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U.N.U. Geothermal Training Programme

Introductory Lecture Course 1982

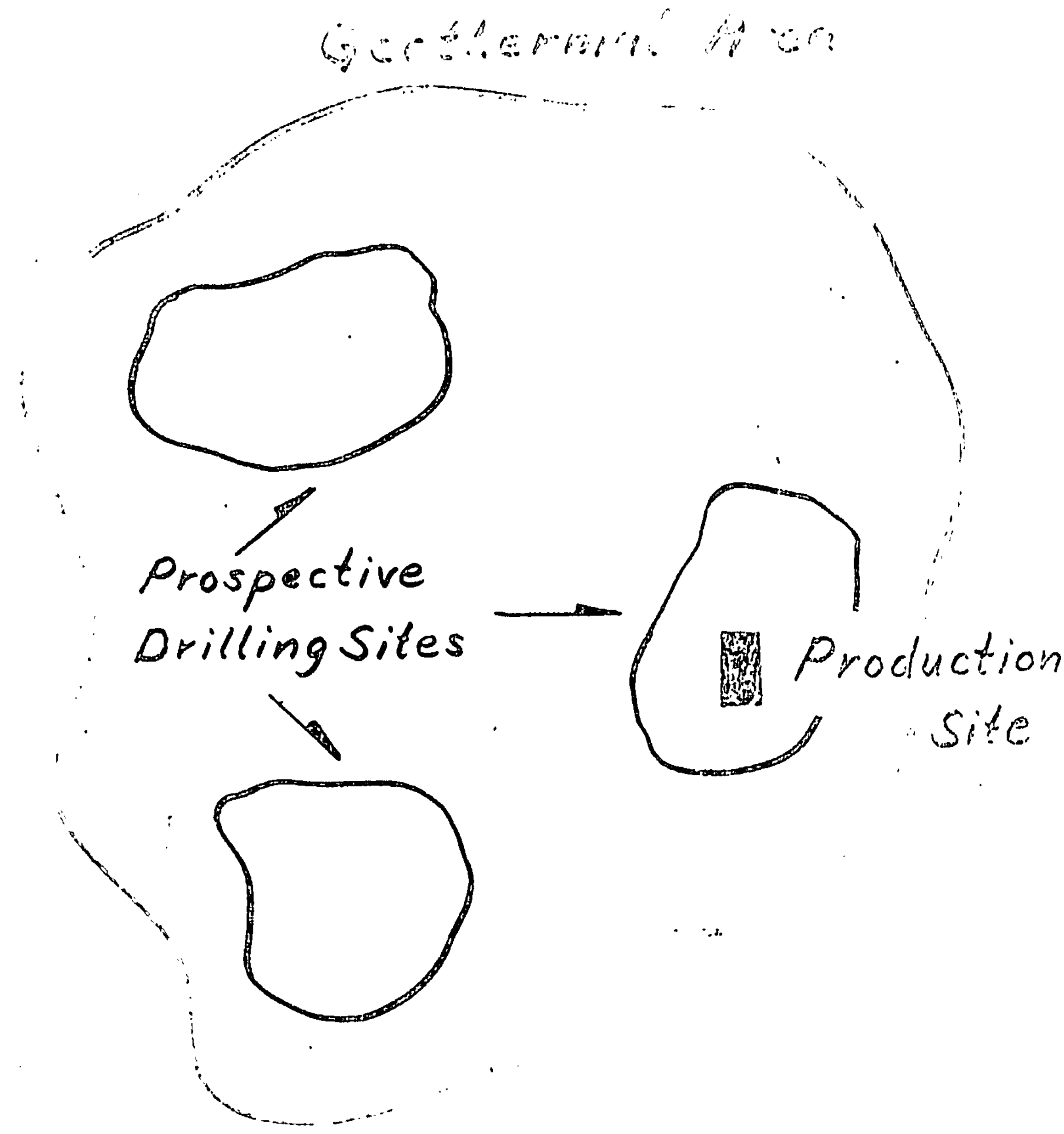
May 18

PLANNING AND ECONOMICS OF GEOTHERMAL PROJECTS

Sveinbjörn Björnsson

Approach to Geothermal Development

Approach	Professional	Economic	Crash
Risk	Minimum	Calculated	High
Cost	Calculated	Minimum	High
Time	Long	Short	Minimum

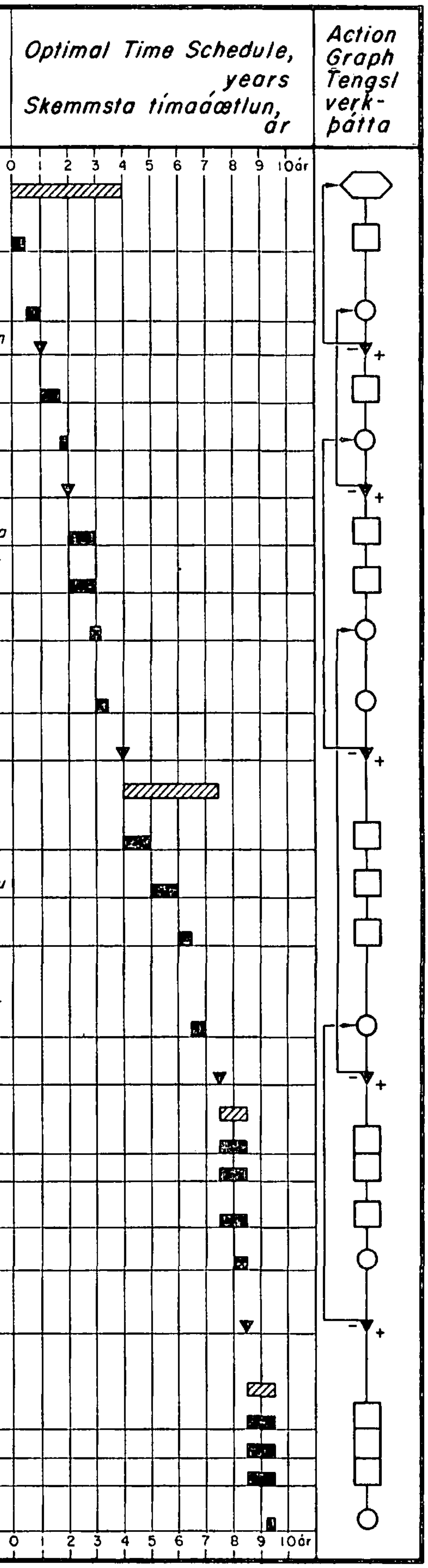

Geothermal Area
Prospective
Drilling Sites
Production
Site

14.4.80 SvE

Phases of Geothermal Development

Preliminary Study	Reconnaissance Survey Prospect Investigation Exploratory Drilling Prefeasibility Report
Appraisal Study	Appraisal Drilling Reservoir Evaluation Feasibility Study Feasibility Report
Project Design	Production Drilling Production Testing Project Planning Project Planning Report
Preparation of Tender Documents	Production Drilling Production Testing Design of Plant Tender Documents

Planning Stages of Geothermal Development SvB 12.08.1979	Áfangaskipting áætlana um virkjun háhita
PRELIMINARY STUDY	**FORATHUGUN**
Reconnaissance Survey	Fyrsta leit að svæði til virkjunar
Reconnaissance Report on Prospect Areas, Investigation Programme	Skýrsla um leit, álitleg svæði, áætlun um rannsókn
Decision on Investigation	Ákvörðun um rannsókn
Prospect Investigation	Rannsókn álitlegs jarðhitasvæðis
Prospect Report - Prospective Drilling Sites	Skýrsla um álitlega virkjunarstaði
Decision on Exploratory Drilling	Ákvörðun um rannsóknarboranir
Exploratory Drilling and Testing	Borun rannsóknarhola og prófun þeirra
Investigation of Drilling Site	Rannsókn virkjunarstaðar
Report on Results of Preliminary Study	Skýrsla um niðurstöður forathugunar
Prefeasibility Report on Prospective Production Site	**Drög að áætlun** um nýtingu
Decision on Appraisal Study	Ákvörðun um frumhönnun
APPRAISAL STUDY	**FRUMHÖNNUN**
Appraisal Drilling and Testing	Boranir og blástur til reynslu
Estimate of Reservoir Properties and Reservoir Potential	Mat á vinnslueiginleikum og vinnslugetu
Feasibility Study	Mat á hagkvæmni áætlaðrar nýtingar
Feasibility Report Proposed Design and Economic Feasibility	**Frumáætlun** um tilhögun og hagkvæmni virkjunar
Decision on Project Design	Ákvörðun um verkhönnun
PROJECT DESIGN	**VERKHÖNNUN**
Production Drilling	Vinnsluboranir
Production Testing	Vinnsluprófanir
Project Planning	Byrjun á hönnun virkjunar
Project Planning Report	**Hönnunaráætlun**
Final Decision on Design Criteria	Ákvörðun um endanlegar hönnunarforsendur
PREPARATION OF CONTRACT DOCUMENTS	**GERÐ ÚTBOÐSGAGNA**
Production Drilling	Vinnsluboranir
Production Testing	Vinnsluprófanir
Design of Plant	Hönnun virkjunar
Contract Documents	**Útboðsgögn**



