GL01487

PARTICIPANT TRAINING PROJECT FOR EUROPE
for the
PARTNERS FOR INTERNATIONAL EDUCATION AND TRAINING
1990 M STREET N.W., SUITE 310, WASHINGTON, D.C. 20036-3426 ☐ TEL: (202) 223-4291 FAX: (202) 223-4289

Info abt funding program

INVITATION FOR APPLICATIONS
INSTITUTIONAL COMPETITION FOR TRAINING PROVIDERS
PARTICIPANT TRAINING PROJECT FOR EUROPE (PTPE)

I. BACKGROUND

In late 1992, The Europe Bureau of the U.S. Agency for International Development (A.I.D.) through an agreement with Partners for International Education and Training (PIET) implemented the Participant Training Project for Europe (PTPE). This project provides assistance to Central and Eastern Europe under the SEED legislation. Countries currently included in the program are: Albania, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, The Former Yugoslav Republic of Macedonia, Poland, Romania, Slovenia, and the Slovak Republic.

Through this agreement, PIET provides support for three program components: 1) assistance to the USAID offices in the region with the selection and processing of candidates for training in the United States; 2) the placement of trainees in the U.S.; and 3) an institutional competition which will provide funding for training programs in the U.S. or on U.S. institutions of higher education with campuses abroad.

II. OVERVIEW

A.I.D.'s Bureau for Europe and the Newly Independent States through Partners for International Education and Training seeks applications from universities, corporations, foundations, non-profits, PVOs, associations, consortia and community organizations which may lead to the award of cooperative agreements to address Support for East European Democracy (SEED) Act legislation priorities in countries of Central and Eastern Europe (CEE). This project is funded through Contract No. FAO-0000-Z-00-3075-00.

Projects eligible under this program will:

- focus on Central and Eastern Europe (Albania, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, The Former Yugoslav Republic of Macedonia, Poland, Romania, Slovenia, and the Slovak Republic);

- place emphasis on identifying and training **leaders and potential leaders** in Central and Eastern Europe who can address the development needs;

- address **SEED Act legislation** priority training areas (listed in order of importance, followed by examples of fields of training):

  Economic Restructuring - investment, market economics, trade, taxation, privatization, capital market development, banking, securities markets, sector reform;

  Democratic Institution Building - election assistance, intragovernmental relations, personnel systems, organizational management, parliamentary processes, communications systems, independent media development, and labor organization development; as well as,

  Quality of Life - environmental protection, energy, medical and health care, housing management, education, and labor issues;

- demonstrate linkages with Central and Eastern European institutions which will support successful and appropriate participant selection and follow-up;

- adopt a regional approach to training, although there is no requirement to provide training to participants from each Central and East European country;

- offer training in the United States or in U.S. institutions of higher education with campuses abroad in order to provide trainees with exposure to U.S. culture;

- provide academic or technical training that ranges in length from **one month (at least 30 days) to one year;**

- demonstrate a commitment to share costs, as shown through the ability to cover a **minimum of 50 percent** of the proposed **total** training program expenses, participant cost and administrative cost; Historically Black Colleges and Universities (HBCUs) must cost-share **a minimum of 25%** of total costs; and

- demonstrate an ability to monitor the program according to Handbook 10 (policies and procedures that regulate A.I.D.-sponsored participant training).

Geothermal Energy
in Eastern Europe

EARTH SCIENCE LABORATORY
UNIVERSITY OF UTAH RESEARCH INSTITUTE
391 CHIPETA WAY, SUITE C
SALT LAKE CITY, UT 84108-1295

DATE 3-28-90

TO Dave Anderson

ORG./LOCATION GRC

TELEPHONE NO. ( )

TELEFAX NO. (916) 758-2839

FROM P. M. Wright

ORG./LOCATION UURI / ESL

TELEPHONE NUMBER (801)524-34~~42~~39

(801)524-3453
TELEFAX NUMBER

THIS TRANSMITTAL CONSISTS OF 4 PAGES.
(EXCLUDING COVER SHEET)
VERIFICATION TELEPHONE NO. **(801)524-3437**

Dave,

This looks pretty much as we designed it. I've made a few comments and corrections. I had no changes on pages 4 or 5, so did not bother to FAX them.

It might be good to say that the schedule could be speeded up somewhat by giving the courses in the late fall or winter, but in that part of the world, winters would inhibit full benefit of the course.

I believe we are ready to bounce this off the AID people to see what they think>

Mike.

PROPOSED PROGRAM

ASSISTANCE IN DEVELOPMENT OF DIRECT-USE GEOTHERMAL ENERGY IN EASTERN EUROPE

Purpose

1. Enhance the level of direct-use technology in Eastern Europe.
2. Create a demand for U.S. geothermal goods and services in Eastern Europe.
3. ~~Aid the rapid~~ Promote more rapid social development ~~of almost~~ through use of a non-polluting source of energy in an area with a dire need for environmental solutions.

Justification

Eastern Europe is blessed with an abundance of geothermal resources for non-electric (direct-use) applications (~~direct use applications~~) at temperatures of 30° to 100°C (86° to 212°F). All of the countries have a geothermal development program, however, the technology used by most is rudimentary or outdated. Those that have a reasonably advanced technological base could also greatly benefit from the exposure to an application of U.S. direct-use technology.

Countries

Hungary
Czechoslovaia
Romania
Yougoslavia
Poland
Turkey

Audience

Employees of government agencies, select private companies and academic institutions.

Existing Contacts

The following list should not be considered complete, but these persons listed and the U.S./A.I.D. contacts can be used to develop a comprehensive list for each country.

1. Andrija Cerovina
   Mlade Bosne 113
   71210 Ilidza
   Sarajevo, Yugoslavia

2. Ioan Cohut
   Geothermal Section
   Romanian Geothermal and Geophysical Institute
   Parcul Petofi Lr. 11
   3700 Oradea, Romania

3. Tomasz Kuzniak

   OS. Spoldzielcze 8/50
   31-944 Krakow
   Poland

4. Peter Ottlik
   Institute of Energetics
   1027 Budapest Ostrom v. 23
   Bem KKP 33/34
   Hungary
   Phone: 561-130
   Telex: 224461 aHEGI

5. Dr. Kiril Popovski
   Metalski Zavod - Tito
   Institute for Development
   Ul. "Dame Gruer" 1-111/16
   91000 Skopje, Yugoslavia
   Phone: 38 (091) 207-170

6. Ing. Vit Stepanek
   Institute of Economics
   Czechoslovak Academy of Sciences
   Politickych veznu 7
   111 73 Praha 1
   Czechoslovakia

7. Asdvian Zerobis - Romania
   Delphi Institute
   1019 19th Street, NW, Ste. 500
   Washington, D.C. 20036
   Phone: 202/466-7951

Project Phases

1. <u>Advanced Team</u>

   Purpose - Collect data on specific country needs for course design~~s~~ and logistical support.

   Team Members - ~~a~~ 1 Resource person, ~~a~~ 1 applications engineer, 1 GDA ~~association~~ liaison person and ~~a~~ 1 U.S./A.I.D. Liaison person (hopefully with an economic background).

   Duration of Visit - Approximately three days in each country - see schedule.

2. <u>Courses</u>

   Format - The format of each course would vary from country to country depending upon the level of their technology, what they would like emphaised and their existing development programs.

Courses would range from 4 to 5 days and ~~will~~ would include technical lectures, problem sets, open discussions and field tours. Simultaneous ~~intrepretation~~ translation of oral lectures will be necessary.

Program - The course program ~~will vary from country to country and will~~ would include a selection of the following subjects:

Geothermal Resources
- Nature and occur~~a~~ence
- Exploration
- Drilling
- Well testing
- Reservoir evaluation

Applications Engineering
- Well completion
- Well-head equipment
- Pumps (downhole and surface)
- Heat exchangers
- Scale control~~s~~ and materials
- Waste-water disposal

Applications Case Studies
- Space heating and cooling
- District heating
- Refrigeration
- Crop drying
- Aqua-culture
- Green housing
- Industrial Processes (milk pasturization, concrete block drying, food processing, etc.)

Economics
- General considerations
- Fuel selection

what's this?
- Advantages of using geothermal energy

Environmental Considerations
- Environmental problems in direct-use development
- Mitigation measures
- Advantages in using geothermal energy over other sources of energy

AUSTRIA

CCI FAX 665-3003-002-274 10 OCT 1990 6:19 EDT PAGE 1 OF 1
From: IAEA,1400 VIENNA,POB100,FAX 43(1)234564
To: FAX 1-8015243453

UNIVERSITY OF UTAH RESEARCH INSTITUTE - ESL
ATTN: MR. PHILLIP M. WRIGHT UURI-ESL
SALT LAKE CITY-USA

FILE REF: 517 MSG NO: 832919 90-10-10

- URGENT - URGENT - URGENT -

MEX/8/017-02 REF YOUR FAX 9 OCTOBER. WE UNDERSTAND YOUR PROBLEM WITH FUNDING. UNFORTUNATELY WE DID NOT RECEIVE THE FAX YOU MENTIONED IN ITEM 1. WE ASSUME THIS WOULD PROVIDE INFO ON THE TOTAL AMOUNT OF SALARY REPLACEMENT REQUIRED. WE WOULD LIKE TO REVIEW THIS BEFORE MAKING ANY DECISION YOU MAY NOT BE AWARE THAT THIS PARTICULAR PROJECT IS DIRECTLY FUNDED BY US GOVERNMENT BUT THE RESULT IS THAT LESS THAN USDLLRS 9000.- PER MAN/MONTH IS AVAILABLE, WHICH INCLUDES TRAVEL, PERDIEM AND HONORARIUM WE MAY BE ABLE TO FIND ADDITIONAL FUNDS INCLUDING DOE RESOURCES ALTHOUGH THIS MAY MEAN DOUBLE FUNDING BY US GOVERNMENT. I WILL TRY TO PHONE YOU TODAY ON THIS MATTER. REGARDS.
R. C. DAY, HEAD EXPERTS SECTIO

I.A.E.A., VIENNA
TLX: 112645 ATOM A
FAX: ++43 (1) 23 45 64

From: IAEA,1400 VIENNA,POB100,FAX 43(1)234564
To: FAX 1-8015243453

UNIVERSITY OF UTAH RESEARCH INSTITUTE
ATTN: MR. PHILIP M. WRIGHT, TECHICAL VICE PRESIDENT
SALT LAKE CITY-USA

FILE REF: 517 MSG NO: 828262 90-09-03

MEX/8/017-02 - PROPOSED IAEA MISSION CFE, MORELIA, MEXICO EXPERTS J. MOORE AND M. ADAMS

MANY THANKS FOR YOUR LETTER RECEIVED 16 AUGUST. PLEASED TO HEAR OF AVAILABILITY MR. MOORE AND MR. ADAMS. YOUR SUGGESTION CONCERNING TWO-MAN INITIAL MISSION FOLLOWED BY MR. ADAMS' SOLO MISSION HAS BEEN PASSED ON TO COUNTERPART TOGETHER WITH BIODATA BOTH EXPERTS. TWO-PART MISSION WILL PROBABLY BE CARRIED OUT IN EARLY OCTOBER AND NOVEMBER RESPECTIVELY. HOWEVER, WE WILL REVERT ON HEARING FROM MEXICAN AUTHORITIES AS TO OUTCOME SUBMISSION BOTH EXPERTS' CANDIDATURE AND DATES PROPOSED BY COUNTERPART. THANK YOU YOUR PATIENCE.

WE SHOULD ALSO BE OBLIGED IF YOU COULD ADVISE US IN DUE COURSE WHETHER MESSRS. ADAMS AND MOORE SHOULD BE CONTRACTED AS PRIVATE INDIVIDUALS UNDER A SPECIAL SERVICE AGREEMENT, OR IF ARRANGEMENTS SHOULD BE MADE BY WAY OF A MEMORANDUM OF UNDERSTANDING BETWEEN UURI AND IAEA.

KIND REGARDS.
R.C. DAY, HEAD EXPERTS SECTION

I.A.E.A., VIENNA
TLX: 112645 ATOM A
FAX: ++43 (1) 23 45 64

CCI FAX 666-2602-007-567 3 SEP 1990 9:13 EDT PAGE 1 OF 1
From: IAEA,1400 VIENNA,POB100,FAX 43(1)234564
To: FAX 1-8015243453

UNIVERSITY OF UTAH RESEARCH INSTITUTE
ATTN: MR. PHILIP M. WRIGHT, TECHICAL VICE PRESIDENT
SALT LAKE CITY-USA

FILE REF: 517 MSG NO: 828262 90-09-03

MEX/8/017-02 - PROPOSED IAEA MISSION CFE, MORELIA, MEXICO EXPERTS J. MOORE AND M. ADAMS

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KIND REGARDS.
R.C. DAY, HEAD EXPERTS SECTION

I.A.E.A., VIENNA
TLX: 112645 ATOM A
FAX: ++43 (1) 23 45 64

INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA)
WAGRAMERSTRASSE 5, P.O. BOX 100, A-1400 VIENNA (AUSTRIA)
Telephone: +43 1 2360-0 (or Ext.) Telex 112645 ATOM A Facsimile: +43 1 23 45 64

MESSAGE No.: 1990-08-01 769262 PAGE ___ OF ___ Total pages

TELEX:

FACSIMILE:

TO:

INFO COPY:

DR. JOSEPH MORE
UNIVERSITY OF UTAH RESEARCH INSTITUTE
USA
TO FAX NO: 801-524-3453

FILE REF. MEX/8/017-02 - IAEA MISSION MORELIA, MEXICO CITY

AGENCY INTERESTED IN AVAILING OF YOUR SERVICES, OR THOSE OF DR. MICHAEL ADAMS OF THE INSTITUTE, TO CARRY OUT A MISSION TO MEXICO AS PER ATTACHED JOB DESCRIPTION. THE MISSION WOULD BE IN TWO PARTS, FIRST ONE FOR A PERIOD OF TWO WEEKS AND THE SECOND FOR A THREE-WEEK PERIOD. AT THIS STAGE THE COUNTERPART IS INTERESTED IN CARRYING OUT THE SECOND PART OF MISSION IN THE MONTH OF OCTOBER. SHOULD BE MOST OBLIGED IF YOU COULD INDICATE TO US AS EARLY AS POSSIBLE WHETHER OR NOT YOU WOULD BE AVAILABLE AT THIS TIME, OR IF NOT, EARLIEST AVAILABILITY DATES THERETO, WHICH WE COULD THEN PROPOSE TO COUNTERPART. SHOULD YOU NOT BE AVAILABLE, PERHAPS YOU WOULD BE KIND ENOUGH TO LET US KNOW IF DR. ADAMS WOULD BE INTERESTED/AVAILABLE TO CARRY OUT THE ASSIGNMENT. WE ATTACH A PERSONAL HISTORY FORM WHICH WE WOULD REQUEST YOU TO COMPLETE AND RETURN TO US AS SOON AS POSSIBLE, IF YOU ARE INTERESTED IN UNDERTAKING THE ASSIGNMENT. WE WOULD POINT OUT THAT THE BIODATA ON ALL IAEA EXPERTS HAS TO BE SUBMITTED TO THE MEXICAN AUTHORITIES FOR OFFICIAL APPROVAL.

WE LOOK FORWARD VERY MUCH TO HEARING FROM YOU. KIND REGARDS.
R.C. DAY/INATOM VIENNA.

Mike
We should talk
about this ASAP
JM

M-43/Rev 3 (Aug 89)

I A E A J O B D E S C R I P T I O N

TECHNICAL CO-OPERATION EXPERT POST IN MEXICO
(country)

PROJECT AND TASK NO. : MEX/8/017

PROJECT TITLE : Characterization of geothermal resources

SPECIAL TASK TITLE : Reinjection experiments.

Duty Station(s) [including name/ address counterpart organisation(s)] :
Morelia, Michoacán, Mexico
Comisión Federal de Electricidad
Apdo. Postal 31-C

When Required : as soon as possible

☐ only after equipment ready (approx.__________ (Date)). Please specify:

Duration [exclusive of travel time] : Two weeks + Three weeks

Duties : To help in planning reinjection experiments in geothermal fields, making use of isotopic and|or chemical tracers. To identify needs in terms of equipment and infrastructure for the equipment.

Note: The expert will pay a second visit to Mexico (3 weeks) to carry out the experiment and help with the interpretation of results.

Suggested expert: Dr. Joseph More, at the University of Utah Research Institute. Fax:801-524-3453. Tel: (801)524-
ALTERNATE: Dr. Michael Adams, same address.

[Work with Radioactive Material/Radiation Source] : ☐ no, ☐ yes: __________ (If yes (Type/Estimated Amount))

Qualifications : Experience in using tracers in reinjection experiments in geothermal fields.

Language : Spanish, English.

Background Information :

The Comisión Federal de Electricidad, Gerencia de Proyectos Geotérmicos, Morelia, is planning reinjection experiments of geothermal fluid in the field of Los Azufres (State of Michoacán). they have no experience in using tracers to identify the flow patterns of reinjected fluid in the geothermal field. The expert should help to carry out the experiment.

Date of Issue: __________ Funding Source: __________

Revision: ☐ if yes, of Task No.__________

Remarks (for computer): __________

Computer processed
__________ (Date)

Technical Officer: R GONFIANTINI Signature: Date: 28/7/1990

CCI FAX 665-3125-004-596 11 OCT 1990 10:34 EDT PAGE 1 OF 1
From: IAEA,1400 VIENNA,POB100,FAX 43(1)234564
To: FAX 1-8015243453

UNIVERSITY OF UTAH RESEARCH INSTITUTE - ESL
ATTN: MR. PHILLIP M. WRIGHT, URRI-ESL
SALT LAKE CITY-USA

FILE REF: 517 MSG NO: 833114 90-10-11

MEX/8/017-02 FOR THE ATTENTION OF DR. JOHN E. MOCK/U.S. DOE INFO CPY MR. P. M. WRIGHT/UURI-ESL, SALT LAKE CITY., INFO MR. L. HARNISH/ANL.

I BELIEVE YOU ARE AWARE THROUGH MIKE WRIGHT THAT IAEA IS ATTEMPTING TO SUPPLY EXPERTS MOORE AND ADAMS TO MEXICAN AUTHORITIES TO CARRY OUT REINJECTION EXPERIMENTS IN GEOTHERMAL FIELDS. WE ARE ABLE TO OFFER ABOUT HALF OF THE SALARY REIMBURSEMENT DEEMED NECESSARY BY WRIGHT I.E.: WE WOULD PROVIDE USDLLS 130.- PER CALENDAR DAY. IN ADDITION WE COULD PROVIDE AIR FARE AND PERDIEM. THERE ARE TWO MISSIONS ENVISIONED. FIRST WOULD BE ABOUT 10 DAYS AND SECOND ABOUT 3 WEEKS. IT HAS BEEN SUGGESTED YOU MAY BE ABLE TO PROVIDE OTHER HALF OF SALARY REIMBURSEMENT DIRECT TO UNIVERISTY OF UTAH RESEARCH INSTITUTE AND THUS ENABLE THESE INTERESTING EXPERIMENTS TO BE CARRIED OUT. I WOULD BE GRATEFUL IF YOU WOULD REVIEW THIS PROPOSAL AND ADVISE YOUR REACTION IN DUE COURSE.

A. REYNAUD/EXPERTS SECT X 6037

I.A.E.A., VIENNA
TLX: 112645 ATOM A
FAX: ++43 (1) 23 45 64

CCI FAX 665-5757-005-872 18 OCT 1990 13:42 EDT PAGE 1 OF 1
From: IAEA,1400 VIENNA,POB100,FAX 43(1)234564
To: FAX 1-8015243453

UNIVERSITY OF UTAH RESEARCH INSTITUE - ESL
ATTN: MR. PHILLIP M. WRIGHT URRI-ESL
SALT LAKE CITY-USA

FILE REF: 517 MSG NO: 833951 90-10-18

MEX/8/017-02 FOR THE ATTENTION OF MR. P.M. WRIGHT-UURI-ESL, INFO COPIES: DR. MOCK/US.DOE AND MR. L. HARNISH/ANL.
FURTHER PREVIOUS CORRESPONDENCE RE FORTHCOMING MISSIONS EXPERTS MOORE AND ADAMS, PLEASE CONFIRM SOONEST

AAA ACCEPTANCE FINANCIAL TERMS OUTLINED OUR FAX DATED 90.09.26, CONSIDERING THAT U S DOE PREPARED TO PROVIDE REMAINING SALARY.

BBB UURI WISHES PROVIDE EXPERTS SERVICES UNDER INDIVIDUAL MEMORANDUM OF UNDERSTANDING.

CCC ADVISE SUITABLE SCHEDULE INCLUDING EXACT ITINERARIES, DATES, TIMES, FLIGHT NUMBERS ENABLING US CALCULATE DSA'S, PROCEED PREPARATION IMOU ACCORDINGLY AND INFO COUNTERPART ETA FOR HOTEL RESERVATION AND AIRPORT PICK-UP PURPOSES.

WE WOULD LIKE TO TAKE THIS OPPORTUNITY TO THANK YOU FOR YOUR SUPPORT OF OUR TECHNICAL COOPERATION PROGRAMME. KIND REGARDS.
R. C. DAY/HEAD EXPERTS SECTION

I.A.E.A., VIENNA
TLX: 112645 ATOM A
FAX: ++43 (1) 23 45 64

UNITED STATES DEPARTMENT OF COMMERCE
FOREIGN COMMERCIAL SERVICE

August 28, 1990

American Embassy - Budapest
U S and Foreign Commercial Service
Szabadsag ter 12 1054 Budapest Hungary
(American Embassy - Budapest
APO New York 09213-5270)

Fax: 36 1 132 8934 Tel: 36 1 112 6450 Telex: 22 7136

8076

To: U.S. Department of Energy

Attn: Marshall Reed, Program Manager

Address: CE-122, Forrestal Bldg., Washington, D.C. 20230

Fax: 202 586 8134 Tel: 202 586 8076

Ref: Your fax of 08/23 Number of pages incl. this 1

Dear Mr Reed:

Please be advised that Dr Miklôs àrpâsi is an oil-engineer and acts as an advisor to the director general of SZKFI. Dr àrpâsi also participates in SZKFI's Geothermal Program. He can be reached at the following address:

SZKFI Hungarian Hydrocarbon Research Institute
P O Box 32
2443 Szazhalombatta, Hungary
Fax: (36 1) 180 0122

Very truly yours,

David Hughes

David Hughes
Commercial Attache

	1	2	3	4
Contacted	DR			
Date/Time	8/29/90			
Opr Ini	AJ			

M. Reed

DOE F 1325.8
(8-89)

United States Government **Department of Energy**

memorandum

DATE: JUN 14 1990

REPLY TO
ATTN OF: CE-122

SUBJECT: Interest of Geothermal Division in U.S. - Hungary Cooperation

TO: Moustafa M. Soliman, IE-12

The Geothermal Division has a research commitment to the characterization and utilization of low- and intermediate-temperature (up to 150°C) geothermal resources. Your suggested involvement of the Geothermal Division in the Agreement for Scientific and Technological Cooperation with Hungary fits well with our ongoing research. The geothermal resources of Hungary are of major historical significance, but their characteristics are only known to DOE researchers through the scientific literature.

Because of other funding priorities, the Geothermal Division will be dependent on the funding to be appropriated for this Agreement by Congress to pay the expenses of U.S. researchers visiting Hungary or for Hungarian researchers to travel in the U.S. Hungarian researchers will be welcome to visit the several research groups participating in DOE-funded geothermal research.

From the material you attached to your memorandum, it seems that the Hungarians have very limited interests for cooperation. The letter from Dr. Arpasi Miklos only mentions an interest in the generation of electricity, and we could provide contacts in industry with experience in using 100°C water to operate 2MW to 5MW geothermal power plants. Additional fields for cooperative research immediately come to mind. The high concentration of carbon dioxide in the water from some Hungarian geothermal systems indicates that the deposition of calcium carbonate scale could be a problem. We have solved the scale formation problems in several geothermal systems and could share this technology. In addition, several U.S. research groups are developing computer models of geothermal systems to predict the response to production and to estimate the useful lifetime of a resource. Many more areas for cooperation could be developed during visits by Hungarian researchers as they receive a first hand understanding of U.S. geothermal research.

Ted

John E. Mock, Director
Geothermal Division
Conservation and Renewable Energy

DOE F 1325.8
(8-89)

United States Government **Department of Energy**

memorandum

DATE: May 25, 1990

REPLY TO ATTN OF: Moustafa M. Soliman, IE-12, 6-5904

SUBJECT: U.S.-Hungary Cooperation in Science & Technology

TO:

Miles Greenbaum, FE-13
R. Loose, CE-34
J. Mock, CE-341

The United States and Hungary have entered into an Agreement for Scientific and Technological Cooperation. This Agreement is similar to those agreements the U.S. already has with Poland and Yugoslavia.

Funds will be appropriated by Congress for this cooperation in FY91 in the amount of $1 million which will be matched by Hungary in Forints. Energy will receive 14% of the total budget while Agricuture, NSF, EPA, NIST, and DOH will receive the rest. Thisbudget is expected to increase in the following fiscal years.

These funds will be used to fund joint research projects, seminars, workshops, and project development trips. Proposals will be reviewed by responsible DOE programs to determine programmatic interest. A program announcement describing the overall U.S.- Hungary S&T program and explaining the procedure and format of the proposals will soon be available for distribution to Hungarian and U.S. research institutions , universities and national laboratories.

During the first US-Hungarian Joint Board meeting in Budapest on May2-4, 1990, I had the opportunity to visit a number of research institutes to explore potential areas for energy R&D cooperation that can be developed under this Agreement. I have found a number of excellent opportunities in the fields of coal technology, enhanced oil recovery, geothermal energy, renewable energy , energy conservation, basic energy sciences, high energy and nuclear physics, fusion, and nuclear safety. Attached, please find the material I have gathered in your program area during these meetings.

Considering the lead time involved in developing research proposals which are of interest to us in DOE, I request that you review these documents and relay to me any specific topics that may be pursued in our future contacts with the Hungarians. Please keep in mind that in certain areas we may have to fund some project development trips before we can develop meaningful research proposals that can benefit the Hungarians as well as DOE domestic programs.

Attachments

The possibilities of geothermal energy utilization for generation of electricity in Hungary.

1. Geothermal energy reserves and occurances in Hungary.

A typical characteristic of the area of Hungary is the strong geothermal overheating. The measurements have shown that the heat glow density makes some 100 mW/m^2 and the geothermic gradient 0.05 K/m in contrast to the world average of 63 mW/m^2, and 0.03 K/m, respectively. Beneath the surface of Hungary the earth's crust is thinning out and the elevated position of the mantle explains the higher heat content of the sediments, filling up the basin. (See Fig. 1).

The geothermic energy reserves are composed partly of the heat content of the subsurface rocks, and partly of the heat content of the thermal waters filling the porous rocks.

The geothermal energy reserves contained in the subsurface waters makes some 53.10^{18} kJ in the depth interval from 0 to

MOHO-HEAT FLOW (mW/m^2)

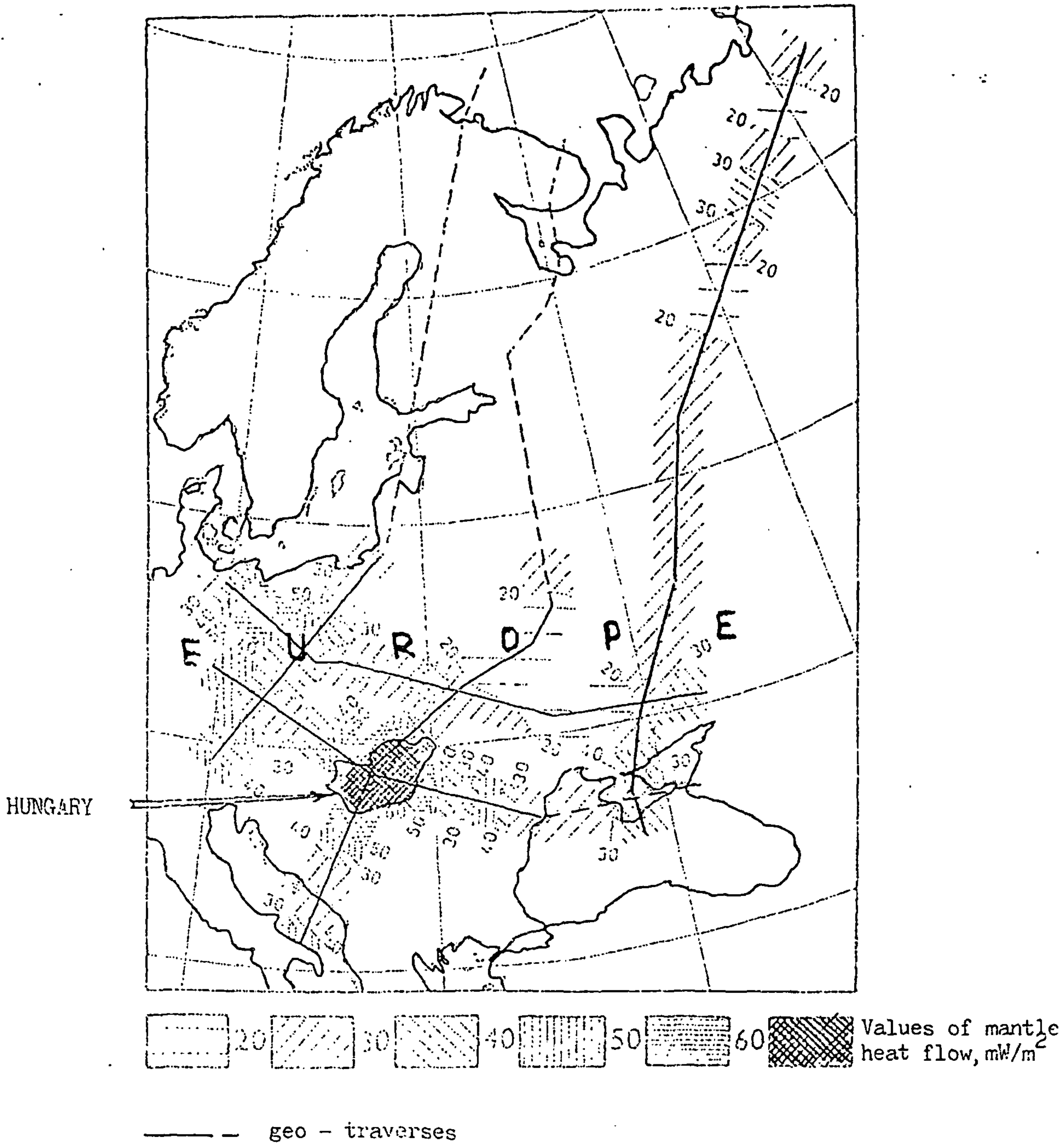

Fig.1. Regional variation of the mantle heat flow (in mW/m^2) along the considered geotraverses in Europe

3000 m. This is equivalent to 1.26×10^{12} tons-oil-equivalent (toe). If the interval between 3000 and 10.000 m is also considered, then the thermal energy reserves in place make some 500.10^{18} kJ corresponding 12.10^{12} toe (2). Naturally the total thermal energy in place can not be exploited fully. If 15% depletion ratio is taken into account then the recoverable thermal energy from the depth interval 0 to 3000 m makes 8.10^{18} kJ, i.e.: 0.189×10^{12} toe. Compared to the recoverable hydrocarbon reserves, estimated in 1976 for the same depth interval, it becomes that the thermal energy reserves are 1380 times more. This represents such a potential possibility the exploitation of which deserves much more efforts.

Geothermal energy is actually depleted from two reservoir systems:
1. regional big systems,
2. local small systems.

The two types of regional big systems, known in Hungary are as follows:

1.1. The upper pannonian sand and sandstone series of multiple horizons and reservoirs extending all over the Hungarian Great Plain (the Pannonian Basin). In the lower and middle section of the upper pannonian formations porosity may reach 20 to 30%, and in the upper section it may exceed even 30%. The reservoir pressure of the upper pannonian reservoirs is hydrostatic. The solution gas content of the thermal waters in the reservoir (hydrocarbon and CO_2 gases) is one of the most important driving factors. E.g. at Orosháza the GWR (gas water ratio) makes some 1.1 to 1.5 m^3/m^3, at Debrecen 1.2 to 1.96 m^3/m^3. The outflow temperature of the thermal waters goes up to 100 ^{o}C (especially in the southern, and sout-eastern part of the Great Plain). At 1600 to 2500 litre/min discharge outflow temperatures of 95 to 98 C have been often observed. The salt content in solution makes max. 2 to 4 g/lit. (mostly sodium hydrocarbonates).

1.2. Triassic fractured, fissured limestones and dolomites, sometimes partly karstic, showing vertical flow patterns. Thickness may reach 4000 to 5000 m. The fissure-fracture system is locally and vertically very variable, it can not be characterized geometrically. The formation has secondary porosity and permeability, areally varying.
The reservoir pressure is hydrostatic with usually negative static water level. The amount of solution gas is small, and the salt content also low (0.8 to 1 g/lit.). Outflow temperatures approach 100 °C locally. Discharges are usually big (1000 to 4000 lit/min).

2. The local small systems of thermal water reservoir include some levantian (pliocene) sediments, tortonian (miocene) reef limestones, and some fractured, fissured paleozoic formations. The reservoirs are of local importance. Reservoir pressures vary between hydrostatic to 100 % over-pressure. The outflow temperature reaches 130 °C (the wells Álmosd-13., Tótkomlós-14, and Nagyszénás-3 yielded wet steam). Salt content varies between 1 to 48 g/lit.

The summary of measured or estimated data in superdeep well Fábiánsebestyén-4 /1985/ (geothermal blow-out)

- Depth of reservoir : 4239 m
- Type of reservoir : fissured and fructured dolomite
- Geothermal fluid : hot water + wet steam
- Production rate of geothermal fluid : 180 - 300 m^3/h
- Cross section area of flow : casing 8 5/8" or well head equipment
- Well head temperature : 140 - 160 °C

- Well head pressure : 360 - 410 bar
- Salt content, g/l : 25 NaCl
  0,82 $Ca/HCO_3/_2$
- Formation temperature : 254 C
- Formation pressure : 763 bar

Combining of 1.1, 1.2 and 2. type of reservoirs it becomes clear that geothermal energy is available all over the country.

In addition to the thermal energy of thermal waters, due to the heat flow well in excess of the world average, the Pannonian basin became during geological times a thermal reservoir suitable for thermal energy recovery.

3. The actual extent of geothermal energy utilization in Hungary.

It was mentioned before that the depletable geothermal energy reserves are 1380 times more than the recoverable hydrocarbon reserves.

At the end of 1986 some 1019 thermal water producing wells of more than 30 °C outflow temperature were listed, out of which 986 produced and 33 were shut off. The summarized geo-technical features for use of geothermal energy for electric power production by Organic Rankine Cycle (binary plants) in Hungary are shown in Table 1.

As well as you have been informed, Hungarian Hydrocarbon Institute to organise the field pilot test with use of a binary geothermal power unit at Zalakaros bath.

We would like to arrange the above mentioned pilot test with available power unit of your company, working by Organic Rankine Cycle (ORC).

Table 1. Summarized geo-techni cal data of geothermal energy utilization possibilities by binary plants in Hungary

Nº	- Number of geothermal wells - average depth of formations, m - lithology	type of fluids	type of flow	Production range m^3/h	Cross-section area for flow (diameter of choke), /"/	Temperatures, °C		Well-head pressure bar	Salinity of fluids g/l
						formation	at the well head (outflow temperature)		
1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
	I. Existing geothermal wells with low enthalpy fluids								
1.	Type 1. (upper pannonian)								
	- approx. 120 wells - 1800-2600 - terrigeniosus rocks	hot water	free flow (80%)	0-150 28 37 150	2 4 1/2 6	100-150	70-100	0-20	0-4 (NaCl)
2.	Type 2. (mesozoic)								
	- approx. 60 wells - 200-3000 - carbonate rocks	hot water	free flow (55%)	0-200	2 3/8 - 7	120-180	70-100	0-30	0-1 (NaCl)
3.	Type 3.								
	- approx. 35 wells - 2500-4300 - terrigeniosus and/ /or metamorphic rocks	hot water and wet steam	free flow (100%)	100-300 240	8 5/8	200-240	100-160	0-400	10-40 (NaCl) (Ca/HCO_3)
	Total amount of wells types 1-3: 215 wells								

Table 1. Summarized geo-technical data of geothermal energy utilization possibilities by lirary plants in Hungary

Nº	- Number of geothermal wells - average depth of formations, m - lithology	type of fluids	type of flow	Production range m^3/h	Cross-section area for flow (diameter of choke), /"/	Temperatures, °C		Well-head pressure bar	Salinity of fluids g/l
						formation	at the well head (outflow temperature)		
1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
		II. Abandoned CH wells (must be recompleted)							
4.	Type 4. - approx. 1000 wells - 1800-5200 - terrigeniosus and carbonate rocks	hot water and/or wet steam	free flow	0-300	2 3/8 - 7	80-260	70-160	0-55	mostly 0-10 (NaCl)
	Total amount of wells types 1-4: 1215 wells								

Total number of binary power units (Organic Rankine Cycle) are required for wells types 1-3:

Capacity of units:	
- max. 250 kW :	approx. 120 units
- max. 500 kW:	approx. 60 units
- 1000 kW: and more	approx. 35 units

The experimental system should be include:

- evaporator (vaporizer exchanger)
- turbine and control system
- generator (assynchronous)
- condenser
- surge tank, oil system, heaters and coolers, associated
- controls, etc.

Hungarian Hydrocarbon Institute would be required to:

- provide the geothermal well with suitable well-head
- equipment and pipe manifolding
- provide electrical switching mechanisms
- technical management for installation testing and period field evaluation test

Fundamental to Institute purchase of this geothermal power unit is that this will succesfully meet the operating parameters as specified by your company.

Successfull compliance of the operating test shall be mutually determined by regular inspections conducted by an appointed HHI engineer and your company's representative.

We hope that your company has a firm belief in the Hungarian market and the opportunities for recovering electrical power from geothermal energy which in conjunction with our company's strategic positions, presents an excellent economic opportunity for incremental power generation.

Please to evalueate our proposal. If we may be of further assitance in providing information, please feel free to contact us at your convenience.

Best regards

Dr. Árpási Miklós
advisor for president

MAGYAR SZÉNHIDROGÉNIPARI KUTATÓ-FEJLESZTŐ INTÉZET

SZKFI

THE POSSIBILITIES OF GEOTHERMAL ENERGY UTILIZATION IN HUNGARY

Hungarian Hydrocarbon Institute

- 1987 -

THE POSSIBILITIES OF GEOTHERMAL ENERGY UTILIZATION IN HUNGARY

SZKFI

The possibilities of geothermal energy utilization in Hungary.

(SZKFI)+

During the last twenty years increasing attention was focused on the utilization of geothermal resources in Hungary due to the specific geothermic conditions of the country, to raising energy prices, to increased energy demand and to environmental protection. In consequence, geothermal energy is a factor of increasing importance to be reconned with in the energy policy of the country, because it represents an additional and replacing energy source and in several cases it is more advantageous than some other energy sources.

Naturally economy is also a condition of the rational utilization of geothermal energy, but also the fact is an important point of view, that it makes the utilizer independent of energy import and to a certain extent, of increasing energy prices, being a locally available energy source.

The prospecting, concluded sofar, clarified the geothermal conditions of the country already. With respect to international comparison, the exploitable geothermal energy resources of the country can be considered as a potentially big.
The thermal water resources of higher than 35 °C temperature existing down to 3000 m depth as thermal energy carriers and the depletable thermal energy is very big, having in addition, the advantage that it can be found all over the territory of the country and it can be exploited over a long time period by a well drilled on location.

The temperature degree interval of most of the geothermal energy, which can be obtained from the Hungarian thermal water fields and rocks corresponds the requirements of heating and warm water supply making up 40 per cent of the total energy consumption.

+ for: Hungarian Petroleum Research Institute.

In addition to utilize geothermal energy for heating and in thermal power stations there are also numerous other possibilities, such as e.g.: in the industry and agriculture, refrigeration, utility warm water, thermal baths, winter sport facilities, etc.

The further investigation of geothermal energy resources in Hungary, the development of their theoretical and practical utilization is some complex task. It shall be solved by the researchers in geology, hydrology, drilling, energy utilization, machine manufacturing, etc.

Some significant results were obtained, first at all in the field of thermal baths and vegetable production, with respect to both, technical solutions and economy as well. Despite the results thus achieved we shall not forget, that the possibilities of thermal energy utilization are manifold more than exploited sofar. The crucial problem of further development is actually the organization. The requirements, the technical possibilities shall be interpreted, the money necessary for the expansion of utilization shall be provided for, and the research to increase efficiency shall be organized in a way as not to contradict each other, to serve the expansion of geothermal energy utilization, and increased economic efficiency harmonically coordinated.

The aim of present paper is to add some new ideas to the existing, complex and multiple stage system of thermal energy utilization. We want to focus some attention on the possibility of organizational actions, on their necessity, on the engagement of research, further on upon the possibilities given by the application of well completions as applied in petroleum production taking into consideration that all these will serve more efficient economical rentability.

Geothermal energy reserves and occurances in Hungary.

A typical characteristic of the area of Hungary is the strong geothermal overheating. The measurements have shown that the heat flow density makes some 100 mW/m^2 and the geothermic gradient 0,05 K/m in contrast to the world average of 63 mW/m^2, and 0,03 K/m, respectively. Beneath the surface of Hungary the earth's crust is thinning out and the elevated position of the mantle explains the higher heat content of the sediments, filling up the basin.

The geothermic energy reserves are composed partly of the heat content of the subsurface rocks, and partly of the heat content of the thermal waters filling the porous rocks.

The geothermal energy reserves contained in the subsurface waters makes some 53.10^{18} kJ in the depth interval from 0 to 3000 m. This is equivalent to $1.26x10^{12}$ tons-oil-equivalent (toe). If the interval between 3000 and 10 000 m is also considered, then the thermal energy reserves in place make some 500.10^{18} kJ corresponding 12.10^{12} toe (2). Naturally the total thermal energy in place can not be exploited fully. If 15 % depletion ratio is taken into account then the recoverable thermal energy from the depth interval 0 to 3000 m makes 8.10^{18} kJ, i.e.: $0.189x10^{12}$ toe. Compared to the recoverable hydrocarbon reserves, estimated in 1976 for the same depth interval, it becomes that the thermal energy reserves are 1380 times more. This represents such a potential possibility the exploitation of which deserves much more efforts.

Geothermal energy is actually depleted from two reservoir systems: regional big systems and local small systems (3).

The two types of big systems, known in Hungary are as follows:

- The upper pannonian sand and sandstone series of multiple horizons and reservoirs extending all over (!) the Great Plain.

In the lower and middle section of the upper pannonian formations porosity may reach 20 to 30 %, and in the upper section it may exceed even 30 %. The horizontal permeability of sandstones below 2000 m depth is 0.05 to 0.2 μm^2, though in the thermal water reservoirs it is alternating between 0.2 to 0.5 μm^2. The reservoir pressure of the upper pannonian reservoirs is hydrostatic. The solution gas content of the thermal waters in the reservoir (hydrocarbon and CO_2 gases) is one of the most important driving factors. E.g. at Orosháza the GWR (gas water ratio) makes some 1.1 to 1.5 m^3/m^3, at Debrecen 1.2 to 1.96 m^3/m^3. The outflow temperature of the thermal waters goes up to 373 K (especially in the southern, and sout-eastern part of the Great Plain). At 1600 to 2000 litre/min discharge outflow temperatures of 369 to 371 K have been often observed. The salt content in solution makes max. 2 to 4 g/lit. (mostly sodium hydrocarbonates) (fig. 1.).

- Triassic fractured, fissured limestones and dolomites, sometimes partly karstic, showing vertical flow patterns. Thickness may reach 4000 to 5000 m. The fissure-fracture system is locally and vertically very variable, it can not be characterized geometrically. The formation has secondary porosity and permeability, areally varying.
  The reservoir pressure is hydrostatic with usually negative static water level. The amount of solution gas is small, and the salt content also low (0.8 to 1 g/lit.). Outflow temperatures may approach 373 K locally. Discharges are usually big (1000 to 3000 lit/min) (fig. 2.).

The local small systems of thermal water reservoir include some levantian (pliocene) sediments, tortonian (miocene) reef limestones, and some fractured, fissured paleozoic formations. The reservoirs are of local importance. Reservoir pressures vary between hydrostatic to 100 % over-pressure. The outflow temperature reaches 303 K (the wells Álmosd-13., Tótkomlós-14. and Nagyszénás-3 yielded steam). Salt content varies between 1 to 48 g/lit.

Combining fig. 1. with fig. 2. (irrespected the local geothermal systems) it becomes clear that geothermal energy is available all over the country.

In addition to the thermal energy of thermal waters, due to the heat flow well in excess of the world average, the Pannonian basin became during geological times a thermal reservoir suitable for thermal energy recovery.

Depletion methods of reservoir fluids for thermal energy recovery.

Depletion of geothermal energy means the exploitation of the heat content accumulated during geological times in the rocks, and in the fluids stored in porous formations. The reservoir fluids, depletable for thermal energy recovery, include the thermal waters, and their solution gas content as well: the non combustible mixed gases composed of hydrocarbon gases, CO_2 and N_2, further on CO_2 gases, occuring usually in the Pannonian basin beneath the upper pannonian regional thermal water reservoirs, which are depletable together with the geothermal energy and may play some important role in the komplex utilization of thermal wells.

Exploitation of thermal energy from the fluidum of a geothermal reservoir.

Conventionally geothermal energy is obtained from the fluidum of the geothermal reservoir. Thermal water can be depleted from wells of positive water level by free flow, or from wells of negative water level.

In case of free flow wells, the flow is promoted by the reservoir energy and/or by the solution gas content of the water, reducing density. Depletion of the reservoir energy can be slowed down by reinjection of the cooled down water, the heat content of which has been utilized already, and if available, also by the reinjection of the produced gas, as it is well known (4). The reinjection of the waste water promotes in some cases also environmental protection (5). Fig. 3. shows the thermal energy in fuel oil equivalent, obtainable from free flow wells. The depleted thermal energy is naturally not equal with the utilized energy, due to the efficiency of the heat utilizing equipment. In addition to the conventional completion of free flow wells, in case of simultaneous exploitation of reservoirs containing thermal water and inert gases, the well structure as shown by fig. 4. can be employed. The down hole valve built into the tubing of 2 7/8 in dia (1) can be regulated by choke (2) (back pressure regulation) and according to this regulation valve (1) transmits gas into the upward flowing thermal water. The valves would begin operation in case the reservoir energy of the thermal water reservoir would drop below the critical value, i.e. the well would turn negative. Fig. 4. shows a well completion scheme used to open up the upper pannonian regional big system. In this case the reservoir, containing inert gases, must be below the water reservoir. In case an older thermal water reservoir is opened up below the inert gas reservoir, the well structure must be changed accordingly due to the change of the reservoir position. The thermal water will flow through the tubing of bigger diameter, while valves (1) and (2) shall be placed to the "gas side".

Fig. 5. shows some well structure for the case, when saltwater of density ρ_2 is depleted causing salt precipitation in the well head. Some freshwater of volume V_1 is injected into the well fluid changing the density to ρ_3 preventing salt precipitation at the temperature of the waste (utilized) water and also no salt is precipitated at the well head at p_2 and t_3.

This production system has also the advantage, that in case of sufficiently long h of the mixing water of volume V_1 it contacts the warm, or hot rocks on a large surface and due to the good heat conductivity of the casing it becomes also warm, thus increasing the heat productivity of the well.

Well completion schemes of free flow wells are shown on figs. 6. and 7. These structures make possible the simultaneous production of freely flowing thermal water and with inert gases mixed gas and provide possibility also for mix-water injection (similarly to fig. 5.). If the well turns negative (free flow ceased) the well structure makes possible the application of the system shown by fig. 4.

In case of wells of negative water level the reservoir energy is insufficient to cause free flow. To produce the thermal water some additional energy is requested, such as submersible pump, mammoth pump or plunger pump especially in case of practically unlimited amount of flow, as e.g. production from the Triassic big system. The utilization of the mentioned pumps and the related operational experience is well known (6., 7.) yet the application of the system, shown by fig. 4., is recommended, utilizing mixed gas as lift gas, instead of additional energy investment, to bring the thermal water to surface.

Thermal energy production from the geothermal reservoir.

The exploitation of thermal energy from the geothermal reservoir is not applied in Hungary. Two such methods can be recommended to this end. Injection of water from the surface into the properly completed well to get it heated up and then to exploit its heat content, or to circulate water between injection and production wells where the geothermic reservoir is also a part of the circulation system.

The circulation of cold water injected from the surface into the well may render some possibility for thermal energy recovery /8/. According to the principle the well structure is heat-insulated sufficiently on the production side and the closed circulation system is well suited for thermal energy recovery, yet this still shall be proved by experiments.

There are several examples abroad for thermal energy recovery by the system of injecting and producing wells. An example is given by fig.8. /8/. This method can be employed economically there, where layers of good water intake capacity are present. In Hungary geothermal energy recovery is planned by such well paires at Szeged /9/. An improved variety of this system is the drilling of several deviated holes from the same drilling location to supply bigger consumers (district heating agricultural combines). In this case the surface equipment can be simplified and the length of heat-insulated surface piping can be reduced.

In New Mexico (USA), under nearly similar geothermal conditions than in Hungary, a steam turbine driven electric generator, utilizing the thermal energy of one well pair, produces 10 to 20 MW electric energy /20/. Depth of the injection well is at 2932 m (bottom hole temperature 470 K) and that of the producing well is at 2708 m (bottom hole temperautre 428 K). The communication between the two wells was made possible through several parallel vertical fractures created by fluid formation fracturing in the precambrian granite.

The actual extent of geothermal energy utilization in Hungary.

It was mentioned before that the depletable geothermal energy reserves are 1380 times more than the recoverable hydrocarbon reserves. This ratio is much more warse if the actual yearly production of the two energy carriers are compared.

In 1978 the number of thermal wells producing thermal water of more than 333 K outflow temperature was 147 and they represented 637 k toe energy. The yearly hydrocarbon production made some 9 M toe, indicating that thermal energy made 7 % of the hydrocarbon production only. The distribution of the thermal energy depleted from the 147 thermal wells, according to utilizing sectors, is given by table 1. /18/.

According to the data of the Central Statistic Office for 1980, the picture is only somewhat more favorable. At the end of 1980 some 842 thermal water producing wells of more than 303 K outflow temperature were listed, out of which 586 produced (69.6 %) and 256 (30.4 %) were shut off. Their distribution according to sonsuming sectors is shown in table 2.

Out of the grand total of 185 Mm^3 per year thermal water produced, actually some 167 Mm^3 per year is utilized representing 30.4 PJ/year geothermic energy (cooled down to 288 K), i.e. 740 k toe which is only 8.2 per cent of the actual hydrocarbon production.

