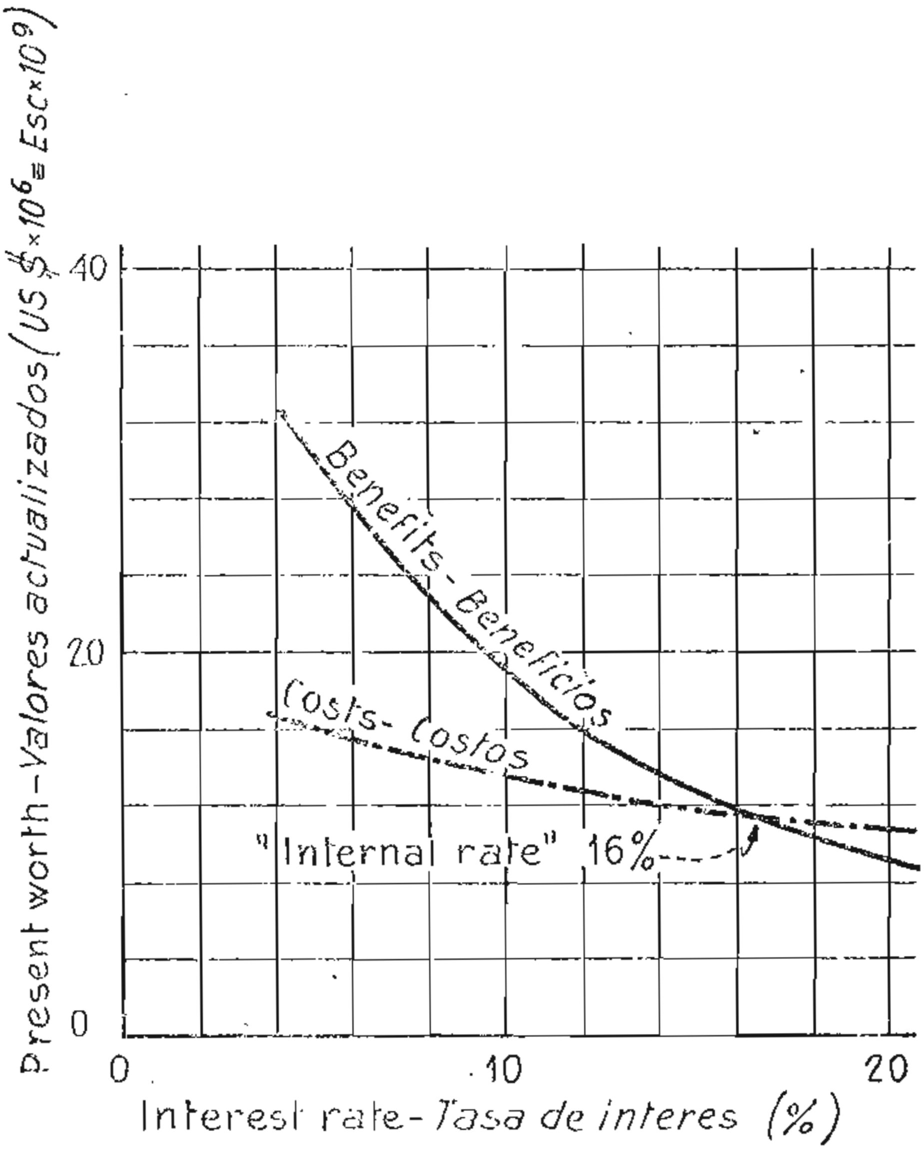


FIG.6/3

6.5 Financial Analysis

In this section the financial aspects of running the geothermal power plant of El Tatio and the transmission line to Chuquicamata are evaluated.

In order to make an analysis, some assumptions have been made in the reconstruction of the two fundamental balances: debits and credits, and cash flow. These assumptions are explained below.

The analysis refers only to the plant and transmission line and ought to be considered in the context of the general budget.

6.5.1 Balance of Debits and Credits

The following Table 6/10 illustrates the annual balance sheet with Debits and Credits referring to the running of the project.

Credits These result from the sale of energy to Chuquicamata-Calama network. The estimate is based on the assumption of 120 million kWh energy or 15 000 kW of net power sale at a rate of 1 700 Esc/kW for power and at an average of 16 Esc/kWh for energy.

The total annual credit is 1 945 x 10^3 US$ (= x 10^6 Esc).

Loans In order to obtain the necessary capital for the construction of the geothermal plant and the transmission line one single total loan is considered. The conditions for the loan are as follows:

4 year grace period (no payment)

annual interest rate of 8%

repayment within 20 years

Table 6/10 illustrates the loan repayment (US$ x x 10^3 = Esc x 10^6).

Table 6/10

PROJECT LOAN FLOW

YEARS	INVESTMENT		DEBT AT END OF YEAR	LOAN DEPRECIATION	
	Capital	Interest		Capital	Interest
1	3 000	120	3 120	-	-
2	4 000	400	7 520	-	-
3	3 950	718	12 188	-	-
4	-	876	13 064	-	-
5	-	-	12 764	300	1 042
6	-	-	12 443	321	1 021
7	-	-	12 096	347	995
8	-	-	11 724	372	970
9	-	-	11 322	402	940
10	-	-	10 896	436	906
11	-	-	10 426	470	872
12	-	-	9 922	504	838

Debits These consist of the cost for running and maintaining the plant and the transmission line, amounting to a total of 490 x 10^3 US$/annum, the depreciation cost of the works and the equipment estimated at 450 x 10^3 US$, and the interest on the loan.