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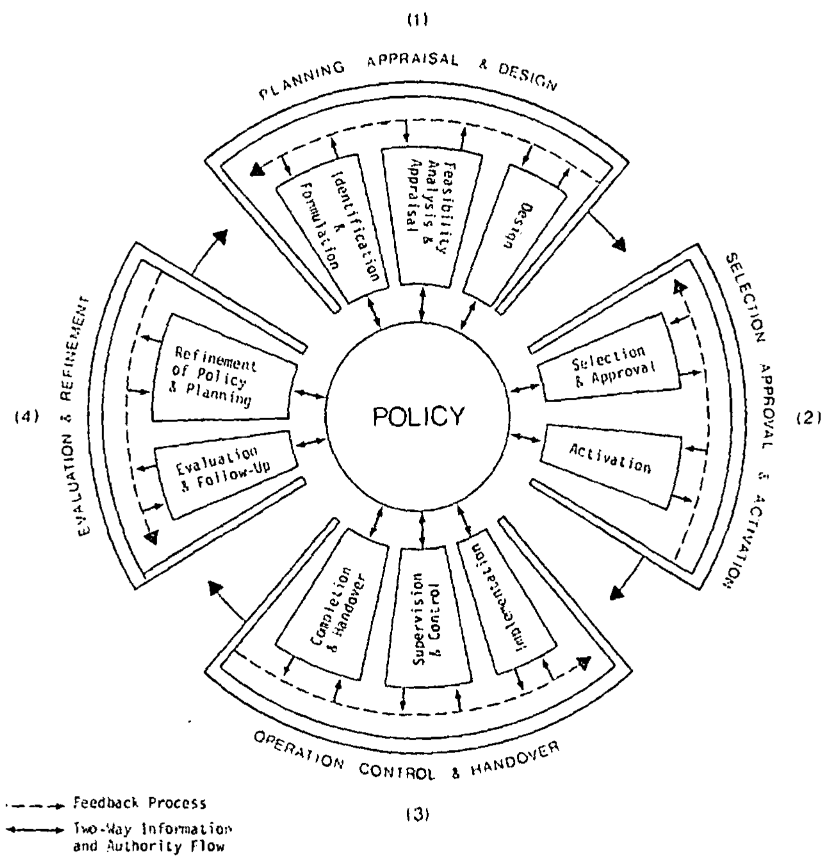
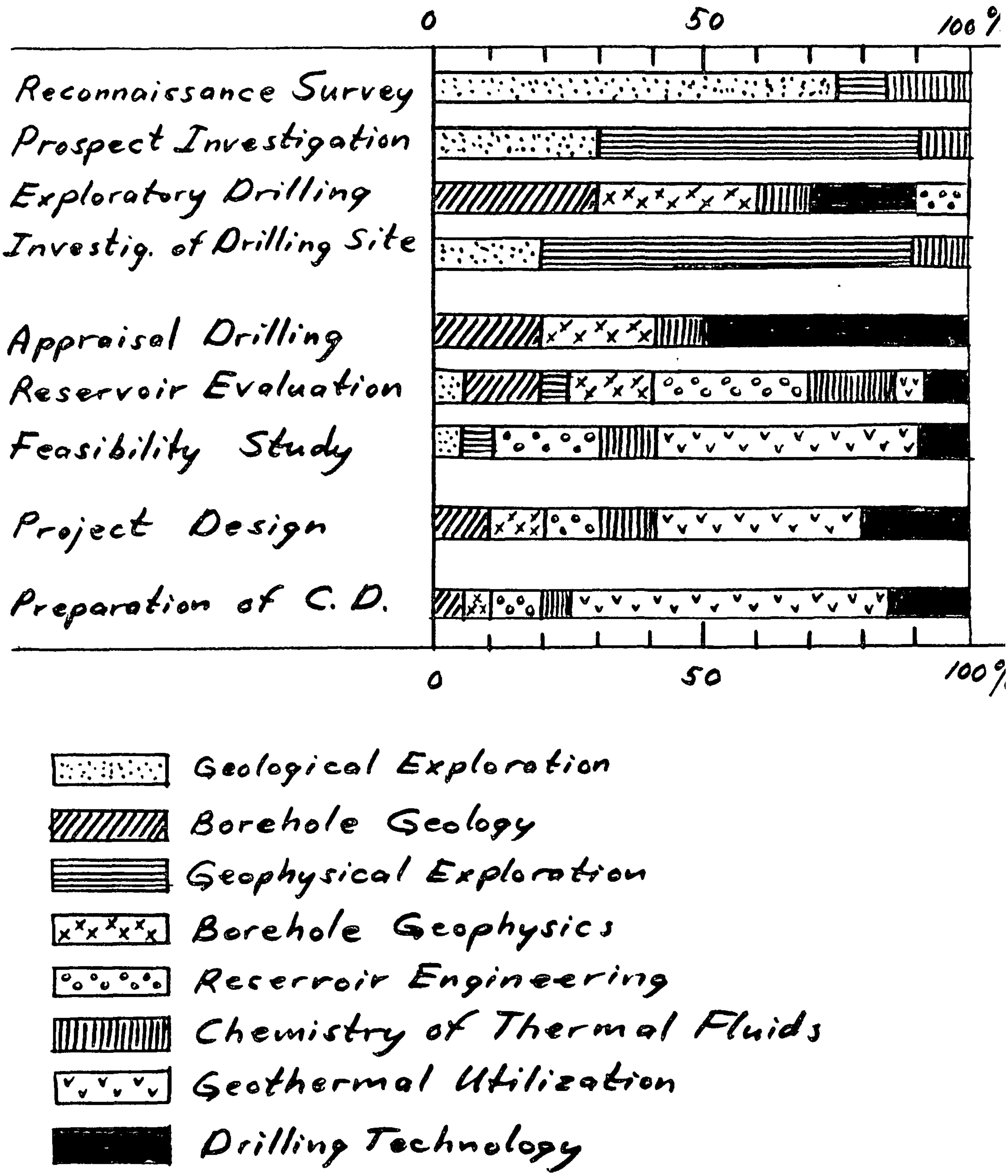


Fig. 1.5. Integrated project planning and management cycle: the four phases.
Source: East West Center, Honolulu, Hawaii.

Approximate relative contribution of each geothermal discipline to different phases of geothermal development.



Cost Breakdown of Preliminary Study

(Example from U.S. National Exploration Technology Program, Ball et. al., Geophysics 44, 1721–1737, 1979)

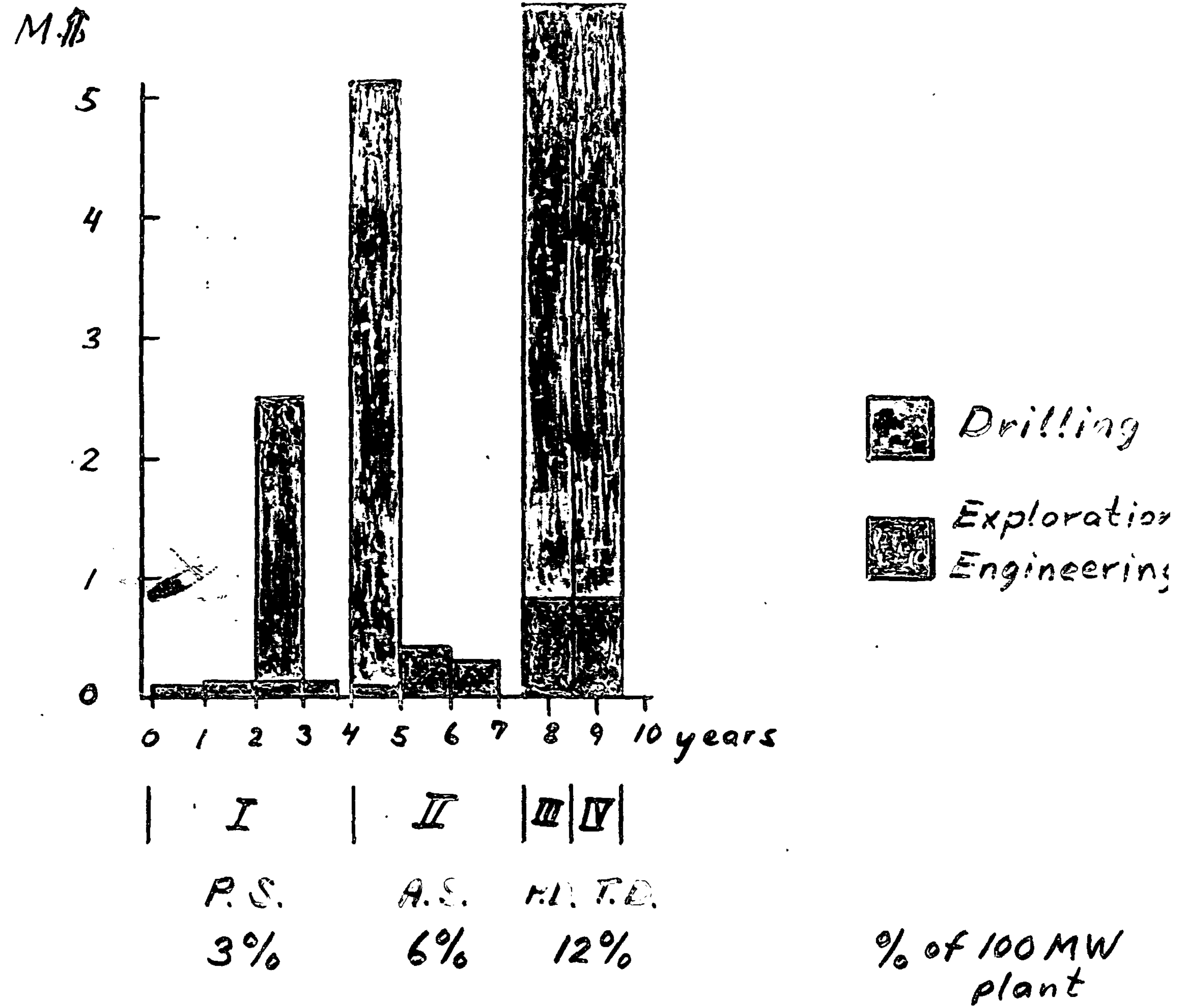
Reconnaissance Survey	Cost (K$)	Cost basis
Literature Search	20	0.25 man yr.
Photogeology	15	0.10 m.y. + 7 K$
Volc. and Structural Geology	20	0.25 m.y.
Chemistry, Isotopes	30	0.25 + 10 K$
Thermal Gradients (avail. holes)	30	0.375 m.y.
	115	1.23 m.y.

Prospect Investigation	Cost (K$)	Cost basis
Drill Gradient Holes	110	0.25 m.y. + 90 K$ (Drilling, 20 holes)
Alteration	20	0.25 m.y.
Temperature Logs	10	0.125 m.y.
Structural Mapping	10	0.125 m.y.
Dipole - Dipole Resistivity	80	60 d. $800/d + 32 K$ Interpr.
Conceptual Modeling	40	0.5 m.y.
	270	1.25 m.y.

Investigation of Drilling Site	Cost (K$)	Cost basis
Intermediate Drilling and Logging	260	0.5 m.y. 2500 ft, 80 $/ft +20 K$ logging
Lithology, Hydrology	30	0.25 m.y. + 10 K$
Chemistry, Isotopes	30	0.25 m.y. + 10 K$
Reflection, Refraction	120	0.5 m.y + 80 K$
AMT/MT Detail	60	0.25 m.y. + 40K
Geophysical Logging	25	0.1 m.y. + 17 K$
Modeling	40	0.5 m.y.
	565	2.35 m.y.