The geothermal energy produced is utilized at fairly big losses. The more significant sources of losses are as follows:

- produced but wasted thermal water, without any utilization,
- temperature reduction in the pipeline between the thermal well and the consumer,
- utilization of high temperature water for lower temperature purposes after cooling,
- the energy content of water discharged from the location of utilization is above 288 K.

The energy thus lost is estimated as 284 k toe (38.4 %!).

One of the restricting factors of thermal energy utilization, mentioned usually on the first place, is the fact, that the thermal energy producing location and the consumer is bound to the same place.

As it will be shown later by an example of the Árpád agricultural association at Szentes, even the connection of thermal wells within a circle of 5 to 6 km radius and the transportation of the energy carrier to a central place is also economic. Naturally it is mroe favorable if the thermal well and the consumer are on the same location, thus eliminating the cost of transport. Since, as it was shown above, geothermal energy can be produced all over Hungary, therefore at the location of any consumer can thermal wells be drilled.

It is not necessary to locate the consumer at the source of energy since the energy supplying well can be located at the place of consumption.

An other counter-argument is that the drilling and installation of the thermal well demands high investment. It is naturally true, but it is valid also for hydrocarbon production and coal mining. It can also not be neglected that a base of thermal energy utilization can be constructed within 3 to 5 years, and thermal energy is relatively cheap. In the USA the specific cost of electric energy produced in a nuclear power station makes 1.55 ¢ per kWh, that produced in a coal base thermal station is 1.45 ¢, while produced by geothermal energy it is 0.74 ¢ only.

In Hungary some calculations were made with respect to economy in the agricultural combine "Árpád" at Szentes. There a greenhouse plant of 136 000 m^2 is heated by thermalwater obtained from 7 wells, discharging some 1177 km^3 per year thermal water of 353 - 358 K temperature (under "year" the heating season of approximately 6 months is understood). During the heating season 240 TJ thermal energy is utilized (the water becomes cooled down to 308 K). The expenses of the equipment delivering thermal energy makes 9 925 000 Ft, including also the depretiation of the wells and heat insulated pipes (it is 10 % = 7 174 000 Ft per year). Further on it includes also the cost of chemicals preventing salt precipitation (25 000 Ft), the cost of electric energy for pumping (1 609 000 Ft) and other expenses (wages, etc. totally 1 117 000 Ft) as well. An index number, typical for the price of thermal energy, is the ratio of the cost of equipment and the utilized thermal energy. This was found to be 41.35 Ft/GJ. The same index would be for fuel oil 277.92 Ft/GJ, for natural gas 117.83 Ft/GJ and for coal 106.81 Ft/GJ.

(With respect to the alternative energy sources only the cost of fuel was considered, without the depreciation of the installations and without some other expenses).

Komplex and multistage utilization of thermal wells.

Fields of application.

The utilization and the technology applied for heat transfer is decisively influenced by the quality of the thermal water (temperature, pressure, salt content, gas content, etc.)

The quality and quantity of thermal waters in Hungary secures the komplex and multistage utilization of thermal wells. Komplex utilization means utilization in series or parallel in the different sectors (e.g. utilization for communal purposes and parallel to it, or following it: industrial utilization). Multistage utilization means serial utilization according to temperature stages (e.g. in an agricultural combine the water is first utilized for greenhouse heating, and following, the cooled-down water is utilized in an intensive fish hatching plant).

In Hungary thermal waters are mainly utilized in the field of agriculture and within this in horticulture. In addition to heat the air in greenhouses (363-318 K water) and to heat the soil (318-308 K water), the thermal water of 308 to 288 K temperature, considered usually as waste water, can still be utilized for many purposes. It can be well utilized in double sheeted plastic tent blocks /10/. Even in case of 248 K outside temperature by the utilization of 308 K water, adequate temperature can be maintained inside the house. The same water is suitable, in addition, to regulate the temperature of the water in the intensive fish hatching plant (naturally applying mechanical filtration, biological nitrification and ion exchange), further on to warm up irrigation water (in the pipe system the irrigation water is warmed up by the thermal water). Thermal water is utilized, in addition to horticulture also in animal husbandry (brooders, henneries, calf-breeding sheds, hog-farms), further on as utility warm water.

In addition to agricultural utilization also industrial utilization would be important. Thermal water can be utilized in addition to heating, and utility water supply also in some manufacturing technologies. Even some salts can be obtained in industrial quantities in certain special cases (NaCl, Br, J, etc.). Abroad, first at all, electric energy is obtained by the utilization of steam from steam producing wells. (There are also in Hungary some wells producing steam). In California an experimental power station of 45 MW capacity is operated by a two cycle geothermal energy utilization system (the thermal water is utilized to heat a secondary liquid of low boiling point (e.g. iso-butane, iso-pentane) and the steam of this liquid drives the turbines) /1/.

The geothermic generator, utilizing the Seebeck principle is well known. In the USA and in the Sovietunion numerous thermoelectric generators are operated. Development in this field is very fast. In 1960 8 to 10 % energy utilization efficiency was obtained and the discharge/weight ratio of the equipment appoached that of the conventional dynamos. Nowdays bigger thermoelectric generators of several hundred, even several thousand MW capacity are produced, as compared to the previous years /16/.

Fig. 9. shows the basic circuit scheme of such a generator. In boiler (1) the ammonium, circulating in the energy producing system, is vaporized by thermal water. (Instead of ammonium also freon can be employed). The steam engine, obtaining 358 K temperature ammonium gas of 46 bar pressure from the boiler drives the electric generator. The ammonium gas, coming from the steam engine, is expanded in condenser (3) and it is pumped back by pump (4) through heat exchanger (5) into the boiler /21/.

A conventional utilization of thermal waters is the communal supply for the population, to provide heating and utility warm water for baths, swimming pools, sanitary institutions, housings communal institutions, etc. The thermal energy of thermal waters can be utilized in many fields also for cooling, a possibility not much exploited sofar. In those fields, where thermal water is utilized for heating purposes during the cold season, it is at hand to utilize it for cooling during the warm season (e.g. in air conditioning, in cold-storage plants etc.)

Several physical principles and equipment are known to utilize the thermal energy of thermal waters for cooling. The change of phases (physical state) are connected with heat generation or heat extraction. For evaporation heat shall be fed into the system. This can be geothermal energy as well. In case of condensation the phase change is connected with heat extraction, which is already some cooling process. This is the principle of the thermotube /11/. The thermotube is a corrugated pipe filled up with some cooling agent, e.g. freon. One end of the pipe is an evaporator, the other end a condenser. It is operated by independent cooling circulation. In case of vertical arrangement the warmer medium (thermal water) shall be introduced at the lower end thus the lower end of the tube is an evaporator, the upper end a condenser. The vapor of the cooling agent (e.g. freon) becomes condensed in the upper part of the tube extracting heat from the environment (from the circulating air or water) then it flows back by gravity into the lower part of the tube in continuous circulation.

The above principle is utilized in the various absorption type refrigerators employed also in the industry /12/. As shown by fig.10. the cooling agent is absorbed (dissolved) in the absorber. Following, the solution goes into a space where through warming up the gas-in-solution can be removed. (Compared to the conventional compressor type refrigerator, the compressing work of the compressor is replaced in this process by the introduction of heat into the solvent). In the later stage of the technological process the gas becomes condensated in the condenser (by cooling water) and the liquid gas is forwarded to the evaporator. The evaporation extracts heat from the space to be cooled. The circulation can be maintained exclusively by the utilization of the thermal energy, practically without any mechanical work. According to the technical literature the absorption type refrigerator is there significant, where waste heat can be utilized and cheap cooling water is available in unrestricted amounts. In the multistage thermal water utilizing system both conditions are fulfilled. During summer, when no heating is requested, the hot thermal water is utilized in boiler (1) for warming. The water leaving the boiler through (3) satisfies the requirements of some other utilizers and returns through (15) to cool absorber (9), condenser (5) and deflegmator (4). The cooling water, leaving the system through (16) can be further utilized, e.g. reinjected into the reservoir to maintain reservoir pressure. In case the thermal water well produces also some inert contaminated gas, instead of conventional cooling agents (ammonium) also CO_2 gas can be used.

The utilization of natural gases obtained from thermal wells is also possible in the Maiuri type diffusion refrigerator. The absorption refrigerator, operating with pressure equalizing gas is employed in high capacity industrial installations. (The same principle is utilized in Hungary in the "Electrolux" household refrigerator). The refrigerator is operating in multiple stages. The cooling agent is diffunded into a neutral agent at varying intensity to establish evaporation of varying degree, and in the evaporator varying temperatures at given points. Mairuri utilized ammonium-water agent pair as cooling agent and hydrogene, or nitrogene as neutral gas to create more moderate temperatures. For very low temperatures a mixture of different hydrocarbons was recommended.

The Carrier Co. (U.S.A.) manufactures an absorption refrigerator of 1200 MJ/h capacity, operating with water-lithiumbromide cooling agent pair, for climatizing purposes. In the boiler steam or warm water! is utilized for heating /17/.

It seems to be reasonable to develop the above described coolers for thermal water utilization. In additon, it seems also to be worthwile to develop a thermal water variety of steam jet refrigerators. As shown in fig. 11. /12/ steam is blown into the ejector of the equipment provoking vacuum in the atomizer. The vacuum sucks away the water steam from the atomizer. The steam pressed into the ejector becomes condensed in the condenser, and some part of it will be pumped into the boiler, and the other part of it goes into the evaporator. The water is sprayed into the evaporator and here some part of the water, thus transformed into mist by the strong vacuum (created by the ejector), evaporates, cools the rest of the liquid and the chilled water can be pumped into the space to be cooled. The steam-jet type cooler is utilized abroad first at all in air conditioners. It is simple and safe, yet its considerable water and steam consumption is considered as some disadvantage.

In Hungary several steam wells are available and most probably still more could be drilled. The steam could be utilized immediately, without a boiler, and that part of the warm water which is pumped to the boiler according to figure 9., could be pumped to the condenser, following multistage utilization, to cool the steam. In areas, where only thermal water is available without steam but with mixed gases, from which hydrocarbon gases could be separated, there steam could be generated by additional heating, utilizing the separated hydrocarbon gas.

Utilization of the gases produced with the thermal water.

As mentioned above already, some thermal water wells also produce some gases therefore their possible utilization shall be considered as well.

Fig. 12. shows the known occurances of natural gases with inert gas content (NGI) /13/. These occurances became known through hydrocarbon exploration therefore the discovery of some more can be expected for, if gas exploration will be aimed also at the utilization of NGI combined with thermal water exploitation.

Table 3. shows some typical characteristics of NGI.

Fig. 13. shows the occurances of CO_2 gases in Hungary. These occurances became known also by hydrocarbon exploration. The areal distribution indicates that Hungary is rich in CO_2 gas occurances /19/. The program aimed at the discovery of more CO_2 gas could begin with the reinterpretation of some well logs of hydrocarbon exploration drillings to reevaluate the pools containing CO_2 gas. It is probable that by this process numerous pools, containing CO_2 gas in solution, can be found

and utilized in a complex system with thermal waters.

The hydrocarbon gases dissolved in thermal waters migrated by dispersion partly from hydrocarbon pools, due to poor cap rocks into the thermal water pools, but some part of them might be autochtonous /14/. Most probably this is the reason why in some areas the solution gas content of some thermal waters is very significant. Some examples are given in table 4.

Both: the inert gases and the hydrocarbon gases in solution in thermal waters play some significant role in the multistage, komplex utilization of thermal waters. The areas of utilization are the followings:

- They supply additional energy in the production of thermal waters. As described above they can be utilized as lift gas to extend the period of free flow production. As it is well known, the quantity of gas in solution influences favorable the production mechanism of thermal waters.
- The gas, produced with the thermal water, can be separated and its components can be utilized in the multistage, complex process. The hydrocarbon gases represent additional fuel the flue gas of which, free of CO, can be used as a fertilizer for plants.

The N_2 gas may reduce the corrosion of the wells and equipment up to 90 %. The CO_2 gas can be utilized in greenhouses as a fertilizer, dissolved in water for irrigation (also some kind of fertilizer), in cold storage plants, as cooling medium, or as protecting medium for big masses of vegetables and fruits (CO_2 gas is slowing down biological processes).

It shall be mentioned, that the separation of the gases produced with the thermal water is not some problem of principles but much more that of economy. Especially in case NGI is produced with the thermal water. The mixture of CO_2 + Hydrocarbongases + N_2 can become enriched in hydrocarbon gases by the removal of $CO_2 + N_2$, but further separation of all the other components is very expensive. While planning an actual utilization process the above aspects shall be seriously considered with respect to economy.

As a summary of what is described above, fig. 14. shows the ideal principles of a multistage, komplex utilization process.

Some of the more significant expenses of thermal water production.

The most costly item of thermal water production is the drilling of the well. For planning purposes the most essential are the expenses of drilling, or the transformation of an existing, unsuccessful hydrocarbon exploration well into a thermal water producing well, and the expenses of water injection. Prices are given by the Lowlands Petroleum Exploration Company for 1982.

Drilling a new well	million Ft
1. to 1200 m depth, with filter	4.5 to 5.5
2. to 1500 m depth, with filter	5.6 to 6.5
3. to 2100 m depth, with filter	7.8 to 8.8
4. to 2100 m depth, perforated: the drilling rig is removed having cemented the production casing string, perforation and formation test will be done by a well-completion rig	
expenses of the drilling rig:	6.2 to 7.0
expenses of the well-completion rig:	0.8
total expenses:	7.3 to 8.1

Expenses to transform an existing duster into a thermal water well

(naturally only if thermal water pays are present). Expenses are not much related to the depth of the pay to be opened up.

1. Simple completion: no technical difficulties, opening up by perforation, starting production, measurements related to quantity, quality, etc.:	0.6 to 0.8

2. Moderately complicated well completion requesting drilling of cement plugs, squeeze cementation if there is no cement behind the casing at the level of the planned perforation, if the casing is damaged at one or more levels, if the hanger of liner is not water proof, if the well discharges sand after perforation requesting the placing of a filter, etc.: 1.0 to 1.7 MFt
3. Severely complicated completion, if the above mentioned difficulties appear combined, or formation stimulation is necessary by formation fracturing, or acidizing, eventually repeatedly: 1.5 to 3.5 MFt

Expenses of water injection.

If the utilized (from its thermal energy deprived) cool water can not be disposed off but by reinjection into the pay, or because it must be reinjected for pressure maintenance, in addition to the drilling or completion of a reinjection well, also some other expenses shall be considered as well. The Lowlands Petroleum and Natural Gas Producing Company reinjected in 1982 altogether 4 331 000 m^3 water. The specific cost made 10 to 11 Ft/m^3.

Some problems associated with geothermal energy production and their possible solutions.

The geothermal energy exploitation has its own peculiar problems, as any other energy production. These problems are solved step by step depending upon the production history of energy resources, the accumulation of production experience, upon the technical development level of the energy production in question and upon the organization (coordination between production plants, technical research and development, and central controlling) of the energy producing branche. The science dealing with these problems is the geotermia. The development of the applied geotermia began only a few decades ago. In consequence the unsolved problems are still numerous reducing the spirit of enterprise. Yet the energy demand and supply of Hungary requests imperatively to replace import energy by the locally availabel thermal energy as much as possible to reduce the cost of energy. Some of the problems of thermal water production in Hungary:

- problemes of exploitation,
- problems related to utilization,
- economic problems.

Problems of thermal water exploitation.

1. Decrease of reservoir energy. Depletion over a long time period will reduce the reservoir energy. From the Hajduszoboszló thermal water pool some 58 million cu.m. thermal water was depleted between 1926 and 1980. Calculation shows that reservoir pressure decreased by 0.14 bar per 1 million cu.m. The initially free-flow production had to be replaced by gas-lift. Static level of the water is actually at -45 m in the wells.

   The thermal water pool at Debrecen discharged 31.5 million cu.m. water between 1932 and 1980. Reservoir pressure decreased by 0.16 bar per 1 million cu.m. water produced. The initially free flow wells, producing also a relatively high amount of associated gas, turned to negativ static level.

   The thermal water pools at Szolnok produced 42 million cu.m. water between 1929 and 1980. Reservoir pressure decreased by 1.85 bar per million cu.m. in the wells producing at higher GWR, but it corresponded the country wide average of 0.1 to 0.2 bar per million cu.m. water produced, in the wells producing at low GWR (0.5 m^3 per m^3).

   The thermal water pool at Szentes delivered 120 million cu.m. water between 1959 and 1980 from about 32 wells. The discharge of the individual wells decreased by some 10 to 20 %, yet they produce still at free-flow.

Solution of the problem.

- To reduce or to eliminate reservoir pressure decline widespread water reinjeciton shall be applied with attention to the hydrodynamic conditions of the reservoir, and to the connections between thermal water and hydrocarbon pays respectively.
- Pressure maintenance by the injection of natural gas produced with the thermal water, or obtained from hydrocarbon wells (if available). Only such gases shall be injected which correspond the reservoir rocks and can not be utilized in the complex thermal water utilization process (hydrocarbon gaes, CO_2, N_2, etc.), or their removal is important due to environmental protection.

2. Random depletion, ruthless exploitation. Usually abandonned petroleum exploration wells, or wells drilled by local, individual iniciatives are exploited in this way unsystematically, thus the production life time of the reservoir, the proper depletion factor (at the given geothermic system), the proper utilization of the reservoir energy to maintain free-flow over a long period is not secured. In consequence the consumers show some mistrust with respect to long operative life time of the wells.

Solution of the problem.

Planned location of the wells and drilling numerous deviated wells from the same location. The life time of the reservoir and the depletion ratio depends to a considerable extent from the location scheme of the producing wells. The drilling of deviated holes from the same location has the advantage of concentrated installation eliminating long insulated, very expensive, pipe systems.

3. The wells of the agricultural combine "Árpád" at Szentes are "twins", i.e. from the same location two wells were drilled each of them exploiting one individual reservoir.

Solution of the problem.

The application of dual, or multiple completion to deplete two or more reservoirs through the same well. If gas pays are present, free-flow production can be maintanined. By this type completion the expenses can be reduced considerably.

4. Improper selection of pays. A typical example is the well Táska-1. in the area of the Buzsák agricultural combine. Out of four wells (T-1, T-2, T-3. and T-4.) only T-1 is producing, because the water is the hotest in this well (355 K outflow temperature), although the water of this well is at the same time of highest salt content (6.7 g per lit.). Therefore the surface installations must be acid treated in every two weeks. Production is obtained from lower pannonian, fractured marl and volcanic tufits, therefore the water is heavily contaminated with solids. Picture 2. shows a strongly scaled valve of the well, and picture 3. the big heap of sandy shale and tuffit produced with the water.

Solution of the problem.

More reliable well log interpretation and more exact knowledge of the geological conditions with respect to the thermal water reservoir. The data base and experiences of hydrocarbon exploration wells can be adapted to this end.

5. By advancing depletion both: the reservoir energy and the discharge of the well decrease. The well turns negative. Production of the desired amount of water can be obtained only by the application of submersible or plunger pumps. This involves usually some well structure modifications increasing the expenses and the energy requirements.

Solution of the problem.

In case some gas pays were also opened up by the well, the gas shall be utilized to secure free-flow production. This will request some proper equipment and regulating system. The gas produced with the water can be further utilized in the complex system.

Some problems related to the water.

1. The salt content is higher than the amount soluble in the water. The surplus precipitates as scale. Several methods are known to prevent, and to eliminate scale formation. The precipitation of salt can be prevented by thermal water production at critical or higher pressure, by the establishment of electromagnetic field around the well head /15/, by the application of inhibitors (e.g. "Árpád" agricultural combine at Szentes) or by the reduction of salt content (mixing fresh water to the thermal water).

Solution of the problem.

Depending upon the chemical composition of the water the salt concentration can be regulated by mixing fresh water at the level of the pay horizon to the thermal water in such a way as to eliminate scale precipitation in the producing and utilizing equipment. An additional advantage of this method is the fact, that the mixing water absorbs heat from the neighbouring rocks increasing its heat content.

At the thermal wells of the bath Zalakaros the scale formation was prevented by mixing fresh water to the thermal water to reduce the salt content and now some experiment is continued to mix the water at 500-600 m depth to prevent scale formation also in the tubing.

Salt precipitation can be removed mechanically (e.g. by drilling out the scale from the pipes), by replacing the involved tubing and equipment or by dissolving the scale with hydrochloric acid.

2. The produced thermal water is contaminated with oil.

Solution.

The oil can be separated fairly well in steel tanks as e.g. at Csiszta--bath, near Buzsák. The water flows into a tank provided with steel plates to change several times the direction of flow, thus promoting the separation of the oil. The light oil swims upon the surface of the water and is discharged by an overflow pipe on the top of the tank. The clean warm water is discharged from the bottom of the tank into the bath. Picture 4. shows the well and the tank, walled by concrete. Some emulson treating methods probably could be also successfully adapted to remove oil contamination from thermal waters.

3. The well is producing with the water also high amount of debris and heaving shales fill up the bottom of the well (see picture 3.).

Solution.

Avoiding quick opening and closing of the well. Producing at optimum ratio. Application of methods to solidify heaving formations. Cleaning the well. Running in filters.

4. The produced thermal water causes corrosion in the casing and in the surface equipment.

Solution.

Application of inhibitors or installation of corrosion proof equipment. Both methods are very expensive. If N_2 can be also produced from the well it cann be injected into the thermal water in a regulated way and may reduce corrosion by some 80 to 90 per cent.

Problems of economy.

1. Drilling the wells needs high investments. The high cost of geothermal energy utilization shall be reduced.

Solution.

- The expenses of drilling and completion of the well can be reduced by proper well structure, well equipment and drilling technology. The drilling of deviated holes from the same location can also reduce expenses if the reservoir can be depleted by this way.

- The expenses can be reduced also by the location of the wells close to the place of utilization. This is possible in Hungary nearly everywhere by one of the two methods: thermal water production, or circulation, thus thermal energy can replace conventional energy for consumers already operating. The expenses to install long insulated pipe systems can be also saved up.

  The utilization of the thermal energy all over the year, or over the best part of the year, can result also considerable savings. (To utilize thermal energy during the cold season for heating and during the warm season for cooling, air conditioning, refrigeration, in additon to other possible applications as described already above.) The utilization of associated gases is an other possibility for further savings.

- An other possibility to reduce expenses is the multistage utilization of thermal energy according to temperature stages. Where steam is available (as in Hungary at many places) it shall be utilized as a first step for power generation, but also the method shown by fig. 9. can be applied as well.

- To reduce expenses careful planning and design shall be requested from the competent planning and research institutions with respect to power generation and mass refrigeration in industrial scale (equipment and technology).

- An other possibility for savings is the application of water and CO_2 gas for irrigation and fertilizing, firtst at all in horticulture (vegetable growing in greenhouses).
  In this respect some promising experiments are conducted also in Hungary.

Summary.

The study is somewhat extraordinary. Instead of giving technical details it suggest such solutions which are available already in the field of water and hydrocarbon production and which can be still further developed promoting the utilization of this, for the future much promising, energy source.

The recognition that thermal energy is available nearly all over the area of Hungary is extremely important, thus the energy can be located at the installation in which it has to be used.

The gases associated with thermal waters (hydrocarbons, CO_2, N_2) can be also utilized to promote free-flow and to expand the field of utilization. The well structures and technology, necessary to this end, are availabe.

To prevent salt precipitation and to increase the yield of geothermal energy, some water circulated from the surface, can be used. There are further possibilities to reduce the expenses, the already very favorable unit cost, as compared with other energy sources, by two new ways:

- Expanding the time of utilization by the elimination of only seazonal consumption (winter heating, summer cooling) and by the expansion of associated gas utilization.

- Extension of multistage utilization, where it is given by nature, as e.g. power generation by steam or gas tubines, by thermal elements.

The application of deviated drilling and multiple well completion is a factor of cost reduction, sofar poorly applied. To solve the related problems the competent research institutions are to be involved. The tasks, as elucidated in the study, request coordination. The increased and improved utilization of thermal energy is one of the most important tasks for the future, especially if we consider that the energy content of an average thermal well (1500 lit. per min., 353 K temperature) is equal to an oil well, producing 10 to 12 ton per day oil.

To make further expansion and increased efficiency possible, the necessary planning organization shall be established and the design and manufacturing of the equipment requested to this end shall begin with as soon as possible. To expand the application of thermal energy and associated resources further scientific research is also needed.

The study, in addition to some technical suggestions, shows a complex, multistage, theoretical scheme the realization of which is the common interest of the consumers and the country.

Literature.

Ábra-feliratok.

Fig. 1. Thermal wells producing from the upper pannonian thermal water reservoir system (the outflow temperature of the water is higher than 333 K) /3/.

1: thermal water well, 2: group of thermal water wells,
3: contour lines on the base of the upper pannonian showing depth below sea level

Fig. 2. Thermal wells producing from the carbonate thermal water reservoir system (outflow temperature of the water is higher than 308 K) /3/.

1: thermal water well, 2: group of thermal water wells,
3: Triassic carbonate rocks

Fig. 3. Thermal energy which can be obtained from thermal water, expressed in fuel oil equivalent

1: energy obtainable in 1 month (temperature of waste water 303 K)
2: toe/month
3: energy obtainable in one year (temperature of waste water 303 K)
4: toe/year
5: Δt = difference between the temperature of the outflowing thermal water and that of the waste water

Fig. 4. Scheme of the production system in case of mixed well fluid.

a: to the separator to separate the NGI from the thermal water
b: to the heat utilizer or to the separator
c: thermal water pay
d: NGI pay

Fig. 5. Well structure for the prevention of salt precipitation. Mixing water: in-take pressure = p_1, quantity = V_1, temperature = t_1, density = ϱ_1, in-flowing thermal water:

pressure = p_2, quantity = V_2, temperature = t_2, density = ρ_2, h = depth of mixing V_1 with V_2; p_3 = well head pressure on the tubing; outflowing water: quantity = V_3 (= V_1+V_2), temperature = t_3, density = ρ_3

Fig. 6. and Fig. 7. Schemes of well structure, suitable for mixed fluid production
a: to the separator to separate NGI from water,
b: thermal water, c: cold water, d: tubing,
e: casing, f: gas pay containing NGI,
g: thermal water pay.

Fig. 8. Heating 2000 apartments with thermal water. (Melun, France).
1: reservoir (pay), 2: heat exchanger, 3: peak boilers, 4: heating, 8: utility warm water supply, 6: sewage, 7: supplementing cold water

Fig. 9. Flow diagram for steam engine.
1: thermal water, 2: further utilization.

Fig. 10. Operation of an absorption type refrigerator with thermal energy.
1: boiler (distiller), 2: heating steam inlet, 3: condensed water outlet, 4: choke valve, 7: evaporator, 8: cooled space, 9: solvent (absorber), 10: solution pump, 11: heat exchanger, 12: intake of enriched solution, 13: regulator valve, 14: intake of lean solution, 15: intake of cooling water, 16: outlet for cooling water

Fig. 11. Operation of steam-jet type refrigerator with thermal energy
1: warmed-up water, 2: steam, 3: atomizer, 4: ejector, 5: boiler, 6: regulator valve, 7: into the space to be cooled, 8: water, condensor, 9: pump, 10: cold water, 11: feeding pump

Fig. 12. NGI occurances in Hungary /13/.
1: symbols, 2: fields containing N_2, 3: inert content, 4: producing fields

Fig. 13. Areal distribution of natural gases contaminated with CO_2 /19/
É = N, D = S, NY = W, K = E, ÉNY = NW, ÉK = NE
1: Key to fig. 13., 2: symbols, 3: anomalies

Fig. 14. Complex utilization of reservoir fluids.
1: summer utilization, 2: winter-summer utilization, 3: water reinjection, 4: well, 5: water, or steam, nat.gas, 6: winter utilization, 7: cooling water, 8: geothermic power generation, 9: cooling water, 10: absorption type cold-storage plant, air conditioners, 11: degasser (gas separator), 12: water, 13: heating of animal husbandry installations, 14: heating of apartments, houses, offices, workshops, 15: additional heating energy, 16: flue-gas fertilizing, 17: utility warm water supply for baths, sanitary institutions, houses, plants, 18: crop driers, 19: soil heating of greenhouses, 20: horticulture, 21: canning house, 22: sewage, 23: irigation water warming, 24: double sheated plastic tent block heating, 25: regulating the water temperature in fish hatchers, 26: outflowing water.

A képek feliratai.

Picture 1.: Producing wells in the thermal water field at Szentes.

Picture 2.: A valve of the well Táska-1. filled by scale, precipitated from the thermal water.

Picture 3.: Sandy shale and tuffite produced by thermal well Táska-1.

Picture 4.: Oil skimming tank at the bath of Csisztapuszta.

Feliratok a táblázatokhoz.

Table 1.

1: utilization, 2: number of wells, 3: water discharge, m^3/min, 4: exploited thermal energy, PJ/year, 5: exploited thermal capacity, 6: 10^3 toe, 7: agriculture, 8: building heating, 9: industry, 10: baths, 11: water works, 12: water reinjection, 13: temporarily shut-in, 14: total

Table 2.

1: field of utilization, 2: number of wells, 3: producing, 4: non--producing, 5: total, 6: industrial branches, 7: agriculture, 8: transport, 9: water economy, 10: others, 11: total

Distribution of not exploited wells:	item
the produced water flows unitilized	16
temporarily shut-in	138
observation well to control water level	50
abandoned	52

Distribution of producing wells according to temperature:

item	temperature of out-flowing water, K	total discharge km^3 per year
286	303 to 313	81 468
179	314 to 333	48 223
121	334 to 373	55 276

Table 3.

Some characteristics of mixed natural gases contaminated with inert gases

1: Name of occurance, 2: initial in place reserves, 10^9 m^3, depletion factor, %

4: gas composition:
hydrocarbons N_2 CO_2
5: heating value, kJ/m^3
6: I. Occurances exploited
7: II. Occurances utilized for the Tisza thermal power station
8: III. Occurances not exploited
9: Prognostic occurances
10: IV. Occurances containing high amount of N_2
11: + N_2 and CO_2 together

Table 4.

Some examples of thermal water wells, showing high gas/water ratio (GWR).

1: location of thermal water wells, and their designation, 2: depth of thermal water pay, m, 3: initial discharge m^3/d, 4: initial GWR m^3/m^3, 5: outflow temperature, K

6: bath, 7: municipal horticulture, 8: horticulture, 9: castle gardens, 10: hospital, 11: agricultural combine, 12: agricultural cooperative, 13: wagon washer, 14: swimming pool, 15: sports ground, 16: sugar factory.

780

EUROPEAN COOPERATIVE NETWORKS ON RURAL ENERGY
RÉSEAUX COOPÉRATIFS EUROPÉENS POUR LES ENERGIES RURALES
REDES COOPERATIVAS EUROPEAS SOBRE FUENTES DE ENERGIA RURAL

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PRESENT STATUS OF GEOTHERMAL ENERGY: USE IN AGRICULTURE OF HUNGARY

Karai J., Kocsis K., Liebe P., Nagy A., Ottlik P. (Hungary)

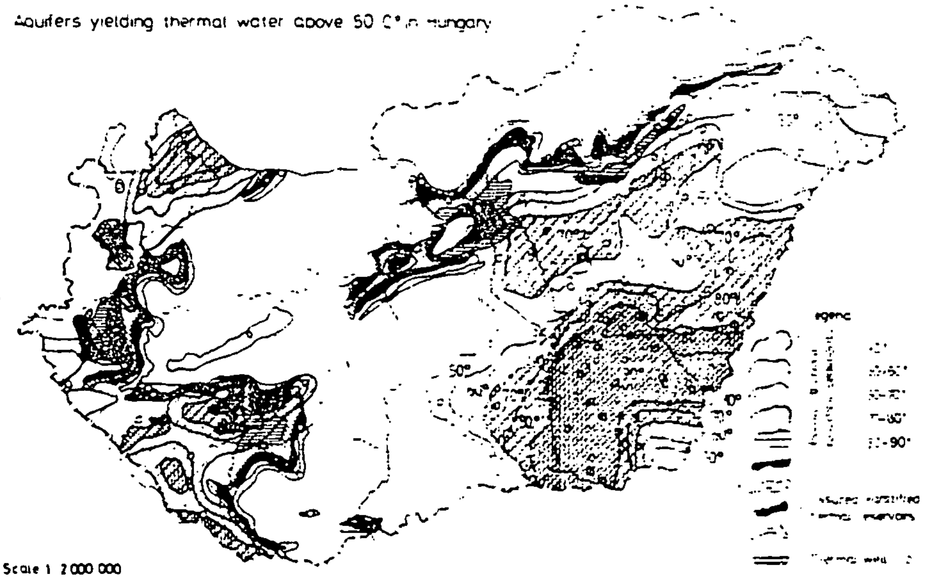

Fig.1.: Aquifers yielding thermal water above 50 °C in Hungary

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1. INTRODUCTION

The FAO European Cooperative Networks on Rural Energy (CNRE) comprises seven Research Networks, viz., Energy Conservation in Agriculture, Production and Conversion of Biomass for Energy, Utilization of Solar Energy, Wind- and Hydropower in Rural Sectors, Integrated Farm Systems and Agricultural Use of Thermal Effluents, the latter including two working groups which deal with the

- Use of Geothermal Energy in Agriculture and
- Use of industrial Thermal Effluents in Agriculture.

In accordance with the general objectives of the CNRE R+D programme, both working groups have organized several technical consultations and workshops to promote the international exchange of technical-scientific information. The main subjects of these events were the presentation of, and discussions on, the results achieved at the pilot projects established and the operating experience gained at the producing plants using geothermal and waste heat in greenhouses. As a result of the cooperative research activities several reports and proceedings have already been published and disseminated, which contain the papers presented and the main conclusions arrived at during these events. The information made available by the participating countries served as the basis of the State-of-the-Art Study on the Geothermal Resources and their Use in Agriculture in Europe.

At the Third Joint Workshop on the Use of Solar and Geothermal Energy for Heating Greenhauses (11-14 April, 1988, Adana, Turkey) a group of Turkish experts presented the first of the CNRE Country Reviews on the "Present State and Prespectives of Geothermal Energy Use in Turkish Agriculture". The document was received with great interest by the members of the working group, as it presented a clear review of the current state of the geothermal resources in Turkey, their potential uses in agriculture and contained also recommendations concerning the wider practical introduction of the existing geothermal heating technologies. Encouraged by the positive experiences the Workshop recommended to extend the country reviews to other countries and subjects as well. The coordinators and cooperating experts of CNRE have expressed their appreciation to the Group of Hungarian Authors for their efforts at compiling the second Country Review.

This document offers a brief overview of the geology of the geothermal resources, further of the results achieved in Hungary in the agricultural uses of this important, renewable kind of energy. The primary aim of this document is to present general information to the scientists, development engineers and decision makers involved in national programmes, but it may be useful also to the professionals of other countries where large geothermal resources are available, but cannot be used in agriculture without addition technological know-how. This document, translated into the languages of several cooperating countries, is expected to find access to farming operations, just as to the institutions involved in agricultural and geothermal development, contributing thus to the spreading uses of geothermal energy for agricultural purposes in Europe.

2. The geothermal resurces of Hungary

Several papers have already been published in English on the results of the extensive studies performed thus far on the favourable geothermal conditions in Hungary. Without mentioning details, these have revealed that - as demonstrated by seismic measurements - the lithosphere under the Carpathian Basin is abnormally thin. Consequent therefrom the geothermal heat flux of 80-100 mW/m^2 is above the average for the continent and the geothermal gradient of 18-25 m/°C is steeper than the normal 30-33 m/°C value.

The fact that the subsiding area was covered by a closed freshwater lake during the late Tertiary Period contributes to the favourable situation in this respect. Subsidence and sedimentation occured at largely the same rate, as a result of which porous sand layers of large extension and containing syngenetic water are also present in the thick sediment formation thus developed. In the deepest parts of the basin such sandy layers have been found even at depths greater than 2000 m.

Owing to the lacustrine, littoral facies, as well as to the oscillating rate of subsidence the porosity and permeability of the layers vary in an irregular pattern both horizontally and vertically.

In these sandy aquifers, at the boundary of the Lower-Pannonian strata the water temperature rises consistently with depth. The highest aquifer temperature registered thus far was 140 °C.

Over 90 per cent of the thermal waters presently used are withdrawn from this reservoir at the highest surface temperature of 97 °C. Favourable conditions have encouraged the development of standard methods including water treatment processes and operative projects for the use of thermal waters.

Besides this hydrogeological-geothermal system consisting of the sandy reservoirs within the basin, large volumes of water are stored also in the Upper-Triassic limestone and dolomite rocks forming the basement of the basin. The water percolating downward from karstified outcrops and along tectonic zones is heated in accordance with the geothermal gradient, so that in the areas, where the basement is situated at depths greater than 1000-1500 m thermal waters can be withdrawn from these formations as well.

The elevated intake areas and the hot waters contained in the deep karstified rocks form an autoregulated hydrodynamic system, in that the heated water of reduced specific gravity tends to rise and emerges to the surface along faultlines at elevations lower than those of the intake.

Substantial differences exist between the two hydrological-geothermal systems:

a. In the porous, sandy reservoir the flow of water is unobstructed, attains velocities of 1 to 10 cm/year, whereas in the fissures of karstic rocks this may be higher by several orders. Depending on the degree of fracturing, the permeability of karstified rocks and sands ranges between the orders of 10^{-2} - 10^{-4} and 10^{-3} - 10^{-6} m/s, respectively.

b. Great depth and overlying impervious clay formations prevent virtually any surface precipitation water from reaching the deep sandy aquifers. Lateral inflow and compressible storage in the secondary rocks are thus the major sources of recharge.

It should be clear from the foregoing and still emphasized separately that the geothermal energy which can be recovered from the thermal waters withdrawn in the Pannonian Basin is a virtually nonrenewable source. This fact is demonstrated also by the regional depression developed in the SE part of country, where thermal waters are withdrawn at the highest rate. Measurements have shown the pressure in the layer to have dropped over the past 10 years at the annual rate of 0.1 - 0.2 bars (0.01 - 0.02 MP) so that the yield from originally free-flowing wells has decreased drastically and pumping had to be resorted to at most of them.

Mention must finally be made of the fact that some deep boreholes sunk to below 3500 m depth in recent years have demonstrated the presence of high-enthalphy resources in the Carpanthian Basin. In the absence of complete hydrodynamic studies, no more than the parameters registered at the well heads are available on these. Wet steam of temperatures between 200 and 300 °C and pressures over 100 MPa and with a very high salts content emerged from this reservoir to the surface. Additional measurements are needed to explore the conditions of, and to estimate the magnitude of the resources stored in these formations.

Of the three types of geothermal energy resources those stored in the sandy aquifers situated at the Lower-Upper Pannonian boundary and available for development over two-thirds of the country have been explored by boreholes sufficiently to permit reliable estimates of their volume and potential.

The data on these resources are indicated on the attached map, compiled at the Research Center for Water Resources Development, VITUKI - and in Tables 1. and 2. The geographic situation of the reservoir is clearly visible from the map, whereas the magnitude of the resources is shown in Table 2. in the form of fractions, the numerator of which represents the volume of thermal water developed and consumed already, the denominator that still available for development.

It should be noted here that in Hungary any water emerging to the surface with a temperature higher than 30 °C is termed officially as termal water. Owing to energy considerations only those warmer than 50 °C have been included as resources in the present report.

The volume estimation date back to 1982, so that the figures are no more fully accurate, but reflect well the geothermal potential in the country.

3. Distribution of the geothermal fields in Hungary

No geothermal fields complying truly with conventional geologic terminology can be distinguished in the Pannonian Basin. Fields are normally defined by the deposit of some useful mineral (petroleum, coal, etc.) with finite extension so that these can be confined by an accurately traced boundary or by negative boreholes. In the Pannonian Basin the principal thermal water reservoir situated under the largest area and yielding water of the highest temperature is - as mentioned before - the formation situated at the Lower-Upper Pannonian boundary, which contains relatively loose sands of high permeability. Besides representing a single large unit, this communicates also with the water horizons situated closer to the surface. The thermal water system extends thus practically from the surface down to the Lower Pannonian clay formations. The successive horizons thereof communicate with each other hydraulically through windows between the interstratified lenticular clay layers.

From the foregoing it will be perceived that virtually no sharp boundaries can be drawn between the thermal waters explored. The thermal water resources are situated over a large area in the main reservoir, differences being observable - at the same depth - in the yield capacity alone. The water temperature was found invariable to increase with depth.

The salt content of the waters stored in the Pannonian thermal aquifers increases normally with depth, but owing to the freshwater origin retains throughout its alkaline-hydrocarbonate character.

Owing to their seawater origin the very slight pre-Pannonian thermal water resources are characterized by a high chloride content.

These resources are, however, too small and contain salts in too high concentrations to be of practical significance.

As mentioned before, no thermal water fields or areas proper can be distunguished, so that it is deemed more correct to speak of thermal water occurrences, although these are not separated from each other by natural parameters, but rather by the influence radius of depression range of the wells developed.

The location of the areas termed thus as occurrences is defined primarily by the wells drilled in response to user demands and by the level of exploration. The demands for power and heating purposes can be met most expediently by using water of the highest temperature available. For this reason users have attained the highest level, where water of the highest temperature and the required volume could be developed. These areas are situated over the deepest parts of the basin in the SE regions of the country.

In the foregoing sense the Szentes geothermal area may be mentioned where 36 thermal wells are being exploited within the town region. Another similarly favourable area is the region of Szeged town, where over 14 wells are operated. The occurrence at Makó, Hódmezővásárhely, Szarvas, Mosonmagyaróvár and several minor geothermal sites are deemed also worthy of being mentioned.

The situation of the users of geothermal energy and geothermal areas is often fortuitous, since most thermal wells have been developed from unsuccessful hydrocarbon exploratory boreholes, the sites of which had been selected for their hydrocarbon potential, rather than by the considerations and needs of thermal water development. The initial encouraging results of users have prompted them to drill additional wells increasing thus the amount of energy to the desired level.

The fact that thermal waters are used primarily in agriculture for power development purposes is attributable in part to this reason. Domestic-communal district heating projects follow next, with wells drilled already close to the demand center (Table 3.). According to statistics, the majority of thermal springs and wells is used in balneology, for medicinal baths, but these yield normally waters in the 30-50 °C temperature range, which are not directly accessible to power development purposes.

The foregoing conclusions are reflected in Table 2. by presenting the values of the geothermal potential by geographic areas. Moreover, as clearly shown by the map attached, these areas communicate with each other and are delineated by the sedimentation (depth, porosity) and hydrologic (infiltration-upward flow) conditions in the basin.

Large volumes of karstic water are stored also in the karstified basement rock which again forms an integrated hydrologic system where no particular fields can be distinguished. Withdrawals from this reservoir by boreholes are confined to minor areas, so that its total volume is difficult to estimate. Examples of these areas are Szigetvár, Zalakaros and Komárom. The lower extent of exploration implies at the same time that the total volume of water used is substantially smaller than that of the flow withdrawn from the main reservoir, the Pannonian sands.

The thermal wells are grouped according to areas and purposes of development in Table 3. presenting the 1985 data, the variations over the last 10 years and capacity available in 1985 (data of the National Water Authority, OVH).

A grouping of the thermal wells according to well head temperature is presented in Table 4. (data of the National Water Authority, OVH).

4. USES OF GEOTHERMAL ENERGY IN HORTICULTURE AND AGRICULTURE

In Hungarian agriculture energy is consumed at the annual rate of 20 TWh ($1{,}7914 \cdot 10^6$ t OE), of which. The share of horticulture is 3.5 TWh ($313{,}495 \cdot 10^3$ t OE), including 2.5 TWh ($223{,}925 \cdot 10^3$ t OE) for heating purposes, of which 1.8 TWh ($161{,}226 \cdot 10^3$), or 72 per cent, are recovered from thermal waters. Of the total energy consumption thermal energy is thus responsible for 9 and 51.4 per cent in agriculture and horticulture, respectively. Thermal waters provide at the present over 80 per cent of the energy demand at the vegetable farms.

Besides greenhouse heating, thermal waters are used also at animal farms, for domestic heating and hotwater supply, but these amount to no more than 5 to 8 per cent of greenhouse heating. The percentage water resources actually used is 20 in terms of volume, or 23 if expressed in terms of thermal energy. This difference reflects the preferential use of waters of higher temperature. Warm waters are used for heating purposes at an efficiency of 50 per cent at farms only, where the heat is recovered in several stages or for several purposes, such as space and ground heating, in greenhouses irrigation water heating, hot-water supply for domestic purposes, etc.

Unsuccessful hydrocarbon boreholes developed into thermal wells are the main source of thermal waters in Hungary, though some wells are drilled to meet higher demands. Negative boreholes are available to farmers at a nominal, very low price, making the capital cost of development highly attractive. Although additional wells are very expensive to drill, these costs are reimbursed in 5 to 6 years thanks to the absence of fuel costs.

The commercial vegetable farms in Hungary are at least 10-12 hectares in size, while ornamentals are grown on areas of at least 6-8 ha to be profitable. The thermal energy needed for similarly large areas can be produced from groups of wells alone, each group comprising several wells, connected by a ring header. The pumps are operated according to a schedule depending on the actual energy demands.

New wells are normally free-flowing as long as the artesian head drops below the terrain level. Beyond this point pumping must be resorted to for obtaining the required flow.

A pumped thermal watersupply scheme is illustrated in Fig.2. Here water is withdrawn by deep-well pumps from three wells on the site which discharge through an atomizer to the de-gassing unit. The water flows therefrom by gravity to a collecting tank and is pumped then to the heaters in the greenhouses. The return flow from the greenhouses has still a temperature of 40 °C. Well water of 82 °C temperature is added to obtain water of 60 °C temperature which is then pumped to the heat exchangers of the foil tents. The 25 °C warm effluent from these latter is collected in a drain canal then lifted into a foil-sealed earth basin.

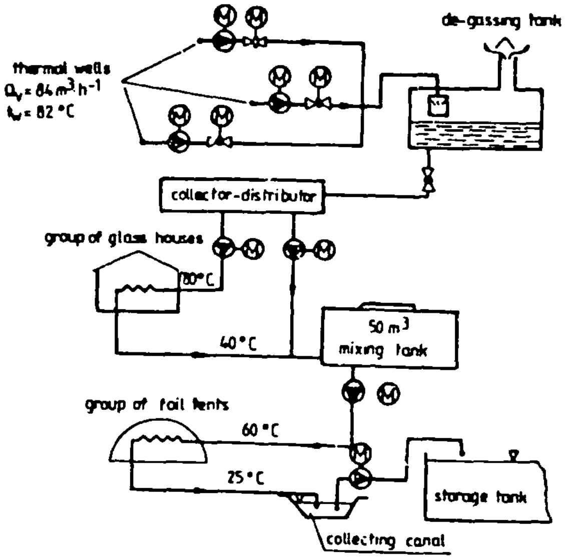

Fig.2.: Scheme of complex geothermal heating system consisting greenhouses and plastic tents with three wells

The water is released therefrom at regular intervals to a nearby recipient as specified.

Conventional radiators fed by forced circulation are used to heat greenhouses. Although the water is de-gassed at the wells, the air vents are usually more generously dimensioned than with conventional water heater systems. Ice and snow on the roof or in the downpipes can also be melted. Some foil tents are heated using conventional radiators situated along the sides and also corrugated plastic piping placed horizontally on the ground (Fig.3). This is called the vegetative heating system and the water from the radiators is passed through it. These pipes have a total length of 100 m and consist of three sections, the diameter of which increases with the temperature drop. The diameters are 1/2", 3/4" and 1", respectively. The discharge from the heating system at 25°C is collected in an open drain and pumped into the basin.

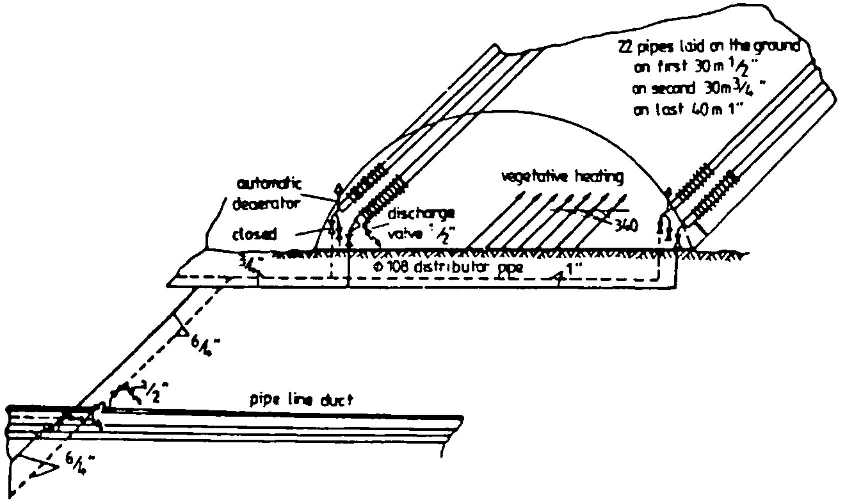

Fig.3.: Scheme of vegetation heating system

The heating system of foil houses used for growing seedlings is shown in Fig.4. Space and soil heating are installed in combination here. The dimensions of the soil heating arrangement are also indicated in the figure. The ends of the soil heating pipes are raised slightly to ensure that the pipes are always completely filled with water.

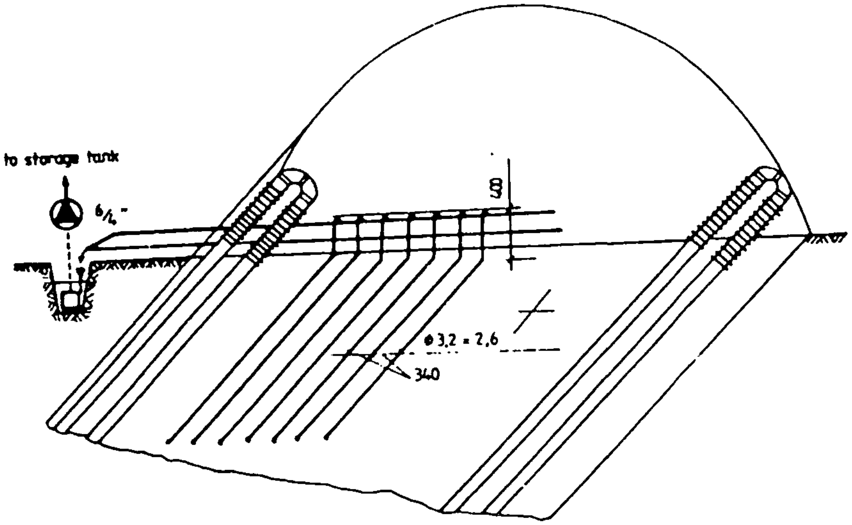

Fig.4.: Scheme of system with the combination of space and soil heating

The gravel-bed soil heating system is illustrated in Fig.5. These are installed experimentally in two foil tents of 100 m length each. The soil is excavated to 430 mm depth under the foil tent. Three layers of sealing foil are spread over the flat base and covered with a 100 mm thick gravel layer. This serves as the base of an 80 mm thick concrete course. The 250 mm thick topsoil is placed on the concrete course. Hot water is distributed in the gravel layer through 22 perforated plastic pipes of 32 mm diameter. The gravel bed is heated to water temperature and the heat is transferred across the concrete course to the soil. The heat flux to the soil attains 80 - 120 W/m^2 and additional space heating becomes necessary to meet higher demands. Thanks to the relatively high heat capacity of the concrete course and the soil, the resulting heat pattern is a uniform one and is thus eminently suited to growing crops which prefer a warm root zone.

