Necessity, experiences and abilities of deep heat mining

A mélységi hőbányászat szükségessége, tapasztalatai és lehetőségei

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Abstract – Today's energy crisis enforced the development of researching renewable energy resources the new types of which bear the possibility of widespread utilisation among which electricity production has greatest significance. Geothermal energy utilisation meant primarily and traditionally the direct or indirect usage of heat excavated from thermal water production. There were only a few examples for electric energy production from which Larderello and Iceland are pioneers. Experimental programmes of fracturing and water circulation based heat excavation power plant types are promising. The present publication reviews the experiences, limits, risks and plantation possibilities of this latter technique in Hungary. The preliminary geothermal heat excavation system models formed on the basis of estimations on areas lacking essential data, were not completely supported by experiments. One of the conclusions is that deep drilling and geophysical reconnaissance researches are expedient.

Összefoglalás – Napjaink energiaválsága szülte a kényszert az alternatív, illetve megújuló energiaforrások kutatására, melyek új típusai a sokszínű hasznosítás lehetőségét hordozzák, de közülük legnagyobb jelentőségű az áramtermelés. A geotermális energiahasznosítás hagyományosan elsősorban a hévizek kitermelésével kinyerhető hő közvetlen vagy közvetett felhasználását jelentette. Elektromos áram termelésre csak igen kevés példa akadt, közülük Larderello és Izland úttörő jellegű. Az ígéretes kísérleti programok közé tartozik a kőzetrepesztésre és vízcirkulációra alapozott hőkivétel erőműtípusa. Jelen tanulmány ennek tapasztalatairól és korlátairól, kockázatáról, valamint a hazai alkalmazás lehetőségéről nyújt áttekintő vázlatot. A gyakorlati kísérletek nem mindenben támasztották alá az adathiányos területeken előzetesen kialakított, becslés jellegű geotermikus hőbányászati rendszermodelleket. Ennek egyik tanulsága, hogy a költségigényes programokhoz mélyfúrásos és geofizikai előkutatást célszerű betervezni és megvalósítani.

Key words: HDR programme, EGS project, Soultz-sous-Forêts, indirect use of geothermal energy
Kulcsszavak: HDR program, EGS project, Soultz-sous-Forêts, geotermális áramtermelés

Introduction

The industrial development of the 2nd part of the 20th century introduced long-term national strategies influencing even world economy and containing scenarios about energy sector and technology development besides monetary economy, internal and foreign trade respectively. Relationships between leader governments (opposition, neutrality, integrity) had a desisive role in real processes, however, these varying relationships made the course of development hardly predictable.

Disproportions, environmental risk, scenarios

In the last 50 years a branch of futurology has been developed step by step in order to give realistic scenarios based on economic and technical data to optimize the middle- and long-term national strategies.

Club of Rome was the first researching group that called attention to disproportions that could cause catastrophes (MEADOWS et al. 1972). Since then numerous institutes and organisations have accomplished national and international surveys, and developed scenarios. Critical processes and their expected results have been approached in various ways regarding content, style and illustration techniques in these studies. Experiences of the last decades show that predictions are appropriate merely in 10–30 years and then become more-and-more unreliable as a consequence of unexpected processes.

There are hundredfold differences in specific energy consumption per capita between the developed and developing countries nowadays (in 2000: Chad 0,4 GJ per capita, world average 69 GJ per capita, Hungary 107 GJ per capita, the Netherlands 781 GJ per capita, Qatar 914 GJ per capita, IEA 2002). Rapid population growth and disproportional intensification may increase the uncertainty of future-modelling. At the given national and international interests, priorities of global problems facing humans are difficult to determine. If sustainable development and associated environmental protection are considered to be the most important common aims, then other aspects have to be subordinated to them at different levels. Of course, it is related to cost effective production, the altruistic technologies, creating and developing nature-friendly energy sector.

The latter supposes the gradual reduction of fossil energy production and consumation that caused numerous environmental problems directly or indirectly, together with the continuous increasing of the rate of alternative or renewable energy both in specific and absolute terms.

A lot of studies were specialized on the solution of the energy crisis in the last decades. MESAROVIC & PESTEL (1974) suggested different solutions for oil-producer and oil-exporter countries. They call attention to energy-saving, and to the replacing of crude oil by other primary energy sources, etc. The report from the group of Dénes Gábor (GABOR & COLOMBO 1976) mentioned the perspectives of alternative energy sources and the potential problems of nuclear energy.

The World Commission on Environment and Development (WCED 1987) studied and analysed numerous models. Fossil fuels, nuclear energy, firewood and renewable energies were discussed as hot issues. They regard energy-efficiency a key factor in development.

MARCHETTI (1980) predicted the probable proportion of different energy resources based on his research. The most important part of this is that natural gas will overtake the leading role of crude oil in the 1990s. The significance of nuclear power plants would exceed that of the coal power plants by 2010 and that of oil power plants by 2030. It became clear soon that the theory was unsuccessful.