Exploratory Drilling	Cost (K$)	Cost basis
Deep Drilling	2250	3 wells, 5000 ft 750 K$/well
Lithology, Hydrology	90	0.75 m.y. + 30K$
Chemistry, Isotopes	90	0.75 m.y. + 30K$
Geophysical Logs	20	0.25 m.y.
Detailed Modeling	40	0.5 m.y.
Prefeasibility Study	200	2.5 m.y.
	2690	4.75 m.y.
Total	3640	9.6 m.y.

Cost of Planning Stages



Example of Estimation of Minimum Economic Yield of Wells

The estimation follows an example given by Armstead et al. 1974, Appendix p. 51-52. Cost figures are updated approximately. These figures are inaccurate and serve only to demonstrate the method of calculation.

Assumed alternative base load energy cost 24 US mils/kWh

Assumed steam consumption of turbine
19.2 lb/kWh = 8.6 tons of steam/MWh generated

Steam required for 100 MW power plant

100 MW x 8.6 tn/MWh =	860 tn/h
+ 20% for spare reserve	172 tn/h
	1032 tn/h

Assume steam is supplied from N wells, including failures

Capital estimate	K$		K$
Exploration, Appraisal, Design	9,000		
Drilling at 750 K$/well			750 x N
Wellhead gear + piping to mains			
180 K$/well			180 x N
Steam mains	15,000		
Generating plant	48,000		
Transmission	6,000		
Duties	9,000		
	87,000	+	930 x N

Annual Production Costs	K$/year		K$/year
Capital Interest 10%	8,700		93 x N
Depreciation			
25 years on 87,000 K$	888		
25 years on 180 K$ x N			1.84 x N
10 years on 750 K$ x N			47 x N
Operation and maintenance	1,500		
Bore repairs and replacements			20 x N
	11,088	+	161.84 x N
Contingencies 20%	2,218	+	32.37 x N
Total	13,306	+	194.21 x N

Energy generated (assuming 85% annual plant factor)

$$100 \text{ MW} \times 8766 \text{ h/y} \times 0.85 = 745{,}000 \text{ MWh/y}$$

Cost per kWh

$$\frac{(13{,}306 + 194.21 \times N) \cdot 10^6}{745 \cdot 10^6} \doteq 17.86 + 0.26 \times N \text{ US mils/kWh}$$

This cost must not exceed the assumed alternative energy cost of 24 US mils/kWh,

$$17.86 + 0.26 \times N \leq 24$$

The number of wells must not exceed

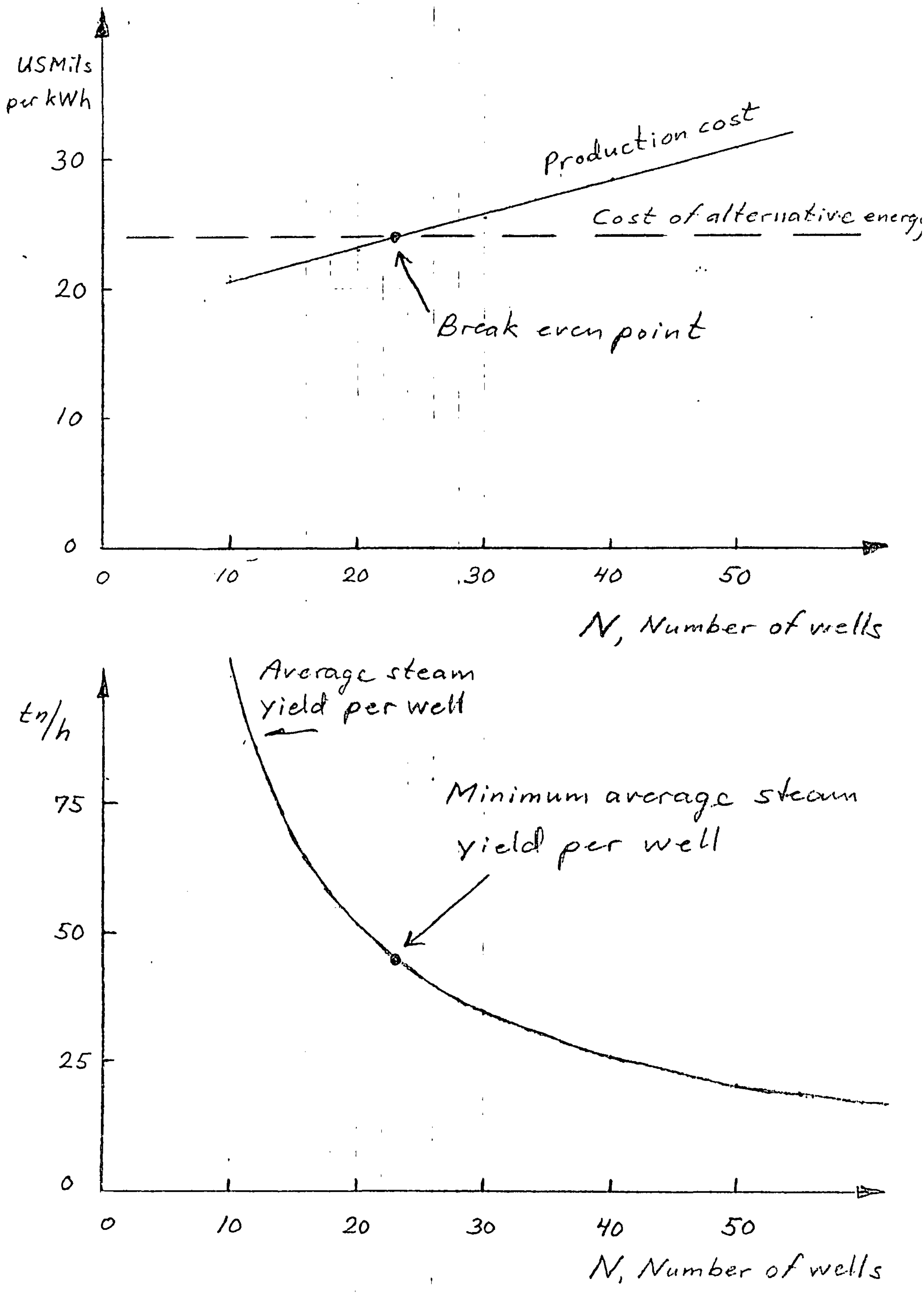
$$N \doteq \frac{24 - 17.86}{0.26} = 23.6 \text{ wells}$$

Minimum average steam yield per well is thus

$$\text{Yield} = \frac{1032 \text{ tn/h}}{23.6} = 43.7 \text{ tn/h per well}$$

This yield is fairly high and may not be achieved in many fields. As can be seen from the graph a lower yield e.g. 25 tn/h would result in 42 wells required and a production cost of 29 US mils/kWh

Production cost and minimum average steam yield per well



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THE PLANNING OF GEOTHERMAL PROJECTS

Sveinbjörn Björnsson

In the early days of geothermal development exploration was largely a hap-hazard enterprise involving much wild-cat drilling. This was because of the limited knowledge then available concerning the conditions normally associated with underground heat reservoirs. In recent years a great body of knowledge has been accumulated that enables exploration to be undertaken, not in the dark but in a logical sequence of operations that ensures that expenditure is minimized. The most costly item of an exploration programme remains the drilling of wells. However, drilling can now be postponed until less costly surface investigations have indicated promising drilling sites with a much lower risk of sinking abortive bores. It is still not possible to select good productive drilling sites with absolute certainty, but by adopting a scientific approach to geothermal exploration the amount of capital at risk can be kept as low as possible.

I shall now attempt to outline a systematic methodology for undertaking geothermal exploration in a logical sequence of operations with the greatest possible economy of expense and effort.

Main points of the lecture:

Preliminary Study

Phase I : Reconnaissance survey to identify specific prospect areas and to assign them priorities for more detailed investigation.

Phase II : Prospect investigations to locate drill sites within a prospect area.

Phase III : Exploratory drilling to discover a geothermal reservoir

Appraisal Study

Phase IV : Appraisal drilling and reservoir evaluation to prove sufficient production for the initial generating plant and provide data for assessing the long-term production capacity of the reservoir.

Phase V : Economic feasibility study to determine capital and operating costs for a generating plant and to compare the cost with the cost of generating power from other available sources.

(McNitt, 1975)

Phases of Geothermal Development

PRELIMINARY STUDY
- Reconnaissance Survey
- Prospect Investigation
- Exploratory Drilling - Investigation of Drilling Site
- Prefeasibility Report

APPRAISAL STUDY
- Appraisal Drilling
- Reservoir Evaluation
- Feasibility Study
- Feasibility Report

PROJECT DESIGN
- Production Drilling
- Production Testing
- Project Planning
- Project Planning Report

PREPARATION OF TENDER DOCUMENTS
- Production Drilling
- Production Testing
- Design of Plant
- Tender Documents

PRELIMINARY STUDY

Reconnaissance Survey

Hot Springs and Fumaroles
Aerial Infrared Imagery
Volcanism and Regional Geology
Hydrogeology
Chemistry of Thermal Fluids
Si and Na/K Geothermometry
Natural Heat Loss

Reconnaissance Report - Prospect Areas

Prospect Investigation

Volcanic and Structural Geology
Alteration
Chemistry and Isotopes of Thermal Fluids
Geohydrology
Resistivity Survey
Heat Flow Studies

Prospect Report

Conceptual Model
Prospective Drilling Sites

Exploratory Drilling

Lithology, Alteration
Chemistry and Isotopes
Geophysical Logs

Investigation of Drilling Site

Detailed Structural Mapping
Detailed Resistivity Surveys
Structural Geophysical Surveys

Results of Preliminary Study

Structural Model
Drilling Properties of the Formation
Casing Programme
Alteration, Caprock
Boundaries of the Reservoir

Excess Heat Stored
Temperature, Pressure, and Chemistry of Potential Aquifers
Porosity, Permeability
Estimated Potential of the Reservoir

Preliminary Reservoir Model

Prefeasibility Report

APPRAISAL STUDY

Appraisal Drilling and Reservoir Evaluation

Detailed Structure and Lithology
Pressure Potential of Aquifers
Temperature and Chemistry of Reservoir Fluid
Reservoir Permeability and Porosity
Enthalpy and Mass Flow of Wells
Production Characteristics, Decline with Time
Corrosion and Scaling Problems
Spacing and Minimum Economic Yield of Wells

Revised Reservoir Model

Detailed Structural Model
Nature of Aquifers and Permeability
Physical State, Fluid Properties
Predicted Production Capacity

Economic Feasibility Study

1. Review of the well test data to verify production capacity and evaluate evidence for drawdown.
2. Determination of capital cost and running charges of the optimum-size plant which could be operated from proven well capacities on the basis of a preliminary plant design.
3. Comparison of these costs with the cost of alternative sources of power.
4. Determination of possible economic uses of the resource

for purposes other than power generation.