Balance is the difference between credits and debits. It represents the gross balance when the interest of the loan is not taken into account. If the interest is included then it is the net balance.

It will be noted from Table 6/11 that the gross balance always results in generation of active cash at approx 1 000 x 10^3 US$/annum, but the net balance gives two negative values when the repayment of the loan begins.

6.5.2 Cash Flow is illustrated in Table 6/12.

Sources of Funds These consist of the generated cash, cash depreciation allowance, the capital obtained with the construction loan and an additional source contribution which is justified by the secondary benefits obtained from the plant.

Table 6/11

EL TATIO PROJECT – BALANCE CREDITS AND DEBITS (US\$ x 10^3 = Esc x 10^6)

DESCRIPTION	YEARS 1	2	3	4	5	6	7	8	9	10	11	12+27
CREDITS												
Sale of Energy	–	–	1 300	1 945	1 945	1 945	1 945	1 945	1 945	1 945	1 945	1 945
DEBITS												
Operation and Maintenance	–	–	300	490	490	490	490	490	490	490	490	490
Depreciation	–	–	–	450	450	450	450	450	450	450	450	450
Interest on Loan	–	–	–	–	1 042	1 021	995	970	940	905	872	838
Total without Interest	–	–	300	940	940	940	940	940	940	940	940	940
Total with Interest	–	–	300	940	1 982	1 961	1 935	1 910	1 880	1 846	1 812	1 778
GROSS BALANCE												
Cash Generation	–	–	1 000	1 005	1 005	1 005	1 005	1 005	1 005	1 005	1 005	1 005
NET BALANCE												
(including interest)	–	–	1 000	1 005	(37)	(16)	10	35	65	99	133	173

Table 6/12

EL TATIO PROJECT – CASH FLOW (US$ x 10^3 = Esc x 10^6)

DESCRIPTION YEARS	1	2	3	4	5	6	7	8	9	10	11	12÷27
SOURCE OF FUNDS												
Cash Generation	–	–	1 000	1 005	1 005	1 005	1 005	1 005	1 005	1 005	1 005	1 005
Depreciation	–	–	–	450	450	450	450	450	450	450	450	450
Loans	3 000	4 000	3 950	–	–	–	–	–	–	–	–	–
Funds	3 000	4 000	4 950	1 455	1 455	1 455	1 455	1 455	1 455	1 455	1 455	1 455
USE OF FUNDS												
Construction	3 000	4 000	3 950	–	–	–	–	–	–	–	–	–
Interest during Construction	120	400	718	876	–	–	–	–	–	–	–	–
Loan Repayment	–	–	–	–	1 342	1 342	1 342	1 342	1 342	1 342	1 342	1 342
Total Use	3 120	4 400	4 668	876	1 342	1 342	1 342	1 342	1 342	1 342	1 342	1 342
CASH BALANCE												
Annual Net	(120)	(400)	232	579	103	103	103	103	103	103	103	103
Cash Accumulation	(120)	(520)	(238)	341	444	547	650	753	856	959	1 062	1 065

Use of Funds These cover the capital needed for the construction, the accrued interest during construction and the repayment of the loan. The quota allowed for the depreciation of the loan is 1 342 x 10^3 US$/annum.

Cash Balance The net cash balance gives a passive total of approx 500 x 10^3 US$ during the first two years when the project is still in the construction phase. An active total begins with the first year of operation until more than one million US$ is accumulated after the first ten years of activity.

7 POTABLE WATER

7.1 Water Supply in the Province of Antofagasta

7.1.1 The Present Situation The principal works, designed for supplying potable water to the main towns in the province of Antofagasta, consist of a hydraulic system made up of a series of long pipelines which take the water from the Cordilleran sources to the consumption centers (see Plan GCI-1019).

In the town of Calama there is a junction of the distribution, in this way it is possible to have an interdependence of the water supply between Antofagasta, Calama, Tocopilla, villages and mining districts.

The main water supply system consists of the mains at Toconce, Linzor and Lequena and its maximum flow is approx 1 300 l/s of potable water.

The secondary water supply systems are Agua Verde, Vilama, Lindsor and Inacaliri with a flow of potable water of 200 l/s and those of Rio Salado and Rio San Pedro with a flow of industrial water of 1 200 l/s (Chuquicamata).

The principal characteristics of the potable water supply in the province of Antofagasta are presented in Table 7/1.

Table 7/1

POTABLE WATER CONVEYANCE SYSTEM IN ANTOFAGASTA PROVINCE

TOWNS	Conveyance	Distance from the source (km)	Pipe Diameter (mm)	Flow l/s	Water Cost (Cts $/m³)
CALAMA	Toconce	94.4	550	495	4.6
	Siloli	123.8	350	140	14.9
	Lequena	103.1	600	550	8.1
	Linzor	113.3	300	115	9.8
ANTOFAGASTA	Toconce	291.0	550	475	17.0
	Siloli	357.8	300	88	41.4
CERRO MORENO	Toconce	310.0	250	18	27.5
MEJILLONES	Toconce	344.4	150	6	55.2
TOCOPILLA	Lequena	270.1	350	120	18.2
PAMPAS SALITRERAS	Lequena	172.1	400	202	12.5
TALTAL	Aguas Verdes	60.7	125	20	21.5
SAN PEDRO DE ATACAMA	Vilama	3.3	100	11	3.6
CHUQUICAMATA	Lindsor	92.5	225	50	21.5
	Inacaliri	102.8	400	119	14.8

The average cost of water supplied to towns was obtained by adding the yearly operating expenses and yearly depreciation costs (the factor for recuperating the capital is 0.10) dividing the total amount by the volumes of water supplied.