The low consumption energy-saving model of GOLDEMBERG et al. (1985) suggested the sufficiency of the energy power of 11.2 TW (350 EJ) by 2020, while some less optimistic predictions calculated with multiple values e.g. HAEFELE (1981) estimated the power of 35 TW (1100 EJ) by 2030, meanwhile the same energy consumption per capita, as in a developed county for every person, would demand 55 TW (1735 EJ).

According to the opinion of the Worldwatch Institute in 1990 (BROWN 1991), the energy consumption would grow only by 10 % from 1989 to 2030. Within this oil will be reduced to its half and coal to its one ninth, while the quantity of natural gas will not change. Nuclear power will be eliminated, consequently the role of renewables become fourfold providing two third of the total energy-demand.

Scenarios were able to foretell the tendencies to 2000 with various certainty and uncertainty is even more probable in the estimates for the next 20–25 years. There are significant differences between opinions on growth and structure, in addition the effects of oil-crises, nuclear disasters, new technologies, political and economical turns, international cooperation can be estimated hardly.

The International Energy Outlook papers of the Energy Information Administration have been published since 1985 containing predictions on energy initially for the OECD countries. Predictions for 1990 were less than the real values with 5–10%. Predictions for 1995 were different by 10% in 1985 and by 5% in 1991 from the real values (288 EJ). The reason for these differences was the underestimation of the growth of energy consumption in the developing countries. The whole energy consumption of the World was overestimated of the real values of 386 EJ in coherence with the disintegration of the Soviet Union and the reduced energy consumption of the former socialist countries (EIA 2000).

In the report of 2000, the prediction for 2020 was about 641 EJ, 45 % of which was associated to developing countries. The summarized energy originate from oil in 38%, natural gas in 29%, coal in 22%, renewables in 8%, nuclear resources in 3%. Two other possible growths were discussed, in the case of great rise the need of 736EJ energy can be expected in 2020, while the moderate version means 524EJ consumption (EIA 2000).

Energy status of the World at the turn of the millennium

In the years after the turn of the millennium the energy consumption of the World's countries exceeded 450EJ (after IEA 2002). The determination of the exact value is difficult, since the consumption of certain regions from renewables (e.g. local wind turbines or photovoltaic systems) can be estimated hard. Annual growth is about 3%.

Electricity generation from 3.3TW installed capacity was 53.4EJ annually derived largely from conventional heat power plants (33.4EJ, 2.3TW installed capacity). Energy from nuclear and hydropower both provide similar values (9.5-9.5EJ), although in nuclear power plants this amount comes from 360GW installed capacity, and that of hydropower, comes from 695GW. Less than 1EJ energy was produced from 45GW installed capacity of other renewables.

Not more than 190.7PJ energy was derived from geothermal sources in 2000. This value is only 0.04% of the total energy consumption (LUND – FREESTON 2001). The direct use of geothermal energy increased to 273PJ with 7.5% annual growth by 2005 (LUND et al. 2005). Leader users are China, Sweden and the USA with 40% of the total applied geoenergy primary trough heat pumps. Geothermal heat pumps became the most important energy transformers regarding both capacity and utilization overtaking even thermal water utilization.

The installed capacity of geothermal power plants reached the power of 8TW in 2000, which grew to 8.9TW with 2% of annual increase by 2005 (BERTANI 2005). Almost the third of the total produced energy of 177,3PJ was derived from the USA, while one sixth of it was derived from the Philippines.

Between 1995 and 2005 considerable increase of installed capacity occurred only in the Philippines (703MWe, increase of 57%), Indonesia (487MWe, 157%), Mexico (200MWe, 27%), Italy (159MWe, 25%), Iceland (152MWe, 302%) and New-Zealand (149MWe, 52%). During this period 5 countries began to produce electricity from geothermal energy, therefore 24 countries owned installed capacity of geothermal energy in 2005. Despite significant increasing of installed capacity by 2100MWe (31%) in this period, geothermal derived electric generation presented only 0.33% of the total electricity production of the World.

In certain regions, however, the indirect use of geothermal energy plays an important role in electricity production. In 2005 geothermal derived electricity gave at least 15% of the national electricity in El Salvador, Kenya, the Philippines, Iceland, Costa Rica, and provided 30 % of the electricity in Lhasa. Developments are continued in these areas, however, in some regions the significant increase of geothermal indirect utilisation and its proportion in the electricity is imaginable.

The majority of geothermal power plants are located near the active margins of the Pacific Ocean, besides only Italy, Iceland and Kenya dispose over significant geothermal power potential. Six countries have less geothermal installed capacity than 10MWe.

Practice of using geothermal energy in Hungary

Wide range of methods using geothermal energy have been developed that use the heat content of the porous or fissured rocks of the upper 2000–3000 m of the crust by techniques of various scale and expense. Most of them are based on tapping the heat of thermal waters. In Hungary, researchers have considered the heat of deep waters as the primary or sole potential of geothermal energy utilisation. Various researchers form different opinion on the dynamic thermal water reserve of the Pannonian Basin, depending on the datasets and information the estimates are based on. Responsible sources (e.g. ÁRPÁSI 2002) gave the amount of this heat as 63.5PJ, only one twentieth of which is utilised although in various ways.