5. Assessment of the environmental impact of development

(McNitt, 1975)

Feasibility Report

PROJECT DESIGN

Production Drilling
Well Testing
Project Planning

Project Planning Report

Optimum Wellhead Pressure
Design Criteria for Well Head Equipment and
Transmission System for Steam and Water , Reinjection
Feasibility of Alternative Sizes of the Plant

PREPARATION OF TENDER DOCUMENTS

Production Drilling
Production Testing
Design of Plant

Tender Documents

Suggested Reading

McNitt, J.R., 1975 : Summary of United Nations Geothermal Exploration Experience, 1965 - 1975. "San Francisco" 2, 1127 - 1134.

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Penetration of water into hot rock boundaries of magma at Grímsvötn

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The Grímsvötn geothermal area is located within one of the most active caldera volcanoes in Iceland in the interior of the ice cap Vatnajökull at an altitude of 1,400 m (Fig. 1). Its setting offers unique conditions for calorimetric measurement of the heat release from the subglacial geothermal system. The melting of ice due to the geothermal activity creates a depression in the surface of the ice cap. Ice and water are diverted towards the depression from a 300 km² drainage basin. The meltwater accumulates in a 30 km² subglacial lake. Periodic outbursts of water (jökulhlaups) drain the lake subglacially down to the Skeidarársandur plain. We propose here that penetration of water into hot rock is the primary reason for the intense heat release (5,000 MW thermal) of the subglacial Grimsvötn geothermal area. Injection of water into boundary rocks of magma should be considered as a method of heat exploitation.

The history of Grímsvötn has been studied extensively[1] and the first report on a jökulhlaup dates back to AD 1332. From 1600 until 1934 about one jökulhlaup occurred each decade with an estimated discharge of 6–7 km³ of water, but since 1934 there have been two outbursts per decade and the observed volume correspondingly smaller, 3–3.5 km³ (refs 1,2). A long-term mass balance of the drainage basin has been given elsewhere[3]. The average accumulation in the form of ice is equivalent to 2,200 mm yr^{-1} of water and the surface ablation amounts to 500 mm yr^{-1}. A long-term steady-state model for the drainage basin proves to be a valid approximation[3]. The water added to the lake is 6.6×10^{11} kg yr^{-1}. About 1.5×10^{11} kg yr^{-1} are melted at the glacier surface by meteorological processes, but the difference, about 5×10^{11} kg yr^{-1} is melted by geothermal heat within the drainage basin. The heat flux required to melt this ice is ~5,000 MW (thermal). The geothermal activity responsible for the melting of the ice is not limited to the lake but scattered over a large area, estimated to be up to 100 km². If the heat released at Grimsvötn is averaged over 100 km² we obtain an average heat flux density of 50 W m^{-2} or some 1,200 h.f.u. To illustrate the dimension of this heat flux, note that it is equivalent to the average global heat flow through an area of 80,000 km² or nearly the whole area of Iceland.

Magma is commonly assumed to be the source of heat for high-temperature geothermal systems. A heat output of 5,000 MW is equivalent to the heat released by solidification and cooling of $\sim5\times10^7$ m^3 yr^{-1} of magma down to a temperature of 400 °C. A magma volume of at least 20 km³ is required to maintain the present heat output at Grímsvötn over the 400 yr of reported jökulhlaups. Given a magmatic source of this size the extraction of heat at the observed rate is still problematic. A conducting wall separating stagnant magma and a hydrothermal system could supply the observed heat flux for a short period after intrusion of the magma, but the wall would soon thicken as magma solidified and the flux would decline below the observed rate.

The difficulty of explaining the thermal output of high temperature systems by conduction from a magmatic source has been recognized[4–6]: Banwell[5] considered steam released from convecting magma to act as a heat carrier. Water could penetrate to the magma through a few deep faults, and diffuse into the magma, but be released when it had circulated to some higher level where the pressure is lower.

White[6] proposed alternatives for the Steamboat Springs systems, either a convection within a magma chamber maintaining magmatic temperatures near the base of the hydrothermal circulation or a fissure system controlling the circulating water and gradually extending deeper into the batholith, as stored heat was removed at higher levels by circulating water. Irvine[7] described a convective process in a magma body where crystals accumulate in the lower part of the intrusion but the temperature near the top remains close to, or above, the liquidus temperature of the magma. This process allows higher rate of heat loss and solidification than would occur if the crystals were frozen to the roof of the magma chamber. Bodvarsson[4] favoured penetration of water into the hot rock boundary of intrusions to compensate for the increased thickness of the solidifying rock that insulated the molten lava from the hydrothermal system. Lister[8] has presented a conceptual model of the downward penetration of water into hot rocks by a process of cooling, thermal contraction and cracking. The cracks enable the water to penetrate to the horizon of solidification, although the horizon proceeds downwards. Thermal insulation of the rock is no longer an effective barrier for heat removal as the water is steadily penetrating into new, hot rock and carrying its heat away by convection.

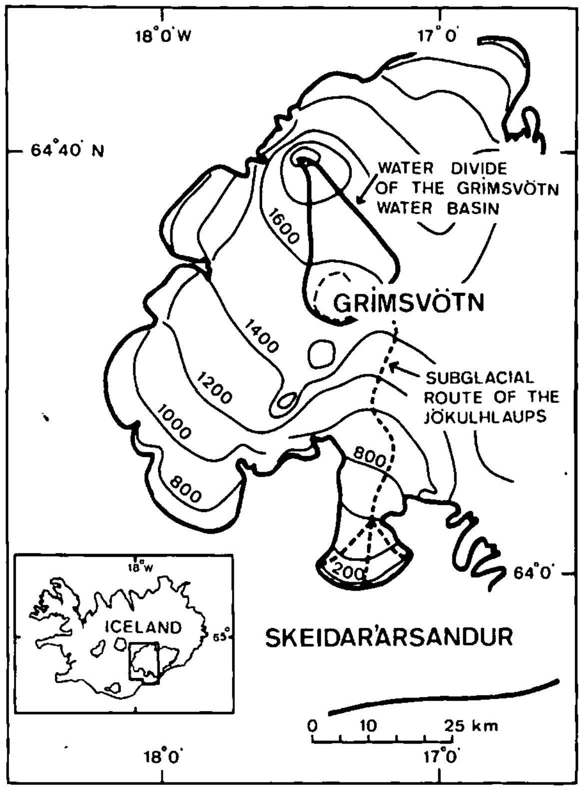

Fig. 1 Location of Grimsvötn geothermal area within the Vatnajökull ice cap in Iceland.

Models of a replenished chamber of convecting magma or steam released from convecting magma, might explain the heat output at Grímsvötn. Recent field evidence obtained by watering of a molten lava flow, however, suggests that the process of penetration of water into hot rock is most likely to be responsible for the heat extraction at Grímsvötn. During the Heimaey eruption in Iceland in 1973 water was pumped onto the molten lava in attempts to impede the flow and divert it away from the town. A flow of 100 kg of water per second, applied in one place, spread over some 7,000 m² of lava, which was engulfed in steam. Drillholes revealed that after two weeks of watering the solidification of the lava had progressed to a depth of ~12 m, leaving the solidified lava at the temperature of saturated steam, that is 100 °C. Temperature logs of the holes indicated that the transition layer, where the temperature rose from 100 to

1,050 °C, was only a fraction of a metre thick during watering. Excavation of lava after the eruption revealed that the structure of water-cooled lava was greatly different from the structure of large jointed blocks where no water had been applied during the solidification. The water-cooled rock was intensely fractured and broken into pieces commonly 10–20 cm across. The structure resembled entablature lava, a formation frequently found in river beds and canyons, where a lava flow has solidified under floods of river water, dammed up by the lava flow[9]. Each cubic metre of lava which solidifies and cools down to 100 °C releases sufficient heat to evaporate 1.4 m^3 of water. To evaporate 100 kg s^{-1} of water spread over 7,000 m^2 of lava the heat flux density must have been ~40 kW m^{-2}.

The propagation rate of the front of solidification was 12 m in 14 days or 0.9 m per day. In model calculations one may view this process as stationary, seen from the solidification boundary. Instead of considering the boundary progressing downward at a constant rate, one may, in calculations, assume that the boundary is fixed, but the lava is moving upwards and solidifying as it passes the fixed boundary. Just above the boundary there is a thin transition layer of solid, uncracked rock, where the heat flux is carried by the moving rock and by conduction. The first cracks which appear above this layer are narrow and filled with superheated steam but the bulk of the rock above has shrunk by cooling and developed cracks wide enough to admit percolation of a mixture of water and saturated steam. Simple calculations based on this model give 0.1 m for the thickness of the conductive transition layer.

There is every possibility that the effective extraction of heat by watering of hot rock at Heimaey can also take place at the boundaries of magma bodies or intrusions at a depth of several kilometres, if water is readily available. The process acts in hot rocks close to solidus temperature, irrespective of whether the heat source is a regular confined magma chamber or a swarm of magma sheets, completely or partially molten. There are, however, two reasons to expect lower heat flux densities than in the surface lava. First, due to higher overburden pressure at depth the cracks will open up at a lower temperature. Second, the heat is transported upwards by a one-phase fluid at pressures exceeding the critical pressure of water[8].

Returning to the problem of heat transfer from the Grímsvötn caldera, a magmatic source of heat must be inferred, but its size and depth has not been investigated. Observations of S-wave shadows at the Krafla caldera in the Northern Volcanic Zone of Iceland suggest a magma body at 3–7 km depth beneath that caldera[10]. Its horizontal extent is ~8 km^2. Assuming 10 km^2 for a similar body under Grímsvötn, water penetrating into that body would have to propagate at an average rate of 5 m yr^{-1} to yield the observed flux of 5,000 MW. At the deep end of the geothermal system, where the temperature may be near 400 °C, a mass flux of 2,400 kg s^{-1} of water is required to transport the extracted heat up to the bottom of the glacier. Vertical permeability is likely to be favourable near the ring fractures of the caldera. A special feature at Grímsvötn is the cyclic loading of the caldera by accumulation of meltwater for 5 yr and a drop of the water level of the lake by 100 m in one week during jökulhlaups. This sudden drop in pressure might help to keep fractures open and it has even been suggested that it could excite magma and lead to eruptions, which sometimes have been observed to coincide with jökulhlaups[1].