The data refer to April 1973 and in particular we have taken into account the costs in US dollars of an exchange rate of 1 US$ = 72 Esc.

The industrial water has the following characteristics:

TOWN	Conveyance	Distance from the source (km)	Pipe Diameter (mm)	Flow l/s	Water Cost (Cts $/m³)
CHUQUICAMATA	Rio Salado	72.8	650	440	3.2
	Rio San Pedro	59.6	700	470	5.1

The average cost for supplying potable water, without considering the supply system is 16.5 cents \$/m3 and that for supplying industrial water to Chuquicamata is 4.3 cents \$/m3.

7.1.2 Demand Projections The various national authorities are concerned about the increasing demand for potable water in the province of Antofagasta as the water resources of the area are limited. The Ministry of Health and Sanitation has undertaken the study of present and future demands for potable water and these are elaborated as below.

The basic parameters of the study are: population (and its growth) and per capita consumption.

Population For the study of the demographic situation are taken into account: data from the census taken between 1885 and 1970 in the principal centers; the urban conditions (i.e. climate, availability of technical and social services); the income expected from local activities (trade, industries, agriculture); as well as all other factors that can affect or modify the local demographic changes.

The Table 7/2 synthetizes the data of the census and Table 7/3 predicts the future population increases for the province of Antofagasta on the basis of three conglomerates: the department of Antofagasta including the town itself and nearby towns (Cerro Moreno, Mejillones), the towns of Calama and Tocopilla including the inhabitants of the pampas.

Table 7/2

POPULATION DATA ON ANTOFAGASTA PROVINCE

Years	Antofagasta	Antofagasta Department	Calama	Tocopilla	Province
1885	7 588	(.....)	897	1 816	33 636
1895	13 530	(.....)	904	3 383	44 085
1907	32 496	60 447	2 856	5 386	113 323
1920	51 531	101 604	3 175	5 207	172 330
1930	53 591	89 998	5 407	15 305	178 765
1940	50 244	68 958	4 961	15 516	145 147
1952	62 123	82 933	12 995	19 353	185 624
1960	88 811	108 369	26 166	20 626	215 376
1970	125 084	132 642	45 863	21 980	251 555

Table 7/3

POPULATION INCREASE FORECASTS FOR ANTOFAGASTA PROVINCE

Years	Antofagasta Department	Calama	Tocopilla and Pampas	Province
1975	157 200	45 900	54 200	282 000
1980	172 800	53 800	57 000	306 000
1985	189 300	62 200	59 800	330 000
1990	206 600	71 000	63 000	360 000
1995	224 800	80 300	67 000	389 000
2000	243 700	90 000	72 200	418 000

For the whole province, the population increase is based on the data from the last three census extrapolated according to a parabole of the second degree.

Factors An average daily consumption per capita can be obtained by dividing the total yearly consumption of a district by the total population and the days of the year.

For each zone, an analysis of the consumption was made taking into account the population density, types of consumers, climatic, social and economic conditions, and obtaining a specific value for each factor.

The amounts obtained for each factor were used for calculating the predicted demand for each zone, as indicated in Table 7/4.

Table 7/4

PREDICTED DEMAND FOR POTABLE WATER (1/d x h)

Years	Antofagasta Department	Calama	Tocopilla and Pampas
1975	295	270	220
1980	305	285	235
1985	320	295	250
1990	335	305	265
1995	345	320	280
2000	360	330	300

Consumption The predicted consumption takes into account the above factors and is illustrated in Table 7/5, which shows, for each of the four zones, the population, the mean and maxima daily consumptions.

From this table it can be concluded that the deficit produced between the available supply and the demand for the next years will be localized basically in the department of Antofagasta.

7.2 Characteristics of the Residual Water from the Geothermal Plant

In accordance with the scheme for utilizing the geothermal fluid, as set out in Chapter 5, the available residual water after the second flash at the pressure of 1 kg/cm^2 abs and temperature of 100°C is about 350 t/h.

The chemical composition of the saline residue with a total of 16 000 ppm is indicated as follows:

Cationes	p.p.m.	Aniones	p.p.m.
Na	4 800	Cl	8 800
K	800	SO_4	30
Li	50	HCO_3	40
Cs	17	B	200
Rb	8	CO_2	5
Ca	210	SiO_2	750
Mg	0.2	H_2S	1÷10
NH_3	2.5		

The pH is variable between 6.7 and 7.3.

7.3 Desalination Pilot Plant

For experimental work on desalination, the British Government through the United Kingdom Atomic Energy donated a pilot plant which was installed by Aiton & Co. Ltd.

This plant has been operating for six months.

The plant processes 900 l/h of geothermal fluid at approx 150°C derived from the No. 2 production well.

The results of this first series of tests are set out in the report of January 1975 prepared for CORFO.