One of the most several problems encountered in the use of thermal water wells is that the decreasing pressure in the vicinity of the surface tends to promote the formation of gas bubbles and the precipitation of salts. This in turn results scale deposits in the gate valves and in the well head, further in reduced flow and heat transfer. This phenomenon is frequently observable at wells yielding wa-

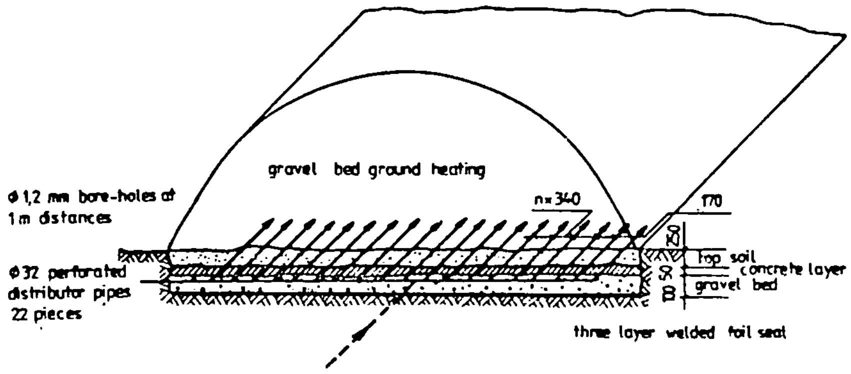

Fig.5.: Soil heating by pebble bed

ter above 50 °C temperature. The mineral salts were formerly allowed to precipitate in a cascade settling tank installed after the degassing unit and water was pumped from the last tank which yielded the cleanest effluent. High-rate wearing of the pump impeller and the stuffing boxes occurred where the settling tank was omitted.

This method of settling proved impracticable, where water was produced by means of submersible, or other types of pump mounted in the well, since the zone encrustation and gas separation extends down to the foot valve of the pump. This is the depth, where the head and, in turn, the partial pressure of the dissolved gases, as well as the solubility of the mineral salts decrease to a level conducive to separation and precipitation. A water softener is therefore added - and this is the solution most commonly adopted in Hungary - preferably ahead of the pump impeller.

The installation of a pump was observed repeatedly to decrease the rate of scale formation. The relatively cheap chemical sodium polyphosphate is widly used in Hungary for water softening. The technique thereof was developed and patented in Hungary at Szentes (Fig.6). The principle underlying this technique is that the softener, e.g. sodium tripolyphosphate, is fed through screens and a valve from a tank to a point situated below the foot valve of the pump. This has the advantage that no external energy is needed for feeding the chemical, since the gases escaping in the depression zone of the well are ducted to the top of the chemical mixing tank, creating thus a closed system, where the pressure in the chemical mixing tank is equal to that prevailing in the well. By balancing the pressures in this way, the softener flows by gravity into the well. The rate of chemical feed can be controlled by the valves with an accuracy adequate for practical purposes.

Fluctuating heat demands are met in several ways, depending on the heat source. A single free-flowwing thermal well with a well head pressure high enough to raise the water into the de-gassing unit can be controlled by throttling effected either manually or by motor-driven gate valves. Withdrawal from a pumped well is controlled by operating the pump intermittently, whereas the pumps in a well group are switched on successively again by manual, or automatic control. Manual control has been found to consume more energy than required. The virtually free availability of thermal water is another factor conducive to overconsumption.

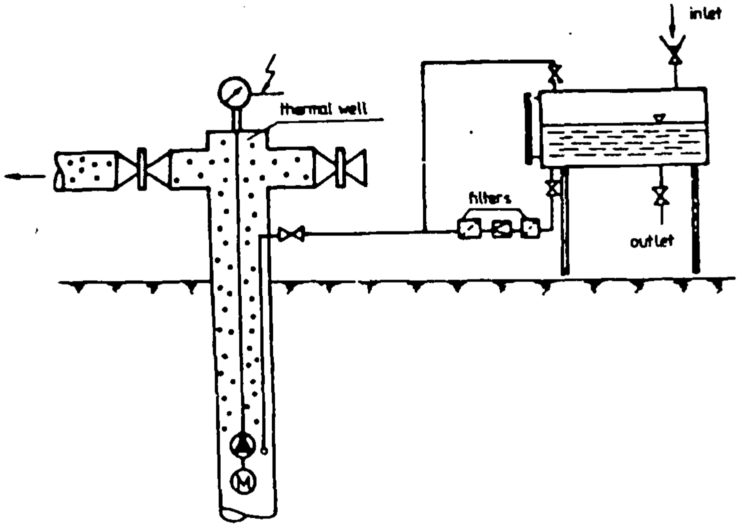

Fig.6.: Scheme of self regulated water treating system

A variety of automatic control methods have been introduced recently, or are contemplated for this reason at several farms. Experience has shown that the capital costs thereof are reimbursed within a brief period of time thanks to the energy saved and the increment crop yield realized through more accurate temperature control. E.g. for a group of three wells the return period has been estimated at one year.

The block scheme of automated control is illustrated in Fig.7. The pumps mounted in the wells, or motor-drived gate valves are controlled of the water level in the gas separator. One, two or three wells are pumped, depending on the actual demand. A sand sensor is mounted invariably into the header connecting the wells, which acts first to throttle the pipe cross section then to stop the pump whenever the turbidity of the discharge surpasses a preset limit value. A flow meter may also be installed optionally into the header to check

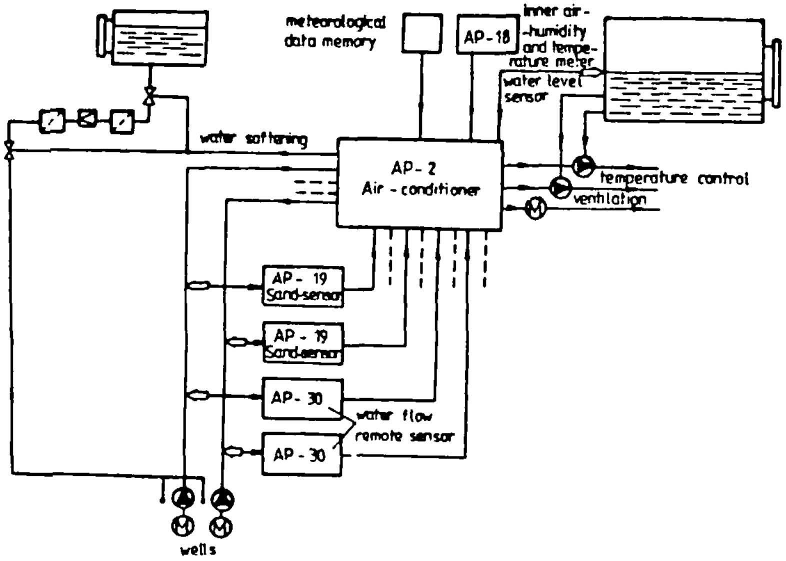

Fig.7.: Computer controlled geothermal heating system

consumption, though this is not essential, since owing to the constant pump discharge, the volume withdrawn can also be estimated from the time of operation.

The pumps connected to the header may be controlled sequentially in terms of external parameters, such as solar radiation, ambient temperature, wind speed or rainfall and the temperature within the greenhouse. The pumps drawing on the mixing tank, which deliver water according to the heat demand of the foil tents of the farm, are also controlled on the basis of the external parameters. A waterlevel control is used to actuate the lifting pumps in the return canal. Of these two should always be mounted, one serving as the stand-by unit, since any breakdown will involve the risk of the entire farm becoming flooded.

In automatically controlled pump operation water softening can also be automated in accordance with operation, since upon starting the pumps an opening signal is emitted to the magnetic valve installed into the feed pipe from the chemical mixing tank. The valve is kept open as long as water is delivered from the well(s). Otherwise the softener is operated continuously, or must be controlled manually.

The automated heating system can be supervised from a single control cabin and operates substantially without attendance.

Two parallel safety are incorporated into the automated control device, in case of any breakdown the sub-system affected is shut down, the stand-by unit is started and simultaneously a warning signal is emitted to the control centre indicating not only the breakdown, but also location and thereof. Thermal waterworks involving withdrawal pumps and pumped water softening have the additional advantage that heating can be dimensioned by techniques similar to those used in boiler heating. Encrustation and drop in well head pressure have been observed formerly to cause well flow losses of up to 150 - 200 $l.min^{-1}$ meaning that after five years a well yielded no more than one-half of the original energy supply.

5. Development potential of geothermal energy resources in Hungary

The development of geothermal energy in Hungary is controlled on the one hand by the availability of resources, on the other hand by the possibilities of improving the efficiency and technological level of the techniques, devices and equipment involved.

The thermal water resources in Hungary, i.e., the water stored in the pores of the thermal water reservoir formations from which water above 30 °C temperature can be withdrawn, are estimated at round 2500 km^3. The majority thereof is stored in the porous formations under the basin areas. Not included in the foregoing figure are the highly saline waters present in the layers older than Upper-Pannonian, whereas the round 50 km^3 stored in the fissured rocks are comprised.

In terms of the average temperature on the surface the thermal energy of the 2500 km^3 large thermal water resources is equivalent to 5.73 x 10-20 J (1,42 . 10^{10}TCE). Together with the heat stored in the skeleton this thermal resource is estimated at 2.6 times this value, and may be up to 10-fold when the amount of heat stored in the non-aquifer rocks is also added.

The present level of exploration and development is far below the potential. The 1067 wells (as of Jan. 1.1987) yielding water warmer than 30 °C represent an original capacity of 1337 thou. m^3/d, but the actual withdrawal should be 500 thou. m^3/d only. From the data of measurements on the wells the total volume of thermal water withdrawn thus far is estimated at 2.6 km^3, round one-half of which originates from storage, the other half from recharge contributed by cold or moderately warm groundwaters. The current yields and uses of the wells are shown by temperature ranges in Table 5.

As a consequence of abstractions the pressure drop in the majority of reservoirs has attained values between 0.1 and 0.5 MPa.In many areas free well flow has ceased and withdrawal by pumping had to be introduced. The highest pressure drop was observable in areas with a number of closely spaced wells, thus in the regions of Szentes towns in Csongrád Country, with values indicated in Fig.8.

The drop in layer pressure imposed an obstacle to the development of geothermal energy. The operational problems encountered thereupon have focussed attention on the importance of more detailed hydrogeological studies and geological explorations on the thermal water reservoirs, including the prediction of anticipated head losses caused by continued and increased rates of abstraction. Regional hydrogeological modelling was initiated on the basin areas in the interest of development. In these models the deep thermal water reservoir is subdivided into several horizons - which communicate with each other vertically - and the changes caused by future abstractions are simulated for each of these using numerical methods. The 10 by 10 km grid of the model presents a fair approximation of the ensuing pressure conditions, but the local effects must be fitted by a variety of techniques into the smoothed depression field produced by the model. The hydrogeological parameters of the model are obtained from the number of boreholes sunk in the basin areas. These parameters are currently being verified by simulating the pressure conditions pertaining to the present withdrawal rate and the verified model will be suited to studying the pressure conditions under different withdrawal strategies. The use of the model is expected to provided eventually an estimate on the magnitude of the thermal water resources available under different conditions. Completion and regular application of the model is scheduled for the next few years.

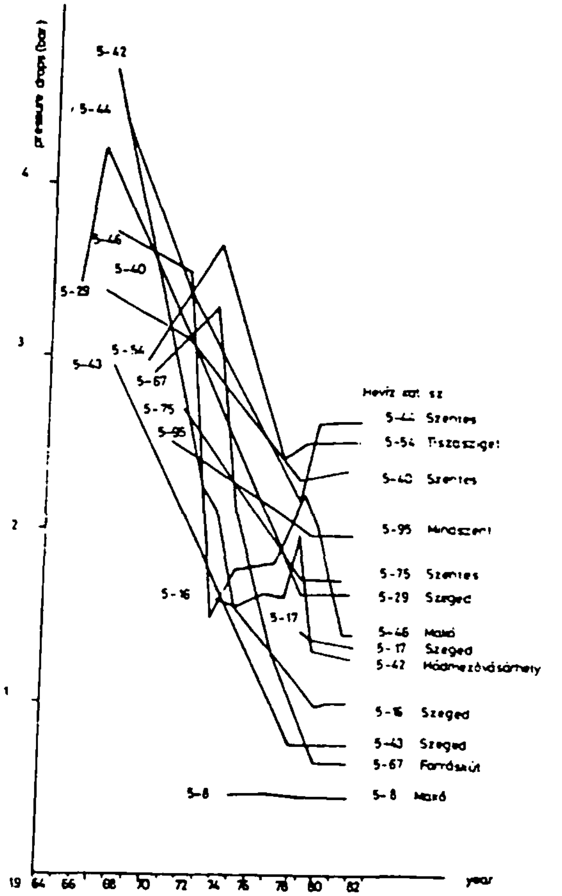

Fig.8.: Highest pressure drops in region of Csongrád county

As mentioned already the drop in free-flowing well yields due the reduction of the piezometric head has prompted a changeover to some kind of pumped withdrawal. Underwater pumps capable of handling waters of high temperature have become recently available, but limitations may be imposed on their use. The water resources available can be increased manifold over the original value by pumped withdrawal. At drawdowns of 100 to 200 m production could be increased five-fold, but this is limited by the load considered acceptable on the recipients, and in the case of replenishment from drinking-water supplies, by the allowable rate thereof. At the same time, inadequate designs of old wells, or their modification presents difficulties to the introduction of pumping.

The problems presented by the disposal of cooled effluents deprieved of their thermal energy are severe enough to prevent any substantial increase of withdrawal. Acceptable solutions to the disposal problem are absolute prerequisites of any further development. In areas, where there is no recipient stream or canal of the required flow rate available in the vicinity of the well, and where the thermal water carries a high salts content, this problem is virtually impossible to solve. The potential solutions for the disposal of minor effluent volumes include temporary storage and infiltration, although the latter may jeopardize groundwater resources. Reinjection into the aquifer appears to offer the solution for the disposal of thermal waters warmer than 40 °C, or having salts concentration higher than 2000 mg/l, which is regarded optimal from the viewpoints of environmental protection and water management alike. Recent reinjection trials in Hungary have revealed the technical feasibility of, but also the difficulties associated with, this method , although the increased costs render its economic feasibility questionable. For reinjection to be successful the effluent flow should arrive at a largely uniform rate and must contain virtually no suspended matter. The results of the same trials have shown thermal effluent reinjection to be uneconomical once the reinjection well head pressure is higher than 2 MPa.

The available water resources could be multiplied in volume by reinjection into the aquifer, though at appreciably higher capital and operating costs. One of the potential solutions in purely energy oriented development would consist of introducing the effluents of lower salts concentration level into coarser grained layers in the cover, enhancing thus the drinking water resources. This solution offers, evidently, no remedy to the head drop in the thermal water aquifers.

As a brief summary it seems safe to conclude that further thermal water development is limited by technicoeconomic, as well as water management considerations. However, reinjection of the effluents will answer these latter. Detailed geological-geothermal explorations are prerequisites to any major increase of the present withdrawal rates.

Another potential avenue of increasing the uses of geothermal energy involves the advancement of technology, with the aim of encouraging more rational uses of this non-renewable resource. As mentioned before, this presumes the introduction of techniques and equipment by which the withdrawal rate can be lowered exactly to the level at which the actual heat demand can be satisfied.

These include automatic valves and gates in the case of free-flowing wells and speed regulation for pumped wells. Any widespread introduction thereof depends substantially on the availability of financial resources. The creation of an economic environment in which the operator is interested in such savings may offer a solution to the problem.

Heat pumps have not been applied in Hungary thus far. Such devices would promote development in two directions, provided that they could be purchased at reasonable prices and could be operated economically.

In a geothermal heating system the heat pump would, on the one hand, improve efficiency by improving heat recovery from the liquid by Δt. On the other hand, the water of higher, 50 - 55 °C temperature could be used at higher ambient temperatures to substitute for thermal water, saving thus these resources. Another advantage of the heat pump would be the possibility of cooling, improving the uniformity and economics of well operation.

Higher complexity levels of use may also be mentioned among the development possibilities. These depend, however, on the opportunities and demands at a particular site.

Considerable advancement could be expected finally from the widespread application of radiation heating system, e.g. floor heating, which utilize a moderate-temperature energy carrying medium. This would make the energy of the 30 - 35 °C thermal water resources available for development.

6. Technico-economic and social aspects in the promotion of geothermal energy development and its uses in agroculture

The problems associated with the production and use of geothermal energy are general in nature and impossible to separate from those observable in the agricultural sector. It is deemed advisable to mention first those of most general, i.e., social character. The fundamental obstacle to the more widespread production and use of geothermal energy is that there is no state agency in Hungary that would be responsible for this kind of energy. Consequent therefrom no officially approved development policy or plans exist and no funds have been allocated for development from the state budget. Since water is the carrier of geothermal energy, the official regulations of the water authority apply to the thermal wells, but these contain no energy provisions, so that the energy uses thereof are not covered by any regulation. Under these conditions any development of this kind of energy is fortuitous, based on the initiative and decision of individuals. The economic appraisal of projects utilizing geothermal energy is likewise controlled by plant-level considerations alone, without regard to broader, national interests.

Geothermal energy is not included in the official listing of energy carriers and does not figure among the energy resources of the country.

Official projects and funds are available only for items related to the technical development of geothermal energy uses. Allocation from these funds can be obtained on the basis of grant applications. The technico-economic council organized under the project is responsible for appraising the applications received and for submitting its recommendations to a ministerial level committee on the acceptance of any application on the sum requested and on the approval thereof.

The uses of geothermal energy in Hungary look back upon a past of more than 20 years, so that the experiences gained this period, and especially in recent years have resulted in the evolution of the methods, techniques and equipment of production utilization and water treatment, so that any uncertainty in the realization of a thermal water based heating plant is confined largely to the amount of water obtainable from a drilled well. Once this information is available, the engineering desings for the heating plant can be completed without further difficulties.

Scaling has been observed in 30 per cent of the thermal wells drawing on the Upper-Pannonian aquifers, necessitating control measures from the very beginning of thermal water development. The simplest mechanical method, i.e., removing the scale by drilling, was used initially. This was superseeded by the slightly more advanced method of flushing the pipes with hydrochlocric acid (HCl). An even more sophisticated and currently still used methods involves chemical water stabilization, where the chemical (inhibitor) is introduced into the well below the depth of bubble separation, ensuring trouble-free operation for extended periods of time. Imported inhibitors were used initially, but such made in Hungary have become since available on the market, improving the economics of operation. Magnetic scale control has been introduced most recently with promising results. Equipment types have been developed, manufactured and patented in Hungary for such purposes. Some special desings are also available.

In the operation of heating systems based on thermal water - especially those realized earlier - the relatively low efficiency, the small temperature drop utilized and thus the rather high temperature of the effluent presents the main problem. A solution thereof is desirable not so much for theoretical, but rather for economic, operational and environmental considerations. The earlier plants have drawn mostly on free-flowing wells without any control facility installed into the system. The changeover to pumped withdrawal prompted by the drop in well yields was conductive to improved management of the resources and to the improvement of efficiency.

The gravest, still unsolved problem encountered is related invariably to the disposal of an effluent under a given set of natural parameters.

Up to the early eighties the water cooled within the heating system was discharged in the manner specified by the water authority, normally to a nearby recipient stream.

In response to the growing need of protecting the environment, the water authorities have refused to issue, or included increasingly stringent restrictions in the licenses for this manner of disposal.

Prompted by this refusal, or the growing costs of meeting the official criteria, several farms have started reinjecting such effluents on an experimental basis, some with encouraging results. Owing to the particular conditions in Hungary, successively higher pressures are needed for reinjection, affecting adversely the economics and increasing the risks attendant to thermal water projects.

Besides the risks involved, any more widespread use of effluent reinjection is hampered by the higher capital and operating costs. At some existing developments problems have been encountered also in finding adequate sites for the reinjection wells, viz. at the necessary distances from those producing.

In the general economic environment prevailing in Hungary, the development of geothermal energy is favoured by the fact that this kind of energy has no price. This results on the one hand in wasteful thermal water uses and, on the other, in low operating costs.

A discouraging economic factor is that all "mining" costs and risks of drilling must be borne by the investor. The construction costs of geothermal energy projects are normally higher than those of heating systems relying on a traditional fossile energy carrier, these latter involve no risk, so that those needing energy tend to decide in favour of an energy carrier which can be developed at lower risks, lower investment costs and operated with less problems. Such decisions are influenced, evidently, also by the actual price of oil and gas.

An agency of national scope would unquestionably contribute to the solution of the economic, risk and some development problems, just as to the improvement of coordination. A functioning agency of this would promote further the evolution of a more favourable economic environment.

7. The potential role of international organizations in furthering the agricultural uses of geothermal energy

Geothermal energy constitutes one of the recognized resources which is spread over areas, considered renewable in some areas and, depending on the thermodynamic and chemical properties of particular occurrences is suited to meeting primarily local, at the same time concentrated demands for heat and power. Although thermal springs have been used for public purposes over several thousand years, methodical exploration and development of geothermal energy has been confined largely to a few industrialized countries. Agricultural and general rural uses of geothermal energy is unquestionably of tremendous importance in the industrialized and developing countries alike. For this reason international organizations and institutions can, and are expected to assume important functions in gathering the relevant technico-scientific information, advanced technologies and practical experiences, as well as in transferring these to the interested, particularly the developing countries.

The various international organizations and institutions can offer support to the national development programmes under the main schemes outlined broadly as follows:

- —Regular organization of technological and scientific information flow, including the organization of professional sessions, seminars, consultations and conferences, further by compiling, publishing and disseminating manuals, papers and guidelines on basic, intermediate and scientific levels.
- —Initiating, organizing and supporting national and international cooperative exploration projects, mapping the geothermal energy resources, as well as studies aimed at the elaboration of the appropriate technologies of development.
- —Initiating national demonstration and pilot projects, offering financial assistance to these in the interest of implementing the relevant technico-economic studies needed for any widespread practical application.

—Supporting the elaboration of international standard specifications, methods of study and technico-economic analysis in order to encourage the practical application of technologically sound techniques.

—Initiating and organizing professional training courses and other forms of education for professionals of the developing countries to import them the knowledge needed for designing, implementing and operating geothermal heating projects.

—Updating continuolsy the results of national and international R+D programmes and of practical applications in order to provide state-of-the-art information to the countries interested in the development of geothermal energy.

International organizations and institutions vary evidently in scope and objectives, and owing to technical and financial constraints they have different possibilities. UN organizations and agencies can be expected to become involved in a modest part only of the broad field of activities outlined in the foregoing. Regional international organizations and associations pursue particular objectives, thus e.g. the working groups of the Economic Commission for Europe are concerned mainly with the methodical exploration of the geothermal energy resources, viz. the compilation and publication of the geothermal maps of Europe. Other international organizations, such as the FAO, UNITAR or UNESCO are engaged in organizing the international flow of information, in formulating and perfecting continuously the forms of professional training with the basic aim of encouraging widespread development of various renewable sources of energy.

As far as the role of the FAO Cooperative Network in the programme on Agricultural Uses of Geothermal Energy is concerned, firm support should be accorded - regardless of the limited funds available for this purpose - to transferring the knowledge and experiences accumulated in Hungary over the past thirthy years to other European and developing countries. Under this broad programme it is recommended to organize an international professional consultation in Hungary, the aim of which would be the demonstration of greenhouses heated with geothermal energy and to discuss the experiences gained over the decades. A similar event would offer excellent opportunities for initiating international research programmes on the subject and for evaluating the results of such cooperative programmes. Moreover, since the greenhouse area heated with geothermal energy in Hungary is among the largest not only in Europe but also on a global scale, the organization of an international training course of longer duration in Hungary would be of mutual interest.

Table 1. MW/day may be gained from producable thermal water when it is cooled till 25 °C

		Temperature of the outflowing water, °C					
		50-60	60-70	70-80	80-90	90	Total
1 Already exploited quantity of thermal water 1000 m^3/day		48.0	59.0	33.0	38.0	46.0	224.0
2. Thermal water quantity to be yet produced 1000 m^3/day (till 200 m depression)		432.0	343.0	195.0	97.0	77.0	1144.0
Capacity to be gained by cooling till 25 °C MW/day	Transdanube	2510.0	2419.0	1394.0	349.0	.0	6672.0
	Great Plain	12558.0	13535.0	9943.0	6420.0	5819.0	48275.0
	Total	15068.0	15954.0	11337.0	6769.0	5819.0	54947.0
Oil equivalent of the capacity tons/day	Transdanube	216.0	208.0	120.0	30.0	.0	574.0
	Great Plain	1080.0	1164.0	855.0	552.0	500.5	4151.5
	Total	1296.0	1372.0	975.0	582.0	500.5	4725.5

Table 2. Thermal water resources of pliocene sediments
Exploited / Exploitable water quantity by pumping. (1000 m^3/day)

		Water temperature °C					
		50-60	60-70	70-80	80-90	90	Total
1	Kisalföld	0/38	10/36	3/19	0/5	0/0	13/98
2	Lenti bas.	0/5	0/2	0/0	0/0	0/0	0/7
3	Zala-Somogy	1/17	0/6	0/2	0/0	0/0	1/25
4	Drávavölgy	1/12	1/8	0/3	0/0	0/0	2/23
	Transdanube	2/72	11/52	3/24	0/5	0/0	16/153
5	Szeged terr.	12/28	8/24	6/12	12/15	7/12	45/991
6	Déltisza bas.	2/92	7/70	11/52	19/40	26/30	85/284
7	Délalföld	1/27	3/26	9/30	7/20	12/26	32/129
8	Békés bas.	2/53	11/52	1/27	0/17	1/9	15/158
9	Jászság	22/88	12/73	0/24	0/0	0/0	34/185
10	Középtisza bas., Nyírség	9/72	7/46	3/26	0/0	0/0	19/144
	Greatplain	46/360	48/291	30/171	38/92	46/77	208/991
	$\sum\sum$	48/432	59/343	33/195	38/97	46/77	224/1144

Table 3. Distribution of the number of thermal water wells according to their utilization

Utilization	Number of wells				Production capacity m^3/min.
National Water Authority data	1975	1980	1984	1985	1985
Public baths, balneology	221	240	262	277	271.13
Drinking water supply	351	416	366	236	196.14
Heating in agriculture	81	97	160	258	255.23
Flat heating, warm water supply	20	20	19	14	21.19
Industrial purposes	15	21	64	70	61.94
Other purposes	21	46	94	128	68.25
Closed	84	58	44	33	19.21
Summarized	793	898	1009	1016	893.09

The summarized quantity of produced thermal water in 1970 was 259 million m^3/year but in 1985 it was already 420 million m^3/years.

Table 4. Number of thermal water wells according to the outflowing water temperature

Temperature of yielded water °C	Number of wells			Production capacity m^3/min.
	1975	1980	1985	1985
below 35	257	297	325	240.05
35-44	223	243	273	195.15
45-59	159	168	196	175.27
60-69	57	75	87	98.34
above 80	57	65	82	121.16
Summarized	793	898	1016	893.08

National Water Authority data:

Table 5. Thermal wells in Hungary 1987. 01. 01.

Temp. 20 °C	Number of wells	Flow rate m^3/min	Utilization						
			Drink.	Balneo.	Agricult.	Komm.	Industry	Other	Closed
30-39.9	516	348.00	211	74	109	1	36	73	12
40-49.9	209	190.11	28	98	25	2	12	39	5
50-59.9	105	96.99	5	44	20	2	12	15	7
60-69.9	92	100.67	1	43	25	3	6	11	3
70-79.9	59	67.39	0	24	23	4	2	3	3
80-89.9	46	62.33	0	5	35	1	1	1	3
90-	40	63.27	0	5	27	4	2	1	1
Total:	1067	928.76	245	293	264	17	71	143	34

Table 1. MW/day may be gained from producable thermal water when it is cooled till 25 °C

		Temperature of the outflowing water, °C					
		50-60	60-70	70-80	80-90	90	Total
1 Already exploited quantity of thermal water 1000 m^3/day		48.0	59.0	33.0	38.0	46.0	224.0
2. Thermal water quantity to be yet produced 1000 m^3/day (till 200 m depression)		432.0	343.0	195.0	97.0	77.0	1144.0
Capacity to be gained by cooling till 25 °C MW/day	Transdanube	2510.0	2419.0	1394.0	349.0	.0	6672.0
	Great Plain	12558.0	13535.0	9943.0	6420.0	5819.0	48275.0
	Total	15068.0	15954.0	11337.0	6769.0	5819.0	54947.0
Oil equivalent of the capacity tons day	Transdanube	216.0	208.0	120.0	30.0	.0	574.0
	Great Plain	1080.0	1164.0	855.0	552.0	500.5	4151.5
	Total	1296.0	1372.0	975.0	582.0	500.5	4725.5

Table 2. Thermal water resources of pliocene sediments
Exploited / Exploitable water quantity by pumping. (1000 m^3/day)

		Water temperature °C					
		50-60	60-70	70-80	80-90	90	Total
1	Kisalföld	0/38	10/36	3/19	0/5	0/0	13/98
2	Lenti bas.	0/5	0/2	0/0	0/0	0/0	0/7
3	Zala-Somogy	1/17	0/6	0/2	0/0	0/0	1/25
4	Drávavölgy	1/12	1/8	0/3	0/0	0/0	2/23
	Transdanube	2/72	11/52	3/24	0/5	0/0	16/153
5	Szeged terr.	12/28	8/24	6/12	12/15	7/12	45/991
6	Déltisza bas.	2/92	7/70	11/52	19/40	26/30	85/284
7	Délalföld	1/27	3/26	9/30	7/20	12/26	32/129
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60-69.9	92	100.67	1	43	25	3	6	11	3
70-79.9	59	67.39	0	24	23	4	2	3	3
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LECTURES ON GEOTHERMICS IN HUNGARY

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PREFACE

Since the foundation of the UNU Geothermal Training Programme in Iceland in 1979, it has been customary to invite annually one geothermal expert to come to Iceland as a UNU Visiting Lecturer. The UNU Visiting Lecturers have been in residence in Reykjavik from one to eight weeks. They have given a series of lectures on their speciality and held discussion sessions with the UNU Fellows attending the Training Programme. The lectures of the UNU Visiting Lecturers have also been open to the geothermal community in Iceland, and have always been very well attended. It is the good fortune of the UNU Geothermal Training Programme that so many distinguished geothermal specialists with an international reputation have found time to visit us. Following is a list of the UNU Visiting Lecturers during 1979-1989:

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

The UNU Visiting Lecturer of 1989, Mr. Peter Ottlik, has during the last decade written several review articles on geothermal utilization and development in his home country, Hungary. It is of great value for the participants of the UNU Geothermal Training Programme to learn about the geothermal work in Hungary, which is the leading user of geothermal water from sedimentary basins in the world. The world potential for harnessing geothermal waters in the sedimentary basins is vast. It is therefore very important to learn from the experience of the Hungarian geothermal community. We are grateful to Mr. Peter Ottlik for giving us an insight into Hungarian geothermics in his five lectures in Reykjavik in September 1989, and for preparing the lecture notes that are presented here.

Ingvar Birgir Fridleifsson,
Director,
United Nations University
Geothermal Training Programme.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Geothermics in Hungary

(P. Ottlik[1])

Introduction

Hungary is a small country in the Eastern part of Middle Europe. It has favourable geothermal conditions.

The whole territory of the country is 90.000 sq km, within the Carpathians, in the so called Pannonian Basin.

The surface of the land is mainly flat, crossed by the Hungarian Central Range. Two rivers flow across the country. One of them is the Danube, the biggest river of this part of Europe. The other river is a smaller one called Tisza. It springs from the Eastern side of the Pannonian Basin and it flows into the Danube in the Southern part of the Basin.

The territory, the area of the country consists of the following geographical regions: Transdanubian region is on the Western part of the country. The Small Hungarian Plain which is on the Northern part in the Transdanubian region. The Great Hungarian Plain is divided into the region between the Danube and Tisza rivers, and East of the Tisza is the Trans-Tisza region.

The crust of the Earth was active during the tercier geological epoch. There have been several tectonic phases of the Alp-Carpathian orogenetic cycle.

The volcanism is related to the orogenetic-tectonic periods and started in the Eocene age and came to its peak point during the Miocene. This volcanism produced mainly andesitic rocks.

The youngest volcanoes are found north of Lake Balaton and are separate basaltic cones. (Figure 1)

In the Hungarian Central Range there are mainly mezozoic formations on the surface. The major part of the total mass of the Central Range consists of carbonatic rocks, limestone and Triassic dolomite.

These rocks are fractured, fissured, faulted by tectonic forces. Triassic limestones and dolomites were on the surface for several geological ages and became carstified.

The geological data show that on a big, extended part of the Pannonian Basin these Triassic carbonates form the bedrock of the young pliocene basin.

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[1] EGI Contracting and Engineering, Budapest

Beside Triassic formations older metamorphic rocks such as shists and gneises are also found in the basement.

The Earth crust had been elevated at the end of the tertiary age so the area of Pannonian Basin became a part of the continent.

Geothermal background

In the Hungarian Plain quite dynamic drilling activity was carried out in the past 40-45 years with the purpose of exploration and opening up of oil reserves. In the frame of this work several thousands of wells were drilled with 1500-4500 m depth. Geophysical exploration was made also by the oil industry.

Long seismic profile were measured in international cooperation along the Alp-Carpathian Chain-mountain to explore the root zone of the mountain. Deep magnetotelluric measurements were also done by Hungarian geophysicists.

By the interpretation of seismic and magnetotelluric data they obtained as a result that the Mohorovicic discontinuity surface is in a greater depth below the mountains, but it is in an elevated position under the basin area.

The Mohorovicic surface is the bottom of the lithosphere. The geological section based on geophysical data shows that the mountains have roots corresponding to the Wegener theory and to the suggestions concerning plate tectonics. (Figure 2)

Besides the structural information the section has the key to the explanation why geothermal conditions are more favourable in the basin within the arc than outside it.

The thickness of lithosphere is in average 30-33 km under the continent. This value is only 18-24 km under the Pannonian Basin.

Consequently the average value of heat flow is about 50 mW/sqm on the continent but in the Pannonian Basin it is 80-100 mW/sqm. These are measured values and isolines which are shown in Figure 3, 3/a.

Corresponding to the heat flow also the value of geothermal gradient is better than the continental average. The normal value of this parameter is usually a temperature increase of 35 °C on each 1000 m. In Hungary according to the small map on Figure 4 in 1000 m depth temperature reaches even 70 °C.

Hydrological systems, geothermal aquifers

The structure of the Earth crust ensures the favourable geothermal condition of the Pannonian Basin. An energy bearer is needed too to utilize this condition, by which geothermal energy can be exploited. This media is the water stored in sedimentary strata. So hydrological, hydrogeological conditions are also of a great importance concerning utilization of geothermal energy.

In Hungary there are two big hydrological systems. One, the more significant, is in the Upper-Pannonian (Pliocene) series. The second one is in the fractured, carbonatic formations.

During the Pliocene-Pannonian age the Pannonian Basin was a sinking area. The trend of subsidence was continuous but the movement itself was oscillating with a rather short periodicity.

The result of this epirogenetical, oscillating subsidence took place in the Lower Pannonian age, a series of sedimentary beds consisting of clay and marble strata with only a few sandy-clay strata imbedded. The character of the whole series is clayey and impermeable.

On the contrary the series developed during the Upper Pannonian age shows a 'sandwich'-like picture by the alternation of loose sand, clayey-sand and clay beds. These beds are rather thin. The thickness varies between 1-25 m but the most frequent value is between 2-5 m.

The measure of sinking and of filling up by sedimentation had been in equilibrium during this time. This fact is evident from the whole thickness of the series which is over 1.000 m at several locations. (Figures 5, 5/a).

The paleogeographical lacustrine, swampy conditions have remained during the period of sedimentations. So within these aquifers there is fresh water with a salt content between 1.000-12.000 mg/l. The solved salt is alkaline-hydrocarbonate.

The stored water is syngenetic with the bed. CO_2 and CH_4 content come to the surface with the produced water. These gases are the results of disintegration of organisms which had lived in the lakes and swamps. The presence of gasses is independent from the temperature of the water.

The specific permeability of these sandy aquifers varies according to the granulometry and clay content of the bed. This variation can be observed both in the horizontal and in the vertical directions.

There is no method to predict the value of this parameter so it is the most severe risk factor in opening up and utilizing of geothermal energy in Hungary. The risk may be reduced by perforating more aquifers into one borehole.

The porosity of the best, i.e. of the loose sand aquifer is about 30%. The value of good porosity comes from the fact that bed and water are syngenetic so compaction, consolidation rate of these aquifers were small. Because of their origin these beds are more or less extended lenses.

The temperature of the aquifers depends on their depths. The deepest part of the Pannonian Basin is on the SE. Therefore here are the best conditions for producing geothermal energy. The main part of exploited water has been produced from these aquifers.

In the last 5-10 years they observed that the flow rate of free outflowing wells decreased and the measurements showed the pressure drop of aquifers too. (Figure 6.) Decrease of pressure is 0.1-0.2 bar/year, that means that the total pressure loss is still now 2-5 bars.

Most of the wells in this region of the country are operated by pumps.

Measurement carried out in observation wells proved that pressure decrease almost reaches aquifers near to the surface, connected with the big amount of exploited thermal water.

This phenomenon shows on the one hand that the exploited quantity of thermal water aquifers is more than the recharge and the recharge comes from the aquifers situated above the tapped strata. On the other hand these data made evident that the Upper Pannonian, and the covering younger strata operate as one big hydrological system.

The porosity of these sandy aquifers has a statistical distribution, from a hydrological point of view they are homogeneous and isotropic.

Locating wells to avoid interaction there is only the distance between the wells to be taken into account, the direction can be chosen freely.

The dimensions of pores are small so the speed of flowing water is very slow because of the big hydraulic resistance of the bed. This is only 1-10 cm/year under undisturbed conditions. By tapping the aquifer - under disturbed conditions - this value increases.

The other big hydrological system exists into carbonatic, fractured, fissured formations, which are carstified on the upper 15 m part. The most significant of these rocks are the limestones and dolomites of Upper Triassic age. The thickness of these formations is several thousand meters, and can be even over 4.000 m. At places where it is in a direct contact with the covering Jurassic, Cretaceous and Eocene limestones it forms a uniform hydrological system with them. The biggest mass of the Central Range consists of these formations. These are on a very extended area on the surface. Because the conditions of percolation, infiltration are very good, the recharge of this system comes from this area. The infiltrating atmospheric water has a cooling effect on the upper part of these rocks. Through deep faults the percolating water reaches big depth where the temperature is high and the water is heated by the rock.

The chemical character of carstic waters is usually very hard because of the big quantity of solved $Ca\ CO_3$. The gas content is usually low and consists of CO_2 only.

This hydrological system differs in two points from the system which exists in the Pliocene series.

First of them is that the dimensions of secondary porosity formed by fractures, fissures are bigger than the pores in sandy layer. By this fact there is a smaller hydraulic resistance in such rocks and the speed of flowing water is higher in natural conditions 1-10 m/year.

The other difference is that secondary porosity arise from tectonic forces which acted from a certain direction so the direction of fractures is determined by their origin. The distribution of these is not statistical, but they occur in zones, therefore these aquifers are not homogeneous and unisotropic. When locating - for example - a production and a reinjection well, besides the distance the direction of the location has to be taken into account as well. Locating two wells on the same fault zone they are in a direct hydraulic contact so the interaction between them appears in a short time.

The water into the carstic system is much younger than the aquifer itself. The rocks of mezozoic age are of marin origin so the syngenetic water would be brine, but is fresh water in fact.

To sum up, in Hungary there are two big hydrological systems with quite different properties. But both of them are heated only by the terrestrial heat flow. The temperature increases with the depth in normal cases regularly. The value of heat flow is relatively high in the Pannonian Basin but low from an industrial, economic point of view so geothermal energy is not or hardly renewable.

Geothermal investigation and resources in Hungary

In the following we are going to give a brief summary about the investigation carried out by VITUKI (Scientific Research Center for Water Management).

The targets of geothermal investigations carried out "in situ" and in laboratories were essentially to determine the reserves. However to achieve this theoretical calculations and practical observations were necessary in a number of fields of this topic as follows:

- Heat loss during production of thermal water.
- Heat conductivity tests were made in laboratory and field conditions.
- Plotting of geothermal gradient maps.
- A method was worked out to determine hydrologic character of aquifers.
- Application of geochemical thermometer: suitable for the Hungarian conditions.
- Determination of the amount of geothermal energy stored in the Pannonian Basin.

Theoretical and practical field and laboratory research was done about the heat loss potential of the rocks.

In working out the method the basic assumption was that convective horizontal heat flow is taking place in the formation.

Further assumptions were used to arrive at the mathematical description:

- the flow is plain and normal to the axis of the well,
- the water production is constant,
- the total thickness of the tapped aquifer layers is known,
- during the time of production the heat exchange is insignificant between the aquifer and the boundary strata,
- the parameters of thermal conductivity (K) and heat density ( ) during the test are constant both in location and time,
- the convective heat flow and flow of the fluid are stabilized immediately.

With the assumptions above the equation of relative temperature was derived

$$T^x = (T - T_k)\ (T_o - T_K)$$

where:

T^x = relative temperature
T = measured temperature
T_k = initial temperature of water reservoir
T_o = constant temperature of the produced or reinjected water

With the recorded and measured data a curve is plotted under the formula which is related to the series of master curves.

In determining the heat conductivity of the impermeable covering layer of the aquifer the well was taken into account as a line-shaped heat source and in its environment only conductive heat transfer was assumed. The measurement can be carried out in case of a stationary heat space.

From the investigation it became clear that the hot water rising in a well provides more significant heating for a relatively small region around the well only. A practically related result is also that the thermal balance of the cooled wells (with drilling mud etc.) is restored only over a longer period of time, that is several months. (Figure 7).

Laboratory heat conductivity tests were made on sediments and artificial samples with the instrument developed at the Geophysical Department of the University in Budapest (ELTE), (Figure 8) with the aim of clarifying the correlation between the thermal conductivity and water content of rocks and to make these measurements, results suitable for extrapolation for field conditions too.

Measuring the dielectric constant (ϵ) of the sample proved the best way to determine its water content. This is so for the good reason that this is the way which causes the least physical damage to the sample. The equipment suitable for this purpose has been designed in the VITUKI (Figure 9).

From the tests the following conclusions can be drawn:

- the K-p% when the sample is dry (p=0%) approaches the value $1\ mcal.cm^{-1}\ .\ S^{-1}\ .\ {}^\circ C^{-1}$, with small deviation.
- Until the saturation value $p \cong 10\%$ is achieved the K value grows relatively quickly.

- From the previous saturation value to the full saturation which is 1.5 to 2.5 times the K value belonging to $p \simeq 10\%$, the K value rises in a linear way depending on the rock type (Figures 10, 11, 12).

The most important is this second part of the curve from the aspect of the interpretation of measurements. This shows that there is a linear correlation between thermal conductivity and the water content percentage. The rise of the curve in this linear stage depends on the rock samples, although the difference is not large.

The significance of the above results is great for the practice because the "in situ" thermal conductivity determination is greatly facilitated therewith.

The water content of the sample core is to be determined just after taking it and before and after measuring its heat conductivity in the laboratory. If the water content does not differ significantly from the "in situ" value, the heat conductivity determined in the laboratory corresponds to the "in situ" value too. In case of the deviation of moisture content the "in situ" heat conductivity can be obtained with the help of model-curves through the extrapolation of moisture content.

In the course of these investigations it became clear that the average heat conductivity of clays and marles is $3x10^{-3}$ cgs while in case of sands this value is $6x10^{-3}$ cgs in water saturated condition. Accordingly, the average heat conductivity can be traced back to the geological construction

$$\frac{K_1}{K_2} = \frac{H_1}{H_2} + \frac{(1-H_1)\,a}{(1-H_2)\,a}$$

where H_1 and H_2 mean the % of sand thickness, and 'a' means the K_{H1}/K_{H2} quotient.

Having investigated many wells of 100 to 250 m depth it was found that the correct geothermal gradient value is obtained if the actual mean ground temperature is used as a starting point. The air temperature average values were also investigated and finally the result was obtained that the annual mean temperature of the ground is 12 °C.

The next task was plotting geothermal gradient maps for the territory of the whole sedimentary basin. The country was divided into squares of a size of 10x10 km. The network thus obtained provided surface elements of 100 km^2. Each such element was then described in terms of the data measured in their boreholes. In the case of elements where no holes were drilled they applied the procedure of interpolation.

In the first subject in the determination of the geothermal gradient the aim was the correction. If the max. error percentage of the determination is specified in 20%, in case of 50 °C/km gradient the surface mean temperature has to be known at the accuracy of 1 °C in order to keep the error below the permitted value. It was found that in the different regions of the country the difference between the values of annual mean temperatures on the surface can be even 2 to 3 °C, and the air temperature also differs from the soil temperature.

On the basis of the T_o data of the soil temperature map the geothermal gradient map was corrected and replotted.

Calculating the values of temperatures measured in well 'T' those were taken into account in which the thermal equilibrium could be assumed.

New results were achieved in the field of determining the hydrogeological characteristics of the hot water containing aquifers. According to the experiences the electrical specific resistance of sandy strata is 2 to 3 times higher than that of impermeable clayey beds. Accordingly, the percentage of sand content was determined for each well.

A new process was worked out for the determination of seepage factor of the hot water aquifers on the basis of specific resistance measurements.

Electric conductivity was assumed to take place in the hydrate envelop on the surface of the grains in the porous rocks. Thus, the conductivity is related to the specific resistance.

The result of the calculation made with the classic assumption contradicted the empirical fact that the seepage factor is larger in the rock of higher specific resistance.

The correlations of the filtration factor and the specific electric resistance was further investigated in the porous rocks. It was found that in grainy rocks the electric conductivity is found on the surface of the grain even in water-saturated conditions.

A method was worked out in which the correlation could be determined as $K = a \times \sigma^2$ thus the formula in SI is as follows:

$$K = 10^{-7.03} \times \sigma^2$$

where

K ms^{-1}, σ is in ohm meter unit.

The hydraulic 'T' transmissivity calculated from the pressure rise and resistance measurement in wells and the geophysical T_q transmissivity values and their correlations are shown in Figure 13.

Further investigation of the application of the geochemical thermometer answered a question of geological nature as well. Namely, if data supplied on the geochemical thermometer shows a chemical composition of higher water temperature than what they actually found, it implies that the water in question is not syngenetic with its present aquifer. If this be the case they can expect hotter water deeper down.

After the evaluation of the relevant special literature they concentrated on the methods for the lower water temperature range in the country. So they made calculations using three formulas. These are as follows:

1) Si thermometer with adiabatic cooling

$$T_1 = 1315.5\ (5.202-\log SiO_2)^{-1}-273.15$$

2) Na - K - Ca, this method is actually identical with Na/K, but it considers the point that after cooling the equilibrium is also modified by the Ca-content of the solution. The dissolved material are given in mol/lit.

$$T_2 = 1648\ (2.24+\log K')^{-1}$$

where log K' (Na/K = b.log (Ca/Na).

where b = 4/3, if Ca/Na_1 and T_6 100 °C

b = 1/3, if Ca/Na_1 or T_6 100 °C b= 4/3 mol

3) Na - K - Ca - CO_2 where the fact is taken into account that in waters below 75 °C temperature the partial pressure of CO_2 may also modify the Na/K value. For this the CO_2 contents or the HCO_3 amounts and the water pH are taken into account. If the dissolved materials are given in mol/lit,

$$T_3 = 1648\ (2.24+\log K'')^{-1}, \text{ where}$$

$$\log K''= \log (Na/K)+(4/3).\log (Ca/Na)-1.36-0.253 \log P_{co_2}$$

where

$$-\log P_{co_2}=pH-\log HCO_3+7.699+4.22x10^{-3}\ T_{water}+3.54x10^5\ T^2\ water$$

From the correlation investigations it is clear that for the warm waters in Hungary, the thermometers T_1, T_2 and T_3 are most applicable (Figures 14, 15).

And, finally, the work also aimed at the determination of the geothermal energy amount. The research of the previous years prepared the foundations for this task.

On the basis of this investigation the geothermal gradient map series of the country was plotted in 500 m depth intervals, one of which is shown in Figure 16 as an example for the depth between 1750 and 2250 m.

Thus, the geothermal reservoir formation maximum temperature map was plotted for the aquiferous sand on the boundary of lower and upper Pannonian sediments. (Figure 17.)

The stored heat quantity is calculated volumetrically. At that time the wells producing water above 35 °C were regarded as hot water wells (this has changed to 30 °C since that time). The map of the isotherm surface depth of 35 °C was plotted together with the isotherm map of the surface of lower-upper Pannonian boundary.

The thickness and extension of the porous water wells were calculated from the boreholes between the two levels of depth with the average porosity and cubic capacity. The total cubic capacity of the warm water holding formations in the basin is 35 x 10^3 km^3.

The regional geothermal gradient map calculated for the thermal water aquifer is shown in Figure 18.

The amount of thermal energy stored in the warm water formations was determined by columns of 100 km^2 base, where the amount of heat equals the volume multiplied by the specific heat and by the temperature difference.

The amount of heat is distributed as shown in the isocalory map. (Figure 19.) The isocalory lines are of 10^{16} value, that is along one line the full energy content of every sediment column of 100 km^2 basic area is 10^{16} kcal or 4.2×10^{19} Ws.

If only the water heat stored in the water is regarded exploitable and that of the rock is not, then the total heat content is $Q_{water} = 21.15 \times 10^{20}$ Ws.

If the conditions are modified by taking the average temperature instead of the bottom temperature, and this is 60 °C then

$$Q_{water} = 28 \times 10^{20} \text{ Ws.}$$

The work was continued by launching a subject "Geothermal Potential, Exploitable Thermal Water Reserves and Related Conditions in the Particular Regions of the Country". The title implies that for waters above 50 °C it is required to supply information besides the quantity of the water about its expected quality, its temperature, water recovery from one well and the depth of a well. And, finally, it was prescribed that the reserves exploitable till a depression of 200 m had to be taken into account.