The above considerations have important implications for the exploitation of geothermal systems which derive heat from an underlying magma body. Drilling of wells for injection of water into the hot rock boundary might accelerate the heat extraction and aid in the generation of steam, where water is deficient, or the access of water to the magma body is hindered by an impermeable barrier. Controlled injection of water might even be used to establish reservoir conditions in temperature, pressure and fluid saturation which are optimal for the exploitation. There are some indications that the Krafla geothermal system[11] in Iceland might be a water-deficient system of this kind. On the other hand, abundant supply of water might explain the fact that geothermal systems with the highest natural heat output in Iceland are found in subglacial areas[12–14].

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DC-resistivity soundings.
Technique, instruments
and interpretation.
LSG/sv

WARD

Technique: We have mainly used the Schlumberger-electrode configuration but also done some work with the equitorial dipole and the quadropole configurations. A standard Schlumberger-sounding has a maximum current arm (AB/2) of 1.58 km, with the measuring points spaced evenly on a logarithmic scale with ten stations per each decade. If necessary and when the conditions are favourable, the maximum current arm can be increased to 3-5 km.

Instruments: They were designed and built in our laboratory. The Schlumberger set consists of three units; power transmitter, voltage receiver and a data processor. The transmitter has a max power output of 500 W with 1000 V maximum voltage. It sends out a regulated steady current square wave with 2,4 or 8 sec between polarity changes. The power source is 24 V drawn from car batteries. The voltage receiver has a maximum sensitivity of ~ 1 μV and balances out s.p. variations. The system can be operated manually and automatically. When working in the automatic mode, the transmitter sends an optic signal to the receiver just before changing polarity. The receivers reading period can be varied but is usually kept slightly shorter than that of the transmitter. The readings are stacked and averaged by the data processor, which makes it possible to get a meaningful result beyond the stage when the telluric noise level exceeds the signal.

Interpretation: Until four years ago interpretation of sounding curves was done by matching the measured curves with published master curves but now it is done with the aid of a computer. Following programs are used: A program which calculates master curves corresponding to any horizontally layered interpretation which might fit the sounding curve, comparison is done visually. The program Circle 2 acquired from Denmark (See Johansen 1975 and 1977)., which does a totally automatic (inverse) interpretation assuming horizontally n-layered earth. Now work is done to make quantitative two-dimensional interpretation possible. (See Dey and Morrison 1979).

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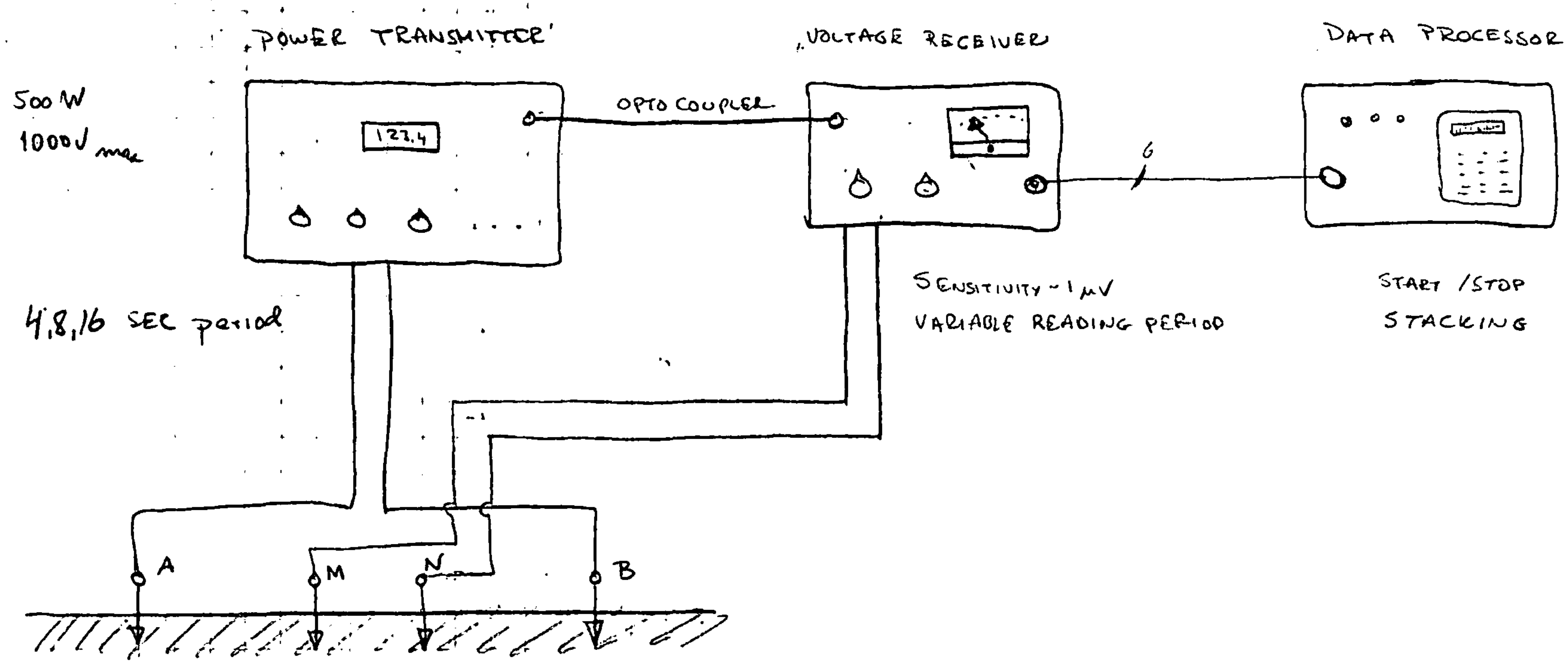
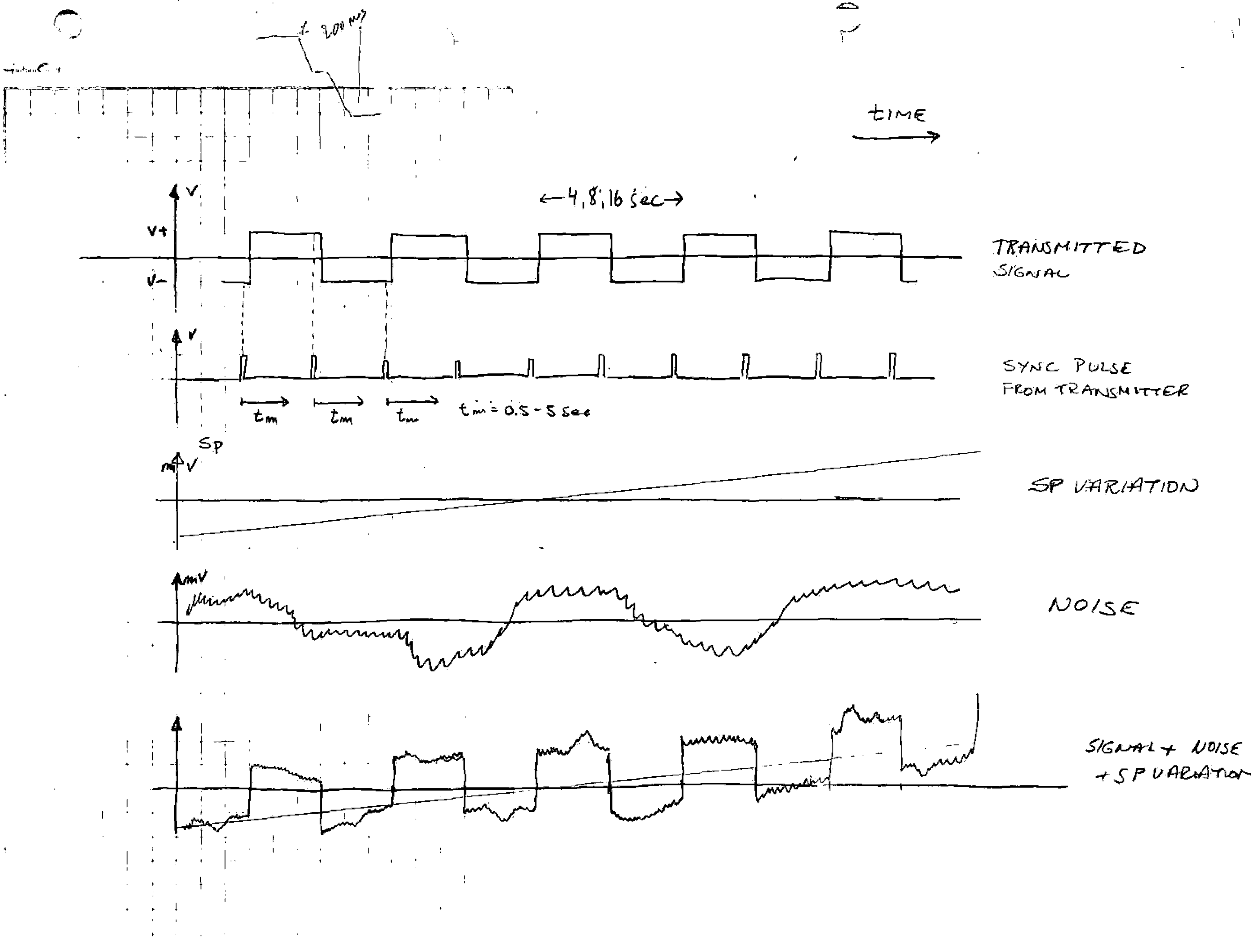
Johansen 1975: An interactive etc. Geophys. Prosp. 23, 449-458.
Johansen 1977: A man/computer etc. Geophys. Pros. 25, 667-691.

