

Chapter 3.1

Development of Hot Dry Rock Technology

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Introduction

Hot-Dry-Rock (HDR) for long time has been a synonym for heat, extracted from deep hot crystalline rock (> 5000 m). 25 years ago. During the first oil crisis this idea was presented for the first time by atomic physicists and technicians from the Los Alamos Scientific Laboratory (New Mexico) at energy discussions. The aim of this concept was to use the inexhaustible and at any place available energy for electricity production by so-called „Man-Made-Geothermal-Systems (MAGES)“. This concept rarely agrees with present day systems for the use of geothermal energy and had been termed as “far future technology” even by sustaining geothermal pragmatists .

The situation has changed: first HDR projects as well as deep and very deep scientific drillholes of past years have shown, that crystalline rock in the deep underground is not dry. Even in great depth fluids and open flowpaths in the shape of joints and faults were detected. Therefore the underground system is not exclusively “Man-Made”, but natural conditions, especially discontinuities, have to be taken into consideration. In 1978 the International Energy Agency (IEA) commissioned the Kernforschungsanstalt Jülich GmbH to act as operating agent for conducting a feasibility study on the pos-

sible use of geothermal energy from so-called Man - Made - Geothermal -Energy – Systems (MAGES) on the basis of available experiences. Objective of the study was a first systematic analysis of all single components of such a complex system, the identification of the problems, suggest possible solutions, and to evaluate the economics for using HDR geothermal energy. The data base was increased by experiences of several HDR- Projects during the last 25 years. The technology was adapted to the conditions underground.

Geology and natural conditions becoming more important and should be taken into consideration of the design of a HDR system. There will be no single HDR technology but several concepts adapted to the regional conditions.

The development of HDR technology is well described in Rummel et. al. (1992) and Jung et al. (1997) and Baumgärtner & Jung (1998). The following compilation based on these publications.

The HDR concept

The first Hot Dry Rock concept based on the assumption that deep crystalline basement rock formations are nearly dry and impermeable for fluids due to the pressure of the overburden rock. Therefore, it was

suggested to induce artificial fractures acting as heat exchange surfaces, through which fluid is circulated via boreholes penetrating these fractures. In comparison to hydro-thermal systems the fluid circulation is performed in a closed loop where the fluid pressure is maintained as such a level to prevent boiling. Steam for electric energy production is only produced in the secondary loop at low pressure or by using secondary fluid with low boiling temperature. Originally electric energy production was the main objective, which only can be achieved economically at temperatures above 140 centigrades. Today a combined use of heat and electricity is considered as being more attractive.

Model estimates demonstrate that a HDR system has to produce a thermal capacity of 10 to 100 megawatts over a period of at least 20 years to get into the range of economy. Such size of a system requires heat exchange surfaces of 3 to 10 square kilometers and circulation rates of 50 to 100 liters per second. The critical fluid pressure for subsurface system operation is a function of the stress field at a depth which varies from site to site. For a HDR reservoir of a depth of 5 kilometers the minimum pumping pressure required is about 40 megapascals. In addition, economic reasons set an operation pressure limit. Today it is estimated that the flow impedance in a HDR system (the difference between inlet and outlet pressure divided by the flow rate at the outlet) should be in the range of 0.1 megapascal-seconds per liter (MPa s/l). Larger impedance values require a much higher pumping capacity for fluid circulation. It is evident, that circulation on a pressure level higher than the hydrostatic rock pressure are associated with enormous fluid losses. Such losses may occur by fluid penetration into the rock matrix.

During the past different types of systems had been proposed and were experimentally tested to some extent:

The initial concept that was investigated and proposed by the Los Alamos Scientific Laboratory (1) conceives the crystalline rock of the deep underground as a homogeneous

impermeable block. The idea is to connect two boreholes by artificially created fractures. This fracture system is created by hydraulic fracturing which leads to approximately planar vertical fractures evoked by strain processes. The heat is extracted in a closed loop system: water is pressed from an injection borehole to a production borehole and the required pressure keeps the fracture surfaces open.

The concept of the Camborne School of Mines (2) (Cornwall), which was proposed some years later emphasizes the fracture network in the underground: the existing joints prevent the extension of huge artificial fractures. However, the existing joints are sheared and widened during the frac-experiments thus causing a fracture network with increased permeability. This process is called stimulation. The advantage of this idea compared to the single- and multiple-fracture concept is a more intensive volumetric flow through the rock formation resulting in a more regular cooling effect.