The most significant quantitative question can be solved from the data of operating wells in such a way that the result is given in a fraction where the numerator stands for the already produced amount and the denominator indicates the still exploitable reserve in the 1000 m^3/day recovery value. The results are given in Table 1. The results of the last evaluation of reserves are shown in Table 2.

Utilization of the geothermal reserves

The distribution of the amount of thermal water produced in the country among the individual areas of utilization is shown in Table 3.

As it is shown in Table 3, about 72 per cent of the wells and a slightly larger share of the water produced are used in the field of balneology, agriculture and drinking water supply.

The most important area of utilization of geothermal energy is agriculture and to a much smaller extent the utility sector (domestic heating and household hot water supply).

Agricultural utilization. In the field of agriculture the horticultural branch is the largest geothermal energy consumer, primarily in the field of heating greenhouses and the plastic tents.

As a result of development, in 1970 there was a total area of 170 ha in Hungary covered with glass and plastic foils. Additionally there was a surface of about 1000 ha which could be temporarily covered with plastic foils in the country.

In about 25% of the green houses covered by glass and in 95% of houses covered by plastic foils vegetables are grown. The most important vegetables are pepper, tomato and cucumbers. The rest of the total area is used for nursing. On the largest surfaces of farm specialized on ornamental plants cut-flowers are grown. As far as efficiency is concerned growing ornamentals is more economical than growing vegetables.

Of the total area covered with glass houses about 70 ha is equipped with houses made in our country, the rest was imported. Hungarian green house production on a large scale started only in the sixties. The most extensively used model is PRIMOR I. which has a structure of galvanized steel and glass mounted on a 25 cm high concrete strip foundation. Sizes of houses manufactured in serial production are 3.2x6.4 m, that is with a ground floor space of 20.48 m^2. Of these units practically any required size can be assembled. The height of eaves ducts is more than the one used generally in Western Europe (2.7 m). The reason for this is to secure efficient ventilation even in case of crops of high growth.

Of the area covered with plastic foil houses about 600 ha is in the possession of large-scale farms, the rest is owned by small farmers. The supporting structure of these houses is usually plastic bent to shape or galvanized steel pipe with spacing of 1.5 m. Standard width is 7,5 m but there are structures manufactured with a width of 6,0 m and 4.5 m. Supporting piles are fixed into pipes hammered into the ground or concrete strip foundations made with stud-pipes placed in the liquid concrete. Spacings are 1.5 m.

Side foils are sealed by earth cover. Plastic foils are usually polyethilene made out of a thickness of 0.15 mm. In order to maintain good efficiency houses are built in a length of 50 m and ventilation is effected through the fronts.

The heating systems generally use the thermal water directly. Where the temperature of the thermal water is higher than 70 °C, the 3-stage greenhouse heating system is frequent. The incoming high temperature water heats the air through ribbed pipes at 1.8 to 2.0 m height. At this temperature the 80 °C heat drops to about 50 to 60 °C. The second stage is the vegetation heating where the heating pipes are located on the surface of the soil. These pipes are also frequently used as the lines for the harvesting trolleys. In the vegetation heating stage the temperature of the thermal water drops to 40 °C. The water of about 40 °C temperature enters the third stage, that is ground heating, and leaves the system after cooling from 25 to 30 °C. The heating pipes of the soil heating in most of the cases are made of plastic and are located in the soil at 20 to 60 cm depth. This is the highest efficiency system where the total useful cooling reaches 50 °C.

In the green-house systems set up 10 to 20 years ago the heating system is even simpler in several places and only one or two stages are used. The first is the already noted ribbed pipe design covering the top half of the interior. The other - and if this is the only heating system, then this one is used - the pipe coil of 2 or 3 threads running in 60 to 120 cm height from the soil surface bent in vertical plain.

There are two sites in the country where the geothermal heating system of green-house plants is fully computerized. In the larger plant the system heats a 20 ha greenhouse and a 30 ha plastic tent with the water of 11 thermal water wells. The system also has its own meteorological station measuring the outside temperature, the solar radiation and the wind speed. In the houses the temperature and the humidity are measured. These are the input data of the system, and the automatic unit controls the amount of water through controlling the operation and flow rate of the wells.

This heat supply system also takes care of geothermally heated egg hatcheries, broiler turkey and geese breeding houses.

The other automated system consists of 6 wells and 6 ha greenhouses. The measured input data are actually identical with the previous one but 50 per cent of the vegetation produced are flower and ornamental plants. This system also has a safety peak boiler which, however, has not yet been needed even in case of the coldest temperature recorded outside, which was below -20 °C.

The heating system of the plastic tents in actual fact is similar to that of the green-houses.

The difference is that in most of the plastic tents only one type of a system operates, that is the vegetation heating. This, with its heating elements located on the ground heats both the soil and the air. The simple plastic tents generally do not operate in the cold winter months.

Experiments have also been carried out with the plastic quilt heating. In these systems the water of relatively low temperature at max. 30 to 40 °C was running through a plastic quilt at low pressure in which holes with welded edges were made of a diameter which is optimal for the plants. The solution was satisfactory because it was partly heating and covering the ground through which its drying diminished and partly the 15 to 20 cm thick quilt provided appropriate temperature for the seedlings and finally the top surface of the quilt set also the temperature of the air.

The spreading of the solution was hindered by economic reasons. The plastic film has a relatively short service life because of the impact of light and heat and also the quilt is very sensitive to mechanical impacts, wherefore it had to be repaired or replaced more frequently than it would have been economical.

Drying produce is one way of using geothermal energy used in a few places. It makes the well more time efficient although it has not spread in the country as yet.

Another more significant area of using geothermal energy in the field of agriculture is animal husbandry, more specifically, the breeding of broiler chickens.

Its heating system in general consists of ribbed or normal pipes running over the floor by 15 to 20 cm along the walls. The number of the pipes primarily depends on the temperature of hot water. The heating system is complemented by the horizontal small surface plain radiators located horizontally also at low height, which are regarded as "artificial mother" as the young poultry have the tendency to lurk under or perch on top of them.

In the breeding of pigs and cattle geothermal energy of not significant amount is used with the solutions described for heating livestock and calf breeding facilities.

Home utilization. The geothermal energy utilization started with the heating of flats and household hotwater supply. At first these heating systems also used the thermal water directly and the impacts were directly felt in the system. One of the difficulties was that the temperature of the water was lower than what generally accepted in homes heating by Hungarian standards. The scale depositing tendency of thermal water was also a problem in the utilization of the water for homes purposes which led to damages in the heating system of a building which could be corrected significantly more expensively and with more difficulty than in case of utilization for farming purposes. The direct household hot water supply was made impossible by the quality of the thermal water very much differing from the drinking water. These direct systems are very simple and therefore very cheap. The basic scheme is the same everywhere. From the well the water enters a basin of 200 to 400 m^3 capacity where at atmospheric pressure the free gas is discharged and in case of an appropriate staying time the physico-chemical equilibrium of the water is achieved, that is the scale depositing takes place in this pool. After leaving the pool the scale deposit in the heating system is practically negligible.

The indirect heat exchanger systems were started only in the last 5 to 10 years. In these systems the properties of the untreated thermal water may cause no problem whatsoever in the secondary heating circuit. In the primary circuit the reliability is ensured by keeping the pressure at the appropriate level or with the application of a reserve heat-exchanger.

Disposal of the thermal water after cooling down. The question of cooled water disposal is integrated in the utilization of the hot water resources.

Up to quite recently the aspects of the environment were of secondary importance for which reason water disposal has not been a problem.

The methods of water use and disposal is specified by the water authority in its licence for setting up and operating the well. According to the central specifications the temperature of water may not be above 40 °C if it is to be introduced into the sewer system or a live water body. The other criterion is the salt content which may not be above 1000 mg/liter. The bigger difficulty is the salt content because in most of the cases it ranges from 3000 to 5000 mg/lit. The Hungarian waters also contain Na-hydrocarbonate which also influences the possibility and the time of the disposal.

The reinjection is the most suitable solution from the aspect of environmental-protection and also of water management and resource depletion. By maintaining the formation pressure of production conditions are also satisfied. Water reinjection experiments have already been carried out. Its spreading is hindered by two main reasons. The first is that the system needs two wells instead of one, which significantly increases the investments costs to which the investment expenses of the filter-pump are added required for water reinjection as well as for the operational costs of water reinjection. The reinjected water may not contain more than 1 mg/l solids.

The other reason can be partly ascribed to the natural parameters. During reinjection in the domestic thermal water reservoirs of frequently lose sandy structure the phenomenon of suffosion is experienced. In actual fact this means that the water flowing with a high speed from the reinjection well drifts the smaller particles among the pores according to its kinetic energy in the medium of heterogeneous granular composition. As the speed and energy of the water discharged from the well decrease; the drifting particles settle down; with this the original permeability of the formation is diminished. Necessarily this process involves a growing excess pressure for the reinjection of an identical amount of water, resulting in the increased output of the reinjection pump, the power input and the price of energy. The process ultimately may lead to the bursting of the aquifer.

In order to solve the problem under Hungarian patents systems were established where according to the local usage the well was lined with a pipe of 7" to the formation to be tapped, e.g. 2300 m. The top part of the well was drilled and cased with a larger than usual diameter and this was perforated between 1600 and 1700 m. In such a way a double-function well could be established which produced through the 7" well and the cold water was reinjected into a higher layer through the annular clearance between the 7" and 9/8" pipes.

Although the drilling is about 30 per cent more expensive because of the bigger diameter drilled to a certain depth as compared to a usual production well, this system is significantly cheaper than having two wells in the system. The disadvantage of the system is that the fluid removed from the tapped formation is not reinjected in the same place, therefore, the water reserve and the formation pressure equally drop. A risk factor is that the water of a deep formation is mixed with the water of a higher water body so colmatation etc. may also occur which reduces the possibility and cost efficiency of the reinjection.

The difficulties in the utilization of geothermal energy

Salt content, scale deposit. The Hungarian thermal waters, generally the upper pliocene waters are chemically of the alkaline hydrocarbonate character. The salt concentration ranges widely from 1000 to 12.000 mg/l. The most frequent concentration is 3000 to 5000 mg/l. Their origin being shallow water or marshland also explains the presence of CH_4 and CO_2 and frequently N_2 gases deriving from the decomposition of organic matter.

About 30 per cent of the water of the Hungarian thermal water wells have the tendency for scale deposition. This partly depends on the dissolved salt content and partly on the CO_2 content.

Protection against scale deposit has been compulsory since the beginnings of the utilization of geothermal energy.

The inhibitors imported from the West were introduced in the mid seventies (Nalco, Hydrogel, Sago, Visco) permitted already long-term continuous operation.

By the 1980s already several Hungarian firms introduced inhibitors containing polyphosphate. In 1982 in well, where the incrustation increased daily by 1 to 1.5 mm, comparative measurements were carried out in such a way that 1 Hungarian made and 4 foreign made chemicals were added under completely identical conditions. Operation was carried on for one week with each of the inhibitors so the result was completely reliable. The experiment was started by adding 15 ppm and as an interesting out-come the lowest concentration was 6 ppm in all the 5 inhibitors, in case of which no scale deposit could be detected either in the top section of the well or in the surface pipelines.

In addition to the development of domestic inhibitors an automatic feeding system has also been devised which provides steady chemical concentration according to the flow rate of the water.

The magnetic water treating equipments are also applied with good results in the geothermal systems although they were not developed for geothermal waters. The advantage is that these systems are significantly cheaper and simpler than the inhibitor technology which in case of overdose makes the water aggressive. It requires no significant maintenance and is not very much sensitive to the water yield. Already a series suitable for different flow rates and pipe diameters is available from domestic sources.

A technical drawback is that in the present design this model may not be incorporated in the well structure therefore the well may not be protected with it. A series of experiments is to be carried out to determine the main parameters of the impact (time of stay, magnetic field, water type) in order to make the equipment plannable for the given system.

Gas content. In thermal water reservoirs of pliocene age and fresh water origin CO_2 and CH_4 are found.

The chemical investigation of the waters has been compulsory in the new wells for several decades now. However, these investigations indicate primarily the amount of the dissolved gases. However, over the last 11 years the analysis of the separated gas has been made compulsory. This can be of full or partial flow. Naturally, the full-flow analysis is more accurate. Where the water authorities specifies the installation of degasing unit, the implementation of the full-scope gas analysis is compulsory.

Methane (CH_4) in itself is chemically neutral.

It is to be noted that due to the identical genetical conditions these gases are also present in the water of top water holding formations used for drinking water supply. In the 1970s several explosions also occurred because the CH_4 discharged into the atmosphere in closed premises.

In order to prevent explosions the waters containing more than 5 Nl/m^3 methane must be degased. The max. allowed methane content in the water supplied through the network is 0.8 Nl/m^3. The regulations also apply to thermal water supply in case of direct systems. Where the thermal water supply in case of direct systems. Where the thermal water runs in a closed circuit without tapping possibilities the specifications are not so very strict. Ventilation is important in agricultural and horticultural systems to prevent CH_4 concentration which might lead to explosion.

CO_2 is a gas separated from the thermal water in large amounts. Its separation intensively influences the chemical balance of the water and it is the main factor leading to the separation of carbonates.

The CO_2 content varies widely in the waters.

Depletion of resources, decrease of formation pressure. The only heat source of the underground waters in Hungary is the terrestrial heat flow. Therefore, water of a temperature above 50 °C which can be used for energy purposes can be generally obtained from a depth below 1000 m.

Usually the precipitation and the percolation from the surface waters, rivers provide recharge for the water reserves. The water from the surface reaches the water storing formations at 1000 to 2000 m depth only indirectly, with a diminished extent and after a long period of time.

This phenomenon became more emphatic by the evolution of the regional depression presented by the large scale thermal water production in SE Hungary. This was primarily manifest after the end of 1960s with the diminishing water flow rate of the wells producing with out-flowing character, which naturally also indicated the reduction of aquifer pressure.

The pressure decrease of a few typical wells is shown in Fig. 6 made by Pál Liebe (VITUKI).

According to the hydrological assumptions 50% is the amount from the reservoir water and 50% from the amounts that can be recharged from the subsurface reserves. The increasing formation pressure drop in the high temperature water reservoirs at a greater depth indicates that consumption exceed recharge.

This is seen as one of the limiting factors of the development of the utilization of geothermal energy. Drinking water reserves would be endangered by this development.

In the territory a significant part of the wells has become negative and can be operated by pumping only. The clearly manifest reduction of the water reserves and the more expensive pumping operation lead to water economy and to the idea of a sounder water management.

The other method of water conservation is the enhancement of efficiency of utilization and the better heat utilization still offers a lot of technical developments. One of them is the installation of a heat pump in the utilization system. This operates in very few places in the country and its location must be based on economic calculations and conditions.

The better utilization of the heat content of thermal water brought to the surface is justified by the fact that the systems established up to now operate without reinjection, so they directly consume the water reserves.

Financial constraints. Regarding the financial questions of the production and utilization of the geothermal energy and the geothermal water disposal, it is convenient to start from the fact that in Hungary as a socialist country every natural resource under the surface is State owned. So a mine can only be State property therefore the expenditures of mining are covered by the State. This is naturally true for the production of fluids, oil and natural gas as well.

The water management law which answers all questions concerning the surface and sub-surface waters decrees that all water reserves are the property of the State but is also declared that every citizen has the right to have healthy drinking water which can be provided by himself. According to the law every citizen has the right to build wells to satisfy his own water demands and the law only regulates that under certain conditions license of the water authority is required for setting up the well.

The geothermal energy is carried by the geothermal water which is a special but integrated part of the water reserves of the country and the rules of the water law apply.

The financial question of the geothermal energy development and water utilization is determined by the legal situation outlined above. Starting a thermal water well requires a licence from the State and own financial funds. Under the domestic price conditions 40 to 60 per cent is the well construction cost, out of the total expenditure of the system consisting of a 1500 m deep thermal water well and the related utilization system.

It depends on the personal decision. This is unfavourable for the development of the geothermal energy utilization because the investor bears every mining risk involved in drilling which in other forms of energy is undertaken by the State.

The investment costs higher than the traditional project costs discourages the entrepreneur also from undertaking high-interest loans.

According to the Hungarian practice 50 to 55 kg per year fuel oil is needed for heating 1 m^2 green-house area. Related to the domestic oil prices the heating cost of the green-houses heated by geothermal energy is 1/4 part of the oil cost. From this situation is obtained that at present only those green-house complexes operated which are based upon geothermal energy.

The economic efficiency of the geothermal energy in concrete terms is hard to characterize because its investment cost is calculated in several ways so these data may not be compared. In a review under the information obtained from several operators the first-cost of 1 m^3 thermal water is a value between 7 and 20 Ft.

The complex utilization concerns the question of economic efficiency. Wherever it is possible efforts are made but not with full vigour; however, there are relatively few places where the multi-stage heat demand permitting complex utilization is localized on one site.

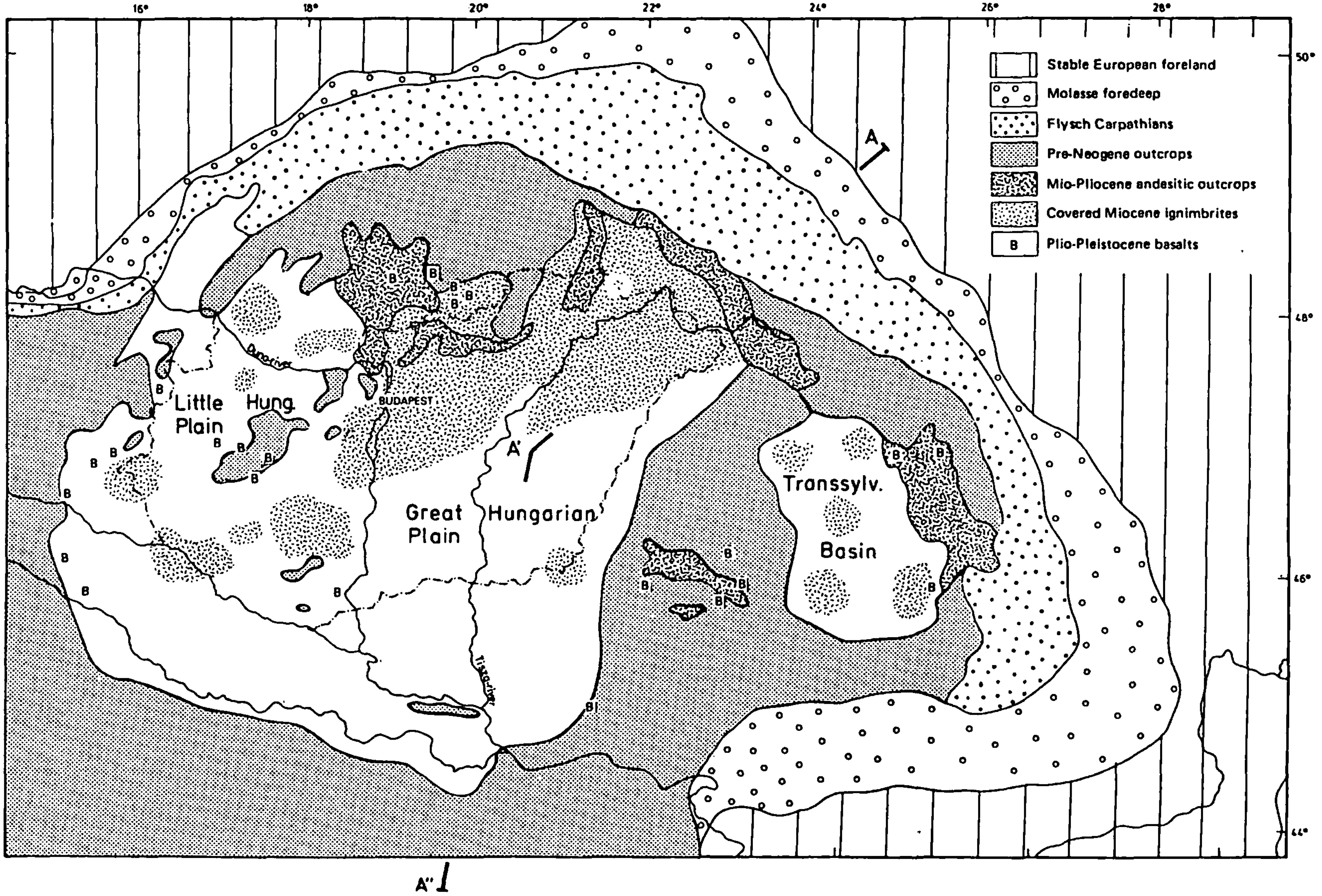

Figure 1. Neogene–Quaternary volcanism of the Carpatho-Pannonian region

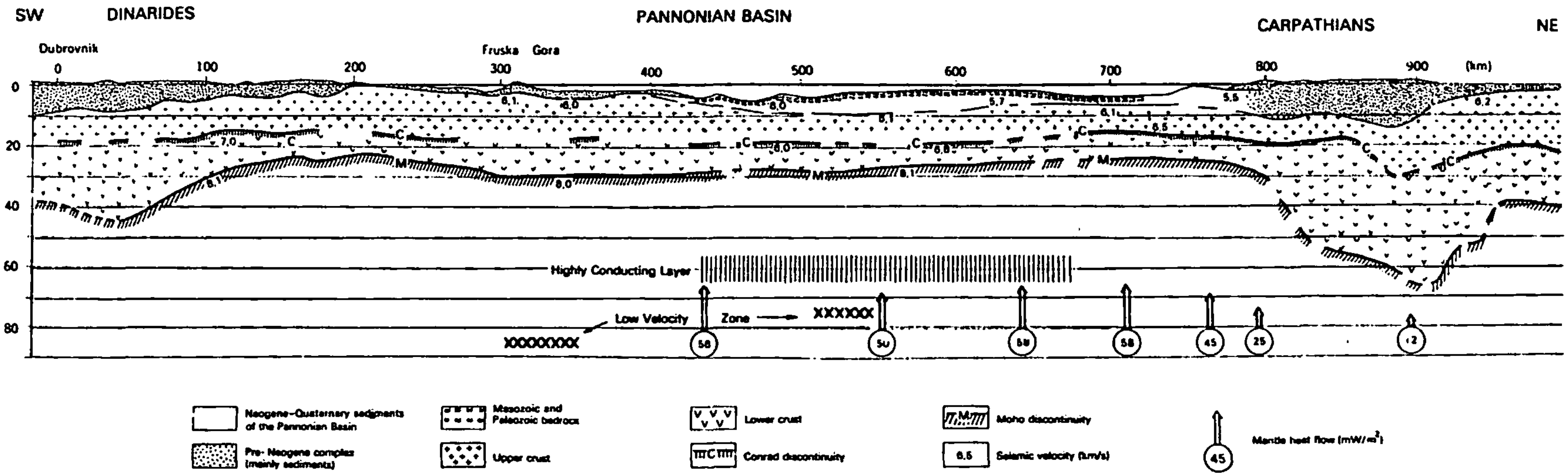

Figure 2. Crustal profile from the Carpathians to the Dinarides, with heat flow values calculated in mW/m^2 for the upper mantle (Buntebarth, 1976), with the position of the high conductivity layer (Ádám, 1976) and of the low velocity zone (Bisztricsány and Egyed, 1973). Geographical position of the profile see AA'A" in Figure 8.5. After Stegena et al. (1975)

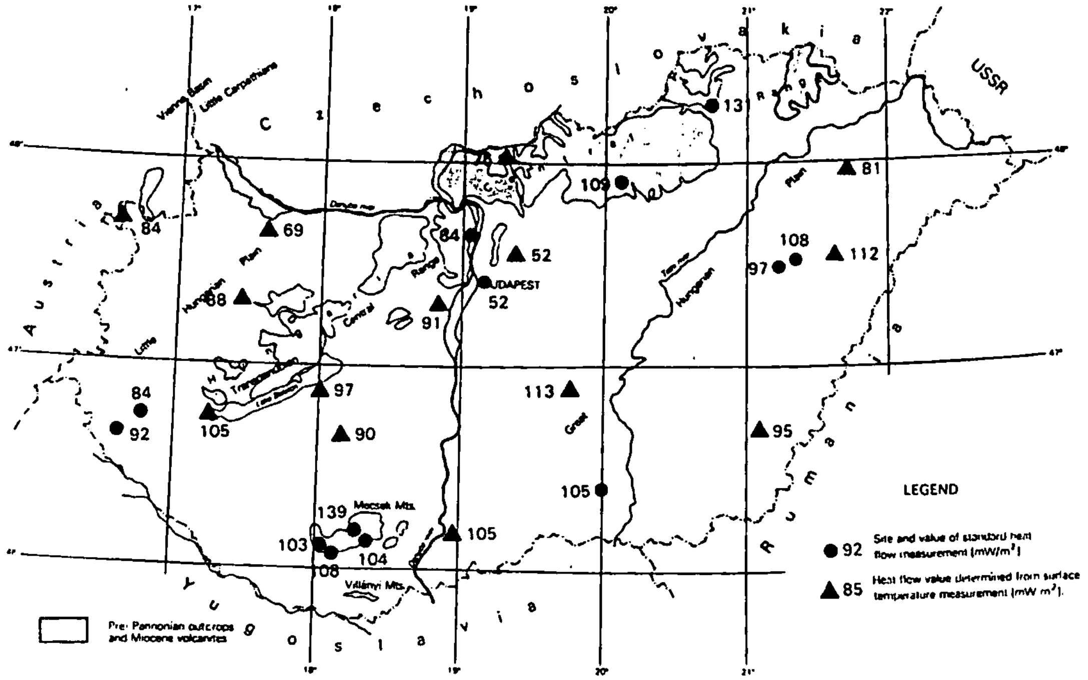

Figure 3. Heat flow data for Hungary, in units of mW/m²

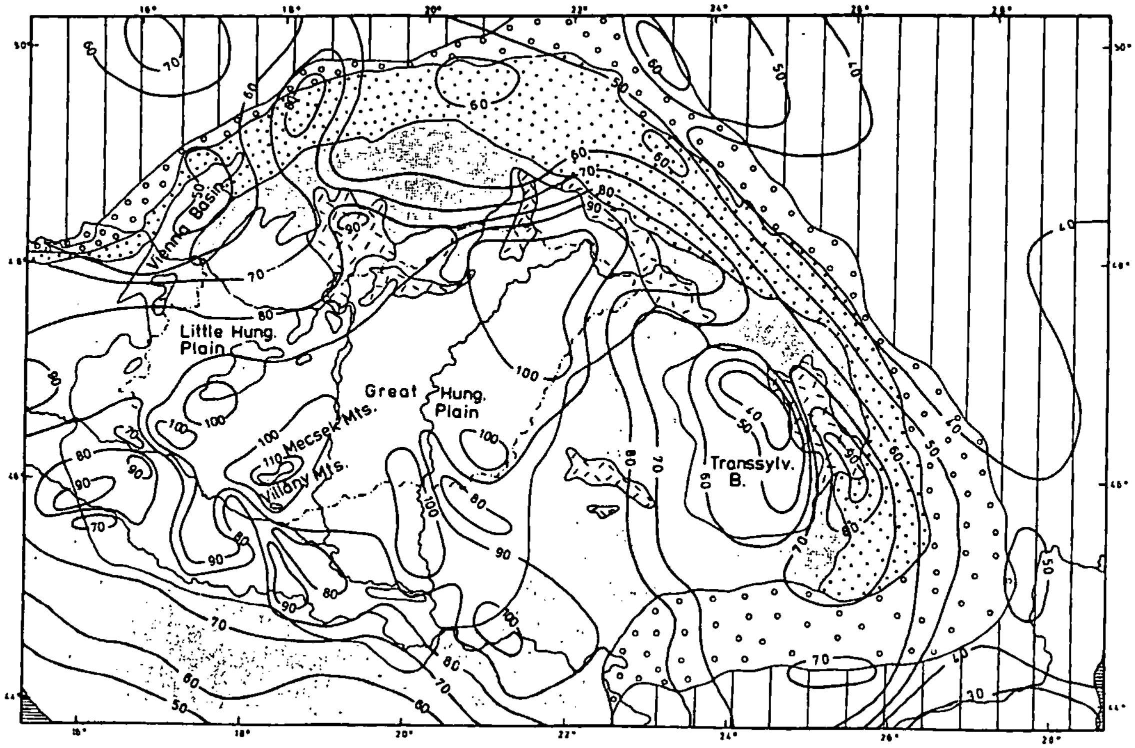

Figure 3a. Isolines of heat flow in mW/m² units for the Carpatho-Pannonian area and its surroundings. Legend see in Figure 8.5 (modified after Čermák and Hurtig, 1979)

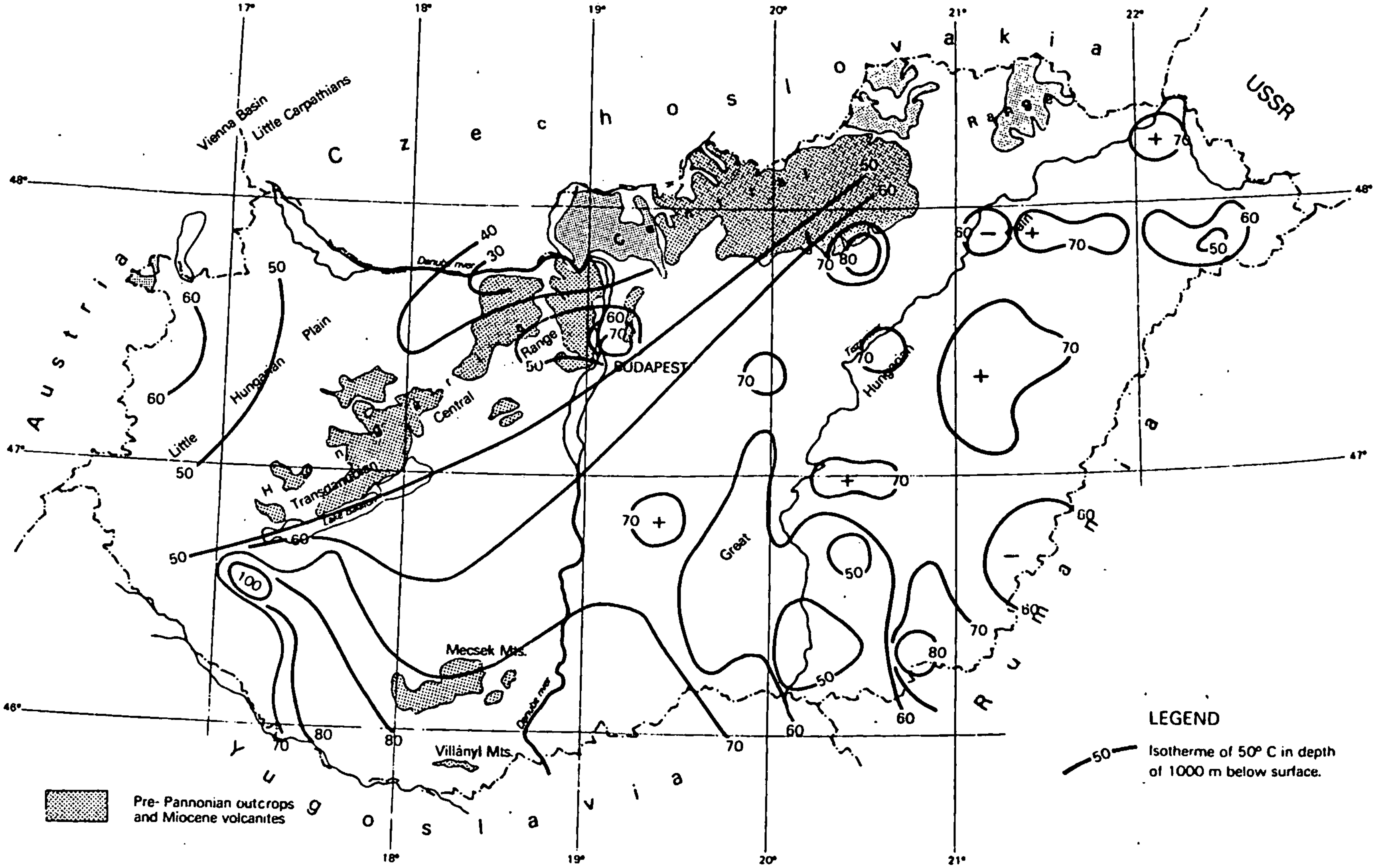

Figure 4. Geoisotherms for Hungary at 1000 m depth. Temperatures in °C

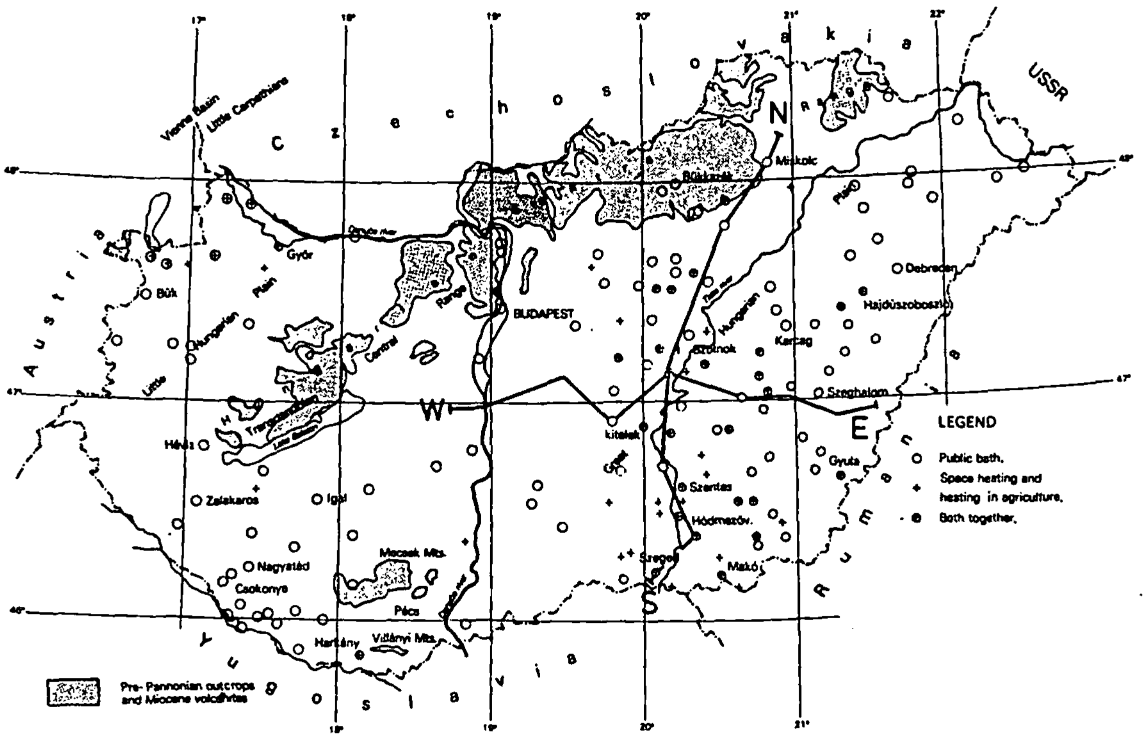

Figure 5. Sketch map showing the utilization of geothermal water in Hungary in 1977-78 (Korim, 1978)

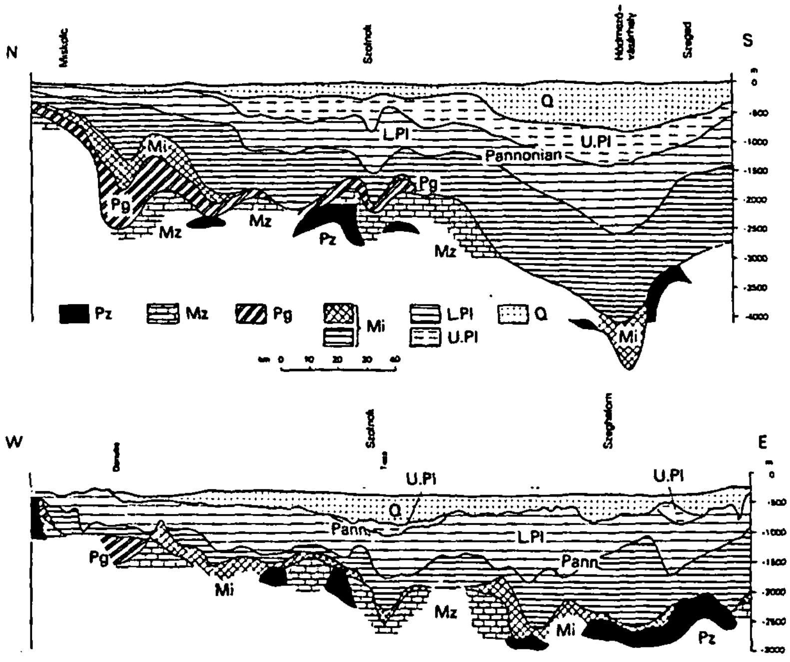

Figure 5a. Geological profiles of strike directions N-S and E-W across the Great Hungarian Plain (after Ronai, 1978). Geographical position of the profiles see in Figure 8.1. Pz: Paleozoic. Mz: Mesozoic. Pg: Paleogene. Mi: Miocene. Pl: Pliocene. Q: Quaternary

No. Hévizkat.szám	location Kút helye	opened intervall. Rétegnyitás (m-m)
5 - 75	Szentes, Árpád Tsz.2.	1640 - 1793
5 - 44	Szentes, Termál Tsz.	1829 - 2192
5 - 40	Szentes, Termál Tsz.	1850 - 1962
5 - 95	Mindszent, Lenin Tsz.	1800 - 1965
5 - 42	Hódmezővásárhely, Kerámiagyár	2112 - 2427
5 - 8	Makó, Strandfürdő	755 - 804
5 - 46	Makó, Kórház	1972 - 2060
5 - 43	Szeged, Felszabadulás MgTsz.	1602 - 1775
5 - 16	Szeged, Székelysor	1750 - 1866
5 - 17	Szeged, Haladás Tsz.	910 - 991
5 - 29	Szeged, Klinika	1727 - 1914
5 - 54	Szeged, Tiszasziget I.	1730 - 1920

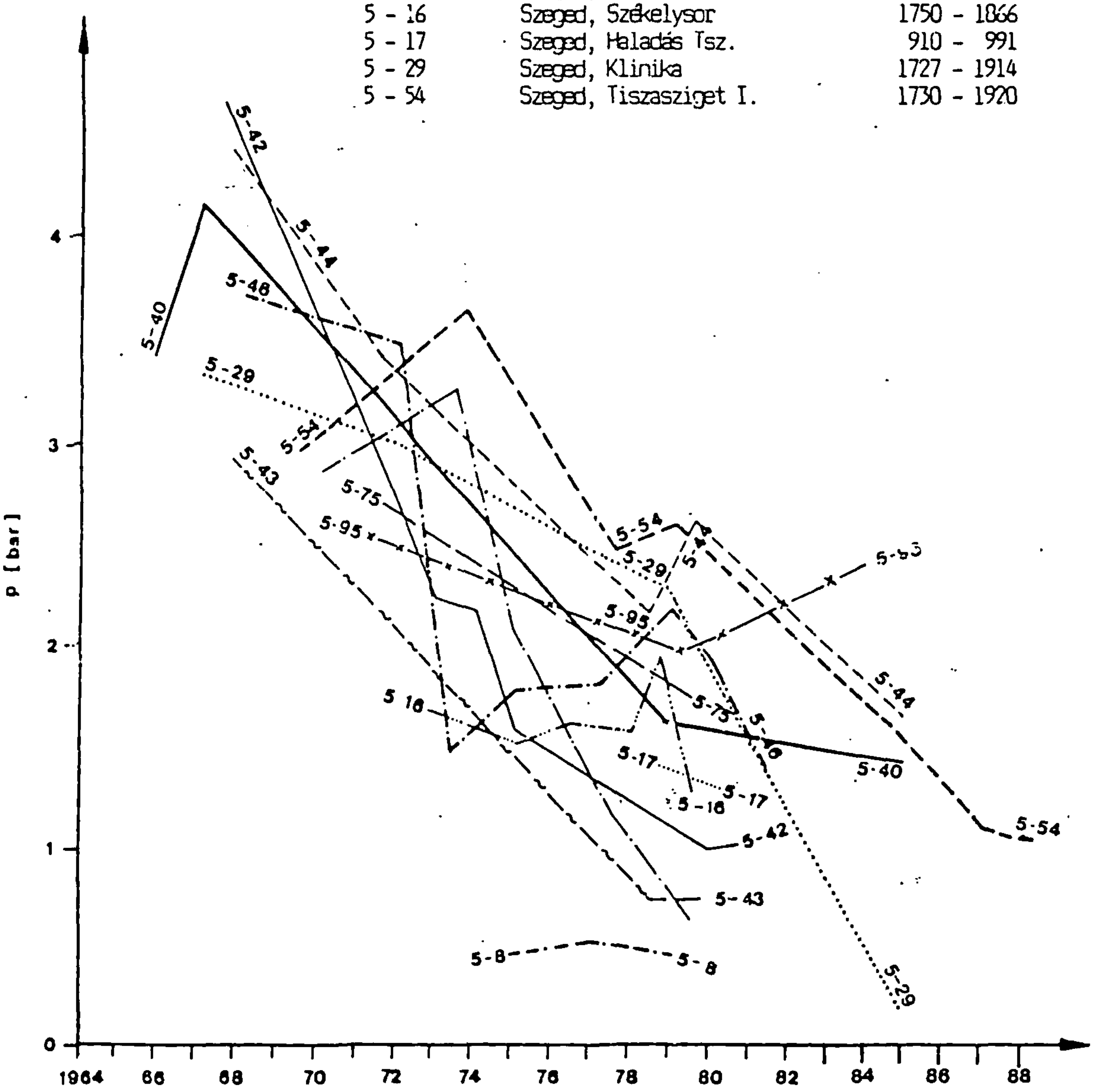

Figure 6. Decreasing of wellhead pressure on geothermal temperature of thermal wells on the S. Alföld