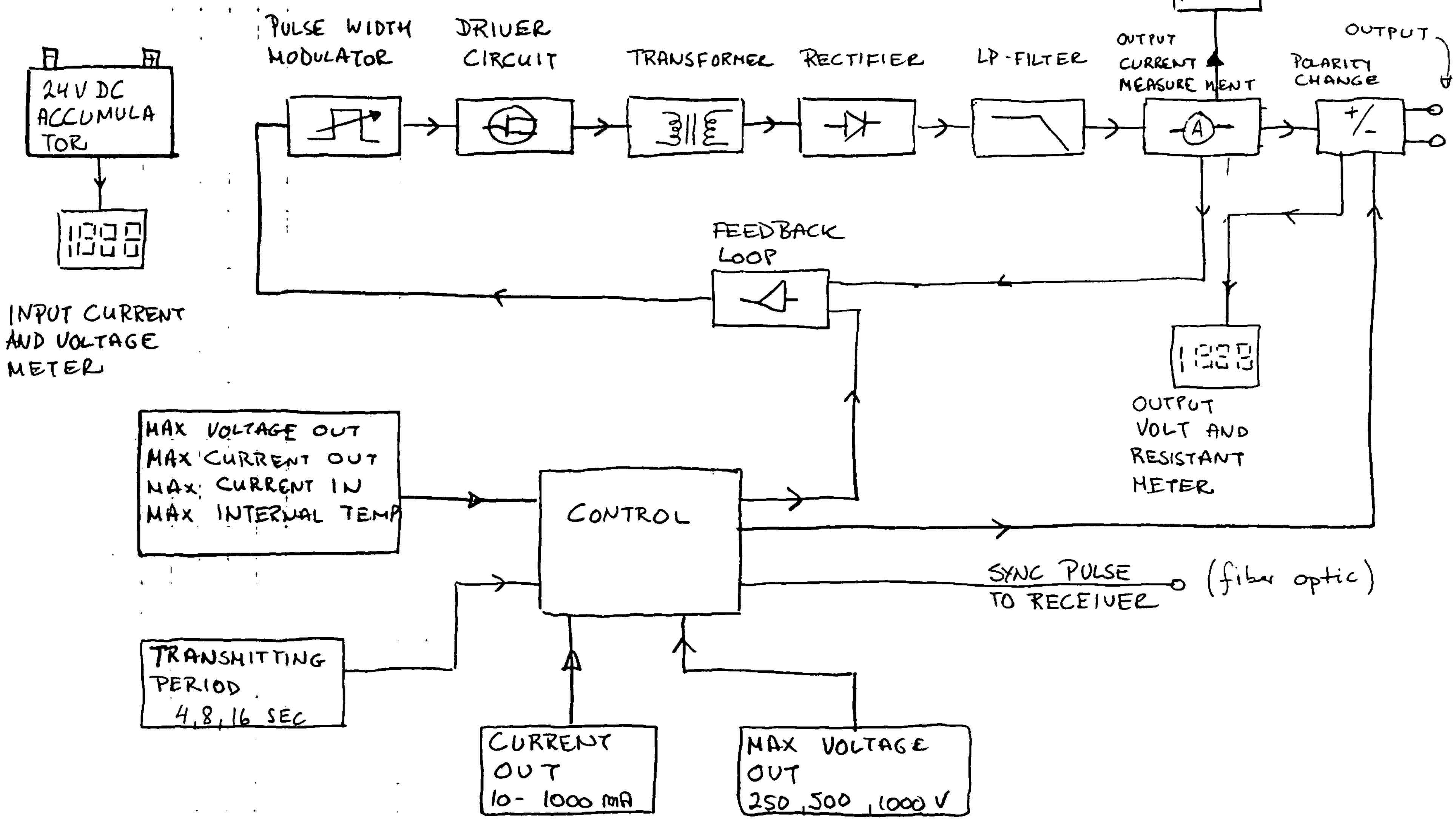

POWER TRANSMITTER
VOLTAGE RECEIVER
DATA PROCESSOR
500 W
1000V max
123.4
OPTO COUPLER
6
SENSITIVITY ~ 1 μV
VARIABLE READING PERIOD
START / STOP
STACKING
4,8,16 SEC period
A
M
N
B