During this first period of testing, high concentration ratios (15 x 10 times) have been applied and it was observed that:

a. The hardness of the silica deposits in the

Table 7/5

POTABLE WATER CONSUMPTION FORECASTS IN ANTOFAGASTA PROVINCE

Years	1975		1980		1985		1990		1995		2000	
	Popul.* (x10³/h)	Consump.* (l/sxh)	Popul. (x10³/h)	Consump. (l/sxh)	Popul. (x10³/h)	Consump. (l/sxh)	Popul. (x10³/h)	Consump. (l/sxh)	Popul. (x10³/h)	Consump. (l/sxh)	Popul. (x10³xh)	Consump. (l/sxh)
Antofagasta Department	157.2	537	172.8	610	189.3	70[illegible]	207.6	803	224.6	898	243.7	1 015
Calama	[illegible]	144	54.0	112	62.0	212	71.0	251	80.0	296	90.0	344
Tocopilla	28.4	72	30.4	83	32.6	91	35.0	107	38.2	124	41.4	[illegible]
Tocopilla Pampas	25.5	65	26.6	72	27.2	79	28.0	86	28.9	93	30.0	104
		–		–		–		–		–		–
Average Daily Consumptions (l/s)		819		943		1 086		1 249		1 411		1 607
Maximum Daily Consumptions (l/s)		1 065		1 226		1 412		1 624		1 834		2 089
Additional Consumptions (10%)		107		123		141		162		183		209
Total Daily Demand (l/s)		1 172		1 349		1 553		1 786		2 017		2 298
Actual Capacity (l/s)		1 265		1 265		1 265		1 265		1 265		1 265
Deficit (l/s)		–		84		288		521		752		1 033

* Popul. = Population

Consump. = Consumption

sedimentation tank depends on the retardation time: the longer the time interval, the softer is the deposit.

Consequently, to obtain a deposit sufficiently soft for easy removal, long standing times are required (more than an hour).

b. The plant and particularly the pipelines in the heating chamber ought to be cleaned between tests by a hot alkaline solution for a period of approximately 24 hours and then brushed to remove the saline deposits.

In this way a constant coefficient for heat exchange in the plant is assured.

c. The above facts are obstacles in the plant operation. Only by reducing the salt concentration by half (which corresponds to a 50% utilization) it is possible to obtain larger operating periods without cleaning.

d. Another requirement for obtaining softer saline incrustations is increasing the pH of the entering fluid to approx 8.5.

All the observations mentioned above confirm that technical problems are not yet close to solution and no data about the feasibility of the project have been obtained.

Furthermore, from the experiment of the pilot plant, it appears that this type of process (multiflash with vertical tubes of evaporation) is not the most adequate to distil a geothermal fluid.

This type of process is, in fact, efficient but it requires high capital and operation costs.

In this case the efficiency is not the principal factor to be considered as the energy source has a low cost but the simplicity of the process is an essential requisite to reduce both capital and operation costs.

In conclusion, for a commercial installation in El Tatio, a plant that utilizes flash distillation in multiple phases is preferable.

7.4 The Problem of Desalination of the Geothermal Water

In recent years, the problem of water desalination, particularly from sea waters, become increasingly important, especially in arid countries that have no resources for obtaining potable water. All over the world, there are many plants in operation of different sizes and nearly all of them employ a multiflash process. The technology of this process is well advanced and potable water can be produced with optimum economy by a combination of desalination and thermoelectric plants.

However, the chemical characteristics of geothermal water of El Tatio are quite different from sea water and there are some unknowns that can affect the feasibility of a desalination plant; these unknowns are as follows:

Incrustations as a consequence of a high silica content (which is low in sea water) in combination with other salts.

Corrosion of Materials The copper-aluminium alloy generally used in the plant can be severely damaged by geothermal waters.

The use of other kinds of materials, for example certain titanium alloys, would increase the economic costs of the process.

Ratios of Concentration Experience in operating desalination plants indicates that the optimum concentration ratio of the residual brine is about 5:1. Therefore the concentration ratio of 20:1 taken by the El Tatio experimental plant should be considered unrealistic.

7.5 Economic Considerations of a Desalination Plant in El Tatio

In spite of the unknowns in relationship to the technological aspects of the process, it is proposed to install a conventional multiflash plant at El Tatio for desalination of the geothermal water and send the treated water to the mains at Toconce for delivery to the consumption centers.

In fact, the distribution center at Toconce in the months of low flow, does not use its maximum transport capacity because of the lack of water and could receive about 100 l/s from other sources, such as the El Tatio plant.

We have made an estimate of the cost of the desalination plant at El Tatio and transport to Toconce in accordance with the following hypotheses:

- Water flow to be desalinated: 350 m3/h;
- Flow of potable water produced: 280 m3/h (5:1 concentration ratio);
- Capacity of "multiflashes" desalination plant: 300 m3/h;
- Pipelines of 20 km in length and 250 mm in diameter to the Toconce distribution center.

In the following Table 7/6 are shown the economic parameters:

Table 7/6

ECONOMIC EVALUATION FOR THE DESALINATION IN EL TATIO

Investments (US $ x 10^6)	
Desalination Plant	7.5
El Tatio-Toconce Piping	2.5
Interests during Construction	1.0
Total Investments	11.0
Yearly Operation Expenses (US $ x 10^3)	
Personnel	50
Maintenance	300
Materials (chemical and electric)	250
Total	600
Yearly Financial Expenses (US $ x 10^3)	
Interests (8%)	880
Depreciation (5%)	550
Total	1 430
Total Yearly Expenses (US $ x 10^3)	2 030
Yearly Production (for 8 000 hours) (m^3 x 10^3)	2 240
Water Cost in Toconce (US $/$m^3$)	0.91

From this table the cost of the desalinated water is 90 cents $/m3.