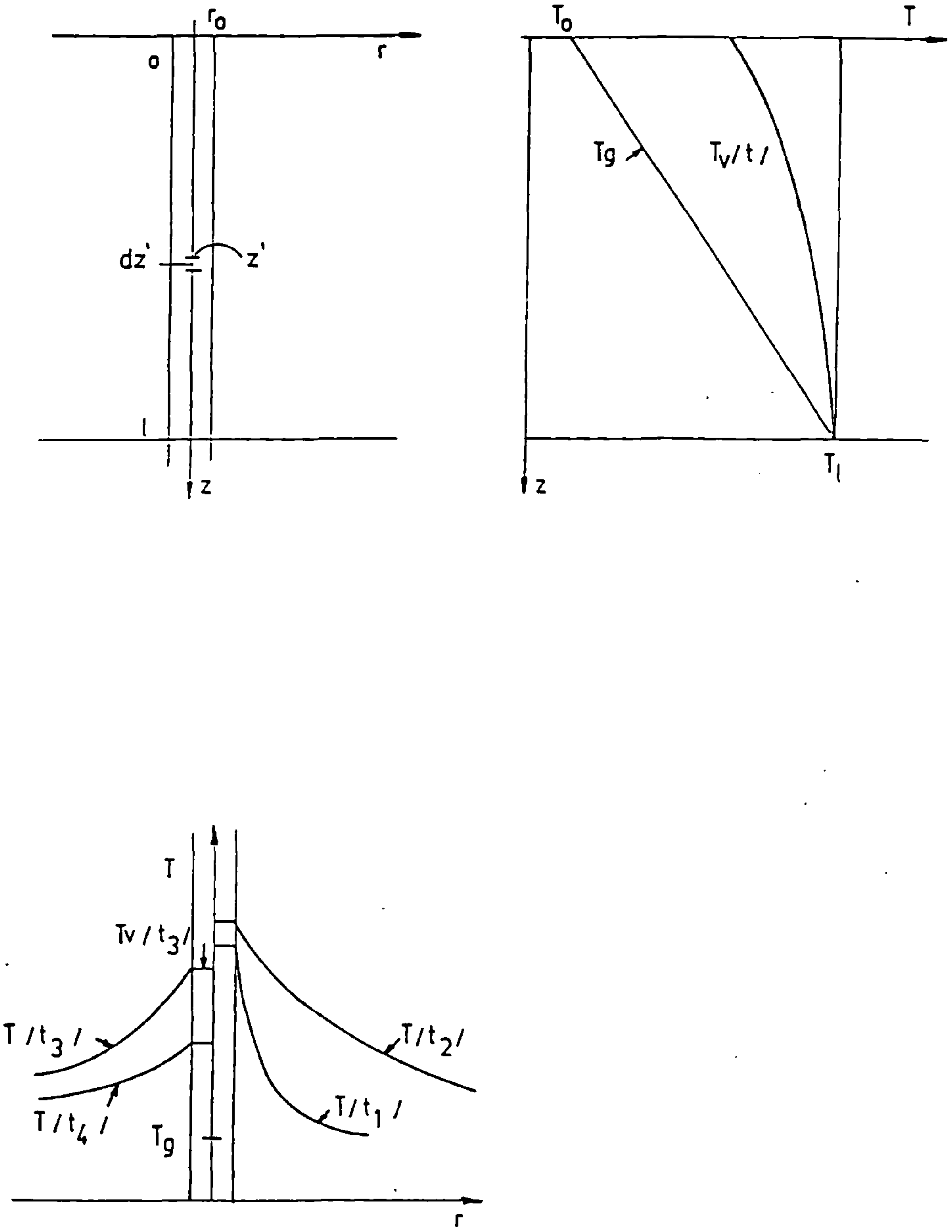

Figure 7. Physical model of heating on and cooling up of thermal water well

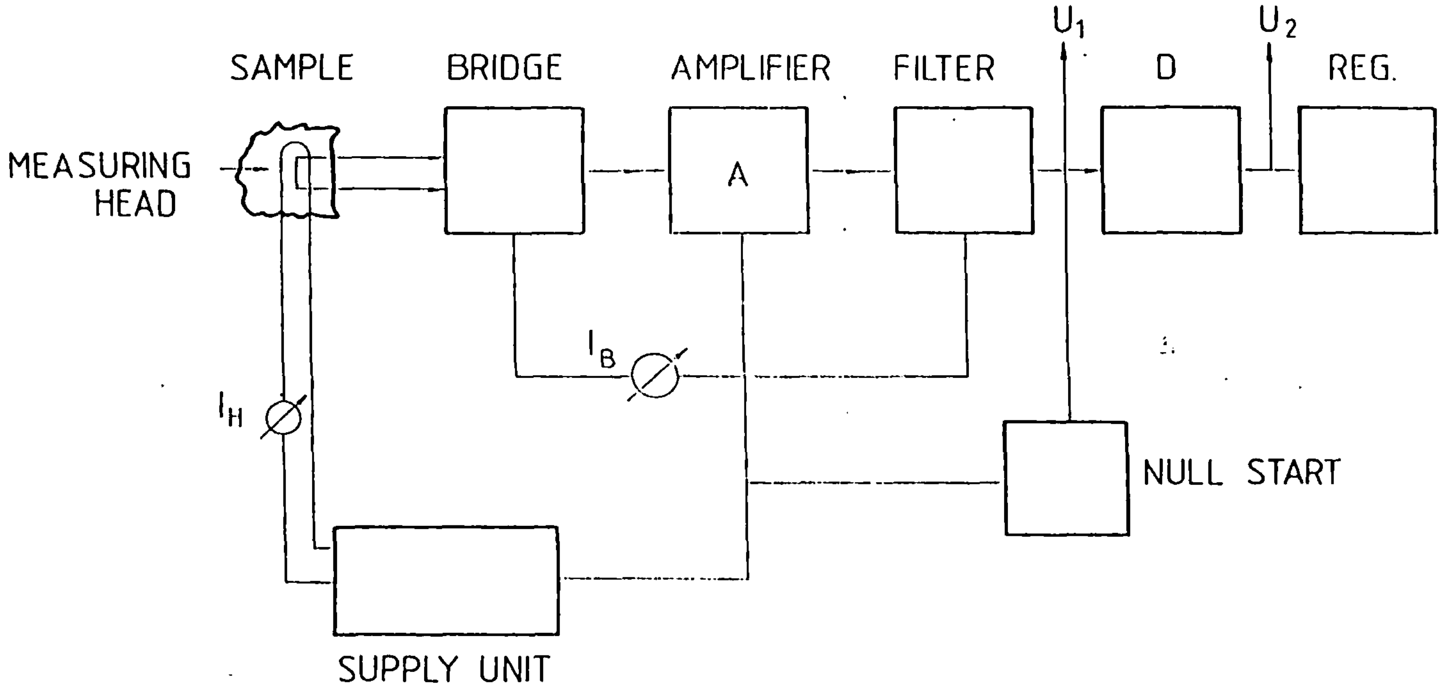

Figure 8. Scheme of heat conductivity measuring instrument

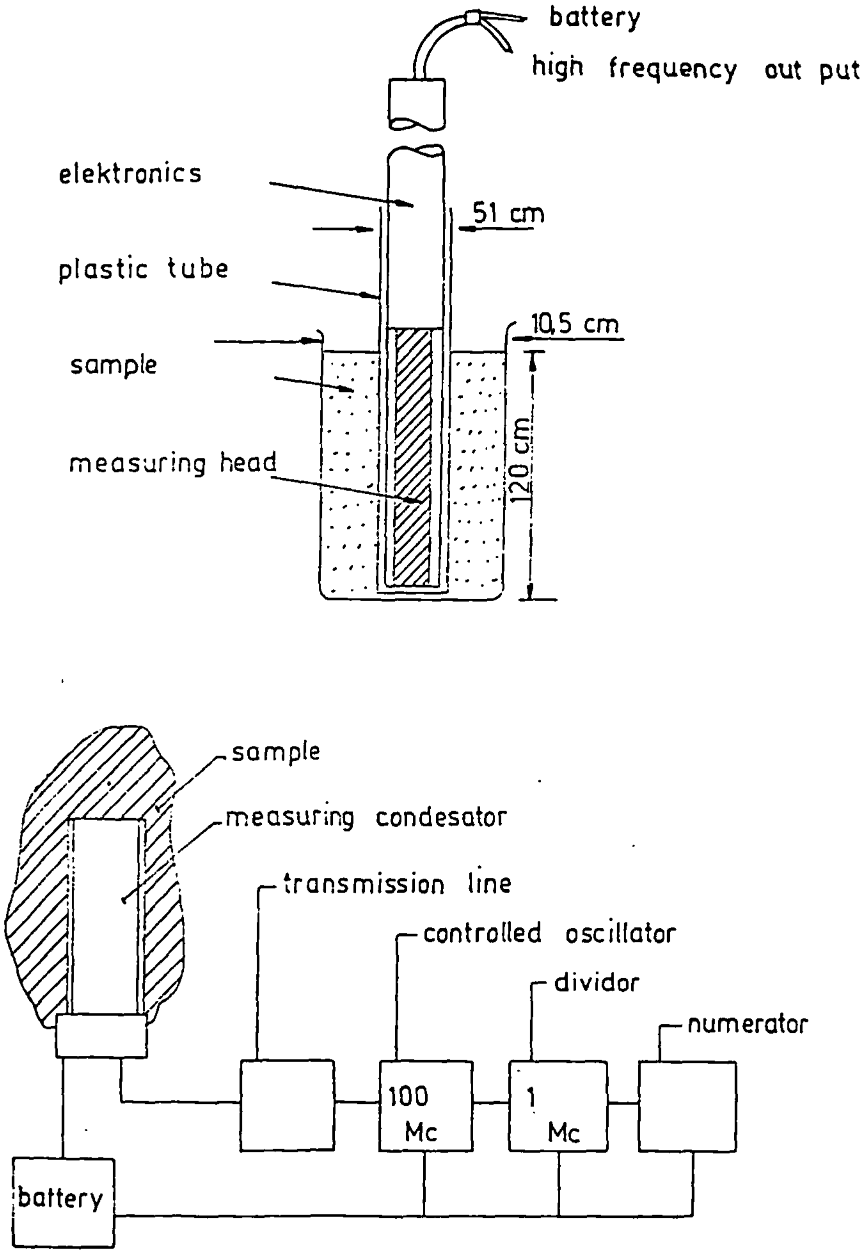

Figure 9. Scheme of permittivity measuring instrument

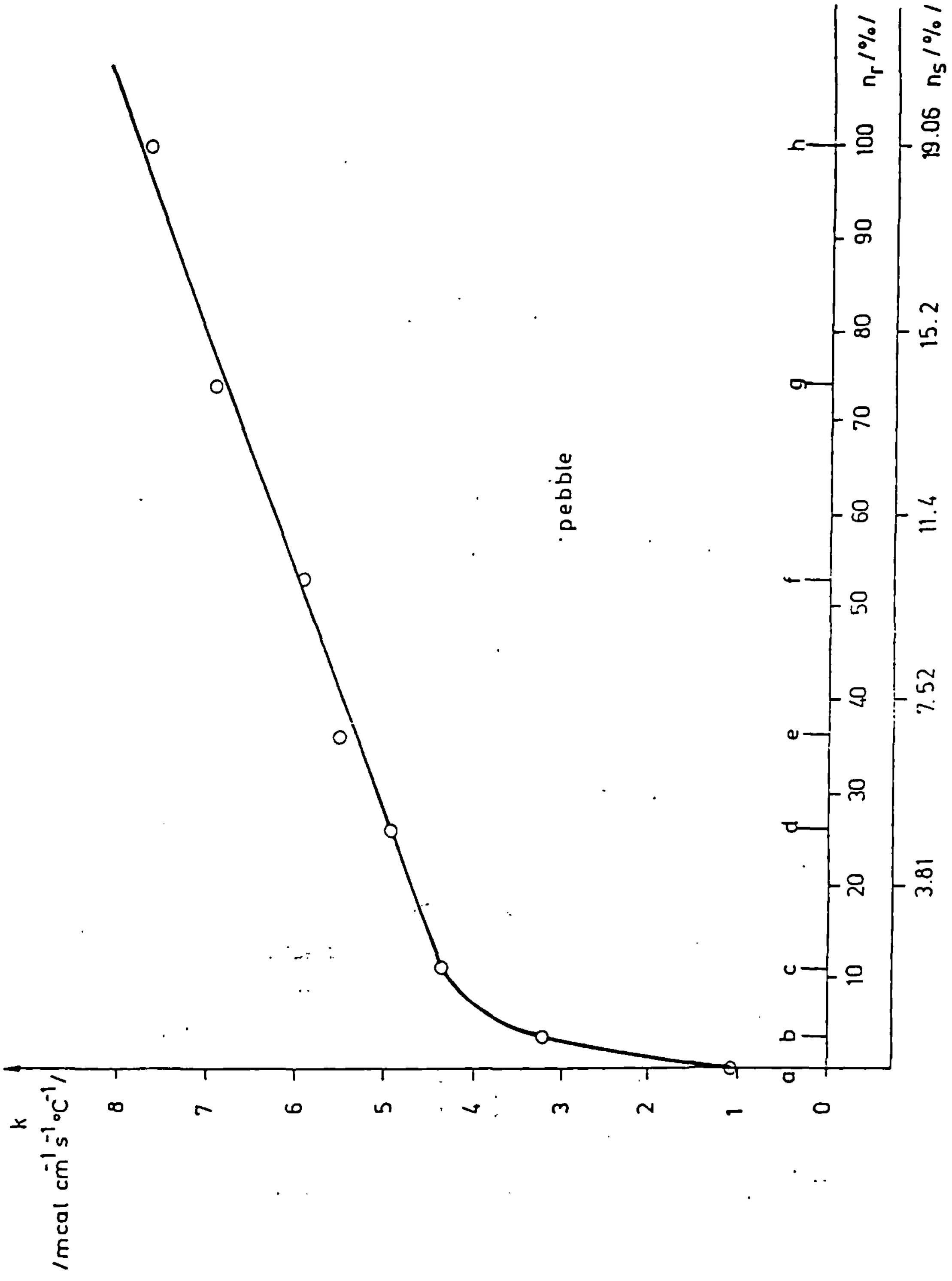

Figure 10. Relationship between heat conductivity and water saturation

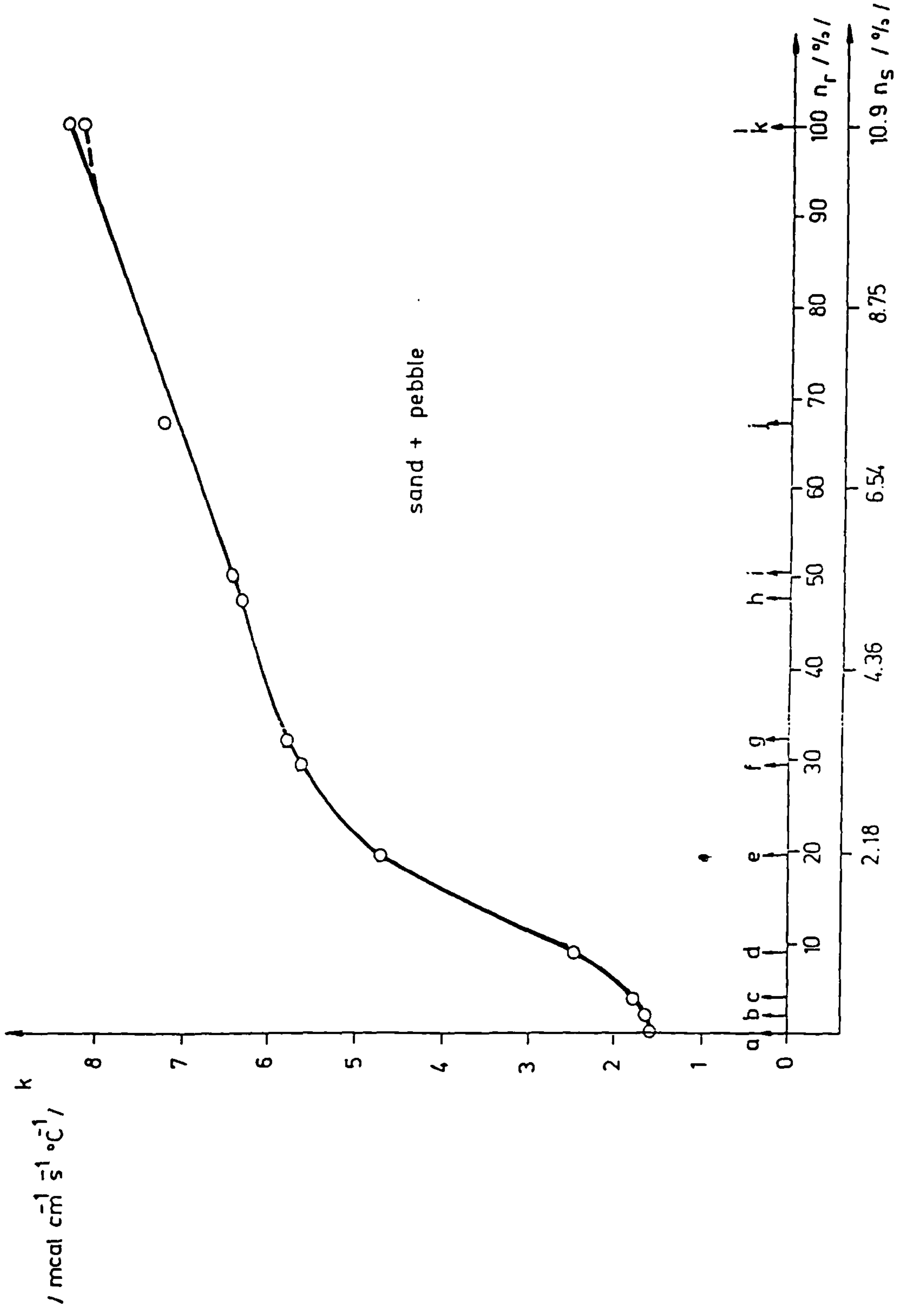

Figure 11. Relationship between heat conductivity and water saturation

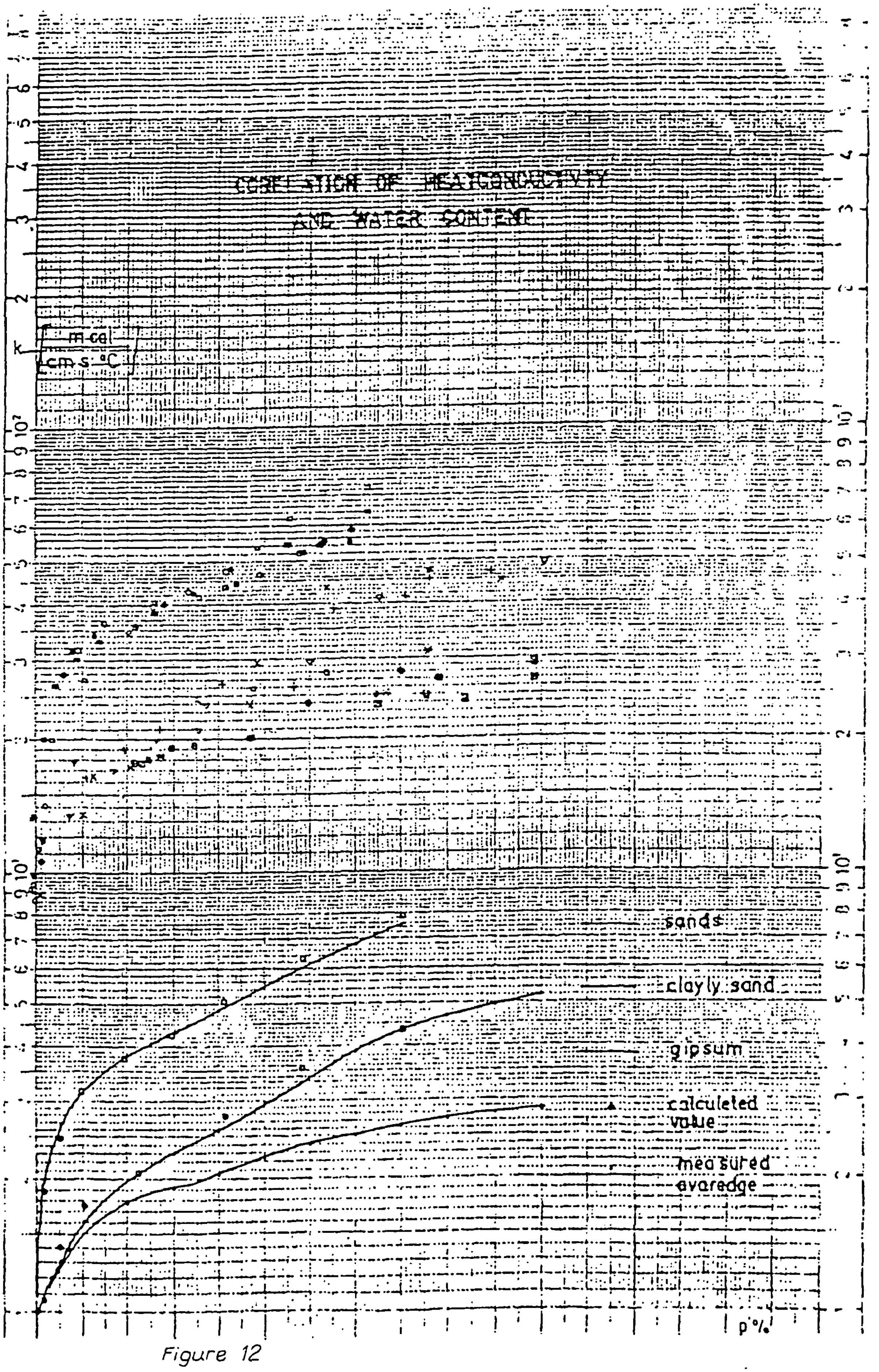
CORRELATION OF HEATCONDUCTIVITY
AND WATER CONTENT
K [m cal / cm s °C]
p %
sands
clayly sand
gipsum
calculeted value
measured avaredge
Az egyik tengelyen logaritmikus osztás 1-1000-ig. Egység 90mm

Figure 12

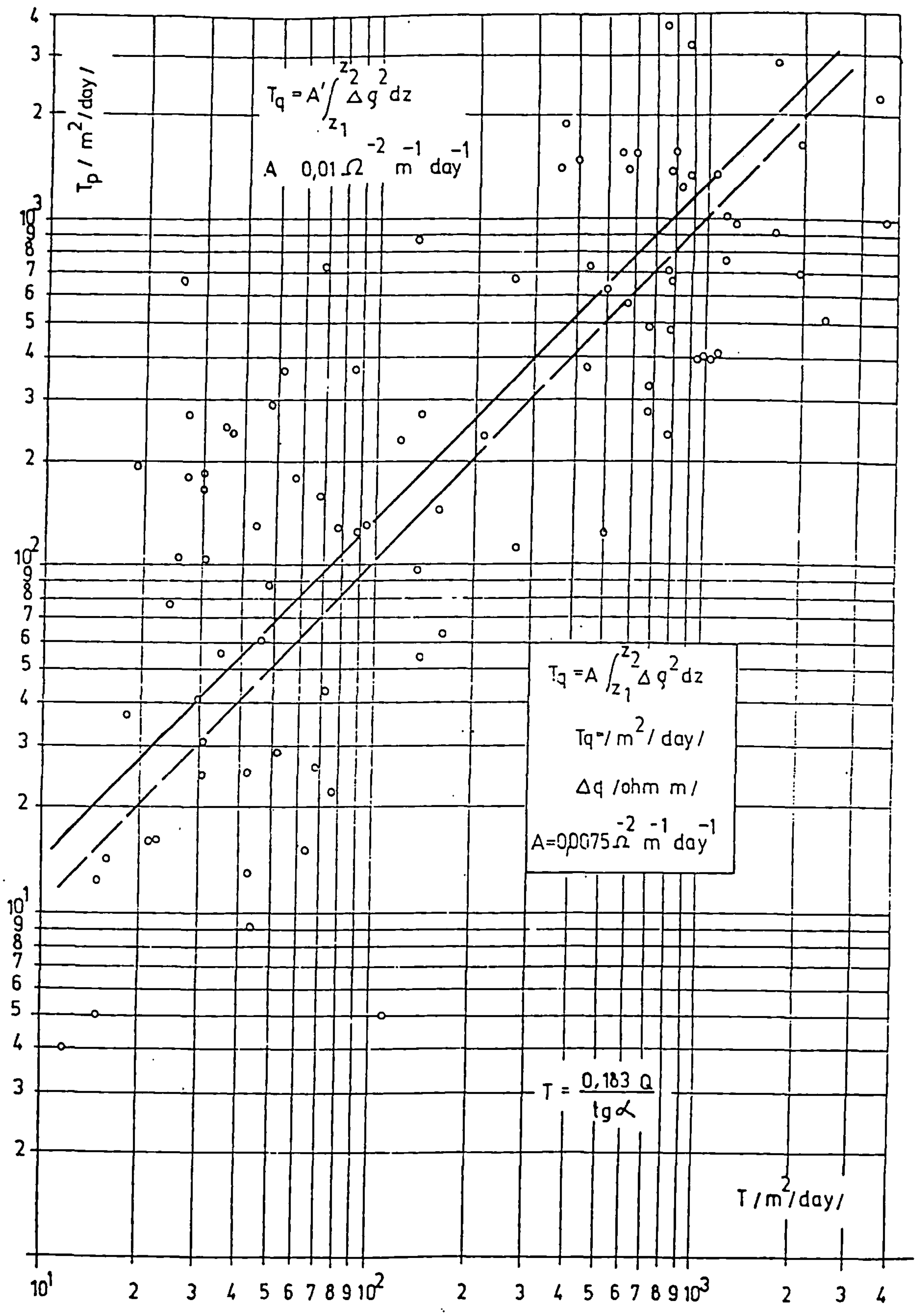

Figure 13 Draft of data of hydraulical transmissivity / T / calculated from pressure raising and resistivity loggings and gaind by geophysical measurements / Tq / for determining corelations

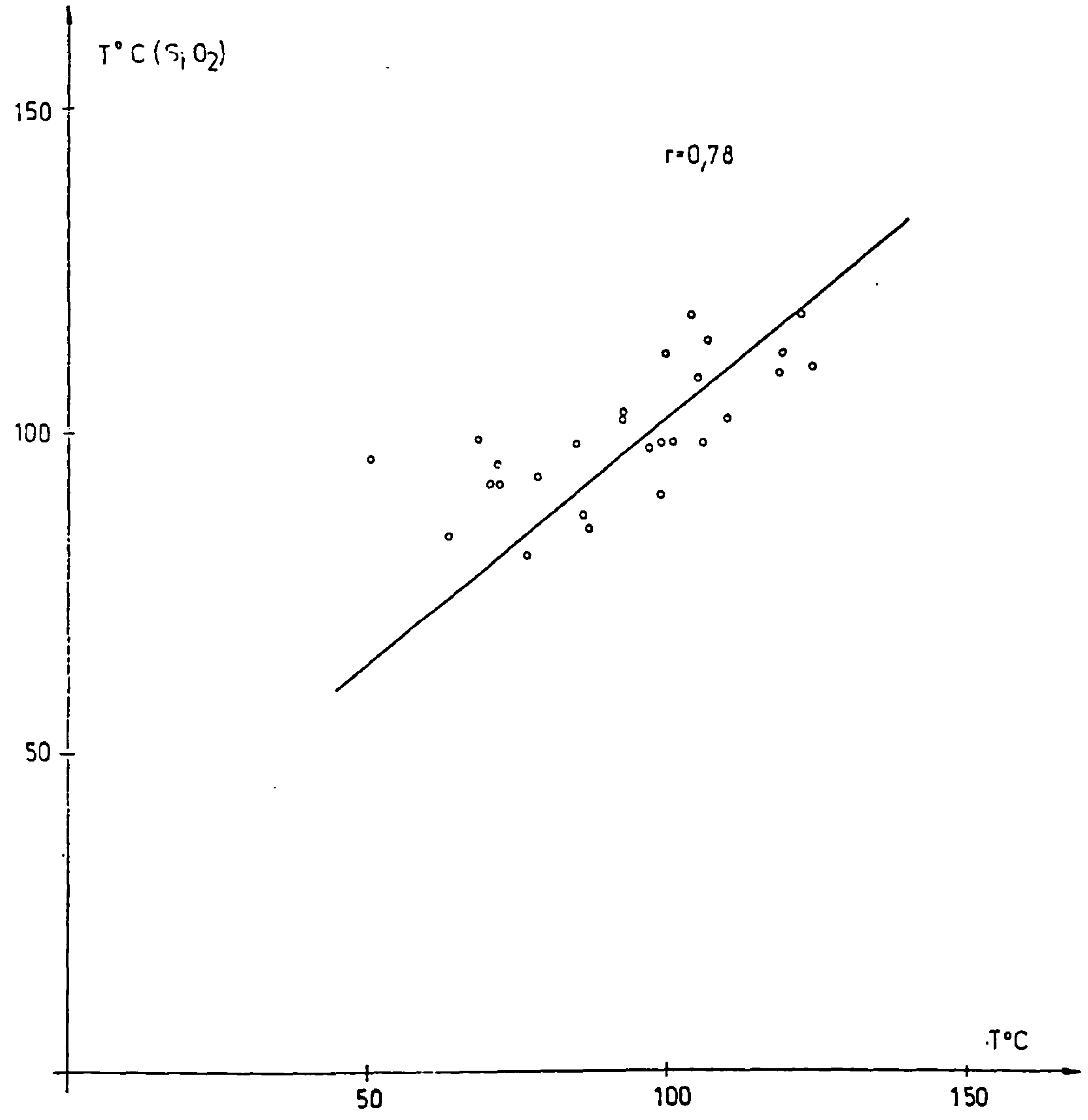

Figure 14 Correlation of temperctures measured by SiO thermo meter cnd the temperature data of aquifers.

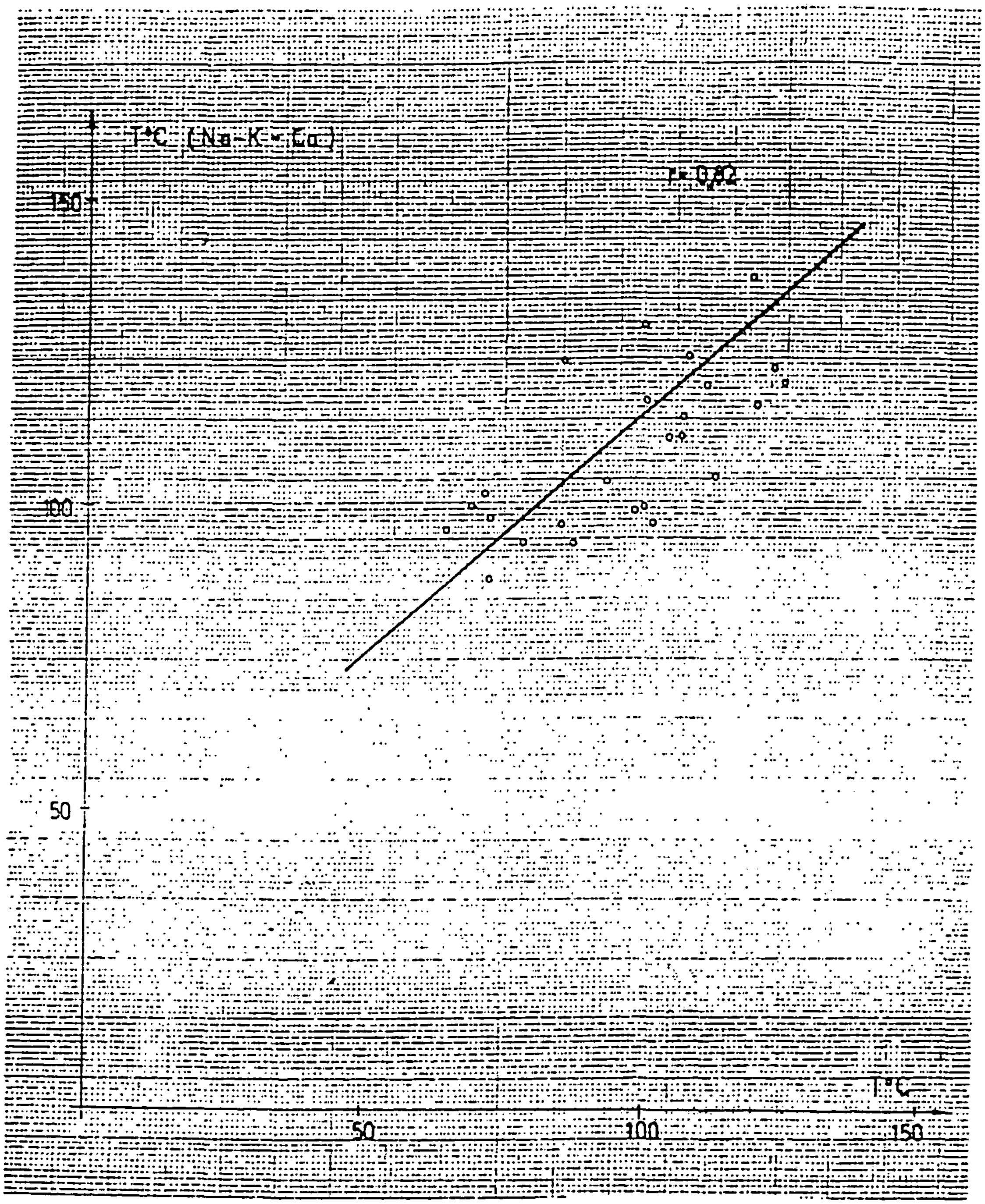

Figure 15 Correlation of temperatures measured by Na,K/Ca thermometer and the temperature data of aquifer

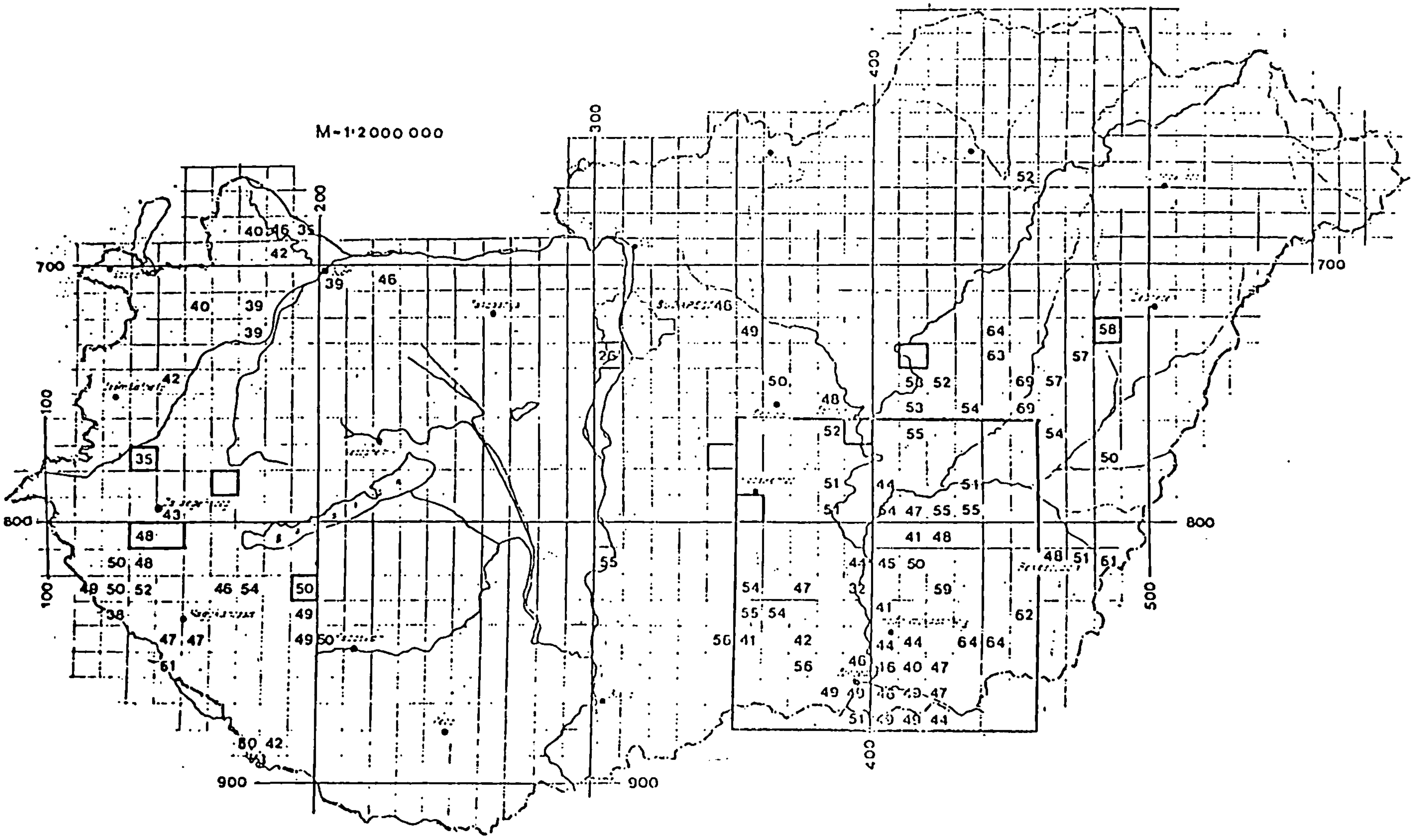

Figure 16 Geothermal gradient map of Hungary in depth interval 1750 – 2250 m

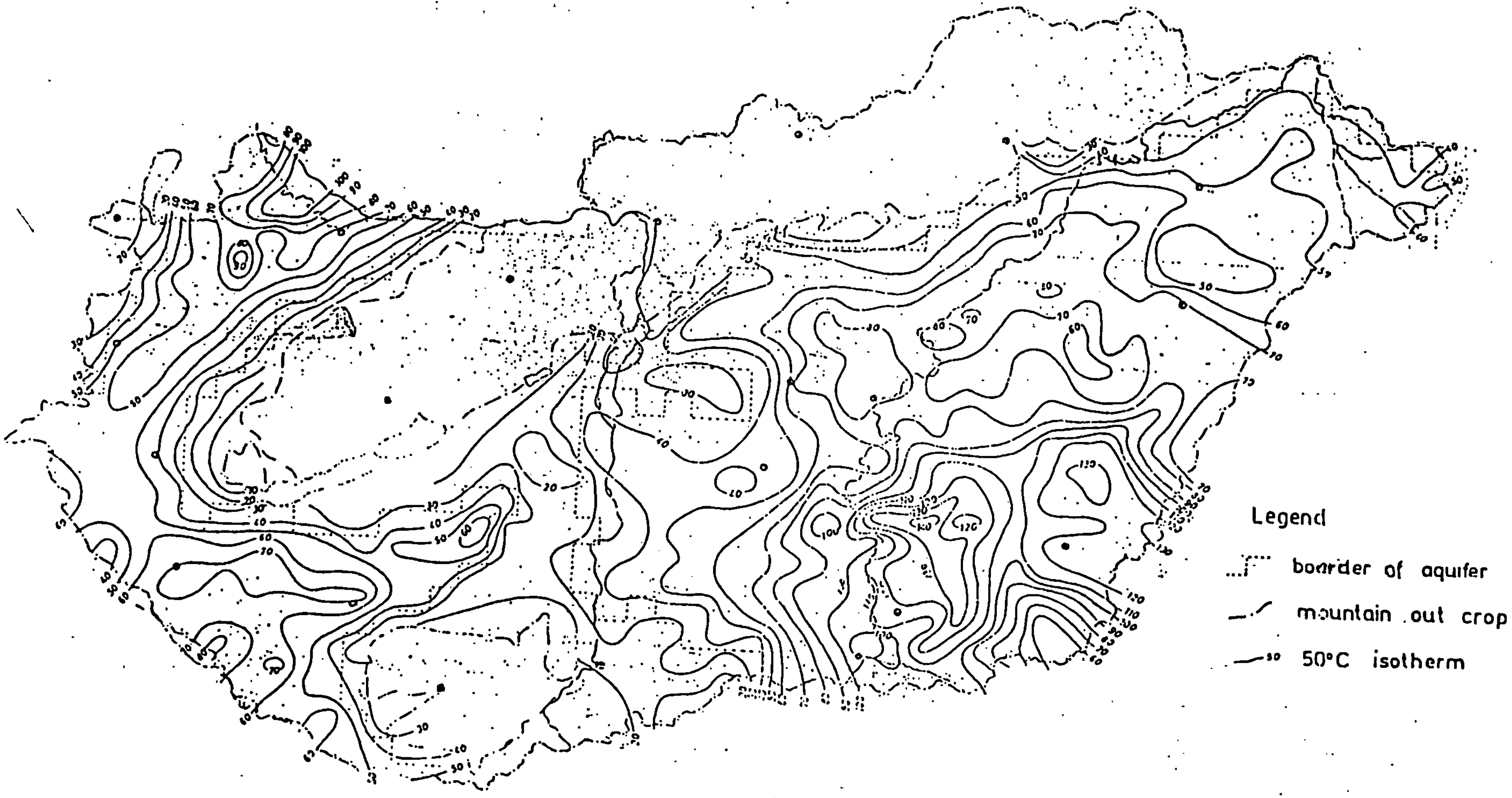

Figure 17. The max. temperature of the upper Pannonian aquifer

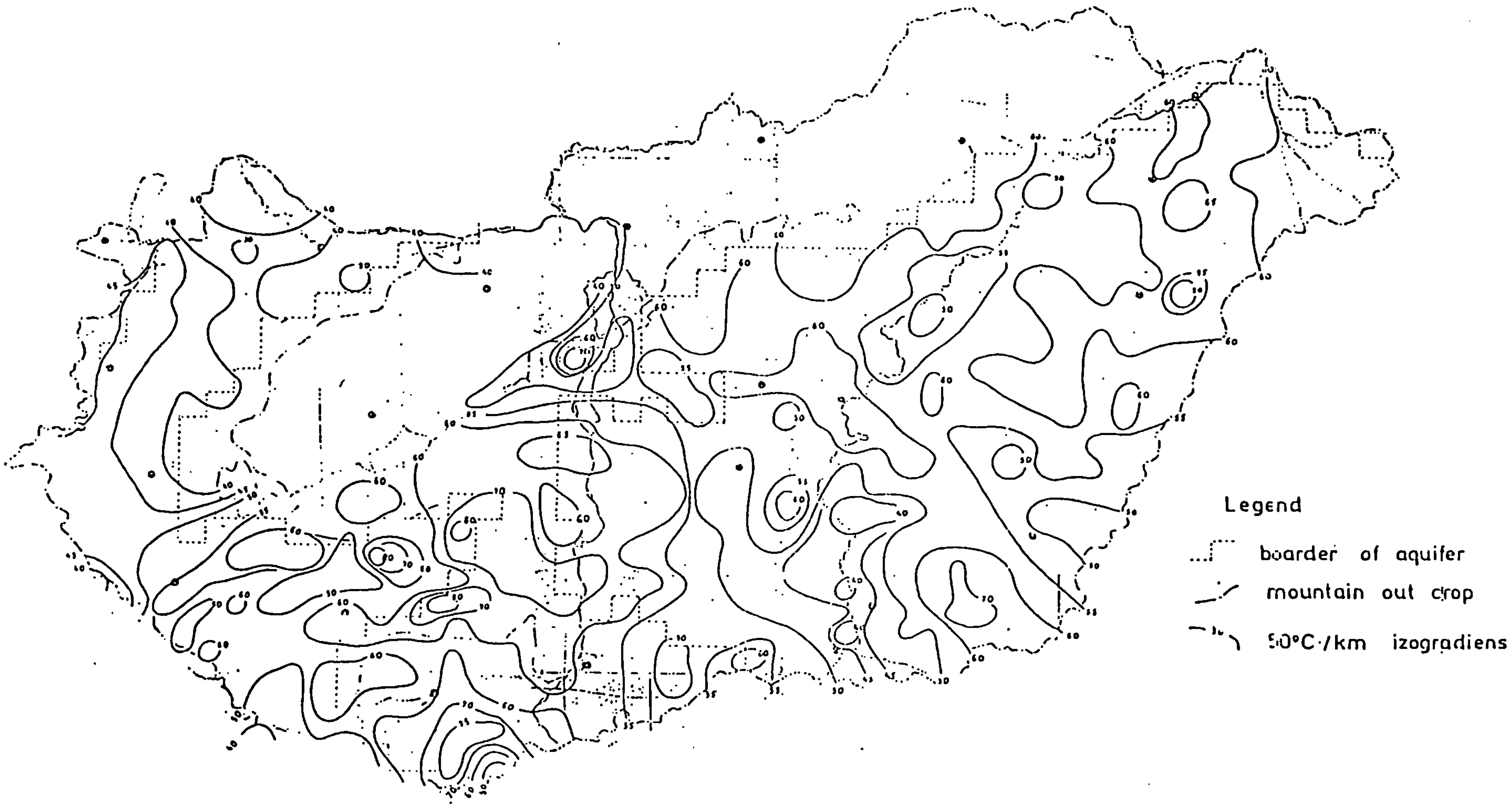

Figure 18. Regional geothermal gradient map concerning the aquifer

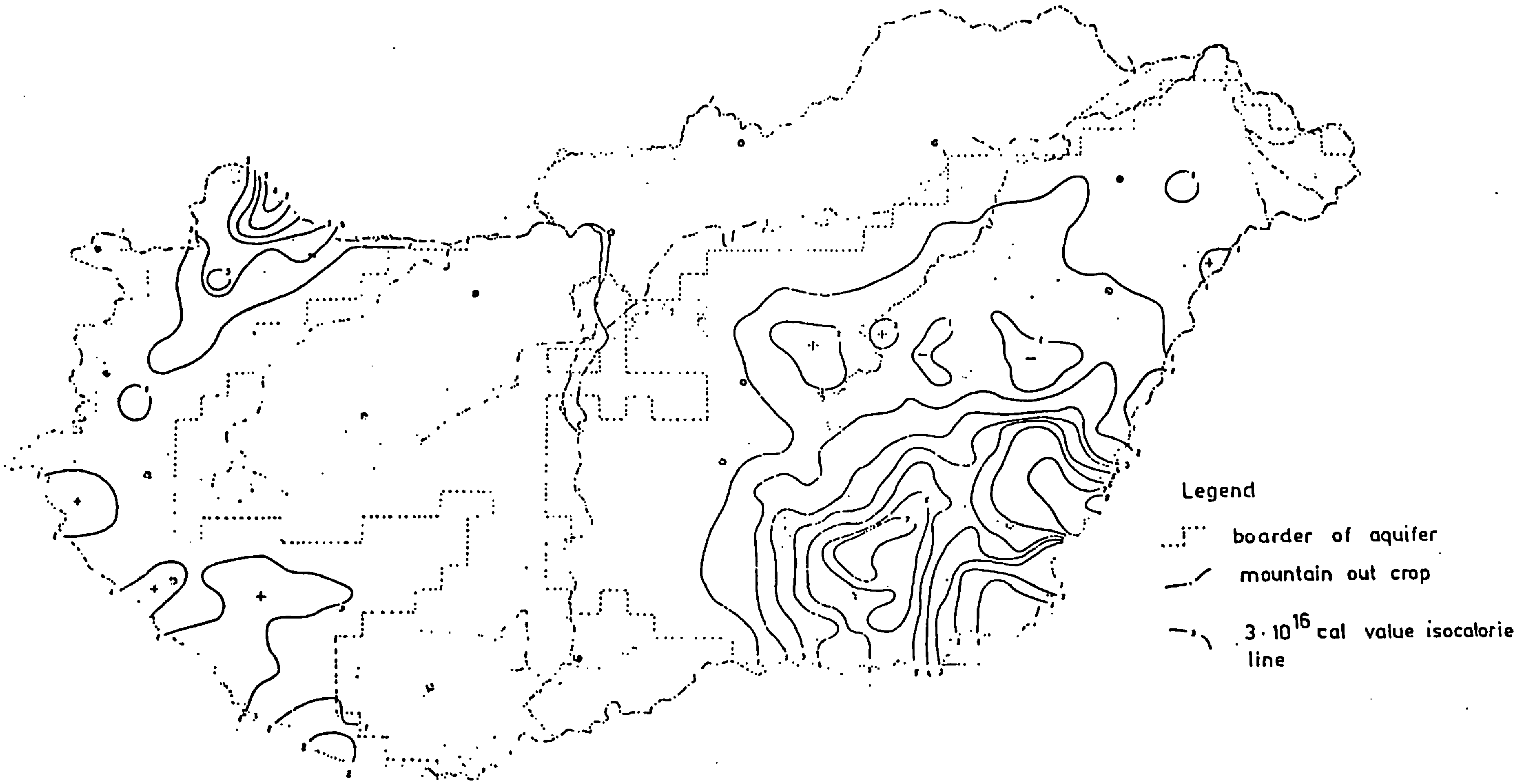

Figure 19. Map of thermalenergy distribution of aquifer

Thermalwater reserves of Pliocene sediments.
Exploited/Exploitable (by pumping 10^3 m^3/d)

Table 1.

Region	kif. viz hőmérséklet /°C/					
	5o-6o	6o-7o	7o-8o	8o-9o	9o-	Összesen
1. Kisalföld	o/38	lo/36	3/19	o/5	o/o	13/98
2. Lenti med.	o/5	o/2	o/o	o/o	o/o	o/7
3. Zala-Somogy	1/17	o/6	o/2	o/o	o/o	1/25
4. Drávavölgy	1/12	1/8	o/3	o/o	o/o	2/23
Dunántul	2/72	11/52	3/24	o/5	o/o	16/153
5. Szegedi ter.	12/28	8/24	6/12	12/15	7/12	45/91
6. Déltiszai sülly.	12/92	7/7o	11/52	19/4o	26/3o	85/284
7. Délalföld	1/27	3/26	9/3o	7/2o	12/26	32/129
8. Békési sülly.	2/53	11/52	1/27	o/17	1/9	15/158
9. Jászság	22/88	12/73	o/24	o/o	o/o	34/185
lo. Középtiszai sülly, Nyirség	9/72	7/46	3/26	o/o	o/o	19/144
Alföld	46/36o	48/291	3o/171	38/92	46/77	2o8/991
	48/432	59/343	33/195	38/97	46/77	224/1144

Table 2.

Results of the information survey of thermal water resources of Hungary

Temp. of outflowing water °C	Aquifer Temperature °C	depth interval m-m	area 10^3 km^2	stored reserve 10^3 km^3	stored heat reserve 10^{15} KJ	present production 10^3 m^3/d	heat effect MW	Producted till now	
								total	from stored reserves
30 - 40	35 - 48	400 - 650	70	0,7	92	200	303	1,0	0,3
- 50	- 60	- 900	50	0,5	92	85	170	0,4	0,2
- 60	- 73	-1200	40	0,5	117	60	162	0,3	0,2
- 70	- 85	-1500	30	0,3	86	55	182	0,3	0,1
- 80	- 90	-1800	25	0,2	68	35	138	0,2	0,1
- 90	-110	-2100	20	0,2	78	35	158	0,2	0,2
-100	-123	-2400	15	0,1	40	30	138	0,2	0,2
				2,5	573	500	1250	2,6	1,3

Utilization of geothermal energy (datafrom Water Authority)

Table 3.

Utilization	1975.	1980.	1984.	1985.	Capacity m^3/h
	pc				1985.
Balneology	221	240	262	277	231,13
Drink water	351	416	386	236	186,14
Agricult. heating	81	97	160	258	255,23
Flatheating+warm water	20	20	19	14	21,19
Industrial	15	21	64	70	61,94
Other	21	46	94	128	68,25
Closed	84	58	44	33	19,21
Summary	793	898	1029	1016	843,1

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GEOTHERMAL ACTIVITY IN TURKEY

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Abstract—Turkey is located on the Alpine tectonic belt with many grabens, acidic volcanism, hydrothermal alteration zones, numerous hot springs and fumaroles. The data gathered indicate that Turkey has a high geothermal energy potential. Geothermal research began in the 1960s implemented by the Mineral Research and Exploration General Directorate (MTA). Exploration began at Denizli–Kizildere in 1968. Further studies revealed the field to be commercially exploitable and a geothermal power-plant with a capacity of 20 MW started electricity generation in 1984. Currently there are numerous fields being explored and developed for electrical and non-electrical uses.

INTRODUCTION

Geothermal research in Turkey started in 1961 with an inventory of Turkey's hot springs by the Mineral Research and Exploration General Directorate (MTA) (Fig. 1). Subsequent investigations revealed the great geothermal potential of this country. To enable full utilization of this potential, Turkey was divided into six geothermal regions which are being individually and systematically developed. In 1963 the first geothermal exploration drilling took place in the Agamemnun (Balcova) field, west of Izmir. At a depth of 40 m the well produced a mixture of hot water and steam at a temperature of 124°C. The first geothermal field utilized for electricity

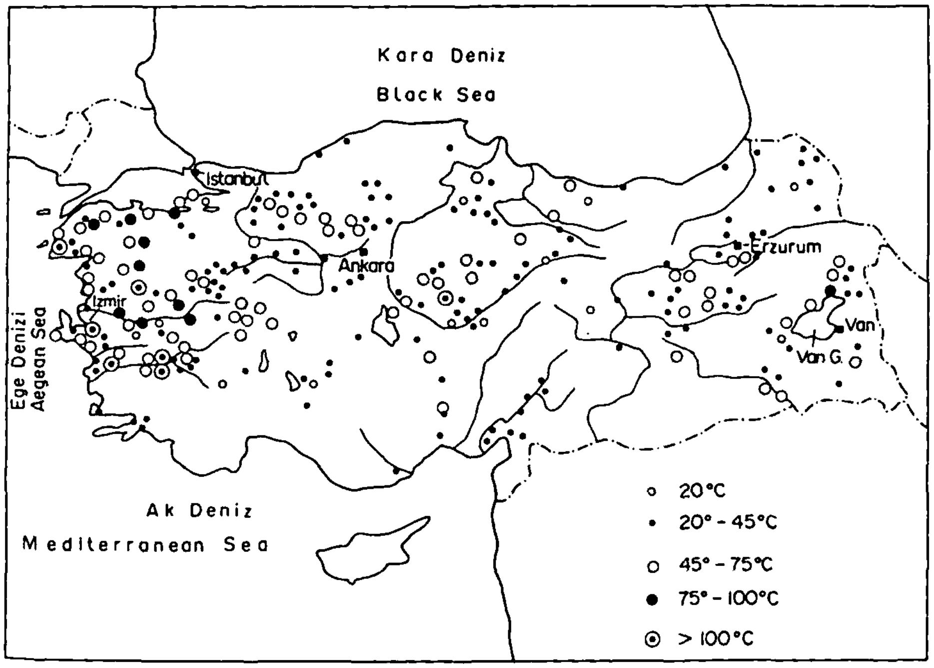

Fig. 1. Distribution of hot springs in Turkey.

Table 1. Geothermal fields of Turkey: characteristics of the geothermal reservoir

Names of localities	Types of reservoir rock	Reservoir temperature °C
Denizli–Kizildere	Marble–Quartzite	212
Denizli–Tekkehamam	Marble	230*
Denizli–Pamukkale	Marble	na
Aydin–Germencik	Quartzite–Calc-Schist–Marble	231
Aydin–Salavatli	na	200*
Izmir–Seferihisar	Limestone	145
Izmir–Balcova	Flysch	124
Izmir–Dikili–Bergama	Volcanic–Limestone	200*
Canakkale–Tuzla	Marble–Volcanic	174
Canakkale–Kestanbol	Granite	73
Canakkale–Hidirlar	Granite	150*
Balikesir–Sindirgi	Limestone	150*
Balikesir–Gonen	Diabase	78
Balikesir–Kepekler	Marble	125*
Balikesir–Pamukcu	Limestone	57
Manisa–Salihli	Marble	210*
Manisa–Urganli	Marble	150*
Afyon–Omer–Gecek	Marble	106
Afyon–Sandikli	Quartzite	110*
Nevsehir–Acigol	Granite	na
Nevsehir–Kozakli	Limestone	95
Bitlis–Nemrut	Volcanic	250*
Van–Zilan	Limestone	200*
Erzurum–Pasinler	Limestone–Basalt	80*
Eskisehir	Limestone	80*
Ankara–Kizilcahamam	Volcanic–Limestone	150*
Kutahya–Simav	Limestone–Granite	143
Izmir–Cesme	Limestone	56

na: not available.
*estimated temperatures.

Table 2. Chemical composition of the fluid from some geothermal fields in Turkey

Names of fields	pH	Measured temp. °C	T.D.S. mg l^{-1}	Chemistry of discharged water (ppm) Na$^+$	K$^+$	NH$_4^+$	Ca^{+2}	Mg^{+2}	B	HCO$_3^-$	CO$_3^{-2}$	SO$_4^{-2}$	Cl	Li	SiO$_2$
Kizildere* Denizli (Second reservoir)	8.9	212	5020	1400	148	3.6	2.2	0.0	28	2117	336	714	122	—	550
Germencik* Aydin (Second reservoir)	8.3	232	4400	1335	45	3.8	6.4	1.0	45	1324	246	37	1586	8	305
Ömer–Gecek* Afyon	7.4	106	4500	1510	116	5.4	143	10	9.1	952	180	487	1790	—	125
Balcova* Izmir	8.7	124	1230	380	29	1.03	12	7	2.8	567	6	174	192	1.6	145
Seferihisar* Izmir (First reservoir)	7.5	137	19 938	6400	650	5.55	425	129	17	88	0.0	323	1348	15.4	140
Tuzla* Canakkale (First reservoir)	7.0	173	70 000	22 250	2125	2.66	5715	101	35	55	0.0	176	44140	74	123
Kizilcahamam* Ankara	7.6	105	2072	670	66	1.3	41	42	8.3	1512	0.0	122	243		112

* Drill-holes.

production is in the Denizli–Kizildere area. Exploration of this field started in 1968. A power-plant with a capacity of 20 MW is now in operation. Another well-known geothermal field that was explored in 1982 is Aydin–Germencik, with a temperature of 231°C. Other well-known geothermal fields are Izmir–Seferihisar, Afyon–Omer– Gecek, Canakkale–Tuzla, Izmir–Dikili–Bergama, Kutahya–Simav and Ankara–Kizilcahamam. The main characteristics of these fields are given in Tables 1 and 2 and are described below (Fig. 2).

Geological and geophysical studies followed the initial research work of 1962, compiling a hot water inventory of the country. The first geothermal fluid was discovered in 1963 in a shallow well drilled in the Izmir–Balcova area, but the 124°C fluid was not utilized at the time due to rapid scaling. Since then, numerous geothermal fields have been discovered and utilized for either power generation, district heating or both.

MAIN GEOTHERMAL FIELDS IN TURKEY

Turkey has both high and low enthalpy geothermal resources.

High enthalpy geothermal resources

Table 3 reports some characteristics of the high-enthalpy fields.