Medicinal and public baths have proved to be the most important utilisation in Hungary, although, multi-purpose public utilisations of thermal water have been established to use the heat content of deep groundwater for district heating, sanitary hot water and greenhouse heating since 1990. The Árpád-Agrár Rt. of Szentes and its predecessor of title were among the first to bring into existence a multi-purpose system (the first well was drilled in 1958), that is still one of the largest agricultural thermal water users in the World. Multi-purpose utilisations with most advantageous economic parameters can be established in the basins of southeast Hungary, due to their favourable overheated thermal water reserves. A geothermal public utility based on this resource in Hódmezővásárhely also proves this. Nowadays the cost of water heating is four times more when heated by natural gas instead of thermal water. Similarily heat energy production is three time more expensive.

Decreasing hydrocarbon-resources and rising economic competition and political tension around the World result in the growth of the rate of local alternative energy resources within the energy sector. With respect to environmental profit due to unemitted carbon dioxide, the use of geothermal water is an important issue; moreover its significant development is justified.

Direct use of geothermal energy from thermal waters has been typical in Hungary having a leading role internationally before the turn of the millennium. Today Hungary lost this position due to the significant weakening of the public sector, unorganised structural reorganisation, and lack of political wish, capital, investment, research and development in this sector.

The Hungarian Geothermal Association prepared a geothermal energy developing and utilisation strategy that could have been realised only partly during its 3 years running period due to the lack of support (ÁRPÁSI 2002). In this plan there were such geothermal reference projects for demonstrations that involved besides direct heat and thermal water utilisation the question of electricity production with re-injection technique sustaining the long term dynamism of the system. The recommended 8 systems would have been based on hydrocarbon exploring boreholes and drillied in the structural basins and on their technical infrastructure. Wellhead temperatures vary usually between 90 and 120°C, however, wells of Fábiánsebestyén and Nagyszénás have temperatures of 170–180°C.

Apart from the zones of thermal karsts with ascending waters in the margins of mountains, filtration depths of thermal wells in the basins of Hungary varies dominantly between 800 and 1200m and occasionally between 1500 and 2300m. Unfortunately thermal waters in Hungary could be utilised for electricity production at only a few special localities without extra heating.

Indirect use of thermal waters

Only steam from the thermal water of hyperthermal fields can be used to generate electricity without extra heating. Italy and Iceland were the first to utilise the thermal water reserve of their hyperthermal areas in large scale for public heating systems and producing electricity.

The geothermal field of Larderello in Italy has been well known since the antiquity. Moreover Tuscany became the classical occurrence of the soffione, which is a sulphuric-boric acid steam effluence. Boric acid was produced from the water of local lakes. The heat of natural springs was exploited for various aims by the chemical industry, while electricity has been generated there from the end of the 19th century.

The steam of Larderello is derivated from Late Triassic and Jurassic permeable porous limestone, dolostone and anhydrite. The reservoir is covered by impermeable Jurassic, Eocene formations of carbonates, shales and ophiolites. The deep reservoir is associated to the jointed part of the basement. According to previous theories the origin of the high heat flow might be a cooling pluton. However, recent researches (BROGI et al. 2003) revealed high heat flow can be the result of thermogravitative convection of thermal fluids and this convection might have developed a connection to the deeper and hotter rocks through the fractures of shear zones near the brittle-ductile transition boundary of the upper crust due to active extension since the Miocene.

The first steam turbine put into operation in 1913 with a power of 250kWe received steam from the soffione. The system was enlarged with two 3.5MWe alternator units in 1923. The electricity generation capacity of the region from geothermal resources was 12.15MWe in 1930, and 132MWe with 3.3TJ annual energy generated in 1943. During World War II except for a demonstrating plant all plants were destroyed.

In the consequence of dynamic rebuilding after the war, the capacity in 1950 was 300MWe, while the production in 1952 was 6.6PJ providing 6.6% of the electricity of Italy. Later actively used source fields were extended both horizontally and vertically and applied techniques were modernised as well (LUND 2004).

The diameter of the Larderello area is approximately 20km, extending over approximately 250km^2. Steam is produced from 13 geothermal reservoirs. The whole amount of electricity was 13PJ from 550MWe installed capacity in 2003. Deepest boreholes tap the steam of 300–350°C and 4–7MPa from a reservoir at a depth of 3000–4000m.

Italy has two other major geothermal fields, both are located in Tuscany. Italy provided more than 70% of the European geothermal based electricity with the help of 32 units of three power plants (700MWe installed capacity in 2003). However, this quantity was merely 1.9% of the Italian produced electricity. (CAPETTI & CEPPATELLI 2005, BERTANI 2005).

Although Iceland is known as one of the most important direct geothermal energy utilisers regarding its possibilities, this country is only the second important geothermal electricity producer in Europe. At present six fields are involved in production with 202MWe installed capacity, 97% of which is derived from the three largest fields (Nesjavellir, Krafla, Svartsengi). Some new plants will be put into operation with further 180MWe power. At Nesjavellir and Svartsengi a multi-purpose utilisation supplies energy for district heating systems (BERTANI 2005).