Up to now, the Toconce water pipeline is capable of receiving additional water only in the periods of low flow. That would correspond to about only 50% of the water made available by the desalination plant. Consequently, the cost of the delivered water would increase to 1.8 US $/m3.

On the other hand, as the greatest increase in the demand for drinking water is foreseen in the department of Antofagasta, a new pipeline from the El Tatio Plant to Antofagasta with a capacity of 100 l/s should be considered.

In this case, the cost of water transported to the consumption centers rises to 2 US $/m3.

For all the above mentioned reasons, a desalination plant at El Tatio is an unfeasible proposition.

The water rejected by the low pressure separators can be safely discharged into Rio Salado. The salinity of the Rio Salado waters will increase from 6 000 ppm (average concentration) to approx 8 000 ppm because of the concentration of salts in the discharged residual water.

It should be noted that the waters of Rio Salado are utilized by Chuquicamata mines in the ore concentration process and in the near future the mines will need an additional water flow of 150 l/s.

The saline waters used by the mine do not require special treatment and it seems reasonable to assume that the increased salt concentrations from the El Tatio plant will not affect the mine workings.

In this case, the residual water from El Tatio would have an appreciable economic value because of its use by the mines.

7.6 Utilization of the Water from Condensing Steam

The steam discharged from the turbine mixes with cooled water in the barometric condenser. In the "humid" cooling tower, 85% of the condensate is lost by evaporation and for this reason, the balance of the discharges from the cooling system will probably yield approx 20 t/h of water. This slightly acid water because of the presence of CO_2 and traces of H_2S contains 200 ppm of salts and, after being neutralized, can be used for various purposes but not as potable water.

In order to recover all the condensate from the steam discharged by the turbine, approx 150 t/h, it is necessary to have cooling tower of the dry type and not the wet type as planned.

The cooling system should be "Haller" type, that is, with the mixing condenser of the same type as for the wet type.

The water should be air-cooled by a system of radiators (dry tower) made of material resistant to corrosion.

The water obtained will be weakly acid and practically without salts (≃10 ppm). To obtain drinking water it is necessary to have a treatment of aeration, neutralization and mineralization.

From the economic point of view, the solution of the dry tower entails a higher investment of 2 million US $.

Furthermore, a power net loss of 5% must be taken into account, owing to the fact that the vacuum in the condenser is less and more energy is needed for auxiliary services.

The unit cost of water produced is approx 0.60 US $\$/m^3$ and this includes the cost of the pipeline to Toconce.

7.7 Alternatives for the Potable Water Supply

From Table 7/5 it can be seen that the deficit of potable water in the province of Antofagasta will start from 1980. In particular, in 1990, and in the Department of Antofagasta alone, this deficit will reach 500 l/s.

7.7.1 Conventional Desalination Plants It is logical to consider, as an alternative to the desalination of geothermal water, the installation of a sea-water desalination plant for supplying drinking water to this center and this presents no unknowns of either technological or economic nature.

The cost of a conventional multiflash sea-water desalination plant with a capacity of 1 500 m^3/h fresh water, could be estimated, on the basis of known operating plants, around 30 million US \$. The resulting production cost would be 0.5-0.6 $\$/m^3$, if the plant is supplied with power from a thermoelectric plant of approx 100 MW capacity, using bunker C at 80 \$/t.

The construction of this desalination plant will also allow the saving of part of the water transported to the department by the present pipeline system (Toconce and Siloli) in favour of the other consumption centers.

7.7.2 Utilizations of Natural Resources The investigations carried out in several areas of the Cordillera to find new sources of potable water (CORFO, DGA, PNUD 1973) seem to indicate that it may be possible to utilize the natural resources of Rio Grande in the vicinity of the department of San Pedro de Atacama.

At the moment the water of the river and its tributaries are used for local consumption for homes and farms but it seems that an additional flow of 1 500 l/s could be available.

It would be interesting to consider the possibility to utilize this water in the department of Antofagasta even if, at present, there are no data on water quality.

Without considering treatment problems, a water mains system with a capacity of 500÷700 l/s requires a 400 mm diam eter, 280 km long pipeline and would imply an estimated cost of 40 million US $.

The cost of the water supplied would result 0.38 cents $/m^3$, based on the following calculations:

Depreciation + interest on 40 x 10^6 US $ investment (12%)	US $	4 800 000
Operating costs (2%)	US $	800 000
Total	US $	5 600 000
Volume of water	15 000 000 m^3/annum	
Cost of water	0.38 cents $/$m^3$	

8 MINERAL EXTRACTION

8.1 Mineral Characteristics of the Residual Water

The following Table 8/1 shows the concentration of the economically important elements in the waters of the wells 7, 10 and 11. The table also illustrates a comparison between these concentrations and those of the better known geothermal brines of "Salton Sea" and the "Grand County (Utah). (See Werner Report TGMA, June 1971)

Table 8/1

IMPORTANT ELEMENT CONTENT OF THE GEOTHERMAL FLUIDS (ppm)

Elements	Well 7	Well 10	Well 11	Salton Sea	Grand County Utah
B	200	200	200	520	660
Li	44	44	44	300	66
K	830	780	820	25 000	18 800
Rb	8.4	8.3	8.5	169	20
Cs	17.3	16.1	17.1	20	-

The annual amount of the minerals contained in the water discharged by the proposed power plant (15 MW) is as follows:

H_3BO_3	4 400 t/annum
LiCl	1 100 t/annum
KCl	6 000 t/annum
RbCl	45 t/annum
CsCl	80 t/annum

8.2 Mineral Market

8.2.1 Prices The average prices (1974) of the above listed minerals are approximately as follows:

H_3BO_3	100 US$/t
LiCl	2 000 US$/t
KCl	20 US$/t
RbCl (technical grade)	110 000 US$/t
CsCl (technical grade)	87 000 US$/t

8.2.2 Outlook on Caesium, Rubidium and Lithium Market Prospects The current production and consumption of caesium and rubidium are poorly documented and information tends to be restricted by commercial confidentiality, therefore statistical data on the consumption and uses of both metals and their compounds are not available.