TIME DIAGRAM
TRANSMITTER — RECEIVER

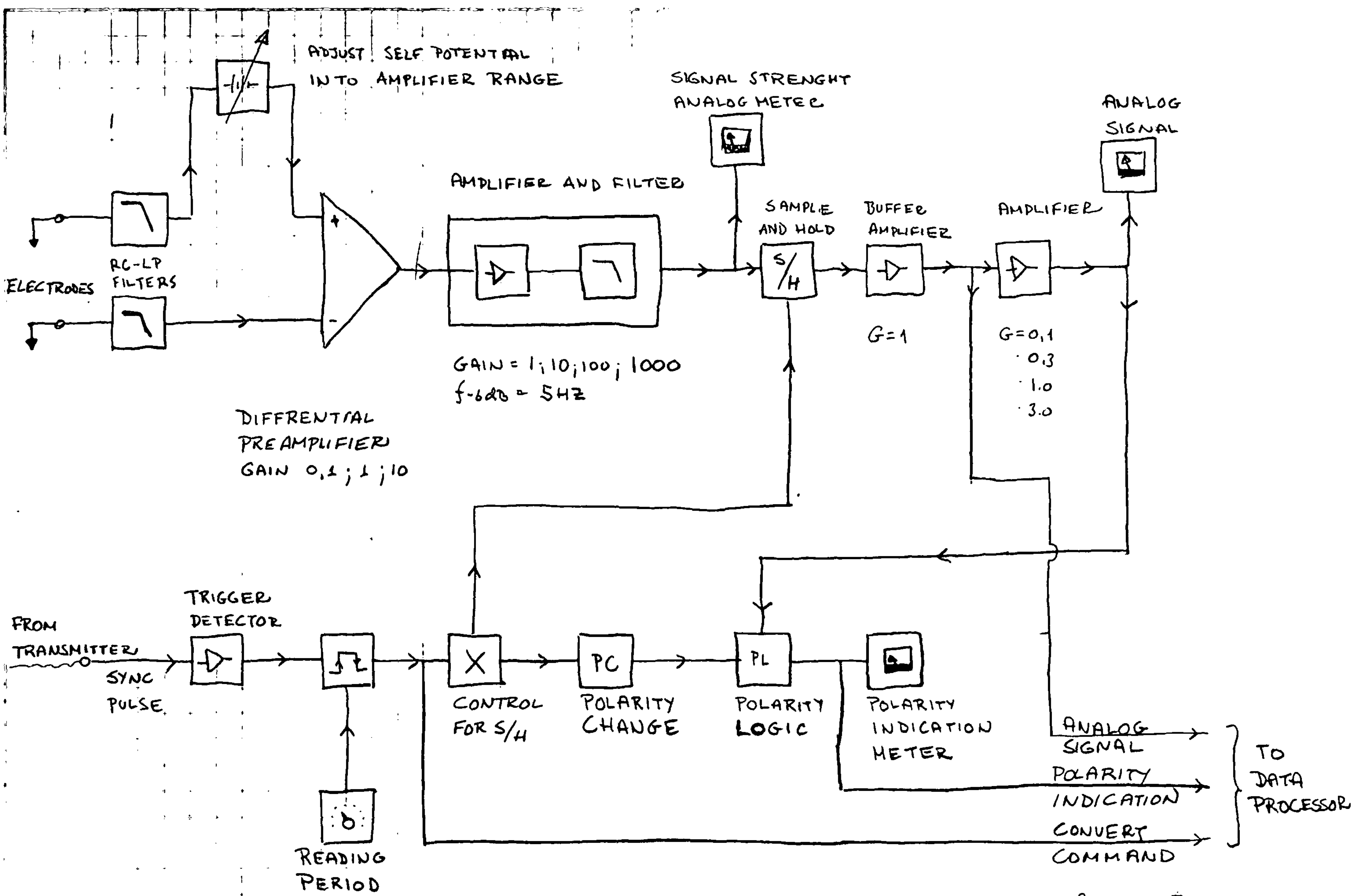
CONSTANT CURRENT TRANSMITTER

500 W (1A MAX AND 1000 V MAX)



POWER TRANSMITTER BLOCK DIAGRAM

JULY 1982 EMH

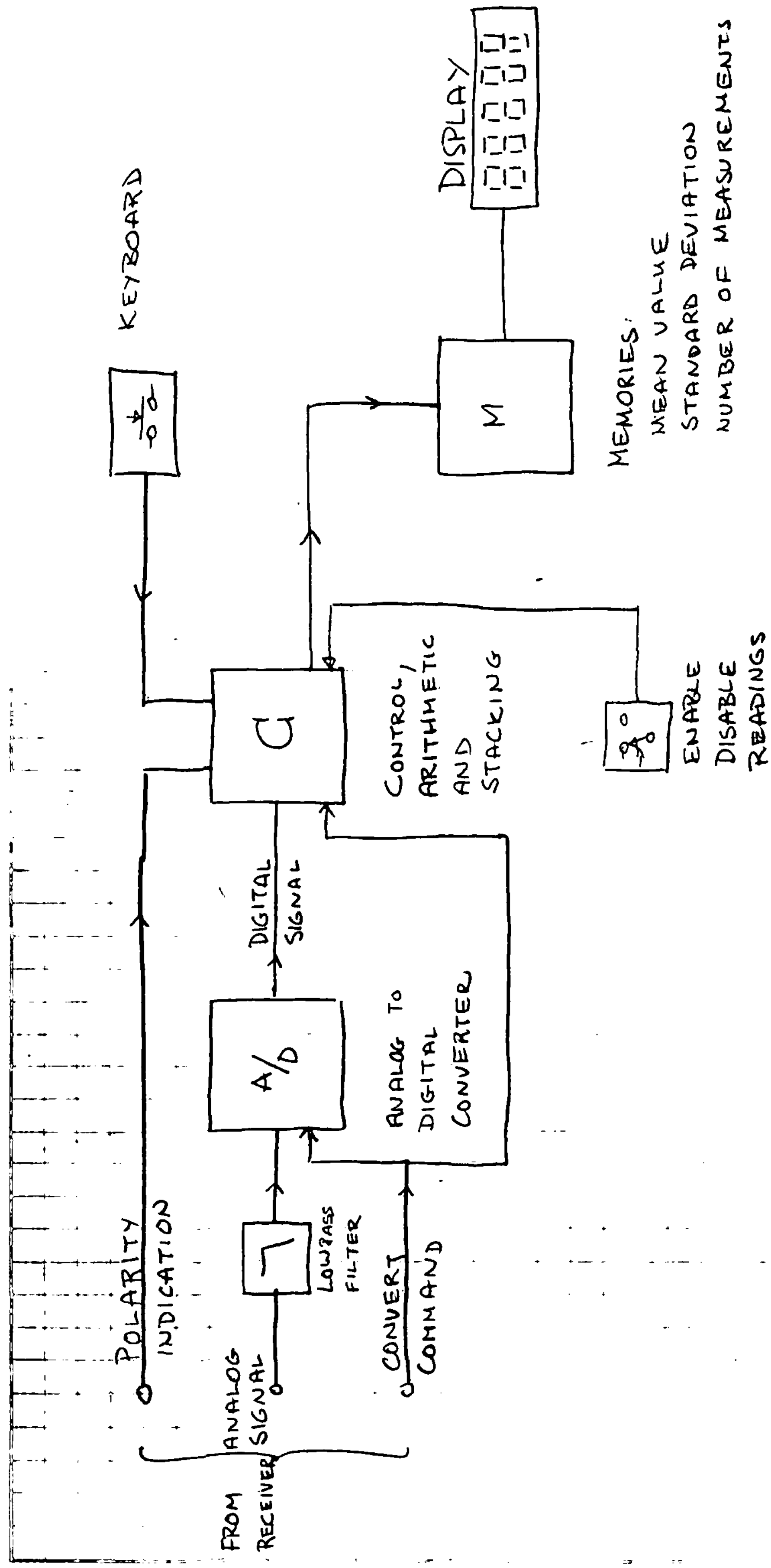


ATTENTION : -6 dB @ 5HZ , -150 dB @ 50HZ
GAIN : 0.1 TO 100 000

VOLTAGE RECEIVER - BLOCK DIAGRAM
July 1982 EHH

DATA PROCESSOR -BLOCK DIAGRAM

JULY 1982 EHH



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THE UNU GEOTHERMAL TRAINING PROGRAMME IN ICELAND 1979-1990

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ABSTRACT

The Geothermal Training Programme of the United Nations University has been operated in Iceland since 1979. A six months course is operated annually for professionals from the developing countries. Specialized training is offered in geological exploration, borehole geology, geophysical exploration, borehole geophysics, reservoir engineering, chemistry of thermal fluids, geothermal utilization, and drilling technology. During 1979-1989, 82 scientists and engineers from 17 countries completed the course, and 11 trainees from 7 countries are expected to complete in October 1990 and receive the UNU Certificate. About 70% of those trained during 1979-1989 are actively working in geothermal in their home countries, and about 20% are working in related fields. Participants normally receive scholarships which are financed by the Government of Iceland and the United Nations University, and in some cases by the UNDP.

INTRODUCTION

The Geothermal Training Programme of the United Nations University (UNU) was established in Iceland in 1979 at the recommendation of an international workshop. It was recognized that because of its diversity, geothermal energy research and development is not taught as a separate subject at universities, but is a field where specialized practical training is required at the post-graduate level. Since then a group of scientists and engineers from energy agencies and research organizations and in a few instances universities in the developing countries have come to Iceland every spring and spent six months in highly specialized studies and on the job training in geothermal science and engineering. All of them are university graduates and have had previous practical experience in geothermal work in their home countries. The training is tailor-made to the individual and the needs of his institution/country. In all, eighty two participants from seventeen countries have completed the six months course during 1979-1989. Eleven participants from seven countries are expected to complete the six months course in October 1990. The number of participants from individual countries and the specialized courses they have taken during 1979-1989 is shown in Table 1.

The Training Programme is operated within the Geothermal Division of Orkustofnun, the National Energy Authority (NEA) of Iceland. It is academically governed by a Studies Board which is composed of specialists responsible for each of the eight specialized courses that are offered, and a chairman who is the director of the Training Programme. The present members of the Studies Board are Kristjan Saemundsson (Geological Exploration), Hjalti Franzson (Borehole Geology), Olafur Flovenz (Geophysical Exploration), Benedikt Steingrimsson (Borehole Geophysics) and Sverrir Thorhallsson (Drilling Technology) from the NEA, Stefan Arnorsson (Chemistry of Thermal Fluids) and Valdimar K. Jonsson (Geothermal Utilization) from the University of Iceland, and Snorri Pall Kjaran (Reservoir Engineering) from the Vatnaskil Consulting Engineers Ltd. Ingvar Birgir Fridleifsson has been the director of the Training Programme from the beginning except for one training season in 1981 when Hjalti Franzson served as director and three training seasons in 1986-1988 when Jon Steinar Gudmundsson served as director.

The United Nations University was founded in 1975 with headquarters in Tokyo, Japan. Its "students", which are all professionals at post-graduate level, have been trained at some 155 institutions in fourty countries in all parts of the world. The number of UNU Fellows varies from year to year, and the recent trend reflects the budgetary restraints of the United Nations system. The total number of UNU Fellows who completed their studies in 1985 was 83, 197 in 1986, 142 in 1987, 40 in 1988 and 41 in 1989. The UNU network is built up mostly of Associated Institutions, which are applied research and university institutions operated in the various countries by the respective governments. The contribution of the UNU to these institutions is in most cases limited to Fellowships (including board and lodging plus international travel) that are awarded to professionals for training at these institutions. The NEA became an Associated Institution of the UNU in 1979. It is the only Associated Institution of the UNU offering training in geothermal energy science and technology. The cost of the operations of the UNU Geothermal Training Programme in Reykjavik is shared by the

TABLE 1

PARTICIPANTS IN THE UNU GEOTHERMAL TRAINING PROGRAMME IN ICELAND, 1979-1989

Country	Geological Exploration	Borhole Geology	Geophysical Exploration	Borehole Geophysics	Reservoir Engineering	Chemistry of Thermal Fluids	Geothermal Utilization	Drilling Technology	Total
Algeria	1						1		2
Burundi	1								1
Costa Rica		1	1						2
China		3	1	1	1	2	7	1	16
Djibouti		1							1
El Salvador				1					1
Ethiopia		1	2	1	2	2	1	1	10
Honduras		1	1						2
Indonesia		2	2	2	1				7
Kenya	1	1	5		2	2		2	13
Mexico	1		1		2				4
Nicaragua						1			1
Philippines		2	2	3	2	2	2		13
Tanzania	1								1
Thailand		1		2		1			4
Turkey		1			1		1		3
Yugoslavia						1			1
Total	5	14	15	10	11	11	12	4	82

Government of Iceland (80%) and the United Nations University (20%). The Icelandic contribution is a part of the development aid of the Government of Iceland.

The background to the establishment of the UNU Geothermal Training Programme was given in a paper at the 1985 International Symposium on Geothermal Energy organized by the Geothermal Resources Council in Hawaii in 1985 (Fridleifsson, 1985). The reader is also referred to a comprehensive description of the four international geothermal centres sponsored by the United Nations system in Iceland, Italy, Japan and New Zealand, given by Fanelli and Dickson (1988).

THE TRAINING

The approximate time schedule of the Training Programme is shown in Table 2. The duration is 6 months. In general, all participants are expected to attend an introductory lecture course that lasts 4-5 weeks (three lectures and a practical each day). The aim of the lecture course is to provide a background knowledge on most aspects of geothermal energy resources and technology, and to generate an appreciation for the interrelationship between the various disciplines necessary in geothermal projects from the initial exploration to the stages of implementation and utilization. Participants have to take two written tests during the introductory lecture course. The lecture course is followed by practical training in a specialized field and the execution of a research project that is concluded with an extensive project report. Study tours are arranged to all the main geothermal fields under exploration and utilization in Iceland.

The main emphasis of the training is to provide the participants with sufficient understanding and practical experience to permit the independent execution of projects within a selected discipline in their home countries. Eight specialized lines of training are offered (Table 2). Each participant is meant to follow only one line of training, but within each line there is considerable flexibility and the training is adjusted to the background of the participant and the needs of his organization/country.

A significant part of the practical training is done in connection with the research projects of the Fellows. In many cases the participants bring with them data from geothermal projects in their home countries and work on the data under the supervision of Icelandic specialists. In some cases, however, the research projects are within geothermal exploration or utilization projects that are in progress in Iceland at the time of training. The project topic is always selected with respect to the conditions of the home country of the participant. Many of the project reports are written in such a way that they serve as manuals for performing certain measurements or interpretations dealt with in respective reports. All the project reports are published by the Training Programme and individual copies can be obtained upon request. The reports are mailed regularly to many of the leading geothermal institutions in the developing countries. The project reports of 1979-1984 were referred to by Fridleifsson (1985). The reports from the training sessions of 1985-1989 are listed by author in the reference list of this paper.

TABLE 2

UNU GEOTHERMAL TRAINING PROGRAMME IN ICELAND

Week	Geological Exploration	Borehole Geology	Geophysical Exploration	Borehole Geophysics	Reservoir Engineering	Chemistry of Thermal Fluids	Geothermal Utilization	Drilling Technology	Week
1									1
2									2
3	Lecture course on all main aspects of geothermal energy exploration and utilization, practicals and short field excursions								3
4									4
5									5
6	Field geology	Drilling	Theoretical	Course on well logging and		Sampling of fluids and gas		Drilling equipment	6
7	Maps and photos	Petrological	studies	reservoir engineering		Scaling and corrosion		Drilling procedures	7
8		logging		Logging and well test practises		Analytical methods	Course on	Safety	8
9	Structure analysis		Field work	Data analysis	Reservoir properties		heat transfer	Well design	9
10	Hydrogeology			Well performance	Reservoir simulation	Thermodynamics	and fluid flow	Management	10
11	Excursion to the main geothermal fields of Iceland								11
12									12
13	Field work in	Alteration	Data processing	Logging methods	Well testing	Chemical	Design of plants	Rig operations	13
14	deeply eroded	mineralogy	techniques and		Reservoir simulatic	geothermometers	and systems		14
15	strata and recent	Aquifers	tools	Data evalution	Responses to	Water rock		Cementing	15
16	volcanic fields	Modelling			exploitation	interaction		Completion	16
17									17
18	Project	Project	Project	Project	Project	Project	Project	Project	18
19	and	and	and	and	and	and	and	and	19
20	report	report	report	report	report	report	report	report	20
21									21
22									22
23									23
24									24
25									25
26									26

All participants receive training in using PC-computers for word processing and interpretation of data. Experience has shown that most trainees have access to PC-computers at home. Therefore most of the computer work is done on PC-computers so that the participants can take their discettes home and continue the work there. Thus there has already been a considerable transfer of computer technology from Reykjavik to geothermal institutions in the developing countries. Participants from institutions that have access to large computers are allowed to work on the main frame computer at the NEA.

THE SPECIALIZED COURSES

The **geological exploration** course offers practical training in basic geological mapping, which is commonly the first step in the geothermal exploration of an area. Participants analyse the geological structure of an area with regard to siting drill holes, both thermal gradient and production wells. Many of the participants have also been trained in mapping surface geothermal manifestations, including shallow temperature surveys and measurement of flow rates of springs. The field work is commonly conducted both in active geothermal and volcanic areas and in deeply eroded areas where the roots of extinct volcanoes and hydrothermal systems can be inspected. Participants should have a degree in geology.