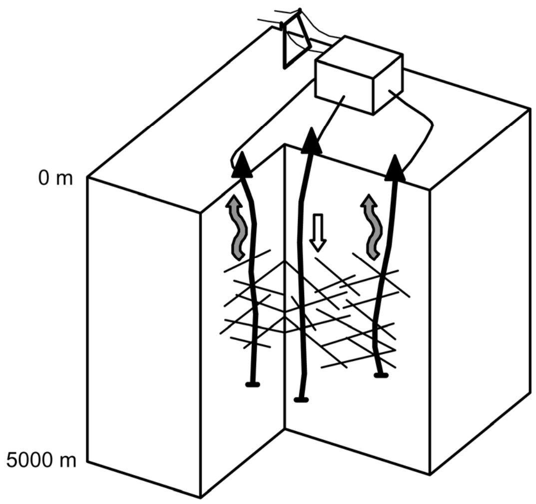

Figure 1 Simplified principle outline of the HDR method for electricity generating
1. ábra Az áramtermelési célú HDR módszer egyszerűsített elvi vázlata

The first appearance of the HDR method

Condition of using geothermal energy to produce electricity is the appropriate energy density in the carrying agent. In the case of fields with high enthalpy the agent is usually hot water with high pressure that is directly usable for electricity generating with appropriate technologies. New methods are required to exploit the heat content of steamless hot dry rocks. One could be a system of water injected into the hot dry rock, it is heated becoming susceptible for energy production. This technique is referred to as Hot Dry Rock (HDR) method. The intensity of heat exchange depends on the heat content of rocks and the size of the contact surface, therefore suitable fractured rocks are needed for this utilisation, or artificial fracturing is required which operates as a heat exchanger system with water agent.

The first HDR experiments began in the middle 1970s at **Fenton Hill**, near the Los Alamos National Laboratory, New Mexico. The site is located at the northern part of the Rio Grande rift zone, at the edge of Valles Caldera, where the Cenozoic rhyolitic domes, lava flows, pyroclastits, and the Palaeozoic sediments cover in a thickness of 730m the granodiorite of the Precambrian basement (GOFF & DECKER 1983).

On the basis of the shallow drillings this area is characterized by high heat flow (up to 250mW/m^2), which played a significant part in the selection of the site. In the first phase (between 1974 and 1980) a shallower (depth: 3km, temperature: 200°C), in the second phase a deeper (4.4km, 300°C) reservoir were studied. Some boreholes were drilled and a series of hydraulic fracturing and circulating tests were run. The permeability of the reservoirs was increased, however, the microseismic events revealed that the desired connection was not created due to an unexpected change in the stress field. Therefore one of the wells was re-drilled into the fractured reservoir in 1985, thus it was possible to begin the test.

In May 1986, 37000m^3 of water was injected, and 66% of that was recovered, while another 20% was recovered during post-test venting. Flow rates were 10.6 to 18.5kg/s, with wellhead pressure in the range of 26.9–30.3MPa. The constant temperature of the extracted fluids was near 192°C. After the test the wall of one of the wells collapsed therefore the well was closed and re-drilled.

At the second test, the relationship between wellhead pressure and circulation was studied. Below a critical pressure of approximately 19MPa there was no fluid loss while the size of the reservoir did not increase. The temperature of the extracted fluid decreased while the temperature of the well was constant.

The first stage of the second phase tests was continued for 112 days in 1992, and closed as a result of pumping failure (DUCHANE). From February to April 1993, a 55-day testing followed the first stage with similar parameters. Cold water was injected with a rate of 6.3kg/s, the produced hot water had constant temperature warmer than 180°C. At the same time, the temperature of the subsurface layers was reduced. Water loss was reduced from the initial 12% to 7%.

Dissolved solids quickly reached their constant low concentration of about 4000mg/l TDS. This is low enough for scaling and corrosion to have no considerable influence on operation. The main dissolved components were chloride- and sodium-ions (25-25%), bicarbonate and silicate (both approx. 12–13%). Dissolved gases reached the values of 2000–3000mg/l, 98% of which were CO_2, in addition, nitrogen, oxygen and hydrogen sulphide were measurable in the water. The gas remained dissolved in the fluids even in the low pressure parts due to their low concentrations.

Extractable heat energy power was 4MWth, while required pumping energy was less than 1/6 of this with diesel pumps and 1/15 with electric pumps.

In 2000, the experiments were closed in consequence of some problems in the last test series.

The Fenton Hill project was the first heat extracting system from hot dry rocks. The tests justified the positive correlation between the formed fracture system and the effectiveness of heat exchange. Consequently, planning the fracturing of the deep heat exchanger is required. Thus the name of the technology was changed to Enhanced or Engineered Geothermal System (EGS).

Over that the connection between the injection rate, pressure, temperature and water losses were recognized.

Experiences from HDR projects in Europe

A few years after the beginning of the Fenton Hill project, a primarily rock mechanical experiment funded by the EEC and the UK Department of Energy began at the **Rosemanowes** Quarry in Cornwall (PARKER 1999). In this quarry the well known Carnmellis granite was mined. Since the temperature of this porphyiritic, at deeper equigranular granite was below 100°C, the aim was to study fracturing processes, not energy production Mining explored the pluton to a depth of approx. 1000m. The geothermal gradient at the site is about 3–4°C per 100m, in addition the highest heat flow values in England (120 mW/m^2) were measured here.