Table 3. Wells drilled for electrical utilization of geothermal resources before April, 1987

Names of locality	Drilled in	Well number		Temperature (°C)	Flow rate (kg s^{-1})
Denizli–Kizildere	1968	KD–1	(E)	198	41.67
Denizli–Kizildere	1969	KD–1/A	(E)	195	37.42
Denizli–Tekkehamam	1968	TH–1	(E)	116	na
Denizli–Kizildere	1968	KD–2	(E)	174	18.61
Denizli–Kizildere	1969	KD–3	(E)	172	na
Denizli–Kizildere	1969	KD–4	(E)	178	na
Denizli–Kizildere	1969	KD–111	(E)	152	na
Denizli–Kizildere	1970	KD–6	(P)	201	104.12
Denizli–Kizildere	1970	KD–7	(P)	208	70.00
Denizli–Kizildere	1970	KD–8	(E)	190	na
Denizli–Kizildere	1970	KD–9	(E)	172	42.78
Denizli–Kizildere	1970	KD–12	(E)	148	na
Denizli–Kizildere	1971	KD–13	(P)	201	115.72
Denizli–Kizildere	1970	KD–14	(P)	210	80.69
Denizli–Kizildere	1971	KD–15	(P)	205	120.78
Denizli–Kizildere	1973	KD–16	(P)	212	177.11
Denizli–Kizildere	1985	KD–21	(P)	204	69.45
Denizli–Kizildere	1985	KD–22	(P)	202	67.23
Denizli–Kizildere	1986	KD–20	(P)	201	69.45
Aydin–Germencik	1982	OB–1	(E)	203	13.58
Aydin–Germencik	1982	OB–2	(E)	231	12.21
Aydin–Germencik	1983	OB–3	(E)	231	84.84
Aydin–Germencik	1984	OB–4	(E)	213	59.92
Aydin–Germencik	1984	OB–5	(E)	221	62.44
Aydin–Germencik	1984	OB–6	(E)	221	166.04
Aydin–Germencik	1985	OB–7	(E)	226	69.45
Aydin–Germencik	1986	OB–8	(E)	218	69.45
Aydin–Germencik	1986	OB–9	(E)	224	97.23
Canakkale–Tuzla	1982	T–1	(E)	173	na
Canakkale–Tuzla	1983	T–2	(E)	171	na
Izmir–Seferihisar	1983	CM–1	(E)	145	20.00

(E): exploration well.
(P): production well.
na: not available.

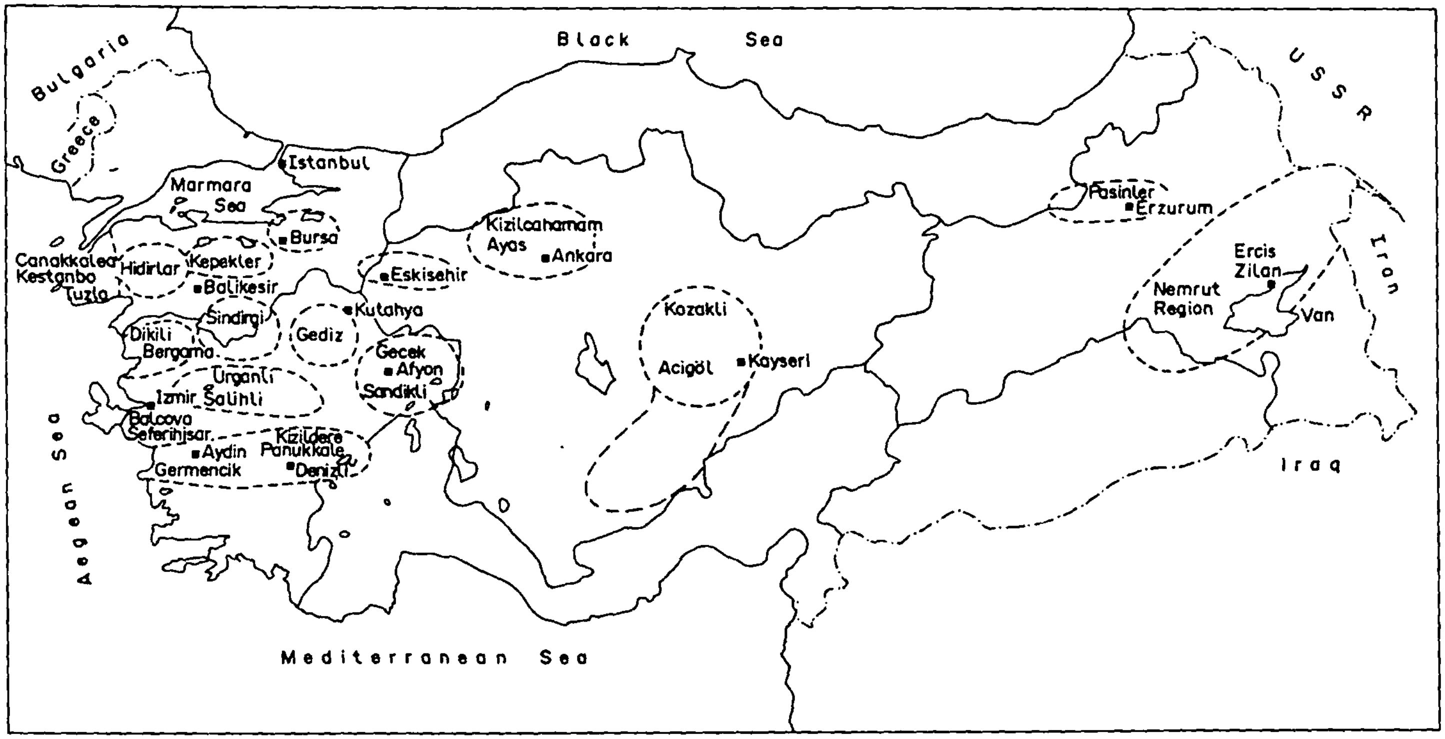

Fig. 2. Geothermal areas of Turkey.

Denizli–Kizildere field. This field was the first commercial field discovered in Turkey. It is located in western Anatolia, in the eastern part of the Buyuk Menderes graben. A total of 108 shallow gradient wells and 20 deep wells were drilled, and two different reservoirs were explored. The first contains geothermal fluid at a temperature of 198°C at 400 m depth on average. The second produces geothermal fluid of 212°C in the depth range 450–1100 m.

A 20 MW power plant has been in operation since 1984 under the Turkish Electricity Authority (TEK). More production wells are planned to reach full capacity because of production losses caused by calcium carbonate deposition.

A carbon-dioxide plant started producing liquid carbon-dioxide and dry ice in 1986 at a rate of 120 t day^{-1}. The heating of greenhouses covering 4500 m^2 using the discharge fluid has proved satisfactory. Studies for heating the city of Denizli with discharge fluid (140°C) from the power-plant are now being carried out.

Aydin–Germencik field. This field is located in western Anatolia, in the western part of the Buyuk Menderes graben. Since 1982 a total of nine deep wells have been drilled in the depth range 285–2398 m. The production rate of these wells varies from 130 t h^{-1} to 450 t h^{-1}, with temperatures of 200–231°C. A detailed test program is now being carried out.

Earlier tests indicated that this field could have an important potential for electricity generation. The discharge fluid could be used for district heating, greenhouse heating, agricultural drying and in industry.

Canakkale–Tuzla field. This field is located in north-western Anatolia, 80 km south of Canakkale and 5 km from the Aegean Sea. The first well, drilled in 1982, is 814 m deep and produced a steam and hot water mixture from the first reservoir in the depth range 333–553 m in volcanic rock, with temperatures of 173°C, a production rate of 130 t h^{-1} and steam content of 13%. Deeper wells are now being planned to find higher temperatures and different production zones.

This field could ideally be used for agricultural purposes as well as power-generation.

Izmir–Seferihisar field. This field is located 40 km south-west of Izmir. During the first deep drilling the first reservoir was encountered in a depth range of 70–720 m, with temperatures of 145°C. In 1986 another deep well was drilled to reach a second reservoir with higher temperatures. This well was drilled to 2000 m, but the results were not as expected as a second reservoir was not found. Three shallow wells were drilled for exploratory purposes and later one of them was utilized with a three-loop down-hole heat exchanger. This system was tested under design conditions and 6 MW_t capacity was obtained. Depending on the heat demand of local consumers either a down-hole or well-head heat exchanger system will be considered for the other two shallow wells.

Nemrut–Zilan–Suphan–Tendurek fields. These fields are located north of Lake Van in eastern Anatolia. In 1986 two gradient wells of 343 m and 215 m were drilled. The results were not encouraging. More detailed geological and geophysical surveys are planned for 1987.

Nevsehir–Acigol field. This field is located in Central Anatolia. Geological and geophysical studies indicated the presence of an active heat source composed of young extrusives at shallow depth. Detailed studies directed at a Hot Dry Rock project are therefore planned in the near future.

Low enthalpy geothermal resources

Tables 4 and 5 give some characteristics of the low enthalpy geothermal areas.

Table 4. Wells drilled for direct heat utilization of geothermal resources, before April, 1987

Names of locality	Drilled in	Well number		Temperature (°C)	Flow rate (kg s^{-1})
Izmir–Balcova	1963	S–1	(E + P)	124	20.00
Izmir–Balcova	1963	S–2	(E)	102	na
Izmir–Balcova	1963	S–3/A	(E)	101	na
Izmir–Balcova	1982	BG–1	(T)	50	na
Izmir–Balcova	1982	BG–2	(T)	51	na
Izmir–Balcova	1982	BG–3	(T)	58	na
Izmir–Balcova	1982	BG–4	(T)	84	na
Izmir–Balcova	1982	BG–5	(T)	81	na
Izmir–Balcova	1982	BG–8	(T)	116	na
Izmir–Balcova	1982	BG–9	(T)	126	na
Izmir–Balcova	1982	B–1	(P + D)	114	20.00
Izmir–Balcova	1983	B–2	(P + D)	112	5.00
Izmir–Balcova	1983	B–3	(P + D)	111	4.00
Izmir–Balcova	1983	B–4	(P + D)	114	10.00
Izmir–Balcova	1983	B–5	(P + D)	124	15.00
Izmir–Balcova	1983	B–6	(P + D)	93	3.00
Izmir–Balcova	1983	B–7	(P + D)	115	10.00
Izmir–Balcova	1983	B–8	(P + D)	104	4.00
Izmir–Balcova	1983	B–9	(P + D)	124	18.00
Afyon–Omer–Gecek	1974	AF–1	(P + D)	98	19.80
Afyon–Omer–Gecek	1975	AF–3	(P + D)	97	33.59
Afyon–Omer–Gecek	1975	AF–4	(P + D)	95	76.92
Afyon–Omer–Gecek	1982	AF–5	(P + D)	79	9.80
Afyon–Omer–Gecek	1982	AF–6	(P + D)	92	9.35
Afyon–Omer–Gecek	1982	AF–7	(P + D)	97	22.22
Afyon–Omer–Gecek	1982	AF–8	(P + D)	80	9.80
Afyon–Omer–Gecek	1974	R–260	(P + D)	95	48.02
Ankara–Meliksah	1974	MH–1	(E + A)	32	na
Ankara–Meliksah	1975	MH–1A	(E + A)	43	35.00
Canakkale–Kestanbol	1976	K–1	(E + A)	73	20.00
Balikesir–Gonen	1976	G–1	(E + A)	74	14.00
Balikesir–Gonen	1977	G–2	(E + A)	78	20.00
Balikesir–Gonen	1985	G–3	(P + D)	74	26.00
Izmir–Cesme	1974	I–1	(E + P)	56	42.00
Ankara–Kizilcahamam	1984	MTA–1	(B + D)	76	13.00
Ankara–Kizilcahamam	1985	KHD–1	(G)	86	35.00
Ankara–Ayas	1986	A–1	(P + B)	31	45.00
Ankara–Haymana	1986	H–3	(B + D)	44	1.50
Ankara–Haymana	1986	H–4	(B + D)	43	52.00
Eskisehir	1986	E–2	(B)	36	6.00
Eskisehir	1986	E–3	(B)	45	6.00
Samsun–Havza	1986	SHC–1	(B + D)	54	55.00
Samsun–Kocapinar	1986	KP–1	(P + B)	38	35.00
Tokat–Sulusaray	1986	SS–2	(P + B)	53	2.00
Tokat–Sulusaray	1986	SS–3	(P + B)	54	21.00
Tokat–Sulusaray	1986	SS–5	(P + B)	27	9.00
Rize–Ayder	1986	AK–2	(B)	55	14.00
Kirsehir–Kaman	1985	K–1	(B)	34	5.00
Kirsehir–Terme	1986	KT–2	(B)	28	45.00
Kirsehir–Terme	1986	KT–3	(B)	40	45.00
Kutahya–Simav–Eynal	1985	EY–2	(D)	158	40.00
Kutahya–Simav–Eynal	1985	EY–3	(D)	147	50.00
Kutahya–Simav–Citgol	1985	CT–1	(P + B)	97	25.00
Kutahya–Simav–Nasa	1985	NS–1	(B)	42	2.00
Erzincan–Ilica	1985	IL–1	(B)	40	11.00
Yozgat–Bogazlayan	1987	BB–2	(B)	46	50.00

E: exploration.
P: pumped.
D: district heating.
T: thermal gradient.
A: artesian.
B: bathing and swimming.
G: greenhouses.
na: not available.

Flow rate (kg s^{-1})
20.00
na
na
na
na
na
na
na
na
na
20.00
5.00
4.00
10.00
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3.00
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21.00
9.00
14.00
5.00
45.00
45.00
40.00
50.00
25.00
2.00
11.00
50.00

Table 5. Present utilization of geothermal energy for direct heat uses

Names of locality	Type of use	Flow rate (kg s^{-1})
Izmir–Balcova	G + B + D	61.1
Afyon–Omer–Gecek	G + B + F	182.8
Denizli–Kizildere	G + I	400.0
Denizli–Tekkehamam	B + G	50.0
Balikesir–Havran	B + G	20.0
Izmir–Seferihisar	B + G	50.0
Afyon–Sandikli	B + D	50.0
Ankara–Kizilcahamam	B + D	50.0
Eskisehir	B + D	50.0
Balikesir–Gonen	G + D	30.0
Canakkale–Kestanbol	G + B	20.0
Main balneological centers of Turkey	Temperature (°C)	
Bursa	82	50.0
Aydin–Germencik	90	10.0
Aydin–Salavatli	42	5.0
Aydin–Gumus	40	5.0
Balikesir–Sindirgi	98	50.0
Balikesir–Kepekler	62	5.0
Erzurum–Ilica	38	20.0
Erzurum–Dumlu	37	10.0
Erzurum–Pasinler	38	5.0
Nevsehir–Kozakli	90	20.0
Kirsehir–Terme	48	10.0
Kirsehir–Mahmutlu	62	28.0
Kirsehir–Karakurt	50	10.0
Kutahya–Simav	98	10.0
Kutahya–Gediz	78	8.0
Manisa–Kursunlu	78	5.0
Manisa–Urganli	90	25.0
Van–Zilan	78	20.0
Izmir–Dikili–Bergama	90	20.0
Canakkale–Tuzla	102	15.0
Canakkale–Hidirlar	80	15.0
Istanbul–Termal	65	10.0
Denizli–Pamukkale	36	50.0
Samsun–Havza	54	55.0
Rize–Ayder	55	14.0
Ankara–Haymana	43	52.0
Tokat–Sulusaray	54	21.0
Samsun–Kocapinar	38	35.0

I: industrial process heat.
F: fish and other animal farming.
D: district heating.
B: bathing and swimming.
G: greenhouses.

Izmir–Balcova field. This field is located 11 km southwest of Izmir. The first well was drilled in 1963 and produced a mixture of hot water and steam at 124°C at a depth of 40 m. Production fell off because of rapid scaling, so little use was made of the fluid at that time. Systematic studies of this problem resulted in the application of a down-hole heat exchanger. As a result a tourist spa-hotel and its recreational facilities, as well as some units of Izmir–Dokuz Eylul University, are heated by this natural resource.

Afyon–Omer–Gecek field. This is another field where rapid scaling was observed. The geothermal fluid is found at an average depth of 120–200 m, at a temperature of 98°C. Flowrate was unsatisfactory because of rapid scaling, so down-hole and well-head heat exchanger systems were successfully tested and installed. This system has been operating for several years now, economically heating a spa-hotel, its recreational facilities, and a 2000 m^2 greenhouse complex.

OTHER POTENTIAL GEOTHERMAL FIELDS

Other possible geothermal areas (Fig. 2) are Aydin–Salavatli, Nevsehir–Kozakli, Ankara–Kizilcahamam–Ayas–Cubuk, Manisa–Salihli–Alasehir, Denizli–Tekkehamam–Karahayit–Pamukkale–Yenice, Kayseri, Izmir–Dikili–Bergama, Balikesir–Sindirgi–Gonen–Havran, Kutahya–Simav, Canakkale–Kestanbol, Afyon–Sandikli and Erzurum–Ilica–Pasinler. Geological, geophysical and geochemical surveys of these fields have already been completed. Drilling in Kutahya–Simav and Ankara–Kizilcahamam areas resulted in producing wells. Aydin–Salavatli and Izmir–Dikili–Bergama are now in the drilling stage.

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GEOTHERMAL EXPERIENCE IN HUNGARY

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Abstract—Geothermal fluids in Hungary are exploited in 650 wells and connected heating systems. The highest emergence temperature is about 95°C. Scaling problems are being tackled by chemical and physical techniques. Reinjection tests are now under way to comply with environmental regulations.

In Hungary there are large quantities of geothermal fluids, especially in the sandy aquifers of the Pannonian basin. The salt content of thermal waters varies from place to place in Hungary. The chemical composition of the thermal waters coming from aquifers of Pannonian age is mainly of the alkaline-carbonate type and these waters also contain methane and carbon dioxide.

Salt content is on average 3000–5000 mg l^{-1}; gas content varies over a wide range. Because of the methane in the thermal water, explosions have occurred on several occasions. There are very severe regulations controlling the gas content in water supplies. Gas content must not exceed 0.8 Nl m^{-3}, but up to a maximum of 5 Nl m^{-3} the water can be utilized in specific circumstances. Above 5 Nl m^{-3} the methane must be separated from the water. Since cold water in Hungary also contains methane, many kinds of degassificators have been developed. In wells producing water with gas, the quantity of gas must be redetermined every two years. The utilization of thermal water is regulated by the Water Authority through a permit. Any person may obtain a permit, so thermal water wells can be owned privately. Oil or gas wells, however, are state-owned. So wells drilled for thermal water that recover gas are taken over by the Government.

The permits issued by the water authorities provide directions on how thermal wells are to be drilled and operated, such as what depth-interval is permitted, how and where to replace waste water. Drilling is assisted by the literature available on oil well operations, but the flow-rate of a new well is difficult to predict beforehand because of variations in granulometry of aquifers even over a short distance.

Well logging techniques are also regulated by law since all data must be comparable. Part of the geothermal wells were drilled for this specific purpose while others were transformed from oil to geothermal wells. The main parameters in geothermal utilization schemes are the temperature and scaling properties of the fluids. The temperature of the water can be predicted within a small error (Fig. 1), depending on the depth of the aquifer.

Scaling properties cannot be predicted with the same probability as temperature, since it depends on the quality and quantity of salt and gas. During production, the physico-chemical characteristics of the geothermal system change, since pressure decreases from several hundred bar to atmospheric pressure and temperature decreases from about 100–120°C to 15–25°C. Consequently the solubilities of the salts and gases also change. The geothermal resources recovered so far in Hungary are of the low enthalpy type. The highest emergence temperature of the water is about 95°C.

Geothermal experience in Hungary is based on the exploitation of 650 geothermal wells and connected heating systems. In systems installed during the last few decades, the thermal water was passed directly through the system. Temperatures dropped through these systems by 40–50°C in the best of cases and the water left the system at 40–50°C. Nowadays when waste water has a temperature of about 30°C the system is considered a success.

Operation costs depend mostly on the quality of the water. In Hungary scaling occurred throughout the system. Incrustations restricted heat transfer and water flow-rate, so the efficiency of the system decreased. The system then had to be shut-down to remove the incrustations. Recently inhibitors have been used but the dosage is of extreme importance as very small concentrations will not inhibit scaling, and very large concentrations will make the water very aggressive. The inhibitor has to be added in the well below bubble-point.

An experiment was conducted in Hungary on different inhibitors: NALCO, Hydrogel, Visco, Sago and a Hungarian product to define the concentrations required. The results indicated that all the inhibitors had the most effect at about 6–8 ppm concentration.

Lately experiments have been conducted on combatting scaling by physical methods and equipment. Only short-term tests of the magnetic technique have been carried out. The results seem to be good but details and conclusions cannot be published yet. Experiments with the ultrasonic method are also planned.

Physical methods have some advantages over chemicals; physical techniques are simple, cheap and unaffected by flow rate.

Modifications have recently been made to the design of the geothermal heating systems. Instead of direct systems only indirect systems have been installed, comprising a primary and a secondary circuit, with thermal water in the primary and fresh water in the secondary. The circuits are connected only by a heat exchanger, so that no scaling occurs in the secondary heating circuit. Degassification is achieved in the short primary circuit.

Opinions vary as to the temperature limit for utilization of geothermal waters, with the lower limit set at 30–35°C, but for energy utilization the temperature must be above 50°C. According to the Hungarian Office of Statistics in 1985 the number of geothermal wells and springs is as shown in Table 1.

The number of wells and percentage of water utilized in the different applications are shown in Table 2.

In 1981 a first assessment was made of the geothermal potential of Hungary. Several thousand data from oil wells were analysed, and used to calculate how much geothermal water could be produced by pumps from a depth of 200 m beneath the surface. They also estimated the distribution of reserves, the quantity of water already exploited and the quantity of reserves which could be exploited in the future. Table 3 reports the present production levels, estimates for the future, savings in oil and the advantages of cooling the water to 25°C.

Geothermal energy is supported by the State under a national Energy Program, which includes a project for promoting the utilization of geothermal energy. As part of this project an

Table 1. Geothermal wells and springs in Hungary by 1985

Temperature of water (°C)	Number of wells			Mineral springs			Flow rate
	1975	1980	1985	1975	1980	1985	(1000 m^3)
<35	257	297	325	23	25	29	4506
35–44	223	243	273	8	11	14	2842
45–59	159	168	196	16	20	22	8474
60–69	57	75	87	8	8	14	7272
70–79	40	50	53	6	8	8	3752
>80	57	65	82	7	8	11	3009
Total	793	898	1016	68	80	98	29,855

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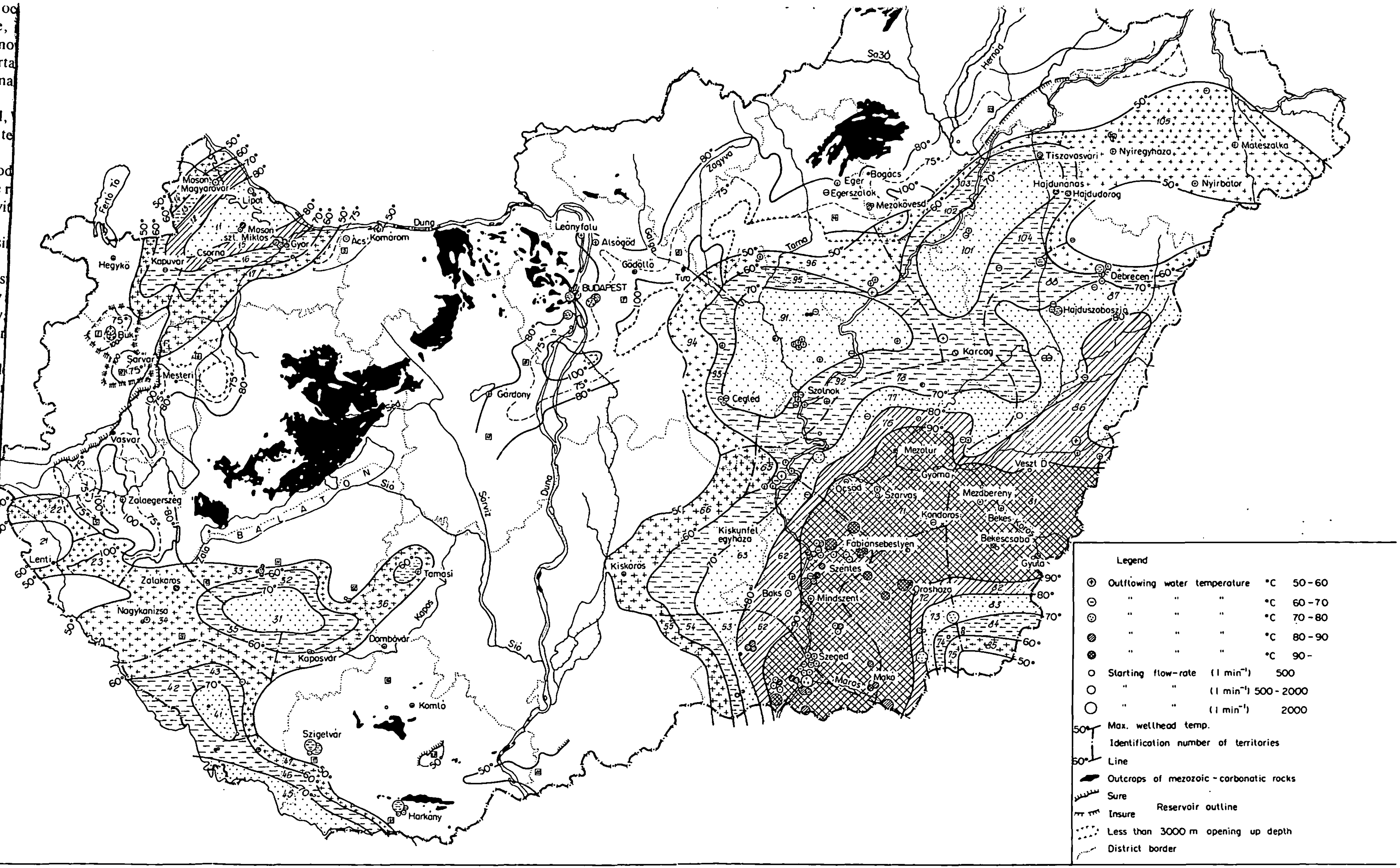

Fig. 1. Map of aquifers containing waters with temeratures > 50°C in Hungary (compiled by Vituki).

Table 2. Number of wells in Hungary and percentage of water utilized in different applications

Utilization	Number of wells 1975	 1980	 1984	 1985	(%)
Spas	221	240	262	277	27.3
Drinking water supply	351	416	366	236	23.2
Agricultural heating	81	97	160	258	25.4
Community heating and hot water supply	20	20	19	14	1.4
Industrial water	15	21	64	70	6.9
Others	21	46	94	128	12.6
Closed temporarily	84	58	44	33	3.2
Total	793	898	1009	1016	100.0

Table 3. Present status and future prospects of the utilization of geothermal fluids in Hungary

	Temperature of the water (°C) at emergence 50–60	 60–70	 70–80	 80–90	 90	Total
1. Produced water (10^3 m^3 day^{-1})	48	59	33	38	46	224
2. Water to be exploited in 10^3 m^3 day^{-1}	432	343	195	97	77	1144
3. % utilized	11.1	17.2	16.9	39.1	59.7	19.6
MW day^{-1} attainable by cooling to 25°C	2510	2419	1394	349	—	6672
	12,558	13,535	9943	6420	5819	48,275
	15,068	15,954	11,292	6769	5819	54,902
Savings in t day^{-1} attainable in TOE	216	208	120	30	—	574
	1080	1164	855	552	500.5	4151.5
	1296	1372	975	582	500.5	4725.5

experimental heating system was installed, in which the cooled water was reinjected into the aquifer. During a preliminary stage the CCC simulation model from the University of Arizona was adapted to Hungarian conditions. Simulation gave very important and interesting results on the effects of reinjection.

The objective of the experiment was to determine the conditions required for reinjection. The only data available previously came from the oil industry where conditions are not comparable with those encountered in geothermal wells.

Reinjection tests were also conducted because this technology is the only means of complying with environmental regulations and those governing water management and production.

All other techniques permitted by the Water Authority do not comply fully with the above regulations. The problem of waste water disposal becomes increasingly important as the environmental laws become increasingly more severe. In future geothermal utilization could be restricted or prohibited because the waste water cannot be disposed of without environmental pollution.

The project also enabled us to collect all data on experiments, techniques, instrumentation and equipment known and used in Hungary in geothermal research and utilization. This material has been edited in five volumes, under the title "Study-aid for planning the utilization of geothermal energy".

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THE GEOTHERMAL INDUSTRY IN ICELAND

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Abstract—Direct (non-electrical) uses of geothermal energy in Iceland in 1984 amounted to 5517 GWh and the installed power was 889 MW_t, assuming 35°C discharge temperature. The bulk of this thermal power was for district heating, called *hitaveita* in Icelandic. In recent years this utilization has increased moderately. The installed geothermal electric power is currently 41 MW_e and is unlikely to change in the near future. Icelandic personnel have participated in many geothermal projects of the United Nations during the last 35 years. Contract work has been carried out by Icelandic consulting firms in several developing countries.

INTRODUCTION

The primary use of geothermal energy in Iceland is for district heating of residential, commercial and industrial buildings. The Icelandic word for geothermal district heating service is *hitaveita* in the singular and *hitaveitur* in the plural. The first such *hitaveita* dates back to 1930 in Reykjavík, when 15 l/s of 87°C water was piped 2.8 km to heat an indoor swimming pool, a school building, a hospital and 70 nearby residential buildings. Other direct uses of geothermal energy in Iceland are greenhouse and soil heating, swimming pools, fish farming and industrial processing. The use of geothermal steam to generate electricity is secondary to direct uses (see Fig. 1).

The purpose of this paper is to discuss the geothermal industry in Iceland, and the work Icelandic geothermal experts have done in other countries, mostly developing countries. Recent reviews of geothermal energy in Iceland include those of Gudmundsson and Pálmason (1981), Gudmundsson (1983a, 1983b), Pálmason *et al.* (1983) and Sigurdsson *et al.* (1985).

ELECTRICITY AND FUELS

The energy market in Iceland is characterized by large hydropower and geothermal resources, and the need for liquid fuels in the fishing industry and for transportation.

In 1985, the total generation of electricity in Iceland was 3837 GWh, of which 3663 or 95%, derived from hydro-power stations. Geothermal electric power stations produced 171 GWh and oil-fired stations 3 GWh. More than one-half the electricity (52%) was used in energy-intensive industries (aluminium, ferrosilicone, ammonia) while 48% was used for general purposes. At the end of 1985, the installed generating capacity of all public electric power stations was 921 MW of which 752 MW was hydro-power, 41 MW geothermal and 128 MW oil-fired stations.

The total liquid-fuel sales in Iceland 1985 were nearly 500,000 tonnes. Almost one-half was distillate fuel at 48%, mainly for fishing vessels, but also for transportation, space heating and industrial use. Gasoline for motor transport amounted to 20% while jet fuel, aviation gasoline

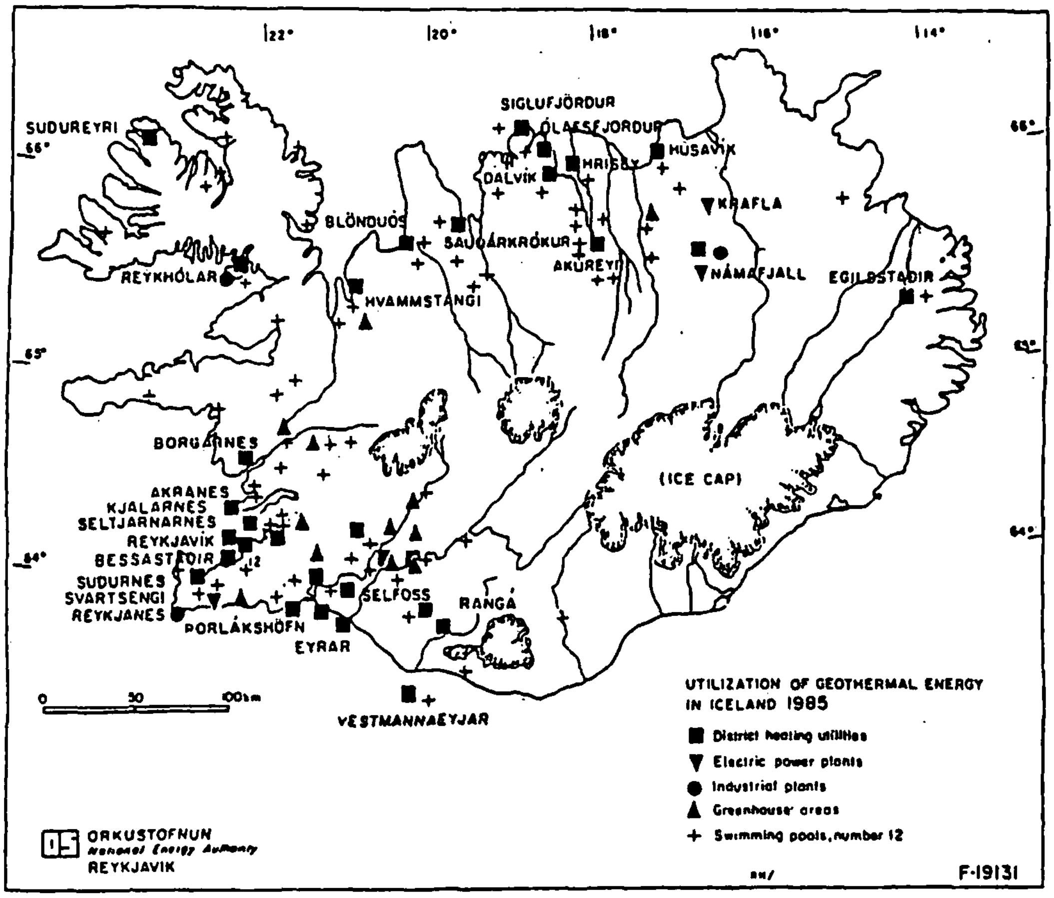

Fig. 1. Utilization of geothermal energy in Iceland, 1985.

and kerosene added up to 14%. Residual (heavy) fuel for use in trawlers and industry was 18%. In 1985, 69,000 tonnes of coal and 34,000 tonnes of coke were imported and mainly used in industry.

ENERGY RESOURCES

Assessment studies have been completed for both the hydro-power (Tómasson, 1981) and geothermal energy (Pálmason, 1981; Pálmason *et al.*, 1985) resources of Iceland (Gudmundsson, 1983a).

The hydro-power assessment is based on a systematic evaluation for the whole of Iceland. It was found that the gross theoretical capability amounts to 187 TWh/yr. The available or usable capability, however, was estimated as 64 TWh/yr, with an associated installed capacity of 7300 MW. These values do not take into consideration the economical and environmental issues, except indirectly. The usable hydro-power is divided into four groups that range from the most economical to marginal. The large hydro-schemes in the highlands (first group) is the most economical with a total generating capability of about 30 TWh/yr; almost one-half the total potential of the country. The associated installed electric power capacity corresponds to about

3400 MW. Therefore, the 752 MW of hydro-power already installed equals about 22% of the most economical, and 10% of the available (usable) capacity.

The geothermal resources of Iceland are traditionally divided into low- and high-temperature fields. The high-temperature fields are within the active volcanic zones while the low-temperature fields are on both flanks of these zones. The two main low-temperature regions are in the south and west of Iceland, at the periphery of the active zones of rifting and volcanism, but other areas are widely distributed. In the low-temperature fields the temperature of the reservoir fluid generally does not exceed 150°C while it is usually 200–350°C in the high-temperature fields.

An assessment of the geothermal potential of the high-temperature fields is based on stored-heat calculations. With certain assumptions regarding the areas of the fields, reservoir thickness and temperature, geothermal recovery factor, and accessibility of the various fields, the total available heat from the high-temperature fields was found to be 10^{20} J. When converted to electricity, this corresponds to 175,000 MW-yr. On the basis of geological considerations, it seems possible that an additional potential of 2–3 times the above values may lie hidden within the neovolcanic zone without direct surface expression. The assessment makes no predictions of the rate at which the energy can be withdrawn, but a considerable body of production data is gradually accumulating (Pálmason *et al.*, 1983; Sigurdsson *et al.*, 1985).

There are about 600 hot springs in 250 low-temperature fields in Iceland. Their natural flow is estimated at 1800 l/s, at an average temperature of about 70°C (Pálmason *et al.*, 1985). With drilling, the total production from the same areas has increased to 4600 l/s or 155% in 1980 (Gudmundsson and Pálmason, 1981; Gudmundsson, 1983a; Gudmundsson, 1983b). The average temperature of this flow was estimated at 80°C. The water produced in the low-temperature fields is used for space heating and other thermal (direct use) applications.

DIRECT AND POWER USES

Hitaveita Reykjavíkur (the Reykjavík District Heating Service) was extended considerably in 1943, when 80°C water was piped 15 km from outside the city. In the 1960s the system was extended to include the majority of buildings in the capital. Today, Hitaveita Reykjavíkur draws water from three low-temperature fields: Laugarnes 290 kg/s at 125°C and Ellidaár 180 kg/s at 96°C within the city, and Reykir 1500 kg/s at 89°C outside the city (Pálmason *et al.*, 1983; Sigurdsson *et al.*, 1985). These flows add up to 494 MW installed capacity, assuming 35°C discharge temperature. Hitaveita Reykjavíkur delivers water to the nearby towns of Kópavogur, Gardabær and Hafnarfjördur, and other communities in the Reykjavík area. At the end of 1985 the service area included about 123,000 people—about one-half the population of Iceland.

There are 29 hitaveitur in Iceland, the largest being Hitaveita Reykjavíkur. Hitaveita Sudurnesja is the second largest *hitaveita* in Iceland, serving the communities on the Reykjanes Peninsula, south-west Iceland, including the Keflavik International Airport and NATO Naval Base. The power plant has a designed capacity of 125 MW thermal and 8 MW of electric power. In 1984, the power plant delivered on average 456 kg/s of 80°C water to its customers, which represents 86 MW for a discharge temperature of 35°C (Gudmundsson, 1985). This gives a load factor of about 70%. The third largest district heating service is Hitaveita Akureyrar, in northern Iceland, serving a population of 13,000 people. At the end of 1985, the 29 public *hitaveitur* served a population of 190,900 people, corresponding to 80% of all Icelanders.

In 1960, the *hitaveitur* in Iceland served about 60% of the population. During the 1960s and 70s there was a steady increase in the number of people served; in the 1980s it levelled off at about 80% of the population (see Fig. 2). When the first oil crisis hit at the turn of 1973–74, therefore, Iceland was well under way to develop its geothermal potential for geothermal district heating. The same was true when the second crisis hit in 1979. The role of electricity in space

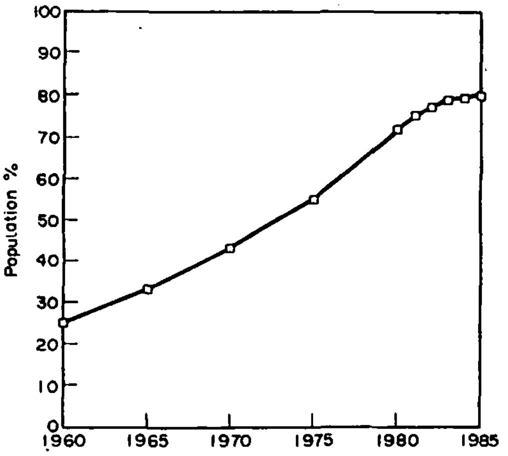

Fig. 2. Population percent enjoying *hitaveita*.

heating has also increased, but to a lesser extent. The use of oil for heating purposes has correspondingly decreased. At the end of 1984, the geothermal energy was used to heat 80% of Icelandic homes, 15% were heated electrically, and 5% by imported oil (see Fig. 3). It has been estimated that in 1985, geothermal district heating saved 4800 million krónur in imported oil, which is equivalent to about 110 million U.S.$.

The cost of heating from a *hitaveita* is in most cases much lower than using imported oil. About 60% of the population pay for their *hitaveita* only 20% of what fuel oil heating costs. The bulk of this low heating cost is that of Hitaveita Reykjavíkur. The heating cost of other *hitaveitur* is in most instances higher; in a few cases higher than electric heating, which amounted to a little less than 60% of oil heating. For some time, fuel oil for heating purposes has been subsidised in Iceland. This practice is now being discontinued due to lower oil prices.

Direct uses of geothermal energy in Iceland and worldwide have been summarized by Gudmundsson (1985). All direct uses in Iceland correspond to a flowrate of 4579 kg/s, installed thermal power of 889 MW, and geothermal energy use of 5517 GWh, hence a load factor of 71%, for a discharge temperature of 35°C. The bulk of this use is for district heating. In 1980, the use of low-temperature fluids above 35°C was estimated at 708 MW, and high-temperature fluids above 100°C at 110 MW, totalling 818 MW (Gudmundsson, 1983a). At that time, the low-temperature use was divided into: district heating 89.2%, greenhouses 5.4%, swimming pools 3.2%, industrial drying 1.9% and fish farming 0.3%. The high-temperature steam use was 50 MW by Hitaveita Sudurnesja, 25 MW for space heating (homes and greenhouses) in the town of Hveragerdi, and 35 MW in a diatomite drying factory in the north of Iceland at Námafjall. The relative use of geothermal energy in these sectors has not changed much in recent years, so about 90% of direct uses are still for district heating.

There is a 30 MW power plant in the Krafla high-temperature field in north-east Iceland. The plant is double-flash of conventional design. Many difficulties have been associated with the Krafla project, ranging from volcanic eruptions to limited steam supply. It is now in full operation. In 1986, the National Power Company became the owner and operator of the Krafla power station. It was previously operated by the State Electric Power Works, under a special agreement with the Government. In Námafjall, there is a 3 MW non-condensing power plant. It is owned and operated by the National Power Company.

There are three back-pressure units in the power plant of Hitaveita Sudurnesja in the

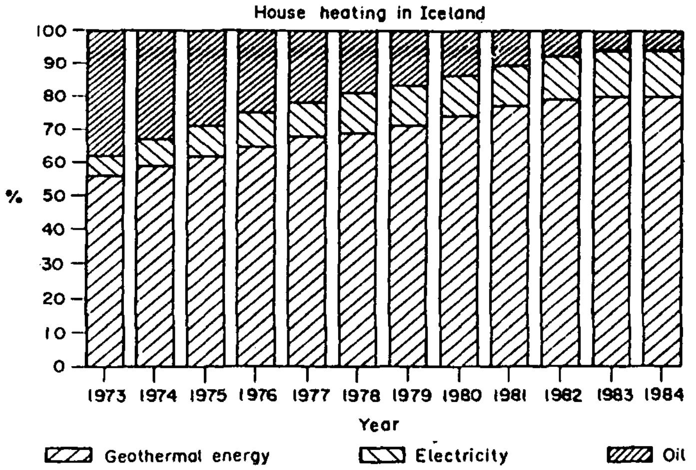

Fig. 3. Percent contribution to house heating.

Svartsengi high-temperature field in south-west Iceland. Two of these are 1 MW and one 6 MW. The Svartsengi power plant is of a unique design, producing district heating water and electric power.

Similar design features to those of Svartsengi are being considered in the Nesjavellir high-temperature field in south-west Iceland, where Hitaveita Reykjavíkur has drilled about 20 wells for steam production and injection purposes. Plans for utilizing this field for a combined power plant for district heating water and electric power are being developed. Experimental work continues at the Reykjanes high-temperature field to produce sea chemicals. Difficulties have been experienced with silica deposition in the crystallization of salt products.

Fish farming has gained in popularity in Iceland in recent years. Several salmon farms have been built and are now in operation—more such farms are under construction. The role of geothermal energy in these operations is to heat fresh water and seawater, both in smolt rearing and large scale fish tanks, where salmon is raised for harvesting. The need for large quantities of fresh water and clean seawater appear to be of greater concern in these operations than is the availability of geothermal heat.

ORGANIZATION

The primary organization of geothermal exploration, development and exploitation in Iceland, is the Geothermal Division of the National Energy Authority. With a staff of about 60, the Geothermal Division carries out all of such work in Iceland, and in some cases in other countries. The National Energy Authority is an organization that (1) advises the Government in the field of energy (2) investigates and conducts research in the country's indigenous energy resources and (3) analyses energy systems and policy options.

The Geothermal Division of the National Energy Authority dates back about 40 years. All this time it has been in the forefront of new equipment and interpretation techniques in geothermal prospecting; geology, geophysics and geochemistry. It has well equipped laboratories in geochemistry and electronics. All logging operations in Iceland are carried out by the Geothermal Division; it has three state-of-the-art logging trucks. Production and reservoir engineering measurements are similarly done by personnel of the Geothermal Division; computer processing is at an advanced stage. Geothermal research is also carried out at the University of Iceland.

Drilling for geothermal water and steam in Iceland is done by the Icelandic Drilling Company Ltd, formerly the State Drilling Contractor. Like the Geothermal Division of the National Energy Authority, it dates back about 40 years. The Icelandic Drilling Company Ltd, owns and operates five main drillrigs: Jötunn (1977) 3600 m; Dofri (1958) 2000 m; Narfi (1978) 1400 m; Glaumur (1971) 1000 m and Ymir (1963) 600 m. It also owns cable tool and core drilling equipment. Fresh water and shallow test holes are also drilled by the company.

Hitaveita Reykjavíkur is owned and operated by the city of Reykjavík. The 28 other public *hitaveitur* in Iceland are similarly owned and operated by the town and communities that receive the hot water. There are a few district heating services that are non-geothermal. They use electricity and imported oil, and serve a population of about 5500.

The design and engineering of all district heating systems and geothermal plants in Iceland is carried out by a number of experienced engineering consulting firms. None of the *hitaveitur*, for example, do their own design work, not even Hitaveita Reykjavíkur, Hitaveita Sudurnesja (Svartsengi field) and Hitaveita Akureyrar. The *hitaveitur* keep a staff of engineers to manage the operation and maintenance of their systems, and to plan additions, but all engineering design and most construction management is done by the engineering consulting firms.

OVERSEAS ACTIVITY

Worldwide consulting work has been carried out by the Virkir Consulting Group, Ltd since about 1976. The group was formed in 1969, to work on large energy projects in Iceland. It then expanded to include international projects in the fields of hydro-power and geothermal power plants, geothermal prospecting, drilling engineering; also fishing and fish processing. The Virkir Consulting Group, Ltd, has a permanent staff of about 90.

In 1985 a new geothermal consulting company was founded in Iceland, called Orkustofnun International Ltd. It is a Government company and has the function of marketing the know-how and experience gathered by the National Energy Authority, mainly in geothermal energy but also in hydro-power projects.

Icelandic personnel have participated in United Nations geothermal projects from the start, some 35 years ago. Currently, five Icelanders are working full-time on U.N. projects. One is inter-regional adviser in the New York headquarters; two are chief technical advisers, one in Kenya and the other in the Philippines; two are project scientists in Kenya. In the period 1951–86, Icelandic engineers and scientists worked 235 man-months on U.N. demonstration projects in El Salvador, Turkey, Nicaragua and Kenya (Einarsson, 1986). On other U.N. projects, Icelanders have worked 226 man-months. From 1980 the inter-regional adviser on geothermal energy has been an Icelander, adding another 72 man-months. Therefore, Icelanders have worked on U.N. geothermal projects 533 man-months in total. Expert missions for other agencies amount to 6 man-months. An Icelander is now the chief technical advisor of a World Bank project in Djibouti.

Contract work has been carried out by Icelandic consulting firms in Tanzania, Kenya, Hungary, Greece, Turkey and China. This work amounts to 231 man-months (Einarsson, 1986). In total, therefore, Icelanders have worked 770 man-months on geothermal projects overseas, which corresponds to 65 man-years. This work has been in 36 countries. The private sector has provided 70% of manpower, the National Energy Authority 30%. Personnel of the University of Iceland are included in the private sector percentage.

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SVARTSENGI FIELD PRODUCTION DATA AND DEPLETION ANALYSIS

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INTRODUCTION

There have been two major high-temperature geothermal field developments in Iceland in the last decade: Krafla in the north-east, and Svartsengi in the south-west. These and other geothermal developments have recently been reported by Palmason et al.[1] The Krafla field will not be discussed here, but details about the field are available in Stefansson[2] and the power plant in Eliasson et al.[3] Several reservoir engineering studies of the Krafla field have been published.[4,5,6]

The Svartsengi field is one of several fields on the Reykjanes Peninsula in south-west Iceland. About 15 km west of Svartsengi, on the tip of the Peninsula, the Reykjanes field is now under development, primarily for seawater chemicals production. The recently drilled Eldvorp field is located in line between these two fields, about 5 km west of Svartsengi. There are also several fields to the east of Svartsengi, at 15-20 km distance.

The Svartsengi, Eldvorp, and Reykjanes fields exist in the same tectonic-volcanic environment, and are surrounded by similar geohydrological conditions, as discussed by Georgsson;[7] see also Gudmundsson et al.8 and Franzson.[4] Optimum development of these and other fields on the Reykjanes Peninsula, requires an understanding of their depletion behavior with time; that is, how the reservoir pressure falls with production. While recognizing that no two geothermal fields are alike, we also realize that an understanding of the depletion behavior of Svartsengi, for example, may prove useful in the development of other similar and nearby fields.

The main purpose of this paper is to report our depletion analysis of the Svartsengi field using lumped-parameter and water influx modeling; we also report the field's production history.

FIELD DEVELOPMENT

The Svartsengi geothermal field is classified as high-temperature and liquid-dominated. The reservoir temperature is in the range 235-240 $^\circ C$, and the fluids produced are in composition two-thirds seawater and one-third rainwater. The Svartsengi field has been developed by the Sudurnes Regional Heating Company, which provides district heating service for the communities on the lower Reykjanes Peninsula; also called the Sudurnes Region. The two-phase mixtures produced by the wells are piped to the power plant and used in a heat exchange process to produce hot water. This is done by heating and degassing fresh cold water; some electric power is also generated. The capacity of the power plant is 125 MW_t for district heating and 8 MW_e of electric power. The power plant and field developments are discussed by Thorhallsson,[10] and Gudmundsson.[11]

The location of the eleven geothermal wells drilled in the Svartsengi field are shown in Fig 1. Wells 2, 3 and 10 are 239 m, 402 m, and 424 m deep. Wells 4-6 are 1713 m, 1579 m, and 1734 m deep. Wells 7-9, 11 and 12 are 1438 m, 1603 m, 994 m, 1141 m, and 1488 m deep. All wells in the Svartsengi field have been productive. The chemical composition of the brines produced is spatially and temporally uniform, suggesting good fluid mixing within the reservoir. The temperature profile below 400-600 m depth is also uniform, again indicating good fluid mixing (convection) within the system. Limited interference testing has shown that pressure transients travel rapidly (in minutes) across the field. This indicates the high permeability found throughout the wellfield area. These and other data suggest to us that lumped-parameter modeling is appropriate for the Svartsengi reservoir.