The recent concept of the European Research Project Soultz (3) uses natural extensive fracture- and fault-systems, which show a relatively high permeability. The aim of frac experiments according to this concept is to connect the discontinuities to the boreholes. The main advantage of this concept is, that it is not necessary to directly connect two or more drillholes by an artificially created or stimulated fracture system, which has turned out to be one of the most challenging problems. Each single borehole only has to be hydraulically connect to the extensive fault-zone.

Moreover by integrating natural fault zones extensive circulation systems can be created. Such a system, which normally is peripheral open, cannot be operated with an overpressure, because this would result in a strong fluid loss. As a prerequisite it is therefore necessary, that the stimulated fractures are sufficiently permeable at hydrostatic pressure conditions. This concept has been shown to be very successful under the conditions of the Upper Rhine Graben, where natural fault zones are present.

In each concept the circulation occurs

within a closed loop at a pressure level, which avoids boiling of the fluid. Steam for generating electrical power arises first in the

secondary cycle. This operating systems guarantees that no toxic material, fluids or gas are released.

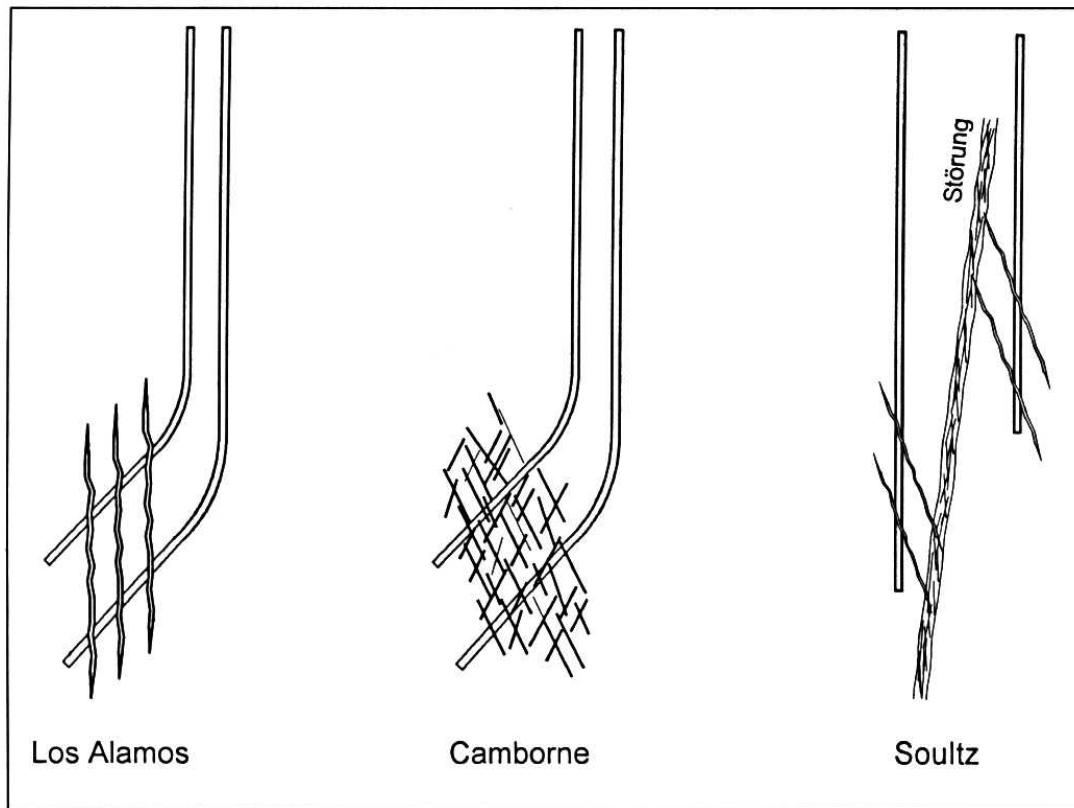


Fig 1: Conceptual Models of HDR systems.

Due to good results of experiences during the last years the generation of multiple fracture systems was suggested. In such a model several parallel vertical fractures are connected by two deviated boreholes. To avoid thermal interaction between adjacent fractures, the distance between the fractures should be in the order of 200 meters. The vertical distance between the fractures boreholes may be in the order of 300 meters. The economic operation of such an HDR system requires about 10 single fractures to be induced during separate hydraulic fracturing operations.