At first some 300m deep wells were drilled, however, researchers considered the stress field not representative for deeper strata. In the next stage, two 2000m deep wells were drilled reaching 80–90°C of bottom temperature. After this, the re-injection and production wells were drilled. During the first testing, water was injected at rates up to 100kg/s (70% water loss) and wellhead pressures of 14MPa resulting in artificial fractures expanding vertically as according to the original fractures. Consequently, the fractured zone became unsuitable for HDR methods.

A new borehole reached 100°C at a depth of 2600m in 1983, however, researchers were able to continue the experiments for 4 years at an average injection rate of 20–25kg/s. During this long-term test downhole temperatures decreased from 80.5°C to 70.5°C. Extraction rate was 4kg/s at 5kg/s of injection rate and 4MPa of wellhead pressure, while it was 15kg/s at 24kg/s of injection rate 10.5MPa of pressure.

Figure 2 Sites of experimental HDR projects in Europe
2. ábra HDR kísérleti projektek helyszínei Európában

Researchers demonstrated that fluids reach the production well too rapidly. After the testing it seems that the joints were tightened or closed. A high viscosity gel with proppant materials (sand) was injected into the fractures to widen them. Water loss was reduced, however, the temperature of the extracted water was reduced as well.

The first results induced several experiments across Europe (*Fig. 2*). In Germany a shallow research began at Falkenberg and a deep well (depth: 4500m) research was lounched in Bad Urach. There was a project involving an 800m deep borehole in Le Mayet (Massif Central, France), while at Soultz-sous-Forêts (Upper Rhine Valley, Alsace, France) there was a French–German cooperation in progress. These experiments besides the aborted continental rift of the Rhine were performed mainly in the faulted-thrust inner belt of the Alps as well as in the foregrounds dissected by deep faults and structural trenches. In 1987 the EEC gave financial support for only one site for economic reasons, and they choose Soultz as the joint European HDR programme.

Since a former oilfield, the geology of **Soultz** was well known down to the depth of 1500m, and the geothermal gradient in the upper 1000m is 11°C per 100m, heat flow was more than 140mW/m^2-t (SCHELLSCHMIDT & CLAUSER 1996), while 176mW/m^2 of heat flow was measured in the borehole (BRESEE 1992). Below the sediments there are thick granite bodies (HOOIJKAAS et al. 2006). In the studied depths the granites are rich in K-feldspar with cm-sized pink K-feldspar and mm-sized quartz, plagioclases, amphiboles and biotites in the porphyric texture. The upper 100m of the granite bodies (approx. the depth of 1450m–1550m) is fractured and weathered intensely. Between 2800–3500m the granite is altered strongly along veins. Beneath 3500m the percentage of biotites and amphiboles increase, therefore the granite becomes darker, while with depth it resembles gradually to standard granite. At approximately 4800m deep is the border of the two-mica granite that appears as dykes in shallower depths (*Fig. 3*). Various studies indicated the age of standard granite as 320–335Ma.

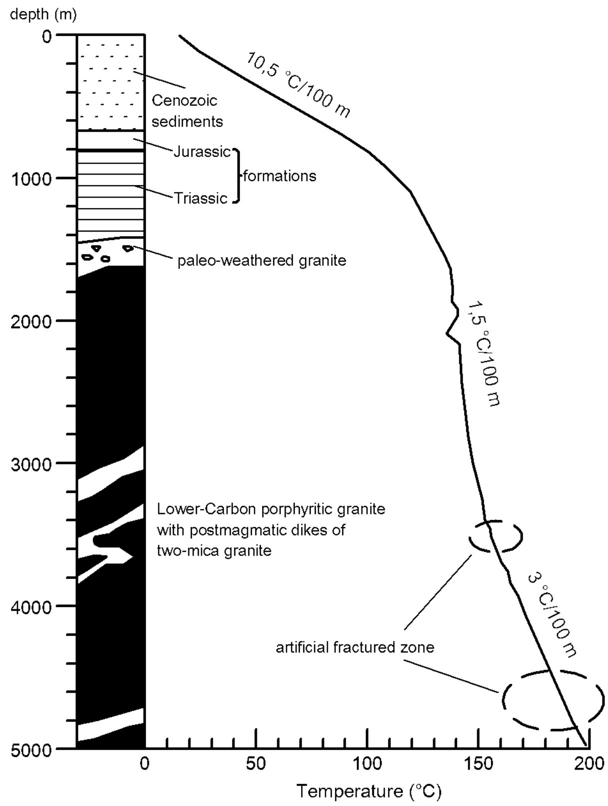

Figure 3 Simplified theoretical outline of the drillings of the HDR projects in Soultz with thermo carottage curves measured at the time of the opening of the section (1) and later (2) (on the basis of HOOIJKAAS et al. 2006 and BARIA et al. 2000)
3. ábra A Soultz-i HDR projektek fúrásainak egyszerűsített elvi rétegoszlopa a szelvény megnyitásakor (1) és később (2) mért termokarotázs görbékkel (HOOIJKAAS et al. 2006 és BARIA et al. 2000 alapján)