Predictions indicate an increasing demand until the year 2000. In that year, the demand for caesium in the U.S. is forecast to be between 5 000 and 17 000 kg and between 4 000 and 14 000 kg for the rest of the world. Demand of these levels by the end of the century is, however, dependant upon continued technological progress in new methods of power generation (thermoionic conversion of heat directly to electricity, without the intervention of fluids of moving parts, by means of caesium ions).

The demand forecast for rubidium is between 500 and 1 500 kg for the U.S. and between 550 and 1 600 kg for the rest of the world. (mining Annual Review 1974).

The high cost and extreme chemical reactivity of both caesium and rubidium may to some extent, inhibit growth in demand in favour of certain substitute, such as germanium, selenium, tellurium, potassium, thorium, etc. for the main uses of the two metals under consideration

The annual amount of caesium and rubidium recoverable fro the El Tatio brines, even if only a 50 % efficiency in the extraction is assumed, corresponds almost to the amount foreseen for the world consumption in the year 2000. Therefore it would be unrealistic to presume that the whole production from the project can be sold in the international market at current prices.

The lithium on the contrary, seems to have much better market perspectives; in fact the estimated world consumption rose more than 30% from 1972 to 1973, reaching 23 000 metric tons of lithium carbonate for that year.

Production statistics are not normally disclosed by the producing countries but the Canadian Department of Energy, Mines and Resources has quoted the following levels of world output:

1970	24 000 t
1971	24 000 t
1972	27 000 t

More than 60 % of the amount is produced by the USA, which is also by far the largest lithium consuming country.

Apart from the use in glass and ceramic industry, the most important use recently developed for lithium, is in the aluminium industry. In fact, the addition of lithium carbonate to the electrolyte during the electrolysis of alumina for aluminium production can both reduce power requirement by up to 10% and also increase throughput by up to 10%. Considering the escalation of the actual energy prices, the general extension of such use is to be expected.

Nevertheless, it can be expected that lithium chloride extracted from the El Tatio brines will not be able to compete economically with lithium obtained from minerals (lepidolite, spodumene, etc), whose lithium tenor is 2-4%.

8.3 Approach for the Feasibility of the Mineral Recovery

The element concentrations assumed by Werner (1971) are confirmed by the analyses carried out by Mahon (1971 and 1974) on the waters coming from producing wells (7, 10, 11).

Some doubts are raised concerning the high silica content in the brines, which could compromise the technical feasibility of the process.

The mineral extraction process proposed by Werner in his report (Fractionated Crystallization) seems to be theoretically feasible.

However, the market review has shown that the rubidium and caesium minerals are not marketable in the amount considered and at the present prices.

As far as the economical feasibility is concerned, without sufficient data and information it is practically impossible to have any ideas about the capital and operating costs of an industrial plant for the mineral extraction.

Besides, extraction of minerals by fractional crystallization requires concentration of residual water by means of evaporation. With this in mind, and having already excluded the feasibility of the desalination plant which could provide a concentration of residual brines, the economic convenience of mineral extraction becomes still more doubtful.

9 CORROSION PROBLEMS

9.1 General Outlook

The geothermal water of El Tatio contains a rather high concentration of dissolved salts, together with a small amount of noncondensable gases in the steam as follows:

Cl	8 700 p.p.m. in water
SO_4	30 p.p.m. in water
NH_3	2 p.p.m. in water
H_2S	30 p.p.m. in steam
CO_2	300 p.p.m. in steam

Considering that the separator does not have 100% efficiency and the steam contains a small amount of water in addition to the noncondensable gases, corrosion of many of the equipment materials can take place when this water comes into contact with them; the degree of corrosion depending on the circumstances.

In order to reduce the water content of the steam as much as possible extraction pots on pipes as well as a humidity separator have been provided.

9.2 Corrosions due to Chlorides

The chlorides carried by the endogenous steam must be kept within the 10-20 ppm limit, as the materials which come into contact with them suffer from slow electromechanical corrosions, uniformly spread over the metal surfaces, with wide and irregular pits only in the places where the first condensate collects (discharges, valve leaks, etc). In the case of pipelines, the vessels and drums made of common carbon steel boxes last long enough.

For higher amounts of chloride, contained in the liquid phase, the chemical etching on metal surfaces become faster and deeper. It is quite possible that Cl be present in the fluids in its original form NH_4 Cl and as far as it has no opportunity of being separated, it does not become aggressive. In presence of a liquid, obviously, salt is separated and soluted. NH_4Cl passes to borate and free HCL swiftly attacks the metal. Therefore, particular attention must be given to the choice of materials which will come into contact with the mixtures of water and steam, separators included.