Fluid extraction and reservoir draw-down in Svartsengi have been monitored since the start of production on October 18, 1976; these data are shown in Table 1. The rate of production refers to the time period since the previous rate; for example, between 388 and 419 days of production, the rate was 51 kg/s. The cumulative production can be calculated from the rate and time period (interval). In the original data set, the draw-down was not always measured on the days when the rate of production changed. Therefore, for some of the draw-down values in Table 1, we used interpolation to obtain concurrent rate and draw-down. The draw-down is measured as water level in a monitoring well. Well 5 was used the first two years, well 6 for about half a year, and well 4 ever since. The fluid extraction has been estimated from the output characteristics of production wells, and their time on line. The total rate of production data are shown in Fig. 2 with time. In the last few years the

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logy of the Hengill central volcano is described by Saemundsson (1967). Extensive geophysical investigations have been carried out in the area and are described by Björnsson and Hersir (1981).

well has discharged dry steam when it was first put on discharge. This behaviour is in agreement with the hypothesis of a steam zone existing below 800 m depth. Later the flowing enthalpy decreased to some 2000 kJ/kg. A detailed study of the reservoir pressure in the five wells NG-6-NG-10 has resulted in far more complex picture of the geothermal system.

Figure 3 shows the reservoir pressure distribution in different wells in the Nesjavellir geothermal field, and fig. 4 shows the location of the wells. Fig. 3 shows that the pressure seems to divide the geothermal system into four different parts of pressure potential.

The reservoir pressure is partly determined as the pivoit point in pressure profiles measured during the heating of wells after completion, and partly as pressure measurement of the first aquifer intersected by drilling beneath the cemented casing. The data points given in Fig. 3 are therefore considered to be fairly good determination of reservoir pressure (Stefansson and Steingrimsson 1980a, Grant 1979).

Comparing the reservoir pressure below 800 m depth (- 500 masl) in wells 6 and 9 shows, that the reservoir is in boiling condition at

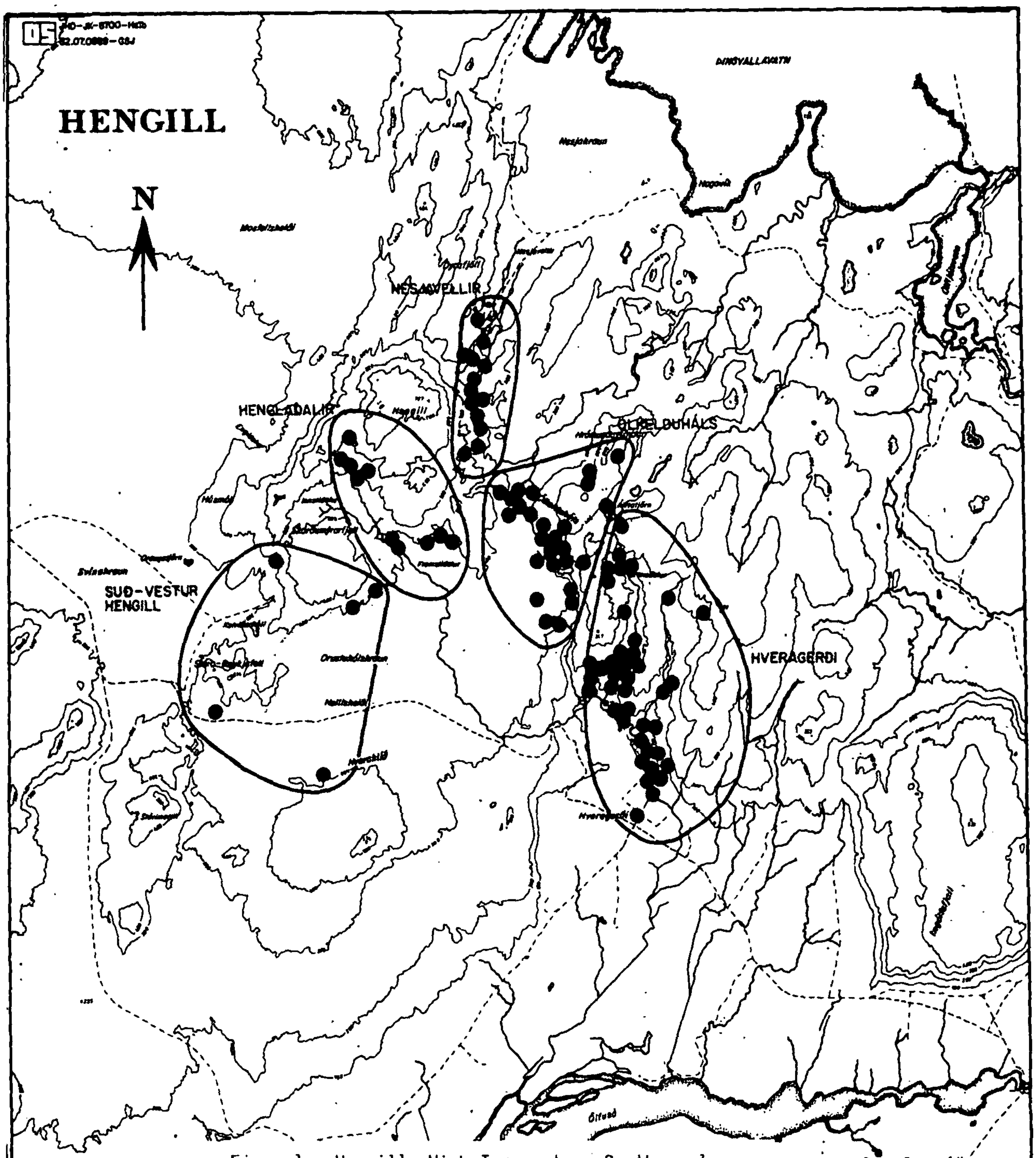

Fig. 1 Hengill High Temperature Geothermal Area. Block dots are steam vents.

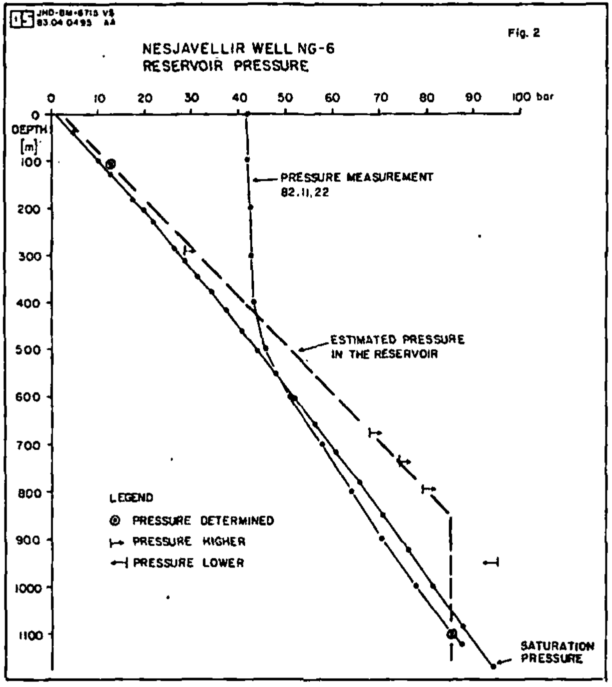

Fig. 2 Reservoir pressure in well NG-6.

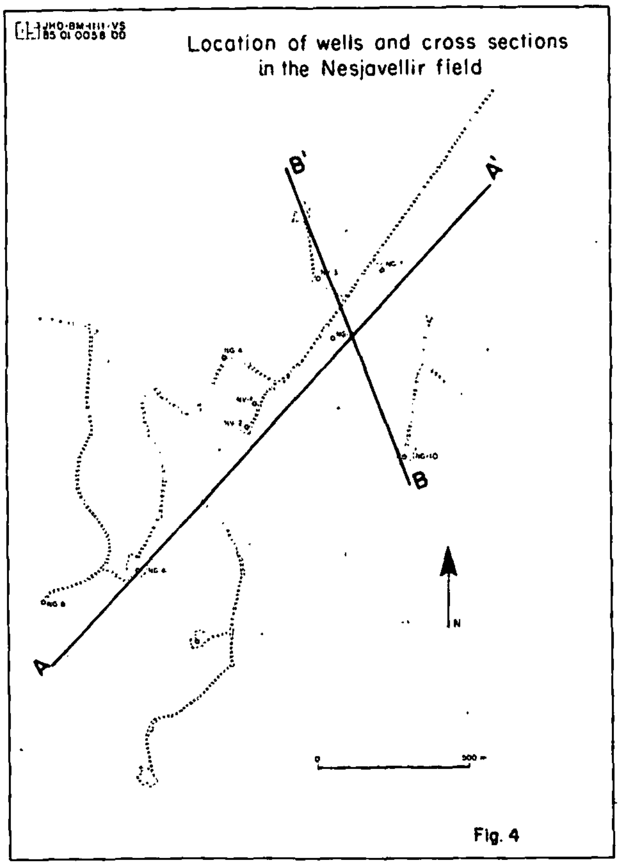

Fig. 4 Location of wells and cross sections in Nesjavellir.

this location and a steam zone cannot be confirmed from the data. The four different parts of the reservoir as defined by the pressure distribution (Fig. 3) are represented on a cross section shown in Fig. 5. It seems necessary to have impermeable barriers both horizontal and vertical in the system. The most remarkable condition is that well 6 seems to intersect three different zones. The geothermal system is highly three dimensional and a two dimensional projection cannot give a true picture of the system.

Figures 6 and 7 show the pressure distribution at sea level and at 500 m below sea level in the Nesjavellir reservoir. In both cases is the pressure highest to the southwest and decreasing towards northeast. There is a large variation in the temperature in the reservoir as well as in the pressure. Figure 8 shows the temperature distribution in the SW-NE cross section and Figures 9 and 10 show the temperature distribution at sea level and at 500 m below sea level.

Both pressure and temperature distributions show highest values in the SW part of the investigated area and decreasing values towards northeast. These circumstances might indicate a lateral flow in the system from SW to NE. The temperature distribution in Figures 9 and 10 indicates, furthermore, that this flow is preferably taking place in the northern part of the area rather than in the southernmost part.

A cross section of temperature distribution from SE to NW in the northern part of the investigated area shows these conditions clearly, Fig. 11. Comparison of pressure and temperature in the reservoir shows that at depth the reservoir is boiling (two phase) in the southwestern part of the investigated area, but is in liquid phase in the NW part. This is also reflected in the flowing enthalpy of wells. Wells 6 and 9 have flowing enthalpy of about 2000 J/g but wells 5 and 7 have flowing enthalpy 1200 J/g.

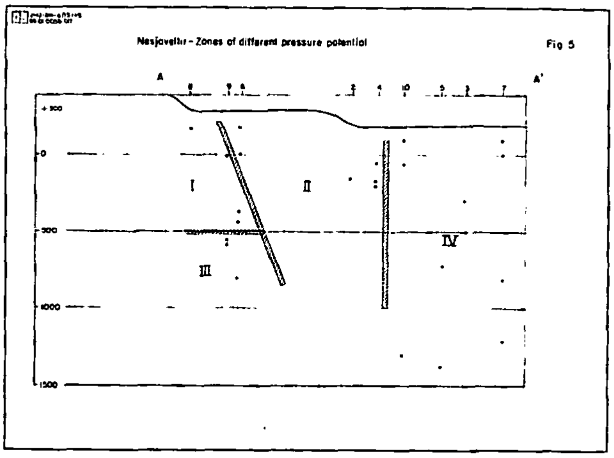

Fig. 5 Cross section of the Nesjavellir field showing the four parts of the reservoir.

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Fig. 3

Nesjavellir – Reservoir pressure

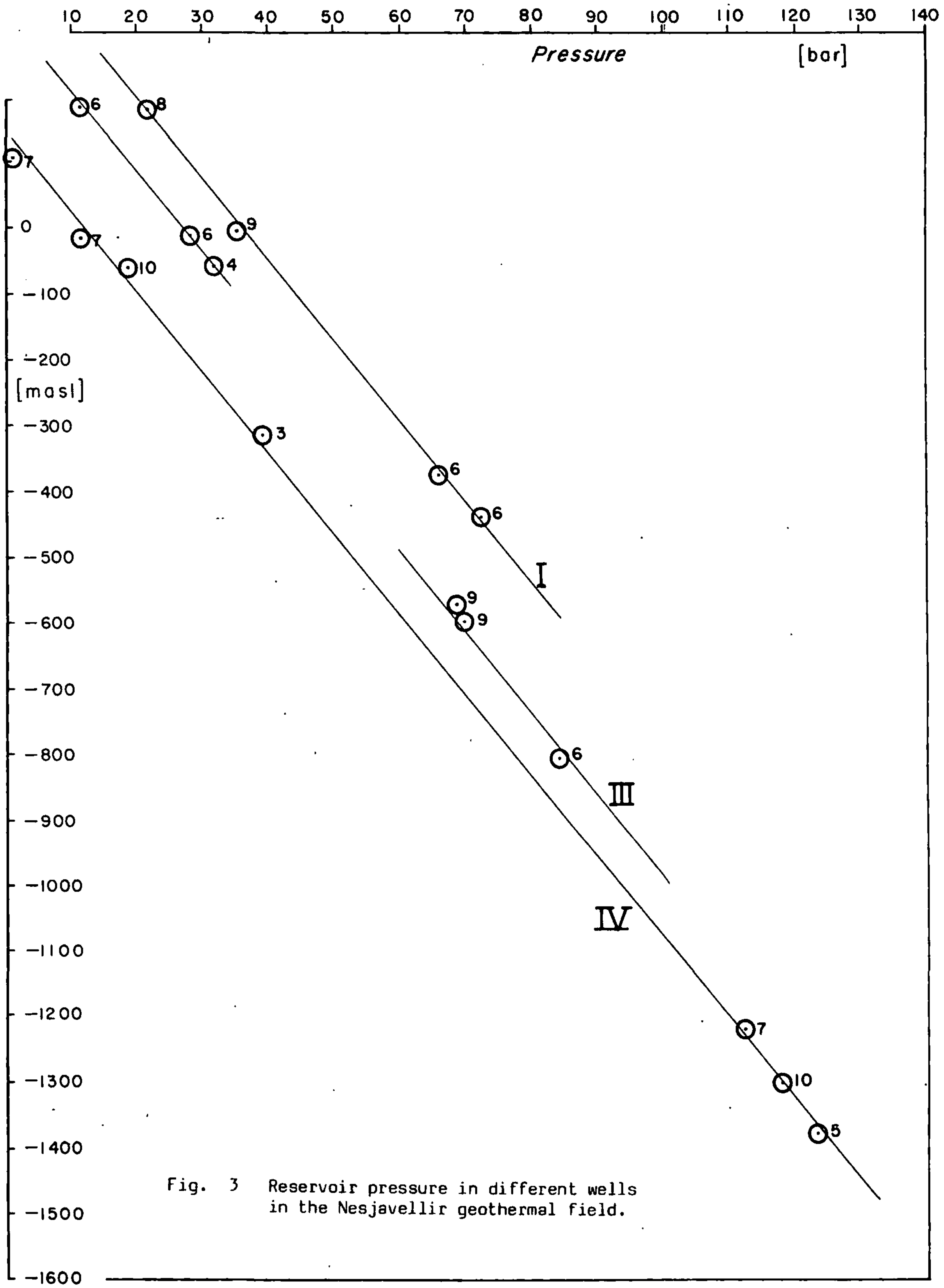

Fig. 3 Reservoir pressure in different wells in the Nesjavellir geothermal field.

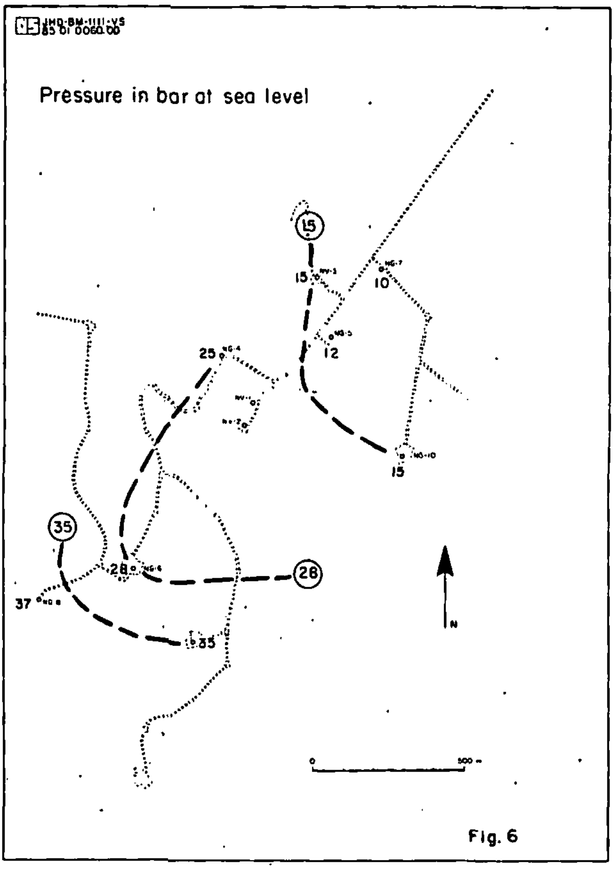

Fig. 6 Pressure distribution at sea level in the Nesjavellir reservoir.

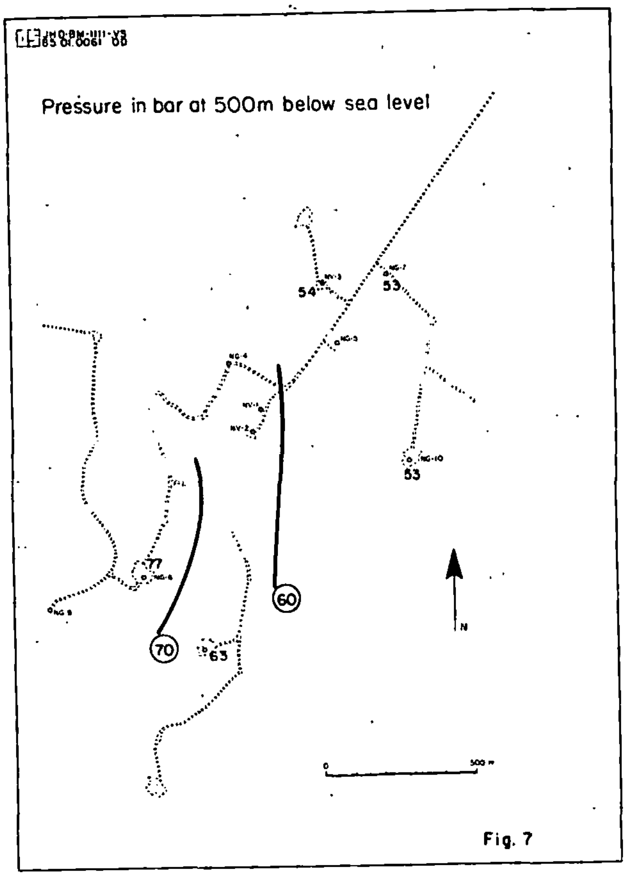

Fig. 7 Pressure distribution at 500 m below sea level in the Nesjavellir reservoir.

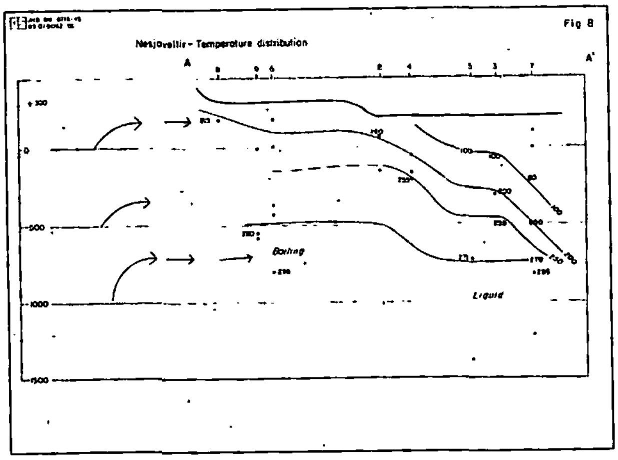

Fig. 8 The temperature distribution in cross section A A´ in the Nesjavellir reservoir.

TABLE 1

HYDRAULIC PROPERTIES OF WELLS IN THE NESJAVELLIR FIELD

Wells	$\frac{kh}{\mu}$	Total flow	Enthalpy	Heat
	$m^3/Pa\cdot s$	kg/s	kJ/kg	MW
NG- 5	1,3	23	1400	32
NG- 6	3,5	29	1920	56
NG- 7	2,1	35	1220	43
NG- 9	3,0	29	2080	60
NG-10	1,7	-	-	-

PERMEABILITY

Information on permeability is at present only available from transmissivity determinations made by injection tests at the completion of each well. It has, however, been demonstrated (Sigurdsson et al. 1985) that carefully analyzed injection tests of 10-20 hours duration in both single phase and two phase geothermal reservoirs give consistent values with recovery tests lasting for several months. It is therefore considered that the injection tests made in Nesjavellir gives fairly reliable values on the transmissivity of different wells in the Nesjavellir reservoir.

Table 1 shows the transmissivity, flow rate, flowing enthalpy and thermal output of wells in Nesjavellir. It is seen in Table 1 that the transmissivity and the thermal output of wells is fairly constant despite the flowing enthalpy varies considerably.

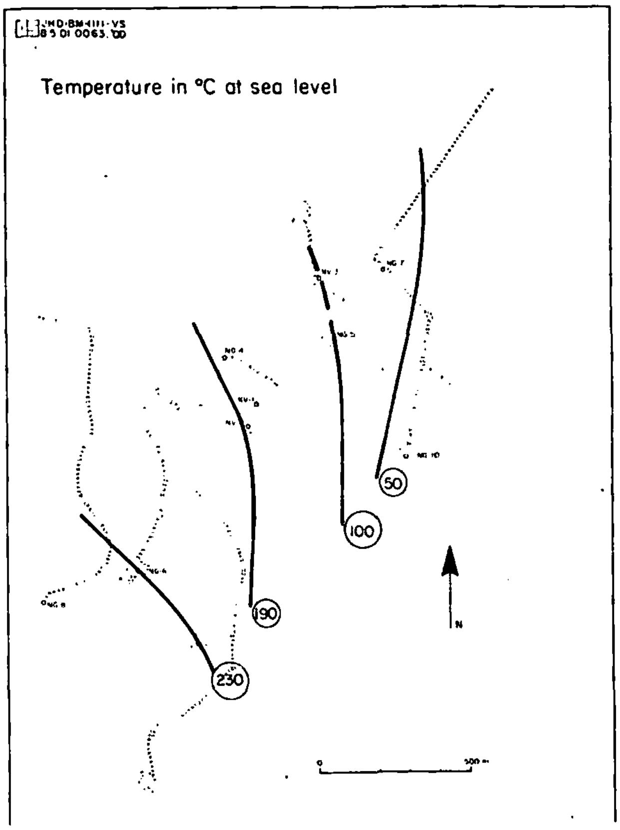

Fig. 9 Temperature distribution at sea level in the Nesjavellir reservoir.

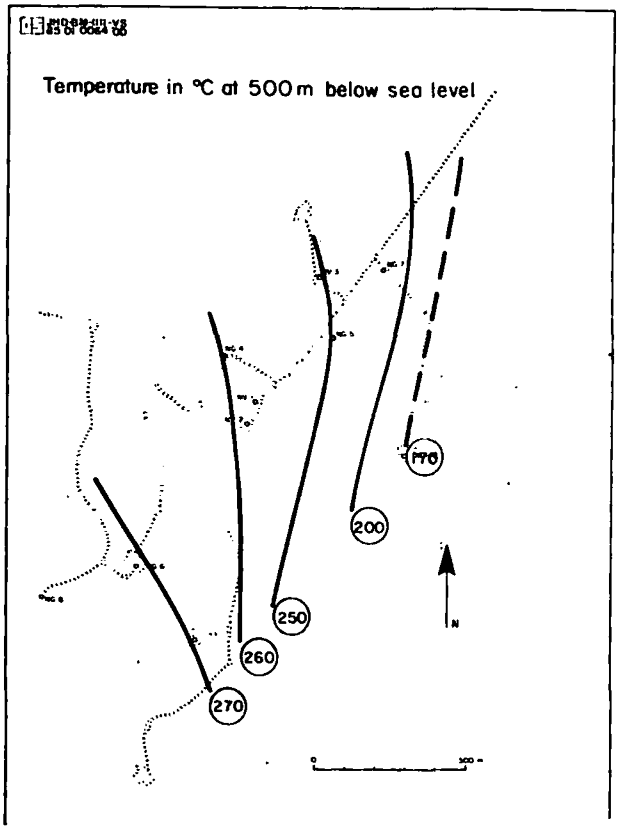

Fig. 10 Temperature distribution at 500 m below sea level in the Nesjavellir reservoir.

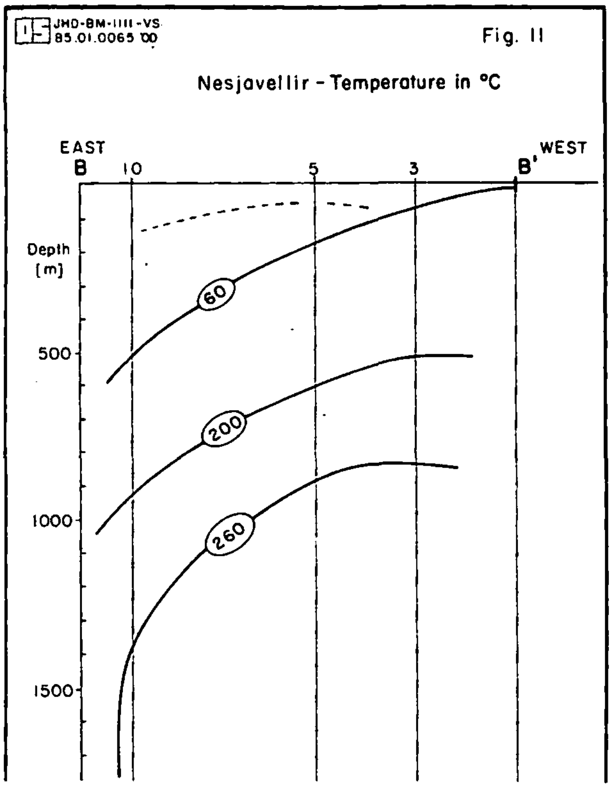

Fig. 11 Temperature distribution in the cross section B B´ of the Nesjavellir reservoir.

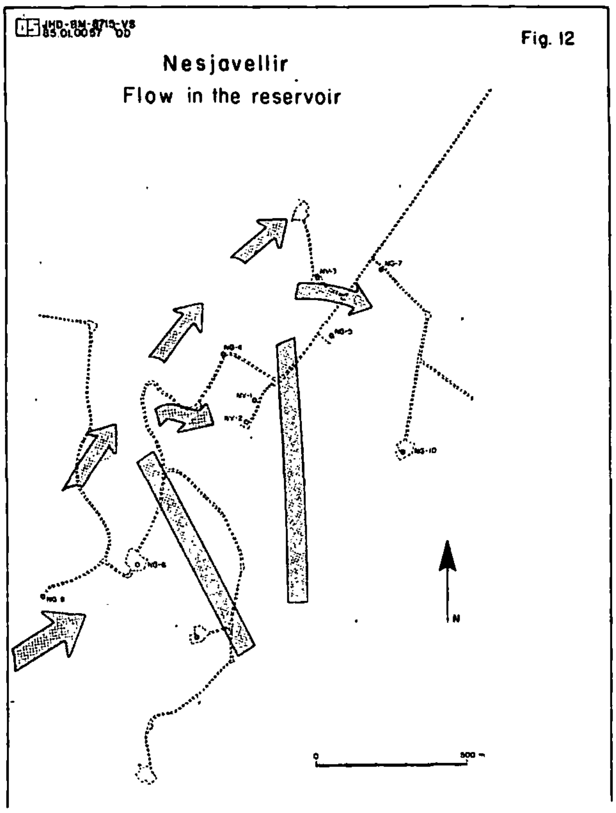

Fig. 12 Flow in the Nesjavellir reservoir.

CHEMISTRY OF THE THERMAL FLUID

Despite the inhomogenity of the physical conditions (pressure and temperature) of the geothermal system at Nesjavellir, the chemical condition seems to be rather uniform. Table 2 shows typical chemical compositions of the fluid discharged from four of the wells in Nesjavellir.

There is a difference in the chemical composition between the high enthalpy and the low enthalpy wells. Especially is the low concentration of Cl in the low enthalpy wells noticeable. In general the chemistry indicates that the fluids in different wells are of common origin.

CONCEPTUAL MODEL

The characteristics of the Nesjavellir geothermal system are:

- The pressure distribution within the system is very inhomogenous in both horizontal and vertical directions. In general, the highest pressure is found in the southwestern part of the investigated area.
- There are considerable variations in the temperature in the system and the highest temperatures are in the SW part of the area.
- The geothermal system is partly in two-phase condition and partly in single phase conditions.
- The chemical composition of the thermal fluid is relatively homogenous and common origin of the fluid is assumed.
- There is little variation found in permeability between different wells, and thermal output of wells are in the range 40-60 MW.

Combining together these items we arrive at a conceptual model where we have to place the main upflow zone outside the area which have so far been investigated by drilling. The pressure and temperature distributions indicate that the upflow zone should be in the SW direction from the investigated area. Furthermore, both pressure and temperature distributions indicate that there is a substantial lateral flow in NE direction just north of the present drilling area.

There seems to be at least four distinct zones in the system with different pressure potential. These zones are separated by barriers both vertically and horizontally. This means that the three dimensional feature of the system is rather pronounced, and a representation of the system in a two dimensional picture is not an easy task.

In Figure 12 an horizontal projection has been selected to describe the conceptual model. In general this picture could show the natural flow in the geothermal system at -500 masl in the geothermal system. The picture shown in Fig. 12 is a large simplification of the observed data from the Nesjavellir geothermal system. However, this model seems to be in agreement with all observations made so far for the Nesjavellir system. Therefore, this simplified picture is chosen at present as a conceptual model even though it will not describe in details the three dimensional features of this geothermal system.

TABLE 2

CHEMICAL COMPOSITION OF TOTAL DISCHARGE
FROM WELLS IN NESJAVELLIR FIELD. CONCENTRATION
IN mg/kg.

WELL	NG-5	NG-6	NG-7	NG-9
DATE	83-06-24	84-09-30	84-09-29	84-11-21
WPH bar	7.2	20	8.8	10.2
H kJ/kg	1240	1828	1220	2185
SiO	531.7	446.5	593.5	285.6
Na	101.3	59.1	132.8	53.1
K	18.3	10.8	20.8	7.1
Ca	0.20	0.03	0.36	0.01
Mg	0.02	0.00	0.00	0.00
SO	27.4	3.65	22.90	1.89
Cl	1.6	43.7	4.58	30.6
F	0.78	0.40	1.11	0.23
CO	1421.0	2668.4	1303.6	2560.0
H S	412.0	801.5	313.9	817.4
H	14.1	40.2	29.0	38.4
CH	4.6	1.75	7.4	3.4
N	53.6	35.8	61.9	33.3
O + A	2.5	2.1	2.1	1.61

ACKNOWLEDGEMENT

The present summary on the Nesjavellir field is based on the work of numerous people. I want to thank Arni Gunnarsson, Einar Gunnlaugsson, Sveinbjörn Björnsson, Gudmundur Bödvarsson, Hjalti Franzson, Hilmar Sigvaldason, Jens Tomasson, Asgrimur Gudmundsson and Benedikt Steingrimsson for fruitful discussions on these investigations. The Reykjavik Municipal District Heating System is thanked for permission to publish data from the Nesjavellir high temperature field.

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The Krafla Geothermal Field, Iceland:
3. The Generating Capacity of the Field

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This paper presents analytical and numerical studies of the generating capacity of the Krafla field. A general lumped parameter model is developed which can be used to obtain rough estimates of the generating capacity of a geothermal field based on the size of the wellfield, the average formation porosity, and the amount of recharge to the system. The model is applied to the old wellfield at Krafla. More sophisticated calculations of the generating capacity of the Krafla field are also performed using distributed-parameter models. Two-dimensional areal models of the various reservoir regions at Krafla are developed and their generating capacities (MW_e) evaluated. The results obtained indicate that the old wellfield can sustain steam production of 30 MW_e for 30 years. The estimated power potential of the new wellfield is 20 MW_e for 30 years. To obtain the required steam production several additional wells may be drilled in the old and new wellfields.

INTRODUCTION

Various methods are available for assessing geothermal reservoirs. The ones most commonly used are volumetric methods, lumped parameter models, and distributed parameter models. These different methods vary greatly in complexity. Proper choice of a method most suitable to a given site and stage of development depends primarily on the amount of available data and the objectives of the assessment (e.g., generating capacity, injection effects, etc.)

Volumetric estimations are relatively simple, as they involve only a calculation of the amount of hot fluid in place [*White and Williams*, 1975; *Sorey et al.*, 1982]. The recoverable energy is then calculated using an assumed constant factor, for example, 25% [*White and Williams*, 1975], or a factor estimated from an idealized production plan [*Sorey et al.*, 1982]. Note that in this approach the important effects of the reservoir transmissivity are neglected. *Bodvarsson et al.* [1982*b*] show that for low permeability reservoirs the recoverable energy may be much less than 25% of the energy in place. Thus volumetric estimations should be used only when no permeability data are available.

When one or more wells have been drilled in a geothermal field, the recoverable energy should be estimated using lumped or distributed parameter methods. These methods have the capability of including subsurface information (especially reservoir transmissivity and fluid recharge) in the reservoir assessment; the lumped parameter method, however, has a very limited capability. Due to their simplicity, lumped-parameter models are useful when (1) the reservoir information is limited and (2) only the average field behavior under exploitation is under evaluation. In the lumped parameter approach the reservoir system is represented by means of one or at most a few interacting boxes which correspond to the different reservoir zones, e.g., wellfield, recharge zones, etc. [*Grant et al.*, 1982]. Spatial variations in reservoir thermodynamic conditions and formation properties within each box are neglected. Coarse representation of the reservoir system employed in the lumped parameter approach makes it unsuitable for matching enthalpy data from two-phase reservoirs. Thus in the case of two-phase reservoirs, lumped parameter models should be applied with caution, as the energy extraction employed in the model may not match the observed energy extraction from the reservoir. More serious limitations arise when lumped parameter models are used to simulate reinjection effects. However, when properly used, lumped parameter models can offer simple and useful initial estimates of reservoir longevity. Numerous lumped parameter models of geothermal fields have appeared in the literature, e.g., Wairakei, New Zealand [*Whiting and Ramey*, 1969; *Fradkin et al.*, 1981], Broadlands, New Zealand [*Grant*, 1977], and Cerro Prieto, Mexico [*Westwood and Castanier*, 1981]. Many of these models are summarized by *Grant et al.* [1982].

Distributed parameter models are necessary when detailed reservoir assessment is required and sufficient field data are available. As the name implies, distributed parameter modeling involves dividing the reservoir system into many blocks (generally tens, hundreds, or thousands of blocks); the number of blocks depends upon the accuracy desired and the amount of data available. In this approach the entire reservoir system (caprock, reservoir, bedrock, recharge areas, etc.) may be modeled with any level of accuracy desired. Distributed parameter models may be one, two, or three dimensional and can treat the reservoir on a fieldwide scale or model each well individually. With increasing dimensionality and complexity of a problem, computation costs increase rapidly. However, other factors are generally more significant when a proper modeling approach is selected. These factors include data quality, problem complexity (two- or three-dimensional problem) and the level of conceptual understanding of a reservoir.

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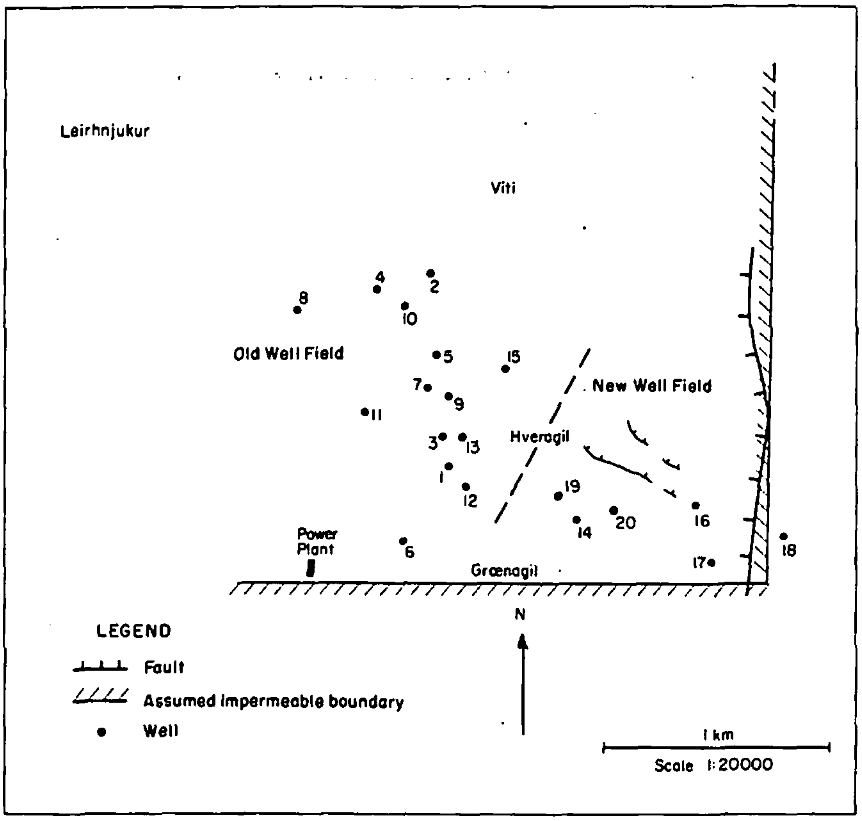

Fig. 1. Well locations and assumed boundaries at the Krafla field.

Various distributed parameter models of geothermal fields, with different degrees of detail and complexity, have appeared in the literature. These include two-dimensional models (areal and vertical) of the Wairakei geothermal field, New Zealand [*Mercer and Faust*, 1979; *Pritchett et al.*, 1980; *Blakely and O'Sullivan*, 1982], Baca, New Mexico [*Bodvarsson et al.*, 1982*b*], Olkaria, Kenya [*Bodvarsson et al.*, 1982*a*; *Bodvarsson and Pruess*, 1981], and Cerro Prieto, Mexico [*Lippmann and Bodvarsson*, 1983] and three-dimensional models of East Mesa, California [*Morris and Campbell*, 1981] and Serrazzano, Italy [*Pruess et al.*, 1983]. *Jónsson* [1978, 1979] conducted preliminary modeling studies of the Krafla geothermal field, Iceland.

In the present paper we will present a general lumped parameter model for predicting recoverable thermal (and electrical) energy from geothermal reservoirs and use it to estimate the electrical power generating capacity of the old wellfield at Krafla. Then we will develop several distributed parameter models of the various reservoir regions at Krafla. These models are two-dimensional areal models (i.e., gravity effects are neglected). In the present work we will determine the generating capacities of the different wellfields (old and new wellfields) and estimate the number of wells that should be drilled to obtain the required steam. In a subsequent paper a more detailed study of the performance of producing wells using a quasi three-dimensional model is described, and future behavior of the wells and the overall depletion of the reservoir system is predicted [*Pruess et al.*, this issue].

APPROACH

The Krafla geothermal field can be divided into two sections, the old wellfield (Leirbotnar) west of Hveragil, and the new wellfield to the east where some of the more recently drilled wells are located (Figure 1). The analysis of the natural state of the Krafla system shows that the two wellfields interact through the fracture zone at Hveragil [*Bodvarsson et al.*, this issue (*b*)]. Figure 1 shows posssible field boundaries as inferred from field data, and major faults in the new wellfield. We hypothesize that the fault zone associated with the Graenagil gully is closed to fluid flow, so that there is no fluid recharge into the wellfields from the south. This hypothesis is supported by the resistivity data from the field [*Karlsdottir et al.*, 1978], which show a sharp increase in resistivity across the Graenagil gully [see *Bodvarsson et al.*, this issue (*a*), Figure 4]. We also assume that the faults between well 18 and wells 16 and 17 act as impermeable barriers. The fact that well 18 is much colder than the other wells in the new wellfield makes this assumption reasonable. Another piece of evidence for the lack of hydraulic communication across the faults in the south (Graenagil) and east is the sharp increase in depth to hydrothermally altered rocks in these directions. For example, the depth to the epidote-chlorite zone is typically 250 m in both wellfields but increases to about 800 m to the south (well 6) and east (well 18; A. Gudmundsson, personal communication, 1982).

In the simulations we only model the lower reservoir in the old wellfield. The fluids in the upper reservoir in the old wellfield are not hot enough to yield high pressure steam (the inlet pressure for the Krafla turbines is 7 bars), and most of the produced fluids come from the lower two-phase zone. However, some of the wells are open to both reservoir zones; the effects of fluid production from the upper, lower-enthalpy zone is studied in the modeling of individual wells [*Pruess et al.*, this issue]. In the new wellfield we also assume an effective reservoir thickness of 1000 m (depth of 1000–2000 m). Most of the wells in the new wellfield produce from the fracture zone

TABLE 1. Parameters Used in the Simulation Studies

Parameter	Specification
Porosity	2–5%
Outside transmissivity	2.0 Darcy meters
Wellfield transmissivity	1.5–4.0 Darcy meters
Reservoir thickness	1000 meters
Heat capacity of rocks	1000 J/kg °C
Density of rocks	2650 kg/m³
Thermal conductivity	2.0 J/m s °C
Relative permeabilities	*x* curves or SGB curves
Residual liquid saturation	0.30
Residual vapor saturation	0.05

at a depth of 1000 m [see *Bodvarsson et al.*, this issue (*a*), Figure 12], with few significant feeds at shallower depths. Deeper feeds (~2000 m) are present in some of the wells.

In the present study we assume a uniform pressure decline throughout the wellfield in response to fluid production; i.e., the wellfield is modeled as one block within which there are no spatial pressure variations. Modeling the wellfield using a single element tends to give rather optimistic results, as the average pressure in the wellfield is higher than the bottomhole pressure in flowing wells. On the other hand, use of an areal two-dimensional model (neglecting gravity) may give rather conservative results [*Faust and Mercer*, 1979]. Some of these approximations are tested in the modeling of the individual wells reported in a subsequent paper [*Pruess et al.*, this issue].

The parameters used in the present study are given in Table 1. The porosities of the reservoir rocks are obviously of major importance; the average porosity of the Krafla reservoirs has been estimated as 2–5% (H. Kristmannsdòttir, personal communication, 1980). The transmissivities of the Krafla wells vary between 1.0 and 4.0 Darcy meters (Dm) [*Bodvarsson et al.*, this issue (*a*)]; a reasonable average value for the recharge areas outside of the main wellfield is 2.0 Dm. A uniform reservoir thickness of 1000 m is assumed for the reservoirs in the old and new wellfields. In the study we use primarily linear relative permeability curves (*x* curves); we also present results for the relative permeability curves suggested by *Sorey et al.* [1980] (hereafter referred to as SGB curves). The simulation studies of the natural state of the Krafla system indicate that the Corey-curves [*Corey*, 1954] are not applicable to the Krafla field [*Bodvarsson et al.*, this issue (*b*)]. Other parameters listed in Table 1 are assigned reasonable average values for basaltic rocks.

In the simulation studies we produce sufficient steam for a fixed power output (e.g., 15, 20, 30, 40, or 60 $\mathrm{MW_e}$). We assume that 2.4 kg of steam are needed to produce 1 $\mathrm{MW_e}$. This requirement leads to a time-dependent mass flow rate, since obviously if higher enthalpy fluids are produced, less fluid mass is required to sustain the power production. In order to satisfy the constant steam requirement, the steam fraction in the separators must be calculated and the total rate at each time-step adjusted accordingly. Following *Bodvarsson et al.* [1982*b*], we use the equations shown below:

$$h_f = xh_v + (1 - x)h_l \qquad (1)$$

$$q_t = Q/x \qquad (2)$$

The symbols are defined in the notation list at the end of the paper. Equation (1) approximates the two-phase flow from the bottom of the well to the separators as an isoenthalpic expansion; heat losses in wellbore and surface piping are neglected. It was used to calculate the steam fraction in the separators, x. The total mass flow rate was calculated using (2). The saturated enthalpies h_v and h_l used in (1) were based on a separator pressure of 9 bars. Saturated steam enthalpies do not vary much with pressure, so that a different value of the separator pressure will not alter the results significantly. The average enthalpy of the produced fluids at Krafla is approximately 2200 kJ/kg. This value was used as a constraint in the determination of the mass flow at each time step; i.e., at early times when the calculated discharge enthalpy was lower than 2200 kJ/kg, the flow rate was constant and calculated based on a discharge enthalpy of 2200 kJ/kg. The simulator MULKOM was used in the numerical studies [*Pruess*, 1983].

LUMPED PARAMETER MODEL

In this section we develop a lumped parameter model and

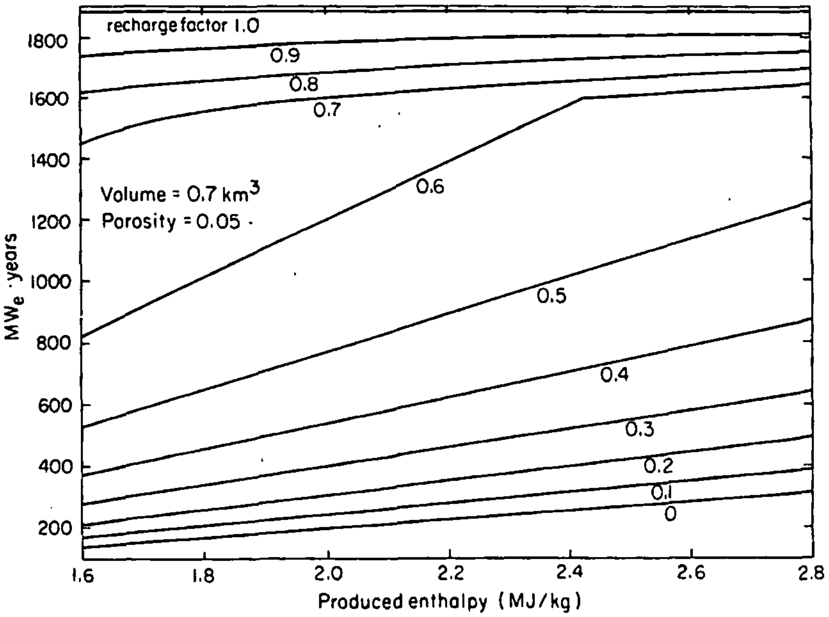

Fig. 2. Lumped model: generating capacity of old wellfield for porosity of 5%.

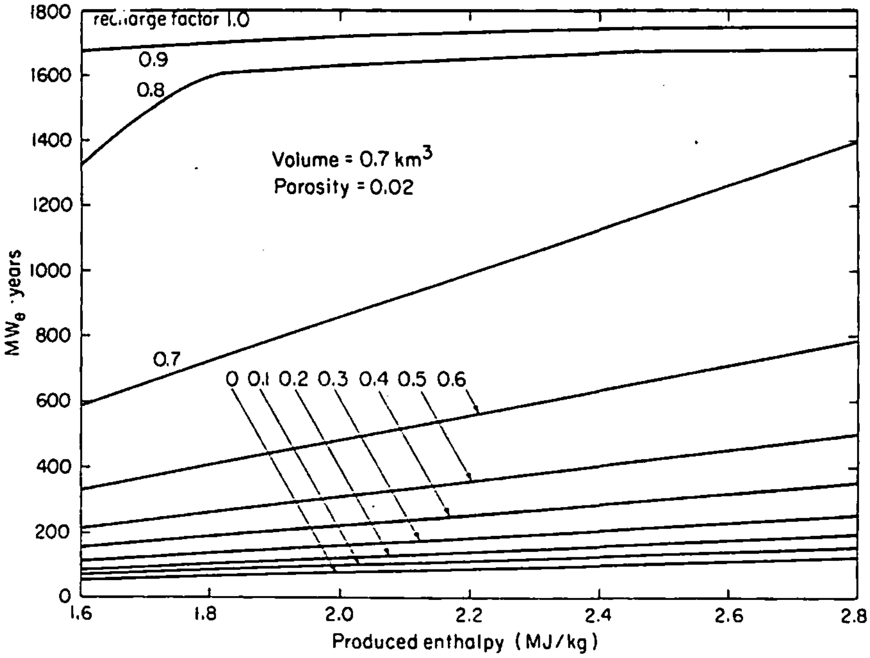

Fig. 3. Lumped model: generating capacity of old wellfield for porosity of 2%.

apply it to the old wellfield at Krafla. The mathematical formulation of a simple lumped model for estimation of recoverable electric power is given in the appendix. From a consideration of mass and heat balances it is possible to predict the total recoverable steam at the separators, which will depend upon parameters such as the reservoir volume, porosity, initial temperature and vapor saturation, the average produced enthalpy, and the degree of natural or artificial (reinjection) recharge. Denoting the amount of steam required per unit of electric work by ξ, the recoverable electric work W is, from (A6) and (A7),

$$W = \frac{M_v}{\xi} = \left(\frac{1}{\xi}\frac{h_p - h_l^s}{h_v^s - h_l^s}\right) M/(1-f)^2 \qquad \text{fluid limited} \qquad (3a)$$

$$W = \frac{M_v}{\xi} = \left(\frac{1}{\xi}\frac{h_p - h_l^s}{h_v^s - h_l^s}\right) U/(h - fh_l^s) \qquad \text{heat limited} \qquad (3b)$$

In Figures 2–4, we plot W in dependence on the fluid recharge factor f and produced enthalpy h_p for assumed reservoir porosities $\phi = 1\%$, 2%, and 5%. Other parameters used in these calculations are $V = 0.7$ km^3 (estimated volume of wellfield), $T = 320°\text{C}$, $S_v = 0$, $p^s = 9$ bars, $\rho_R = 2650$ kg/m^3, $c_R = 1000$ J/kg°C, and $\xi = 2.4$ kg/MJ $= 7.56864 \times 10^7$ kg/MW$_e$ yr.

In these calculations we have estimated the areal extent of the old wellfield as 0.7 km^2 and assume a reservoir thickness of 1.0 km. Figures 2–4 show the total electric power W (in MW$_e$ years) that can be produced from the reservoir as a

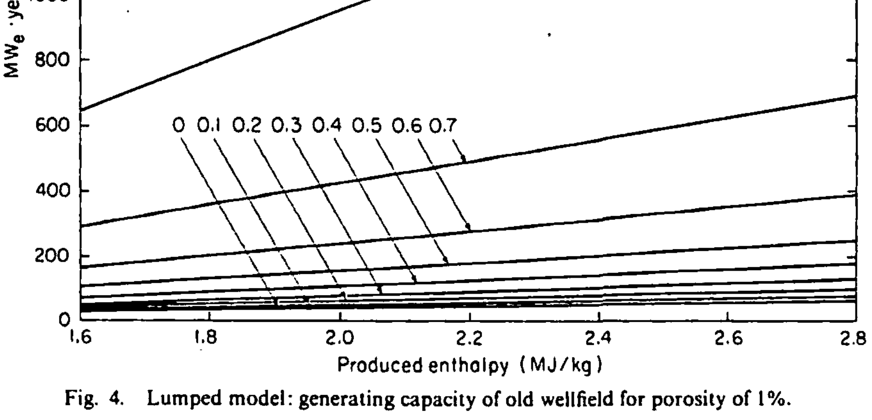

Fig. 4. Lumped model: generating capacity of old wellfield for porosity of 1%.