The first well (GPK1) was drilled down to depth of 2002m in 1987 (GÉRARD et al. 2006), however, the borehole temperature was 140°C instead of the predicted 200°C estimated from high geothermal gradient in the sediments, in consequence of low geothermal gradient (1.5°C per 100m) in the lower part of the series. The measured characteristic geothermal gradient of the granite bodies is 2.8°C per 100m, while heat flow is 82mW/m^2. In 1990, a former oil well (EPS1) was drilled down to the depth of 2227m reached 150°C at the bottom. In 1991 high flow rate re-injection was performed at depths of 1420–2002 m in the borehole GPK1. In the course of the artificial fracturing microseismic events revealed 10000m^3 of fractured volume. The borehole was drilled to 3590m where it encountered 168°C instead of the expected 180°C at 3200m. Injections elsewhere showed that larger scale injection is required to creat the connection between the injection and production wells in this slightly tensional rock than predicted.

Well GPK2 was accomplished in 1995 reaching the depth of 3876m, with borehole temperature of 168°C (BARIA et al. 2000). The distance between the two boreholes was 450m with two fracture systems supplying brine with high concentration of dissolved solids (TDS: 100,000mg/l; 10w% PAUWELS et al. 1993, AQUILINA & BRACH 1995). GPK2 stimulations in 1995 proved the connection with GPK1 in addition a 0.24km^3 microseismic cloud was developed. In 1995–1996 water injected to the system (40°C, 21kg/s) achieved 136°C and produced thermal power of 9MWth. Continuing this experiment at the average injection rate of 25kg/s and pumping power of 250kWe, the thermal power of 10MWth was produced without measurable water loss in 1996 (TESTER 2006). GPK2 was drilled further in 1998 and the temperature of 200°C was reached at 4950m (*Fig. 3*).

In the 21st century two new boreholes were drilled from a common platform with GPK2 down to the depth of approx. 5000m (GPK3 in 2001, GPK4 in 2003–2004). Seismic events caused by the testing of GPK2 and GPK3 intensified social resistance against the project, therefore the injection-production practice had to be changed. During the stimulation of GPK4, an aseismic barrier zone without water flow was developed between the wells (SANJUAN et al. 2006, GÉRARD et al. 2006). To solve this problem, a second injection was performed with acid fluids, thus a low permeable zone was formed between the wells.

Experiments of Soultz revealed that the primary joint system determine the fracturing parameters of EGS systems through the widening effect of injection. The correlation between the rate of injection and wellhead pressure is linear, refering to the porosity of the host rock.

At **Fjällbacka** (West-Sweden) a hydro-mechanical HDR experiment was run in the Bohus granite. In 1984 three boreholes were drilled down to the depths of 200, 500 and 700m to develop a reservoir, which was drilled to the depth of 500m in 1988. A 40 days long circulation test was performed, however, there was a high impedance between the wells (WALLROTH et al. 1999). The experiment was finished in 2001.

In **Falkenberg** the homogeneous Falkenberg granite with low fracture density was studied at small depths between 1977 and 1986. With low injection rates a fractured zone with an area of 15000m^2 was developed to perform numerous rock mechanical and hydraulic tests (TENZER 2001). During the longest circulation test (14h, 3.4kg/s) a temperature decrease of 1°C was measurable (TESTER 2006).

In the surroundings of the geothermal anomaly of Urach (**Bad Urach**, Swabian Alps) some important researches were completed in 1977–1980 to investigate the properties of the anomaly and its heat storing or heat extracting abilities. Before the project two 800m deep boreholes were drilled down to the Middle Triassic Muschelkalk (in 1970, 1974). In 1977 a well was drilled down to 3334m, continued later to 3488m. At this depth the temperature of the metamorphic gneiss is 147°C. Following a one-well stress field measurement in this borehole 12 tests were conducted to examine the fracture system and its variation. At the next stage it was drilled down to 4349m, where the temperature was 170°C with a geothermal gradient of 2.9°C per 100m. According to studies from 1990–1996 the extractable energy power in Bad Urach is 3MWe or 17MWth (TENZER 2001).

The Swiss HDR project called *Deep Heat Mining (DHM)* includes two sites one in **Basel** and another one in **Geneva**. According to the original concept, the geothermal energy is not used for electricity generation alone, but for local district heating as well, therefore it had to be planted in a densely populated area like the industrial part of Basel. In Basel the DHM technology based on a well triplet reached 200°C at about 5000m in a basement granite. Theoretical considerations estimate 30MWth power at water injection rates of 100kg/s. The type of electric generation had not yet been decided, since the plant would be combined with the waste incineration of the municipal water purification plant and a gas turbine. This plant could provide electric energy more than 0.4PJ and 0.15PJ thermal energy annually for district heating. Basel is located in the strongly seismic Rhein Graben, therefore the first aim is to become acquainted with background seismicity and induced seismicity with the support of some monitoring wells. During injection some earthquakes occurred with magnitudes greater than 3, consequently proceedings were suspended (www.geopower-basel.ch).