Steam will not present problems because with adequate separators humidity can be reduced to very low values (about 5%). Therefore chlorides could be maintained within normal values for geothermal plants, easy anyway to be neutralized by means of alkaline washing just it is common practice since years in the Lago Power Station in Italy.

9.3 H_2S and CO_2 Corrosion

As for the corrosion over metal structures by H_2S and CO_2, no problems are foreseen at El Tatio. The temperature of the steam is much lower than that necessary for H_2S to etch the iron, forming a compact film of FeS, while it is too high for H_2S and CO_2 to become chemically agressive in the condensation phase.

Some problems may be caused instead by the formation of deposits on the equipment due to leakages from the flange joints.

9.4 Stress Corrosion

Particular attention should be paid to stress fatigue. It is known that halogen ions in contact with some stainless steels can destroy the protective sheath formed by chromium oxides. The underlaying surface acts as an anode of an electrolitic cell whose cathode is the passive surface layer.

The etching is of a localized nature, because the electromotive force developed protects the cathode surface from later etchings. The intensity of corrosion increases with the concentration of the corrosive agent and temperature. When the static stress reaches a certain value, generated by internal stresses or by externally applied loads (as in the case of expanding joints, in turbines subject to frequent temperature changes and in turbine blade joints), the point corrosion is easily transformed into stress fatigue.

In effect, when the microfissures deepen on the edge, a concentration of stresses is produced, whose value determines the limit for the flow of the material. A plastic deformation is produced and the fissure progresses. As the fissure widens, new metallic surfaces, which are not passive, are revealed, and the corrosive agent acts with increasing velocity, enhancing the phenomenon. Generally, the attack continues along crystals (corrosion below transcrystalline forces) weakened by high stresses and damaged materials.

At other times, because of modest stresses and inadequate thermal treatment which provokes precipitation of carbides, carbon corrosion continues along the borders of the crystal (intercrystalline low stress corrosion). The intensity of stress corrosion increases with the temperature and the magnitude of stress and depends on the redox potential of the corroding agent with respect to the steel, the pH values, and metals present in the alloy.

9.5 Corrosion in Civil Works

Finally, the possibility of corrosion and erosion of the civil works which form part of the hydraulic circuit of the geothermal power plant (discharge canals, pumps, etc) are examined. In general, these works are constructed of concrete (reinforced or not) whose well known and advantageous construction characteristics offer optimum qualities of resistance to the chemical agents.

In general, these structures are noticeably corroded only on the surface contact with water-gas mixtures. The corrosion is appreciably reduced if the works are completely submerged in endogenous waters.

A rich gas and vapor mixture in the presence of oxygen from the atmosphere can attack the cement components, separating and transforming the calcium into grains or crystals of $CaSO_4$-$2H_2O$, dispersed in a chaotic mixture of various salts, boric acid, sand and silica. The first component to be attacked is the calcium held as free calcium and the second is the calcium in the form of carbonate/bicarbonate and the third is that part of the calcium combined with silica and the mineralogical component of the cement. There is also a series of double exchange reactions between iron, calcium and ammonium salts that determine the sequence of the reactions of the attack.

Corrosion of the concrete is promoted by penetration of the salts, gas and vapours within the aqueous solution into the interior of the less compact and impermeable constructions. When these corrosive substances come in contact with the reinforced steel of the concrete, oxides and salts are formed that considerably increase the volume and cause fissures in the structures.

If the concrete is very compact, the expansion is counterbalanced by the resistance of the material and the attack takes place slowly or only on the surface. In the disintegration process, in planes parallel to the water line, the cement looses its consistency and is swept away by the waters. The corrosion cycle proceeds to the next underlying layer, in a series of alternating corrosion-erosion processes.

The surfaces below water are subjected to a slow process of solution of the Ca present in the concrete due to the CO_2 present in the water. There is then a decalcification process by bicarbonitization, which occurs when the pH is less than 7, but takes place very slowly (the reduction of the thickness is of the order of mm/year).

From the above discussion it is possible to derive some specifications for the concrete which can resist the corrosive action by fluids and endogenous waters:

Instead of calcareous use siliceous sands and gravels and rapid setting cements of pozzuolana or aluminium type;

Take care that the reinforcement bars are sufficiently covered within the concrete (for a thickness never less than 40 mm) to prevent easy infiltration of the corrosive gases;

Take care in the compaction of the concrete and its superficial finish with a good dressing (reinforcement) of gunite;

Allow the holes (cavities) to dry completely so that the setting and hardening are complete before being exposed to chemical agents;

The parts that will be most affected by the fluids can be covered with ceramics (bricks or tiles made of sandstone).