Results in the European HDR project enable to run the system with submersible pumps using the natural fracture network after massive hydraulic stimulation. This avoids/ reduces the water losses by high

injection pressure during circulation.

Generation of fracs by hydraulic stimulation

The aim of a HDR system is to create large heat exchanger fracture systems. Presently, the only method by which such fractures can be generated is the method of hydraulic - fracturing. This was first used in the oil industry. Fracturing is achieved by injection of fluid into the borehole by high capacity pumps. When the fluid pressure reaches a critical value an axial tension fracture will originate at the borehole wall and will propagate into the rock with an orientation perpendicular with respect to the minor principal stress direction. Results show that the induced fractures reach a length of several hundred meters and a

vertical orientation.

In comparison to sedimentary rock formation of oil and gas reservoirs, crystalline rocks of HDR systems are characterized by extensive natural joints and fractures which certainly may play a dominant role in the fluid circulation system. Results of experiences from hydrofrac operations show that the case of crystalline rocks water can be used as stimulation fluid to enhance rock mass permeability. The use of propanants is not necessary.

Image tools for fracture detection

The development of Borehole Logging tools enables to measure the orientation of single fractures on the borehole wall and to determine the fracture network in the rock mass.

Most common high resolution tools are the Acoustic Borehole Televiwer (BHTV) and the Formation Imager (FMI). The BHTV produces an acoustic image of the hole circumferential borehole wall. The borehole wall is a good reflector. Fractures intersecting the borehole absorb acoustic energy and show a reduced reflectivity.

The FMI measure the joints with electrical sensors on 4 pads. While the intact rock mass is an electric insulator, fluid filled joints show low electric resistance. In hydrothermal altered zones the FMI tool shows

large dark sections. The BHTV tool is more advantage in these zones.

The development of high temperature tools ($>200\text{ }^{\circ}\text{C}$) is needed.

Seismic Monitoring

A comprehensive understanding of the fracture distribution and hydrogeomechanical processes occurring during operation provides valuable information for reservoir development and optimization of production. Some of this information can be

obtained from well logs, but they only provide direct information about conditions near the well. Microseismic (MS) monitoring techniques can be primary methods for obtaining detailed information about reservoirs and fracture systems as far as 1 km from boreholes (Fig. 2). The opening of fractures during hydraulic stimulation induce microearthquakes. The origin of these events can be located.

The events are frequently distributed as a seismic "cloud" and it is possible to visualize a blurred image of the seismically active region from this cloud.

New processing methods like "collapsing" enables to improve absolute and relative locations of microseismic events. Collapsing uses the existence of neighboring seismic events to obtain better locations of all events. The collapsing method is based on the observation that a cluster of points occupies more volume when each point is perturbed by random errors than it does if no errors are present. This method was developed in an international collaboration known as "MTC More than Cloud" -Project. Using the collapsing method after stimulation tests and microseismic observations at Soultz it can be shown that only seismicity that occupies the volume of rock that is experienced critically elevated pressures during stimulation from each well (intersection) on Figure 2.

Additionally seismic waveforms from active seismic sources are used extensively for seismic imaging. method (Reflection method) and multicomponent signal processing was improved.

Improved measurements of the overall distribution and relative location of induced seismic events will allow construction and testing of models that include locations of potentially permeable fractures that are seismically active. Such models will help us make quantitative predictions about the relation between seismic events and reservoir performance.