Edifications of the HDR experiments – limiting factors, risks, dangers

Subsurface heat mining faces with numerous difficulties using the HDR method as well. Information on deep structure, temperature profile, possible volume of reservoir, size of fractures and exchanging surface is required to assign the appropriate location. In the case of running projects either data for much less depth of the boreholes is used or only 20–25% of the required depth was planned to be investigated preliminary. Petrological, petrophysical, geothermal data derived from these wells did not represent the conditions of the reservoir to be enhanced much deeper, consequently they proved to be of limited service.

Based on the experiences, planning uncertainty can be significantly reduced with existing or drilled boreholes, with the depth of which achieves 70–90% of the planned reservoir depth. It is even more important in heterogeneous or structurally strongly dissected basins, where the thermal and physical properties of the basement and the overlying beds are significantly different from each other.

The assumption of homogeneous half-space is only possible in areas that lack data. However, it holds the risk of unexpected rapid variations of the quality of the material towards greater depths presenting possibly breakings with negative effect, i.e. sections of decreasing gradient in vertical heat distribution.

Fracturing induced microseismicity might be dangerous for earthquake-sensitive buildings near the epicentres. The fracturing systems in the depth 4000–6000m function as a heat-exchanger, however, their occasional renewing is required as the compriming effect of lithostatic pressure reduces their volume. In order to increase efficiency the increase of reservoir volume would be required, which, on the other hand results in growing risk of seismicity, increasing costs of production, and the gradual decrease of the heat content of the concerned volume. During and after injections in the case of both Soultz and Basel earthquakes occurred with magnitudes higher than 2.5 (BARIA et al. 2005, www.geopower-basel.ch). By reason of these earthquakes, the social and political antipathy became stronger, mostly in Basel, where the project running in an urban area.

Dissolvable or toxic minerals and rocks were not reported in the projects, however, it can solute into brine (from e.g. salt rocks, ore occurrence) causing negative environmental effect through acid treatments or long term operating. Water exploited may contain huge amount of non-toxic dissolved elements, which might be deposited during the electricity generating processes damaging the turbine and the pipes. Greate volume of dissolved gases may leave the water, for example carbon dioxide, methane and hydrogen sulphide causing the increasing of the number of anaerobic bacteria.

Unknown subsurface agent is able to contain primary or secondary porosity, structural fragmentation, breccias etc. that are able to influence unfavourably the expansion and direction of fracture system to be established. This takes and diverts dynamic compression waves. Similarily it may orientate such folded and faulted forms associated to former tectonic deformations that although may be either closed or filled later causes the formation of disadvantageous joint network when reactivated in the course of artificial fracturing. In Rosemanowes as an extreme case, preformation caused a subvertical expansion of the fracture system, forming vertical thermogravitative convection inside the reservoir.

In complex folded, faulted, thrust formations this strongly mosaic character together with significant local differences in rock type and heat conductivity are disadvantageous. Variability in petrophysical parameters makes modelling more difficult.

Some important lessons are learned at the European HDR project, the most important is that high heat flow values measured on the surface and high geothermal gradient at shallow depths are not regarded as certainty of more than 200°C in the depth of 2000–3000m.

Experiments without given and calculated values suggested that the expansion, geometry, heterogeneity of the heat exchanger, and the idealized shape in which the heat streamline system changes can be defined hard. Consequently the range and expansion of cooling together with the reheating time were not determined precisely in the tested systems.

Prospects of Hungary in the adoption of HDR technologies

With the generalisation of experiments at Soultz, GENTER et al. (2003) published a study in which they research areas in Europe same as Soultz regarding geothermal, petrologic and tectonic properties to designate locations of the least economic risk to HDR technology. The most important factor of this work was the more than 200°C temperature at the depth of 5000m. Consequently, uncertain extrapolated temperature data were left out.

The research revealed two regions that seemed to be appropriate for HDR technologies apart from the West European Rift, one in Tuscany and another in the Pannonian Basin.

Based on the structure and hydrocarbon exploring boreholes, temperature increases linearly as a function of depth in the deeper middle-basin sediments. The most significant reason for this could be that the relatively young sediments are compacting significantly and fluids migrate upward, in addition the aquiclude clay strata are finite lenticular bodies with shear zones, since fluids can percolate round or through these bodies. Reliable information is not available to understand the process properly.

Core sampling is usually sectional while the interpretation of geophysical parameters is not completely accurate depending on strata thickness and material together with the applied method. The various lacustrine Pannonian sequences and the deeper settled Badenian-Sarmatian volcanic rocks and volcaniclastic deposits are not considered as homogeneous space, however, the spatial diversity in properties and layer thickness make regional modelling difficult.

In the Pannonian Basin GENTER et al. (2003) designated a geothermal axis with an orientation of WNW–ESE form South Transdanubia along the Dráva river to the southern Great Hungarian Plain. Another preferred area is a double anomaly located in the region of South Nyírség–Middle Trans Tisza and the Békés basin.