9.6 Selection of Materials

The general observations illustrated in the previous paragraphs, and the experience gained in Italy, New Zealand, and Japan suggest the selection of the following materials for the principal parts of the Plant.

a. Pipes for transporting non aerated endogenous fluids: - Steel Type ASTM A53, Grade B, without welding up to diameters of 18-20" with thickening to resist corrosion of the type "melting" which are inevitably present.

b. Valves and equipment for closing, discharge, etc of the non-aerated geothermal fluids: steel body of carbon reinforced with stellite.

c. Expansion of the pipes transporting endogenous fluids with curvature angles between 135 and 150°: steel type ASTM A53, Grade B. Corners with 90° angles and bellows expansion or telescopic joints should be avoided.

d. Valves at turbine inlet - as in b.

e. Box with the turbine blades: cast iron type ASTM A27, internally reinforced with stainless steel type AISI 316, superimposed by welding.

f. Turbine rotor: alloy steel type ASTM A293.

g. Turbine blades: stainless steel, type AISI, 410 L. The last two threads of the blades should be treated with stellite.

h. Expansion joint between the turbine and condenser: rubber.

i. Condenser: high resistant cast iron or carbon steel covered with a layer of stainless steel AISI 316 L, two mm thick.

j. Pressure tubing: steel type ASTM A53, Grade B covered with a layer of stainless steel AISI 316 L, two mm thick.

k. Water circulation pumps: stainless steel AISI 316 L.

l. Water circulation pipes: stainless steel AISI 316 L.

m. Cooling tower: structure and padding of redwood or pinewood, screws and bolts of stainless steel, ventilating blades of polyester reinforced with fibreglass.

n. Terminals of the substation: aluminium.

o. Civil works in contact with the residual or condensed waters: whether reinforced concrete or not, with pozzuolana or aluminium cement, siliceous sand or gravel, reinforced with gunite.

10 EFFLUENT DISPOSAL

In Chapter 7, the possible utilization of the residual water was discussed and the feasibility of potable water production from the residual water by desalination was examined. The conclusion which has been based on the production and distribution cost of water is to reject the treatment process and to discharge the water coming from the low pressure separator into the river Salado which is the major drainage for the area.

Here, consideration should also be given to the fact that the Chuquicamata copper mine utilizes the water of the river Salado in the ore beneficiation process and an increase in its production is planned in the near future. It is thought that an additional water flow of 150 l/sec will be needed when the planned increase in production takes place.

When the effluent from the geothermal plant is discharged into the water of the river Salado, the salinity of the river Salado will increase from 6 000 ppm to 8 000 ppm. This increase in salinity will not affect the foreseen industrial use of the water, as even sea water with very high salinity is used in the mineral preparation processes of flotation and leaching.

Therefore, in conclusion, with the level of production as set out in this report, the problem of effluent disposal can be solved in the most appropriate and simple manner, that is by discharging these wastes into the Río Salado, so that they can be used downstream by the Chuquicamata copper mine. If, in future, there will be an increase in the geothermal exploitation with a consequent substantial increase in the geothermal effluent, the following two alternatives can be considered:

a. Re-injecting the water into the permeable formation underground;

b. Discharging the water into dams constructed at the Site, and allowing the water to evaporate.

The second alternative will be easy to carry out as far as the necessary hydraulic and civil works are concerned and it would be the choice if re-injection proved not to be feasible. Furthermore, the second alternative could facilitate mineral recovery from the geothermal brines should the market conditions for the sale of these minerals alter favorably in the future, as discussed in Chapter 8.

11 ENVIRONMENTAL IMPACT OF THE GEOTHERMAL PROJECT

The environment of the El Tatio area can be described as follows:

- Region of the Andean Cordillera, with an altitude greater than 4 000 m;
- No population centers;
- The vegetation consists of two species of grasses: Stipa Ichu, a grass used for grazing sheep, and Azorilla Yareta, a moss used for firewood;
- The fauna is restricted to the Auquénidos family, of which the Vicuña and the Guanaco are wild species and the Alpaca is a domestic species. All these animals, including the sheep, graze on the Stipa Ichu;
- The surface drainage collector is the Rio Salado into which drain the waters of thermal springs, with the result that waters of the Rio Salado are saline and the salt content can be as high as 6 000 p.p.m.;
- The ground waters, both hot and cold, are saline;
- The local outcropping and subsurface rocks, as already explained in Chapter 4, are all of volcanic origin, and sufficiently compact and competent.

The possible causes of negative effect on the environment connected with the exploitation of the geothermal resources in El Tatio are the following:

Extraction of Fluids from the Subsoil In some geothermal fields in exploitation (Wairakei in New Zealand) the intense and extended extraction of hot water has produced soil subsidence.

In the case of El Tatio, it can be concluded that the possibility of soil subsidence is not probable, because of the limited amount of fluid that will be extracted, the compactness of the subsurface rock formations and the fact that the permeability of the geothermal reservoir is limited and exclusively of a secondary nature through fractures and fissures.

Even if some localized and occasional phenomena of soil subsidence occur, they will not have any practical effects because the area has few inhabited centers and installations.

Discharge of the Residual Waters As already mentioned in the previous chapters, the residual water of the geothermal process will be discharged into the Rio Salado. Rio Salado natural flow has already a high salinity (6 000 ppm), so that its use is limited to industry (the Chuquicamata mines) and is excluded for human, animal or irrigation needs.

The discharge of the residual waters with its additional salt contribution into the river, will not alter essentially the present situation , because the salt concentration, within a certain limit, does not affect the mining pressures.

Gas Discharge in the Atmosphere The weight content of non-condensable gases of the steam discharged from the vacuum pump of the barometric condenser is 0.3% for CO_2 and 0.003% for H_2S.

The quantity of uncondensed gases, therefore, discharged per hour is 300 kg of CO_2 and 3 kg of H_2S.

These quantities of gas cannot cause any appreciable pollution of the atmosphere and are easily dispersed by the wind.

It can be concluded that the operation of the geothermal plant at El Tatio will not generate any detrimental impact on the natural environment.

Milan, March 12, 1975
DOM/ORL/SIG/ALU/IVA

ANNEX 1 - REFERENCES

DRAWINGS