The **borehole geology** course gives training in making geological logs from drill cuttings and cores. The identification of alteration minerals (microscope and x-ray diffraction) and the interpretation of the alteration mineralogy forms an integral part of the course. Many of the participants receive training in collecting and interpreting data on aquifers and in making geological models of geothermal reservoirs based on their own data and data from other disciplines. Participants should have a degree in geology.

The **geophysical exploration** course is for practical training in conducting geophysical surveys of geothermal areas and/or interpretation of such data. The essentials of heat flow surveys, magnetic and gravity surveys, as well as resistivity depth soundings and profiling are covered. During the latter half of the training a selection can be made between further specialization in electrical surveys (Schlumberger, dipole, head-on profiling, TEM, MT, AMT, SP), magnetic surveys and gravity surveys. Emphasis is put on the application of PC-computers in the interpretation of geophysical data. Participants should have a degree in physics, geophysics or engineering.

The course in **borehole geophysics** covers the essentials of geophysical measurements in boreholes used for geothermal investigations, with the main emphasis on temperature and pressure measurements, but including lithology logs such as electrical resistivity, caliper, porosity and density logs, and well completion logs such as CCL, CBL, inclination and spinner logs. The participants undertake well measurements, but most of the time is devoted to the interpretation of logging data. Participants should have a degree in physics, geophysics or engineering.

The **reservoir engineering** course covers the methodology needed to obtain information on the hydrological characteristics of geothermal reservoirs and to forecast the long term response of the reservoirs to exploitation. Both surface and downhole measurements are considered and the interpretation of flow tests of wells, injection tests and interference tests. It is also possible to specialize in production engineering of geothermal fields. The course requires a sound background in mathematics. Participants should have a degree in engineering, physics, geophysics, mathematics or hydrogeology.

The course on **chemistry of thermal fluids** gives an insight into the role of thermal fluid chemistry in geothermal exploration and exploitation, including sampling, analysis of major constituents and the interpretation of results. Much emphasis is placed on the application of chemical thermometers and the calculation of mixing models. Environmental aspects of the thermal fluids are also considered. The participants need a solid background in chemistry. They should have a degree in chemistry, geochemistry or chemical engineering.

The course in **geothermal utilization** deals with the civil, mechanical and chemical engineering aspects of geothermal fluids in pipes, equipment and plants. The feasibility of projects and environmental factors are also considered. Due to the wide spectrum covered by geothermal engineering, the participants have to be very selective in their specialization. Most of the participants specialize in the design and/or fesibility studies of district heating systems and/or in the application of geothermal steam and water in industry. One specialization is the selection, installment and operation of downhole pumps in geothermal wells. Participants should have a degree in engineering.

The course in **drilling technology** provides engineers with the information and on-site training necessary to prepare them for the work of drilling engineers or supervisors. The course is thus training in the planning and supervision of drilling and not in the task of drilling itself. The course deals with the selection of drilling equipment, the design of wells and casing programs, as well as in cementing techniques. The cleaning and repairs of production wells is furthermore dealt with. Participants should have a degree in engineering.

TEACHING MATERIAL

Most of the teaching is done by tutorials and practical work where the teacher works with two or three trainees and use is made of available textbooks and articles in journals as appropriate. In some instances, however, a special effort has been needed in compiling text material and manuals as teaching material for the training. Most of this work has been done by the regular teachers of the Training Programme, who are mostly staff members of the National Energy Authority and the University of Iceland. Some texts have also been written by visiting scholars from other countries. Some of the teaching material has been published in reports, and is available from the Training Programme. As examples can be mentioned texts on hydrogeology (Sigurdsson, 1987), on finite element resistivity modelling (Zhou et al., 1987), on geothermal logging (Stefansson and Steingrimsson, 1981), on reservoir engineering (Kjaran and Eliasson, 1983), on geothermal reservoir physics (Bödvarsson, 1987), on geothermal district heating (Karlsson, 1982), and on the direct use of geothermal energy (Lund, 1987). Special attention should be given to a text on one dimensional inversion of Schlumberger resistivity soundings (Arnason and Hersir, 1988) which contains the description of a computer program, user's guide and a discette for a PC-computer. A few of the teaching texts are already into second and third editions.

One guest lecturer with international reputation is invited every year as a UNU Visiting Lecturer to give a lecture series and to lead discussions with the trainees. The UNU Visiting Lecturers have stayed from about two weeks to two months in Reykjavik. The following have been UNU Visiting Lecturers:

1979	Donald E. White	USA
1980	Christopher Armstead	UK
1981	Derek H. Freeston	New Zealand
1982	Stanley H. Ward	USA
1983	Patrick Browne	New Zealand
1984	Enrico Barbier	Italy
1985	Bernardo Tolentino	Philippines
1986	Russel James	New Zealand
1987	Robert Harrison	UK
1988	Robert O. Fournier	USA
1989	Peter Ottlik	Hungary

Most of the lectures of the UNU Visiting Lecturers have been published by the Training Programme and are listed by author in the reference list of this paper. Some of these have served as important teaching material. Copies of the publications are available on request.

BUILDING OF SPECIALIST GROUPS

Table 1 shows where participants have come from during 1979-1989 and which of the specialized courses they attended. It is apparent that 63% of the participants (52 out of 82) have come from four countries, namely China, Ethiopia, Kenya, and the Philippines. This is no coincidence, as the aim of the UNU Geothermal Training Programme is not to train individuals from all countries with geothermal potential, but to concentrate the training efforts so as to assist in building up a cadre of specialists in the geothermal departments of selected countries. Priority for training is given to candidates from carefully selected institutions from developing countries where geothermal exploration and development is already under way. This has been somewhat difficult in a large country like China, where the geothermal work is spread over the different provinces and autonomous regions.

The efforts of the Training Programme have been particularly successful in the Philippines, where the leading geothermal agency in the country (PNOC) has received training of two or three people in six of the specialized courses. The level of competence was already very high within the company in geological exploration and drilling technology, and they would not have been able to learn much more in the specialized courses in these topics in Iceland than they could at home. The width of the specialized training received by PNOC personnel can be seen in the titles of their research reports which are listed by author in the reference list (Bagamasbad, 1979; Reyes, 1979; Baltasar, 1980; Sarmiento, 1980; Layugan, 1981; Regalado, 1981; Ignacio, 1982; Jordan, 1982; Catigtig, 1983; Maceda, 1983; Paete, 1983; Gimenez, 1987; Soriao, 1987). In Kenya and Ethiopia the Training Programme has also assisted significantly in building up strong geothermal groups.

The aim of the Training Programme in the near future is to assist more countries in building up groups of specially trained people so as to strengthen their capacities in geothermal work. The limiting factor is in some cases the availability of sufficiently qualified staff in the recipient institutions. The fact that participants must speak English fluently has for example hampered the participation from certain parts of the world such as Latin America.

SELECTION OF PARTICIPANTS

Specialized practical training is considerably more expensive than group training because of the high teacher to student ratio. On average, a full time teacher takes care of three students during the intensive training. The total cost of training per student in Reykjavik (including international travel and per diem) is over USD 20,000. Much care is therefore taken in selecting the participants. The selection procedures of the UNU are adhered to, which involves site visits by representatives of the Training Programme to the countries of potential candidates and personal interviews with all candidates. The potential role of geothermal energy within the energy plans of the respective country is assessed, and an evaluation made of the institutional capacities in the field of geothermal research and utilization. Based on this the training needs of the country are assessed and recipient institutions selected.

The directors of energy institutions are invited to nominate candidates for training in the specialized fields that are considered most relevant to promote geothermal development in the respective country. Nominations, including the curriculum vitae of the candidates, should be sent to the Training Programme in Iceland. The training starts in late April and ends in late October each year. Nominations must be received in Reykjavik before 1 August each year for participation in the training starting the following year. Due to the high cost of international travel, site visits for interviewing candidates cannot be held in all requesting countries every year. Therefore interviews are held in a given country for candidates for two or three years at a time. Participants normally receive scholarships financed by the Government of Iceland and the UNU or UNDP that cover international travel, tuition fees and per diem in Iceland. The participants do therefore not need other funds for the training. The training has so far been exclusively for participants from developing countries. Qualified participants from industrialized countries can also be accepted on the condition that they obtain similar scholarships from their own institutions/countries.

EVALUATION OF THE TRAINING

Evaluation of the training has mainly been in the form of interviews with trainees from the early years of the Training Programme and their directors. A representative of the Training Programme visits the main recipient countries every few years, and meetings are also arranged in connection with international geothermal conferences. Some changes have been made in the detailed contents of some of the specialized courses based on the feedback from the trainees and their institutions. But generally speaking, the tailor-suiting of the training to the abilities of the individual and the needs of the recipient country/institution seems to have been successful.

All the participants are selected by private interviews by staff members of the Training Programme and at the recommendation of the recipient institutions. It is thus no wonder that many of the former trainees have become the leading specialists in their countries in their given fields. Out of 82 participants during 1979-1989, our records indicate that about 70% are actively working in geothermal, 20% are working in fields where their specialized training is of some use (e.g. a geologist working within the hydropower sector instead of geothermal), and 10% are doing something completely different. Of the last group, five former trainees have left their countries in the years after their training was completed.

FUTURE OUTLOOK

The UNU Geothermal Training Programme has never paid for an advertisement on its activities. But still there is a steady flow of requests for training from all corners of the world. The eleven participants of the 1990 class are selected from about fourty applicants, all of whom fulfill the formal requirements needed for acceptance. Thus there seems to be a significant demand for the type of specialized training offered. It is therefore planned to continue with the same type of training in the near future.

Workshops on geothermal training needs sponsored by the UNU in Iceland in 1978 and in Italy in 1980 foresaw the possibility of regional geothermal training centres to be established in different parts of the world, e.g. Asia and Africa. Such development has not materialized yet.

Plans for establishing a regional training centre for Asia in the Philippines is being discussed. The UNU Geothermal Training Programme would welcome this. The training needs are certainly larger than the international centres can cope with at present. The demand for specialized training increases worldwide as the number of countries harnessing geothermal resources increases.

An extension of the training in Reykjavik by offering an option that would lead to a M.Sc. degree is being considered. This option would be particularly designed for people who have completed the present UNU course with distinction. The level of specialization that can be achieved during the present six months training is certainly limited. Extending the training for outstanding individuals by approximately one year might be a significant contribution to geothermal development in the respective countries. The M.Sc. degree would be awarded by the University of Iceland, as the United Nations University does not award academic degrees but only certificates of training. Establishing the M.Sc. option would, however, require additional financing both for academic fees and scholarships. As yet, the contribution of the Government of Iceland to international geothermal training has been considered best used in the intensive six months training courses.

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