The study describes the tectonic, geothermic and economic considerations of selecting the mentioned regions. Despite the aim of selecting similar areas to Soultz, all of the sites in the Rhein Graben, Tuscany and Pannonian basin have dissimilarity in at least one aspect.

The composition and structural properties of the basement along the Drava-lineament are uncertain. In the Nyírség huge volume of Miocene volcanic beds are intercalated between the Pannonian–Pleistocene aquifers and the unknown basement. Overheating as a provisional local heat accumulation is presumed beneath the insulating sediments. Tapping of a heat accumulation like this, may cause unknown spatial and temporal changes in heat content. Regarding the basement some boreholes on the margins of basin (e.g. Komoró-I SZÉKY-FUX et al. 2007) provide information that is difficult to extrapolate. The extent of the reached graphitic shales is unknown, such as the presence of Palaeogenic sediments above the Palaeozoic basement of the volcanotectonic depression. Although the basement of the Békés basin is known better, data about the extent, thickness, and thermal properties of basement formations are not available.

Based on the above mentioned it can be stated that calculations based on downhole temperatures of deep wells and large scale or speculative tectonic literature involve uncertainty and risk for planning a project. The shape of isotherms in geothermal maps depends on the studied depth. DÖVÉNYI et al. (1983) reports a temperature map about Hungary for the depth of 2km that is based on numerous real borehole data, nevertheless the reasons of local anomaly can be determined difficulty. With increasing depth the influence of covering beds and thermogravitative convections decrease, while the position, compactness and heat convection of rock bodies have an important role to specify the boundary and focus of anomalies.

Consequently the estimated temperature distribution at 5–6km must show different anomalies than the shallow distributions. The map of GENTER et al. (2003) was complemented with predictable anomalies from the combinative occurrence of the heat dome of Palaeozoic rocks and the strong structural dissection buried partially by composite volcanoes, volcaniclastic deposits (*Fig. 4*).

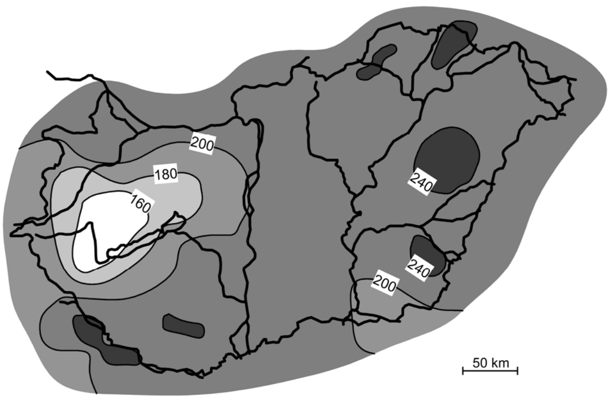

Figure 4 Estimated temperature distribution at 5 km depth in the crust, Hungary (after GENTER et al. 2003, modified)
4. ábra Magyarország 5 km-es tengerszint alatti kéregmélységére becsült hőmérsékleti eloszlás valószínű izotermái (értékek °C-ban) (GENTER et al. 2003 felhasználásával, módosítva)

In our opinion the surroundings of the outcrops of the good heat conductor Palaeozoic basement are suitable to provide information on the geothermal characteristic, heat flow and heat supply of the basement by appropriate petrophysical, geophysical investigations in boreholes. At these locations the disturbance of local anomalies is least expected as the result of the lack of basin-wide general thermal aquifers and aquicludes. In extended Pannonian aquifers and thermal deepkarsts overheated heat accumulation reservoirs may occur locally and occasionally that are only subsystems in a larger region but appear as positive anomaly sections in the bottom temperature and thermal carottage data of of boreholes that reached them. In these systems permanent water or heat extractions may cause significant cooling, moreover at deeper levels the thermal values may turn out to be less than predicted.

Ten thermal wells were drilled down to the lower levels (2000–2500m) of the geothermal field of Szentes. In the case of these wells the 100°C isotherm was found at 1800m, while 120°C isotherm was detected at 2200m (KORIM & LIEBE 1973). With linear extrapolation of this dataset 260°C can be estimated at 5000m, however, the boreholes in the southern part of the Great Hungarian Plain, which were drilled down to similar structures as at Szentes, support not this prediction, consequently the geothermal gradient drops below the thermal zone.

Buried composite volcanoes intersecting the partially granitoid basement of the volcanotectonic depression located at depths of 2000–4000m may be perspective for heat mining due to Neogene vents and intrusions that provide a compact heat conductor channel to the middle deep crust.

Unfortunately no significant deep borehole was drilled in these areas, the boreholes are drilled rarely with measured geothermal parameters or to greater depth than 1000m, furthermore if the basement was reached, it was not explored. Consequently a comprehensive geothermal programme should include expensive preboring investigation.

Trully perspective areas would be aseismic, or slightly seismic hyperthermal fields of active volcanic zones where heat flow values are permanent, vertical temperature function is near linear. In these case both HDR and closed system deep heat pump (KOVÁCS & KOZÁK 2007) technologies can provide energy for electricity generating. The power capacity of these power plants at low, low-middle and middle terms could exceed the 1500MWe capacity of The Geysers, USA at some optimal location of the World.

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