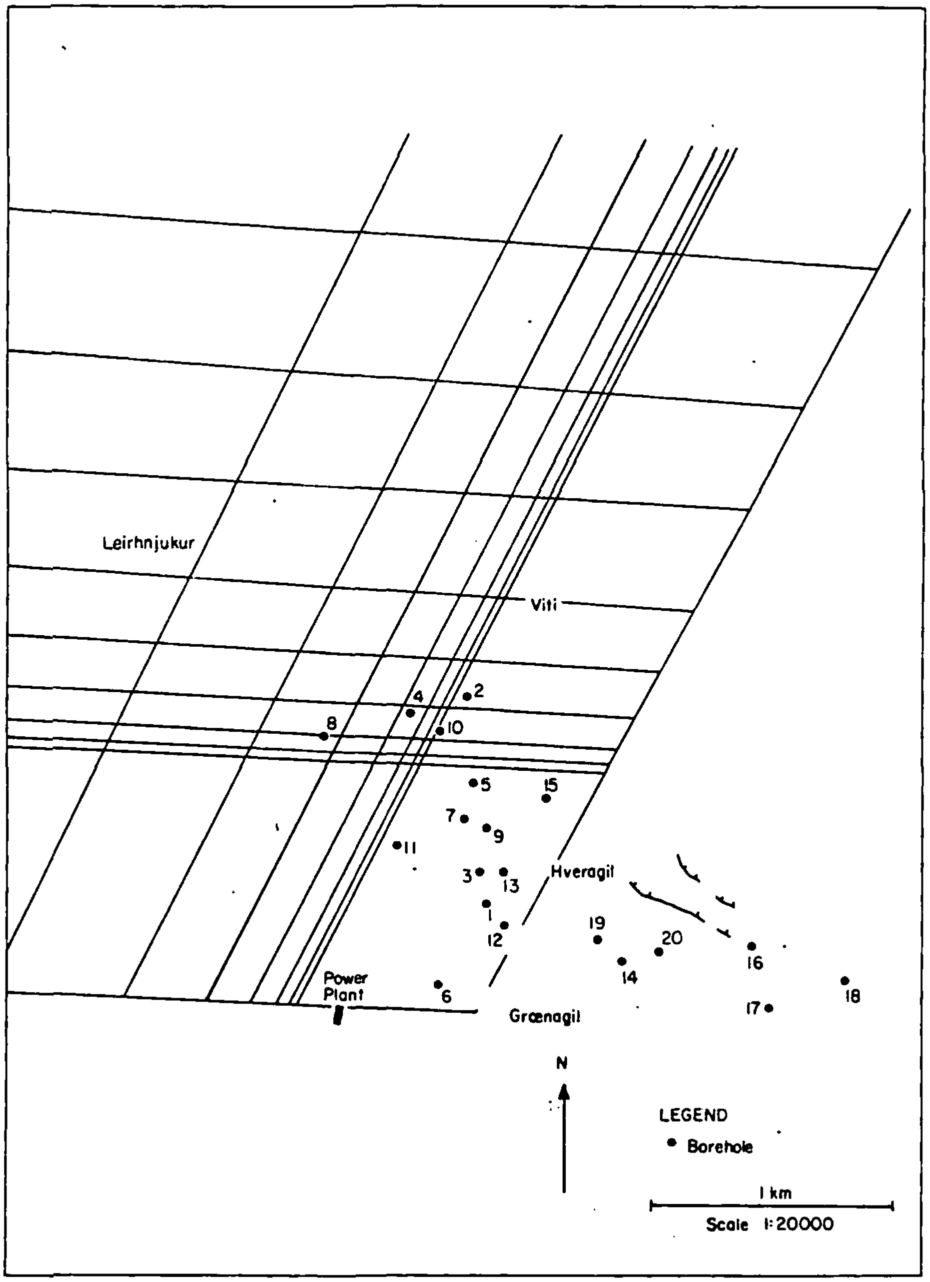

Fig. 5. Mesh used in simulation studies of old wellfield.

function of the enthalpy of the produced fluids and the recharge factor *f*. On the basis of the figures, the following observations can be made:

1. An increase in the recharge factor increases the total electrical energy that can be generated.

2. The higher the enthalpy of the produced fluids, the more electrical energy can be generated. The higher the produced enthalpy, the less fluid mass per MW_e needs to be extracted.

3. If the recharge rate is limited (i.e., the reservoir is limited in fluids rather than heat), the porosity greatly affects the total electrical energy that can be generated. Higher porosities will result in higher values of recoverable electric work.

4. When the recharge factor is greater than 0.7, 0.8, and 0.9 for porosities of 0.05, 0.02, and 0.01, respectively, the reservoir generating capacity is limited by the heat content of the reservoir rather than by the fluid capacity. For these cases the porosity and enthalpy of the produced fluids have very little effect on the generating capacity (MW_e years).

5. Under the most favorable conditions, the maximum generating capacity of the system considered is approximately 1800 MW_e years, or 60 MW_e for 30 years. However, one must consider that the enthalpy of the recharge fluids used in these calculations is 740 kJ/kg (corresponding to liquid water at separator conditions) and the areal extent of the reservoir corresponds to that of the old wellfield (productive wells) only.

In summarizing the results of the lumped model, we feel that it is a valuable tool for first-cut estimates of the generating capacity of the Krafla field. Obviously, for accurate determination of the generating capacity of the Krafla field, one must carefully evaluate the recharge factor *f*, which for most cases is not constant but time dependent.

Due to the low transmissivity of the Krafla field, it is unlikely that the recharge factor is much higher than 0.5. Thus one

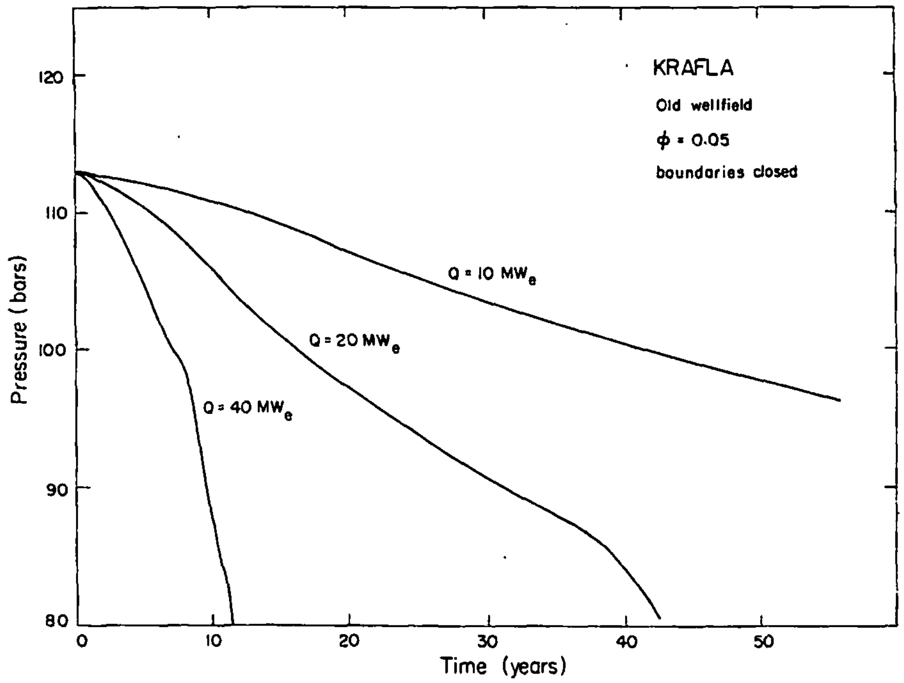

Fig. 6. Pressure decline in old wellfield: boundaries closed, porosity is 5%.

would expect that the field will become depleted of fluid rather than heat and that the generating capacity is of the order of 20–30 MW$_e$ for 30 years (see Figures 2–4). More sophisticated mathematical models will be used to address this question in the next sections.

NUMERICAL MODELING STUDIES OF THE OLD WELLFIELD

In the studies of the generating capacity of the old wellfield the basic grid shown in Figure 5 is used. The entire wellfield (i.e., the area enclosing productive wells) is modeled using a single block, thereby assuming uniform depletion of the wellfield region. We are interested in finding how much recharge from outer regions will flow into the reservoir and help sustain the power output. Thus the heat and mass flow into the wellfield is modeled in detail using fine gridblocks. In the numerical simulations we consider various cases with different boundary conditions.

The parameters used in these simulations are those given in Table 1. As the reservoir is modeled as a single layer, gravity and recharge from lower permeability zones underlying the 1000-m thick reservoir are neglected. The heat flux from below is also neglected. The natural state simulations show that this approximation is reasonable. As the mesh in Figure 5 shows, we also assume that the inferred faults in Graenagil and Hveragil are closed to fluid/heat flow. Data from resistivity surveys at Krafla have indicated that the Graenagil fault(s) represent the southern boundary of the geothermal system

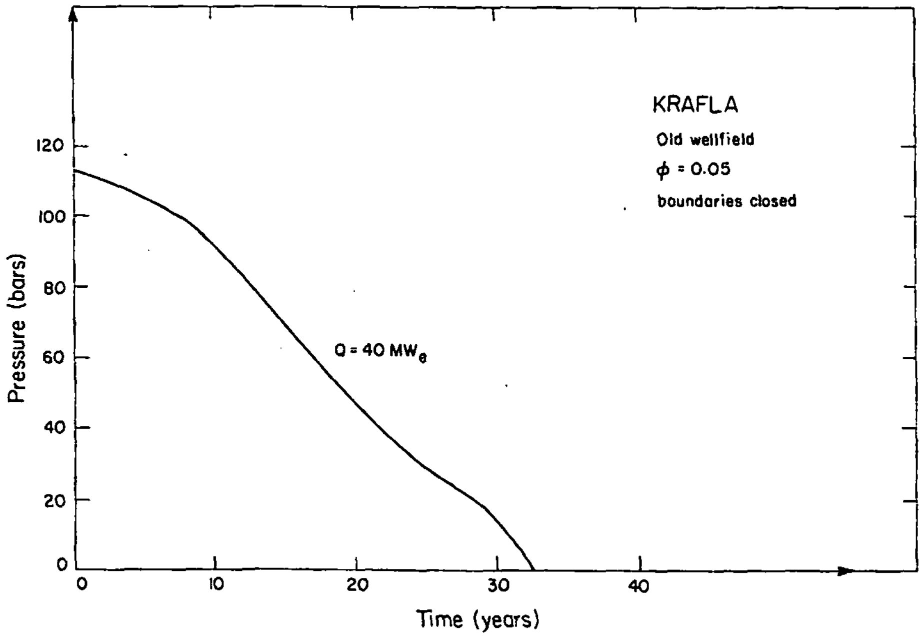

Fig. 7. Pressure decline for 40 MW$_e$ power production: boundaries closed, porosity is 5%.

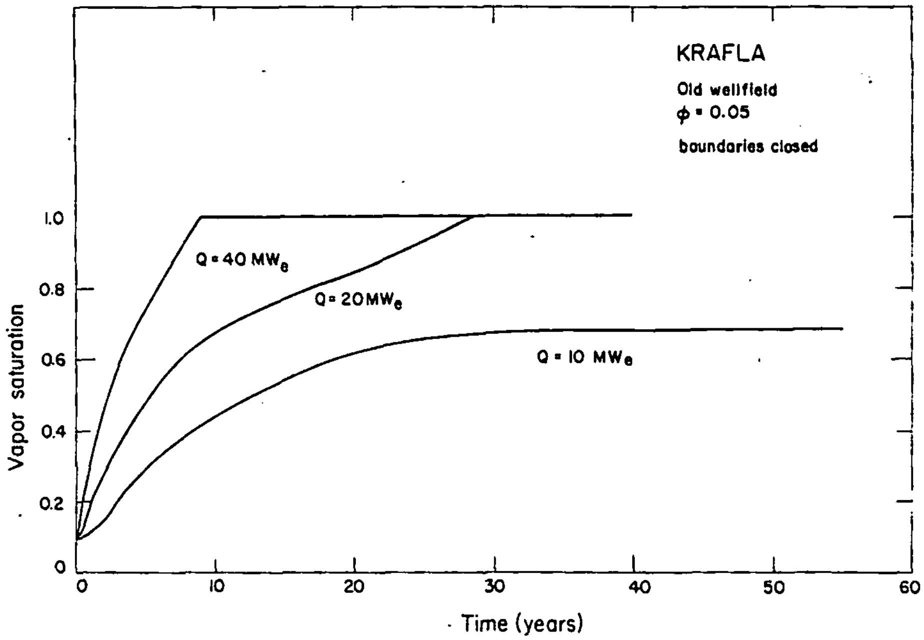

Fig. 8. Vapor saturation in old wellfield: boundaries closed, porosity is 5%.

[*Karlsdottir et al.*, 1978]. Therefore it seems reasonable to use a no-flow boundary condition at Graenagil. In modeling the old wellfield it is also considered reasonable to assume a no-flow boundary condition at Hveragil, since fluids at comparable rates are produced in both wellfields. This assumption will give conservative estimates of the generating capacity of the individual wellfields, which are of value to field developers when plans for future drilling in the area are considered. The grid shown in Figure 5 extends 10 km to both the north and the west.

Figures 6–10 show the results obtained when steam rates equivalent to 10, 20, and 40 MW_e are produced from the block representing the wellfield. In this case we assume that the Graenagil and Hveragil faults are no-flow boundaries, and that the average porosity of the reservoir is 5%. Figure 6 shows the pressure decline in the production area due to steam production equivalent to 10, 20, and 40 MW_e. The figure shows a rather slow decline for the lower power outputs (10 and 20 MW_e) but a quite rapid pressure decline in the case where steam equivalent to 40 MW_e is produced. The results shown in Figure 6 indicate that for the conditions modeled, the reservoir in the old wellfield can easily provide steam equivalent to 20 MW_e for 30 years. Additional results given in Figure 7 show, however, that it is questionable whether the reservoir in the old wellfield can maintain a power output of 40 MW_e for 30 years, since the pressure falls below 20 bars after 28 years.

Figure 8 shows the vapor saturation transients in the production region. The figure shows that single-phase vapor conditions will prevail in the production area after 9 and 29 years

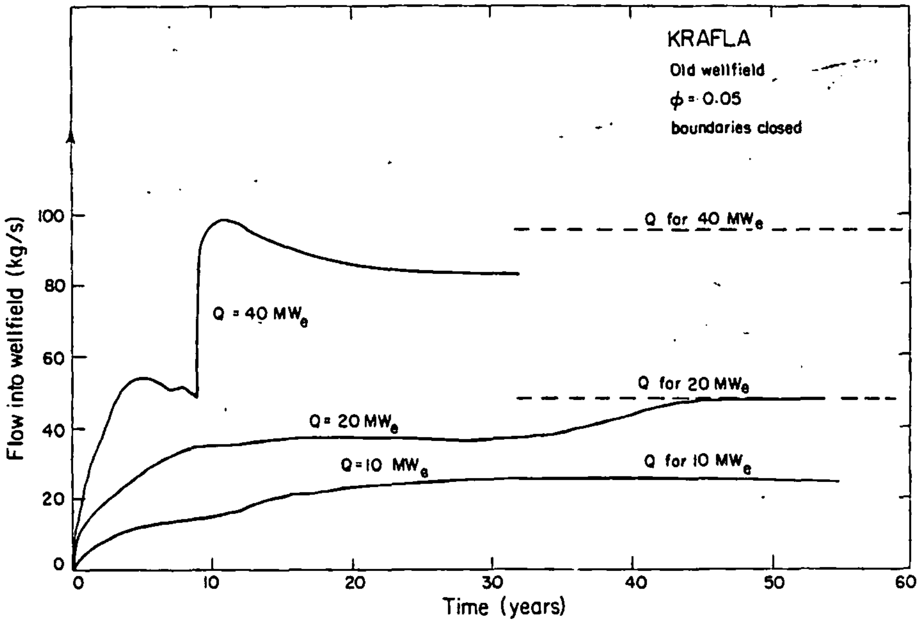

Fig. 9. Flow into old wellfield: boundaries closed, porosity is 5%.

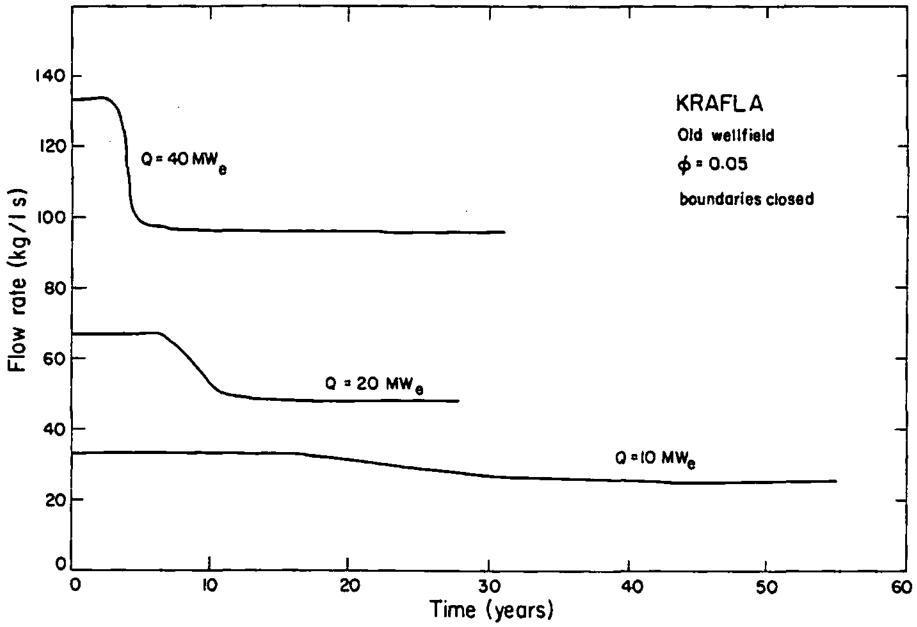

Fig. 10. Production rate in old wellfield: boundaries closed, porosity is 5%.

for a power production of 40 and 20 MW$_e$, respectively. After single-phase vapor conditions are reached in the production area, the pressure starts to fall rapidly [*Bodvarsson et al.*, 1982*b*]. This is evidenced by the kinks in the curves shown in Figure 6.

In the case of 10-MW$_e$ production, Figure 8 shows that single-phase vapor conditions will not be reached in the production area within 50 years (the end of the simulation). Our experience indicates that in this case the reservoir in the old wellfield can sustain the 10-MW$_e$ power production until all of the fluid in the reservoir is exhausted. Although the average transmissivity of the Krafla reservoir is low (2.0 Dm) the low fluid extraction rate (equivalent to 10 MW$_e$) will enable continuous recharge into the production region equaling the fluid extraction rate. This is illustrated in Figure 9 where the mass flow into the production region is plotted versus time. The figure shows that for the cases of 10- and 20-MW$_e$ power production, a quasi steady state condition will develop (i.e., the fluid flow into the production region equals the extraction rate). Steady flow is approached more slowly for the case of 20-MW$_e$ power production. In the case of 40-MW$_e$ power production the recharge rate is only half the extraction rate until (1) single phase vapor conditions are reached in the production region and (2) the pressure gradient between the production region and the surrounding region becomes high. However, in this case the mass influx cannot be sustained

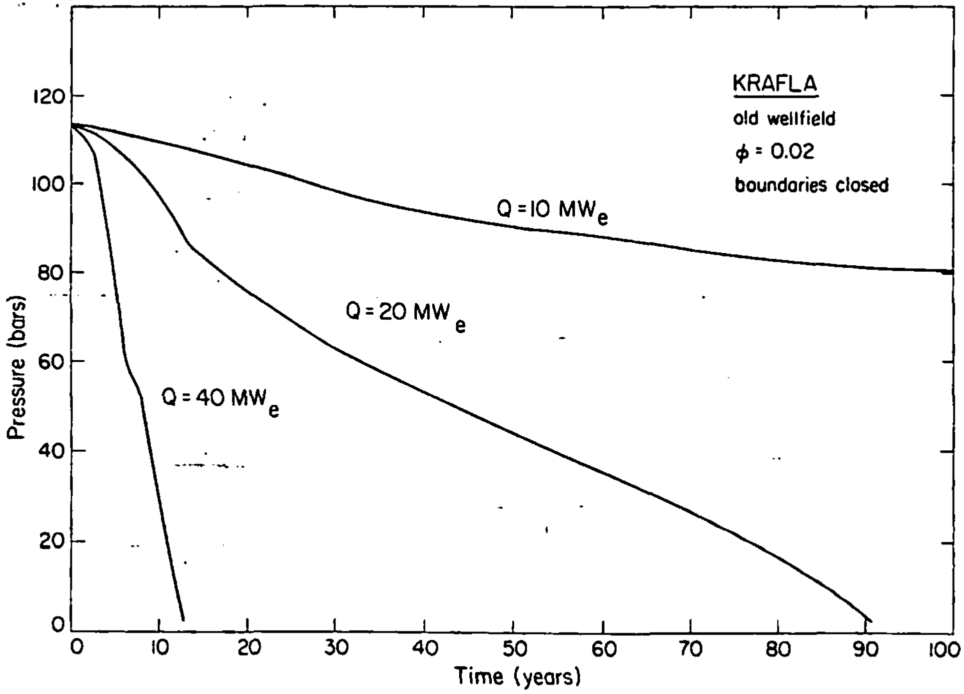

Fig. 11. Pressure decline in old wellfield: boundaries closed, porosity is 2%.

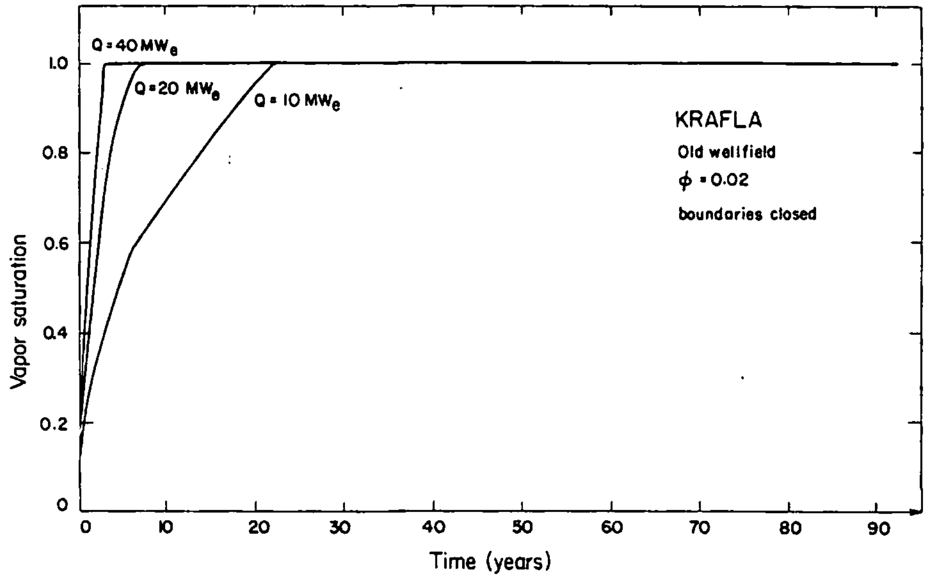

Fig. 12. Vapor saturation in old wellfield: boundaries closed, porosity is 2%.

because of a rapid rise in the vapor saturation in the elements close to the production region and a consequent reduction in flow due to relative permeability effects.

Figure 10 shows the mass generation rate as a function of time for the three cases 10, 20, and 40 MW$_e$. At early times the production rate is constant, as fluids are produced at a constant enthalpy of 2200 kJ/kg. Later on, when the flowing enthalpy exceeds 2200 kJ/kg (the present average enthalpy of the Krafla wells) and less fluid mass is required to produce the required electrical power output (10, 20, or 40 MW$_e$), the production rate declines. When only steam is produced, the extraction rate equals the theoretical steam requirement for the simulated power output.

We have carried out similar simulations for an average reservoir porosity of 2% (Figures 11 and 12). Figure 11 shows that even if the average reservoir porosity is as low as 2% the reservoir can still maintain a 20-MW$_e$ power production over a period of 30 years. However, the figure also shows that the reservoir can sustain a 40-MW$_e$ power production for only 11 years if the porosity is as low as 2%. When the porosity is low, there are limited amounts of fluids present in and around the production region and consequently the vapor saturation will rise rapidly. This will rapidly decrease the mobility of fluids recharging the production region due to relative permeability effects. Figure 12 shows the vapor saturation transients for this case. The figure shows that even when the power output is limited to 10 MW$_e$, single-phase vapor conditions will develop in the production region after only 21 years.

A brief study was conducted to explore the dependence of the results on the relative permeability curve used. The results from the natural state simulations indicate that the Corey curves [*Corey*, 1954] are not applicable to the Krafla reservoir [*Bodvarsson et al.*, this issue (*b*)]. We therefore use relative permeability curves suggested by *Sorey et al.* [1980] (SBG

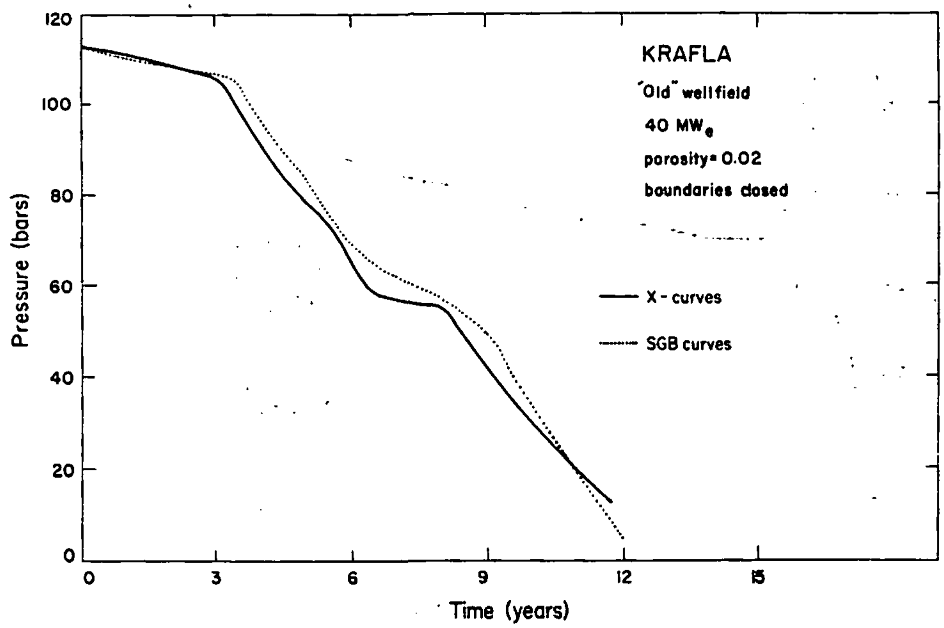

Fig. 13. Pressure decline in old wellfield: comparison between SGB and *x* curves.

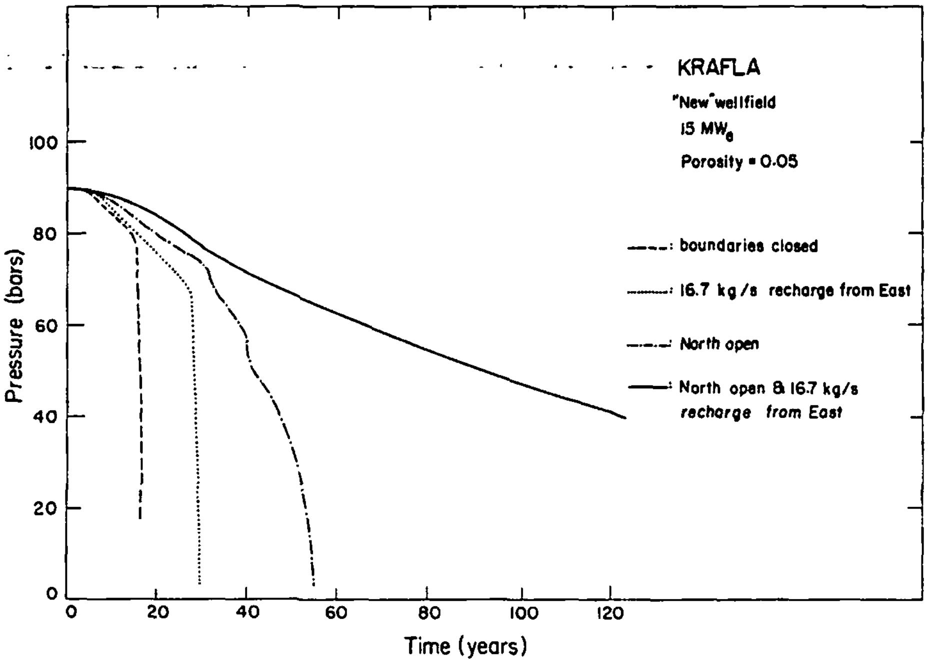

Fig. 14. Pressure decline in new wellfield: 15-MW$_e$ power production, porosity is 5%.

curves) to test the dependence of the results on the relative permeabilities [see *Bodvarsson et al.*, this issue (*b*), Figure 20]. Figure 13 shows a comparison between the pressure decline for SGB and x curves for the case of 2% porosity and 40-MW$_e$ power production. The figure shows that the pressure decline is almost identical for these relative permeability curves. The vapor saturation transients and recharge rates are also very similar for the two curves [*Bodvarsson et al.*, 1983*b*]. The reason for this close agreement is that x curves and SGB curves do not exhibit large interference between the phases (liquid and vapor) so that the sum of the relative permeabilities is close to unity for all vapor saturations. Therefore both curves affect the total kinematic mobility and the flowing enthalpy in a similar manner [*Bodvarsson et al.*, 1983*a*]. The Corey curves, on the other hand, exhibit large interference between the phases and, consequently, the sum of the relative permeabilities falls far below unity for intermediate vapor saturations. Additional simulations of the old wellfield at Krafla are discussed by *Bodvarsson et al.* [1983*b*].

In summary, the simulations of the old wellfield indicate that it is capable of providing steam for a power generation of 30 MW$_e$ for 30 years. These results indicate that several new wells can be drilled in the old wellfield. The effect drilling additional wells in the old wellfield will have on future productivities of existing wells and reservoir depletion are studied in a subsequent paper [*Pruess et al.*, this issue].

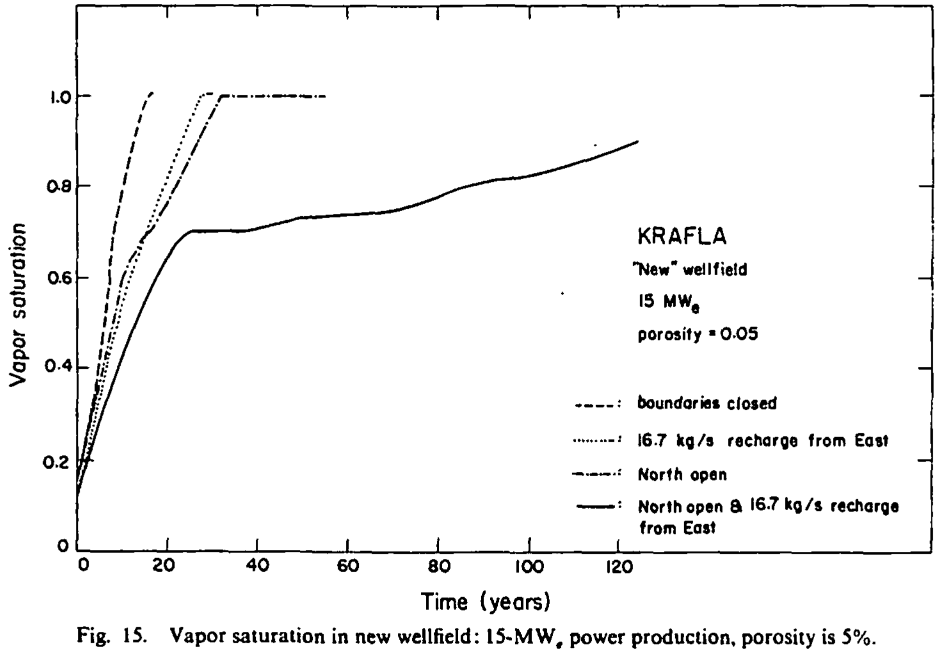

Fig. 15. Vapor saturation in new wellfield: 15-MW$_e$ power production, porosity is 5%.

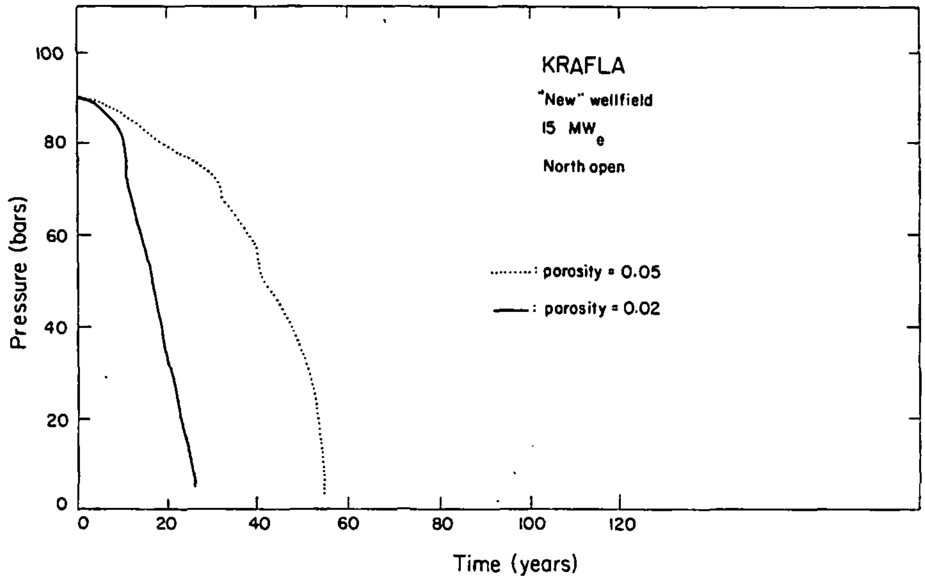

Fig. 16. Pressure decline in new wellfield: effect of porosity.

NUMERICAL MODELING STUDIES OF THE NEW WELLFIELD

In this section we estimate the generating capacity of the new wellfield. As before, we will assume that the faults in Hveragil and Graenagil are no-flux boundaries. The fault that is thought to be located between wells 17 and 18 is also assumed to be closed to fluid flow (see Figure 1). In the modeling of the natural state of the Krafla system, a recharge rate of 0.01 kg/s m for the new wellfield was determined [*Bodvarsson et al.*, this issue (*b*)]. A reasonable value for the total distance over which this recharge rate applies is 1 km. Consequently, under natural conditions the total recharge rate through the upflow zone in the new wellfield is 10 kg/s. However, one would expect that this recharge rate would increase as field pressures decline. Thus in the following discussion we will consider the two extreme cases of no fluid recharge through the upflow zone and a rather large rate of fluid recharge, 16.7 kg/s (~70% higher than the rate determined by the natural state modeling study).

For the simulation studies of the new wellfield, we use again the parameters given in Table 1. The average transmissivity of the new field (excluding well 18) is around 2.0 Dm [*Bodvarsson et al.*, this issue (*a*)] and the thickness of the main (fractured) reservoir is assumed to be approximately 1000 m (there are few significant feeds above 1000 m depth). However, for initial average thermodynamic state of the reservoir, we assume a temperature of 300°C (P = approximately 90 bars) and a vapor saturation of 0.1. Other details of the simulations are given by *Bodvarsson et al.* [1983*b*].

Figures 14 and 15 show the pressure and vapor saturation transients in the production area for four different cases: (1) all boundaries closed (Hveragil, Graenagil, east and north faults), (2) 16.7 kg/s recharge through upflow zone (in the eastern part of the new wellfield), (3) north open, and (4) north open and 16.7 kg/s recharge through upflow zone. In these simulations

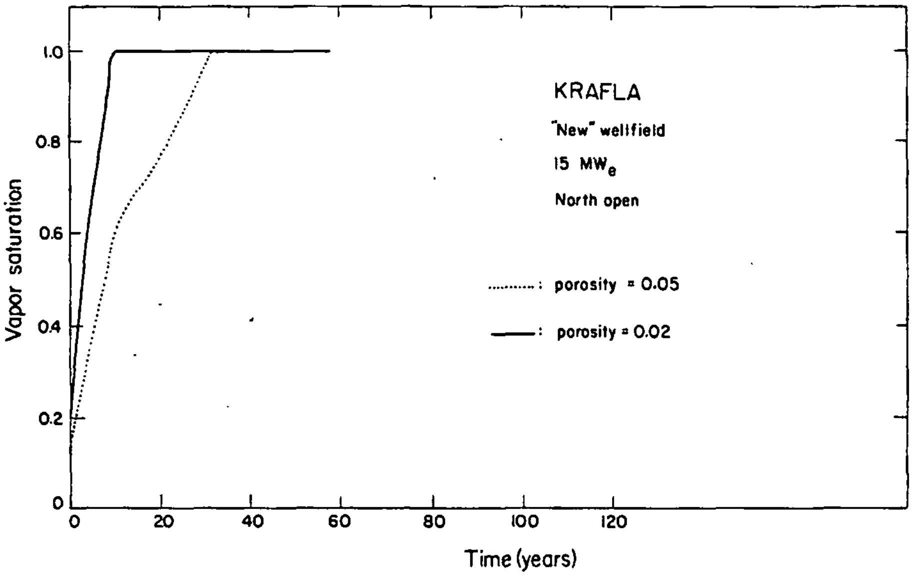

Fig. 17. Vapor saturation in new wellfield: effect of porosity.

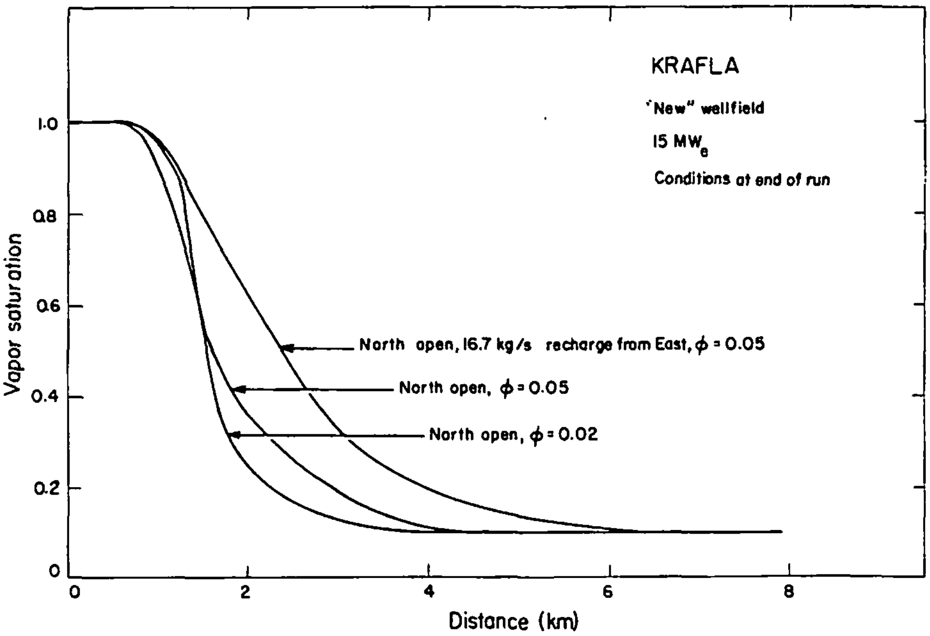

Fig. 18. Vapor saturation profiles: 15-MW_e power production. The abscissa represents distance to north from Graenagil.

we assume an average reservoir porosity of 5% and a power production of 15 MW_e. In the cases identified as "north open," we accurately model recharge of fluids from the north using elements extending to a distance of 10 km away from the wellfield.

Figure 14 shows that in the case of a closed reservoir, 15-MW_e power production can be sustained for 17 years. In this case we only use one grid block and assume that during exploitation all of the fluids in place in the wellfield can be extracted. When a 16.7-kg/s recharge from the east fault is considered, the longevity of the reservoir based on a 15-MW_e power production is 29 years. In the other cases, where fluid flow from the north is modeled, the longevity of the reservoir is in excess of 50 years. The vapor saturation transients in the reservoir for the same four cases are shown in Figure 15.

The effect of porosity on the results is demonstrated in Figures 16 and 17. We compare results for 2% and 5% porosities for the case of recharge from the north. The figures clearly illustrate the importance of porosity on the reservoir longevity, since for 2% porosity the reservoir can only sustain 15-MW_e power production for half as many years as in the 5% porosity case.

Figure 18 shows the vapor saturation profiles to the north at the end of the simulations. In all three cases, very little of the mass in place has been extracted, due to the low transmissivity (2.0 Dm). For a low porosity ($\phi = 0.02$) the vapor saturation changes are very localized. Another similar set of runs was made for a power production of 30 MW_e [*Bodvarsson et al.*, 1983*b*].

The results obtained showed that under the most optimistic conditions (5% porosity, north open, 16.7 kg/s recharge through upflow zone), the new wellfield could sustain a power

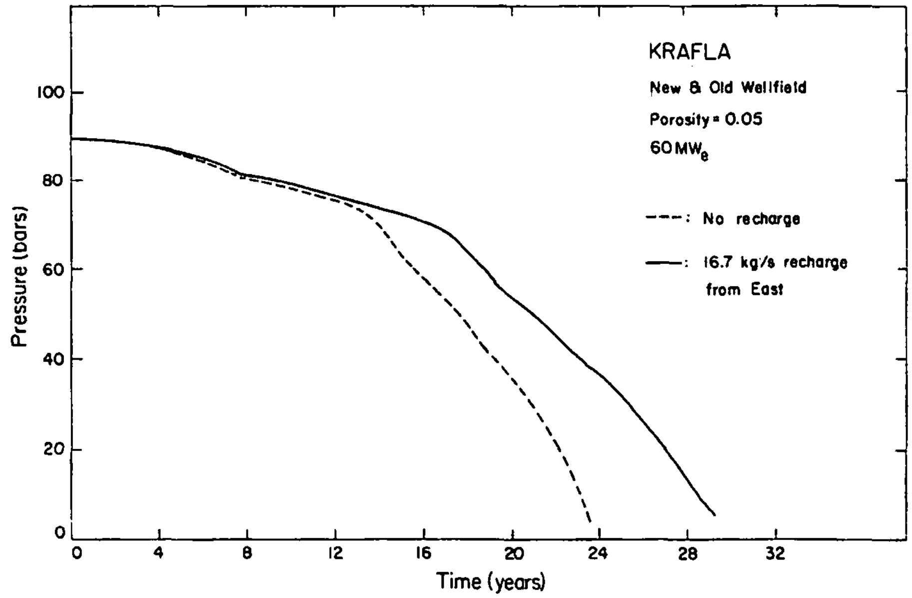

Fig. 19. Pressure decline in whole wellfield.

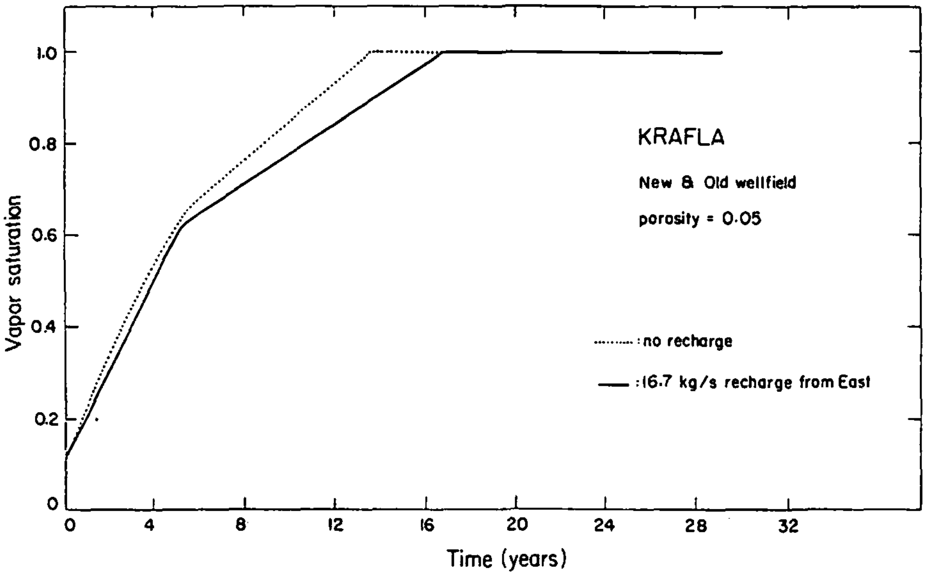

Fig. 20. Vapor saturation changes with time in whole wellfield.

production of 30 MW_e for 30 years. In other cases, the 30-MW_e power production could only be sustained for 12–20 years [*Bodvarsson et al.*, 1983*b*].

In summary, a realistic assessment of the generating capability of the new wellfield is approximately 20 MW_e for 30 years. The limiting factors for a larger power potential are the small areal size of the wellfield, the low transmissivity of the reservoir, and the lack of recharge from the south and the east.

Fieldwide Simulation Studies

We have made a brief study of the behavior of the entire field (old and new wellfields) under exploitation. Again we model the area enclosed by productive wells (1.35 km^2) as a single block but use a rather fine mesh for recharge from outer regions. As before we assume the fault(s) in Graenagil to be closed to mass/heat flow, as well as the fault(s) to the east between wells 17 and 18. The parameters listed in Table 1 are used in the simulation, and we assume that the initial conditions correspond to 300°C fluids with a vapor saturation of 0.1. In all cases the power production and the porosity are fixed at 60 MW_e and 5%, respectively. Further details are given by *Bodvarsson et al.* [1983*b*]. Figures 19 and 20 show the pressure and vapor saturation transients in the production zone for the cases of no recharge and 16.7 kg/s recharge through the upflow zone in the new wellfield. The vapor saturation increases quite rapidly for both cases, and single-phase vapor conditions are reached after only approximately 15 years. At that time the pressure starts to decline quite rapidly, to the extent that for the no-recharge case the reservoir can only sustain the 60 MW_e for 23 years. When the 16.7-kg/s recharge from the upflow zone in the east is modeled the longevity is 28 years or only 5 years more than in the no recharge case. It is obvious that simulations using a porosity of 2% will give considerably less favorable results.

In summary, the fieldwide simulation studies show that it is unlikely that the present wellfields at Krafla can sustain steam production equivalent to 60 MW_e for 30 years. These results agree well with the modeling results for the individual wellfields. As the power plant is designed for 60 MW_e, additional steam must be sought from other nearby areas. Partly on the basis of these results, a Krafla well (well 21) was drilled in a new area 2 km south of the old wellfield. Geophysical surveys indicate the presence of a rather small resistivity anomaly in that area [see *Bodvarsson et al.*, this issue (*a*), Figure 3]. The results of the drilling are good, since well 21 is at present the best producer at Krafla.

Conclusions

Analytical and numerical techniques are used to evaluate the generating capacity of the Krafla geothermal field. A general lumped parameter model that can be used to obtain rough estimates of generating capacities of geothermal systems is developed. The model is applied to the old wellfield at Krafla, and the results show the effects of parameters such as porosity and recharge on the generating capacity. In order to obtain more reliable estimates of the generating capacity of the wellfield, several areal two-dimensional distributed parameter models are developed. In these models the wellfield is simulated using a single block, but the recharge into the wellfield is modeled in detail. The results obtained indicate that the generating capacities of the old and new wellfields at Krafla are 30 and 20 MW_e for 30 years, respectively. Consequently, several additional wells can be drilled in the old and new wellfields.

Appendix: Tank Model for Estimation of Total Recoverable Electric Work

Consider a reservoir with mass reserves M given by

$$M = V\phi\rho \tag{A1}$$

and total heat reserves U relative to separator temperature T^S:

$$U = Mu + V(1-\phi)\rho_R c_R(T - T^S) \tag{A2}$$

The reservoir is being produced with average discharge enthalpy h_p yielding a steam quality at the separators given by

$$X^S = \frac{h_p - h_l^S}{h_v^S - h_l^S} \tag{A3}$$

Equation (A3) approximates flow between reservoir and separators as an isoenthalpic expansion. Quantities with superscript S refer to separator conditions (typically, P^S is approximately 9 bars).

Natural recharge and reinjection of produced fluids effectively increase the mass reserves. If a fraction f of produced fluid is replenished by these mechanisms, effective fluid reserves are

$$M_{\text{eff}} = M/(1-f) \tag{A4}$$

Assuming an enthalpy equal to h_l^S for recharge or injection fluids, effective produced enthalpy is

$$h_{\text{eff}} = \frac{h_p - fh_l^S}{1-f} \tag{A5}$$

The amount of steam which can be recovered at separator conditions depends upon whether the reservoir is limited by fluid reserves or by heat reserves. From (A3) and (A5) an effective steam quality X_{eff} at the separators can be computed. When combined with the effective mass reserves (equation (A4)), the following expression is obtained for the total recoverable steam in the fluid-limited case:

$$M_v^{\text{fluid}} = X_{\text{eff}}^S M_{\text{eff}} = \frac{h_p - h_l^S}{h_v^S - h_l^S}\frac{M}{(1-f)^2} \tag{A6}$$

The reservoir may run out of heat before the quantity of steam indicated by (A6) can be produced. From the condition that total producible heat is limited by the total reserves (A2), the following limit for producible steam is obtained:

$$M_v^{\text{heat}} = \frac{h_p - h_l^S}{h_v^S - h_l^S}\frac{U}{h_p - fh_l^S} \tag{A7}$$

The recoverable steam M_s is given by the smaller of the two values M_v^{fluid} and M_v^{heat}.

NOTATION

c	specific heat, J/kg.
f	fraction of produced fluids replenished by natural recharge or reinjection.
h	enthalpy, J/kg.
M	fluid mass reserves, kg.
P	pressure, bars.
q	mass flow rate, kg/s.
Q	theoretical steam requirement, kg/s.
S	saturation.
T	temperature, °C.
u	fluid internal energy, J/kg.
U	heat reserves, J.
V	reservoir volume, m^3.
W	recoverable electric work, MW$_e$ years.
x	steam fraction in separators.
ρ	fluid density, kg/m^3.
ϕ	porosity.
ξ	steam required per unit of electric work, kg/MJ.

Subscripts

eff	effective.
f	flowing.
l	liquid.
P	produced.
R	rocks.
t	total.
v	vapor.

Superscript

S	separator conditions.

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