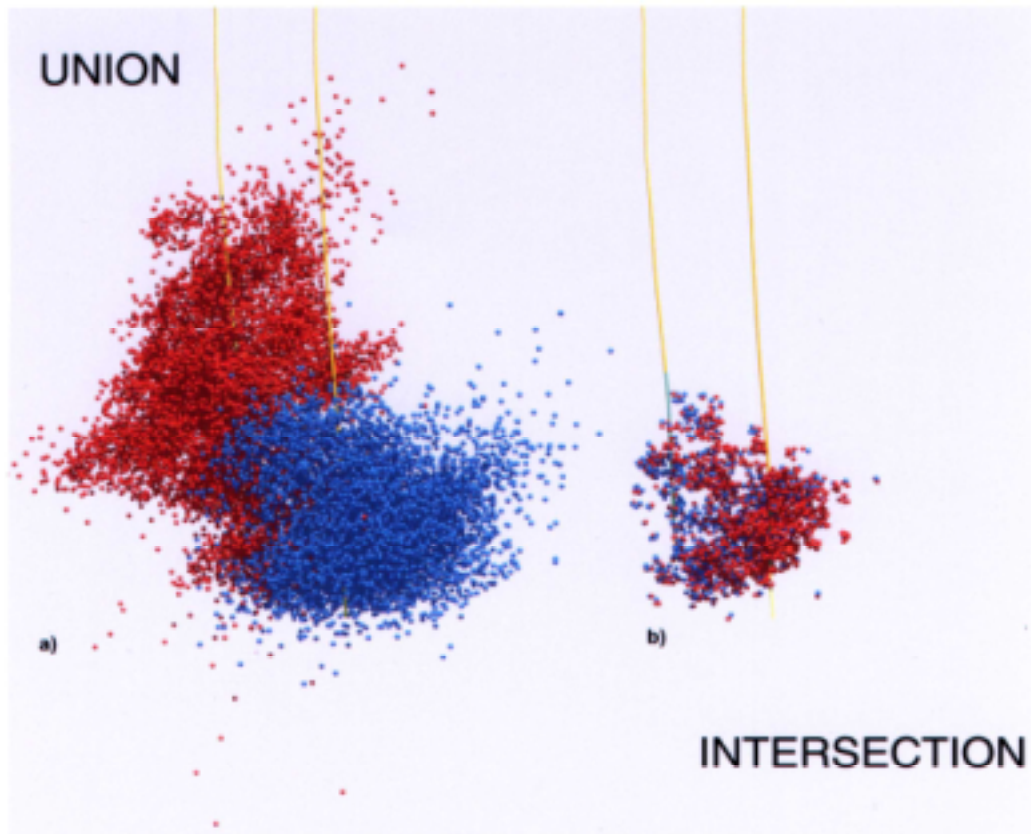


Fig 2. Seismic cloud

HDR - history

The table show the technical milestones of the development of HDR systems

- 1970** Proposal of the Los Alamos Scientific Laboratory in New Mexico 1 USA to use heat from the hot dry rocks of the crystalline crust.
- 1973** First HDR experiments at Fenton Hill on the east - side of the Valles - Caldera near Los Alamos.
- until 1979** Phase 1 of the LASL - HDR project with circulation experiments at 3 km depth at temperatures of about 195 °C.
- since 1980** Phase II of the LASL - HDR project at a depth of 4.5 km at temperatures of 330 °C with circulation experiments at about 3.6 km depth.
- 1980-1986** Participation of FRG and Japan in the LASL - HDR project.
- 1974-1977** HDR feasibility studies in

Japan.

- 1975** Start of preparations for the Urach research drillhole
- since 1977**
- 1977** HDR feasibility studies at shallow depth (500 m) in Falkenberg, Germany (until 1986), Cornwall, Camborne School of Mines (CSM), UK and Massif Central, France
- Start of the Urach geothermal drillhole Urach 3 to a depth of 3.334 meters (143°C) and hydraulic testing programme.
- 1978-1979** The MAG ES - study (use of man – made - geothermal - energy - systems) initiated by the International Energy Agency, operated by KFA Jülich and carried out by Preussag A.G.
- 1977-1981** HDR studies in the former German Democratic Republic at Mellin, Altmark.
- 1980** Deepening of the Cornwall drillholes to 2.6 km depth (80°C)

- 1980-1986** Deepening of the Urach borehole to 3.488 km (147°C) in Phase III and hydraulic testing programme (single borehole system)
- 1984-1989** Fundamental investigations in the Le Mayet de Montagne - project in France at a depth of 800 meters (University of Paris).
- 1986** Start of the German - French HDR project at Soultz - sous - Forêts in Northern Alsace (F).
- 1987** Phase 1 of the Soultz project by drilling a first 2 km deep hole (140 °C) and investigation of the crystalline basement in the Rhine-Graben.
- 1986-1991** HDR experiments in Japan in Hijion (NRIPR) and other locations (Sendai University).
- 1989** The Camborne School of Mines (the English HDR project group) joins the Soultz HDR project. Foundation of an industrial consortium to organize planning and technical operation of an European HDR - project.
- 1990-1993** Phase II of the Soultz project: drilling a second 2 km deep and deepening the first drillhole to 3.5 km depth to a temperature of 160 °C and geothermal reservoir identification. The second drillhole was used as a seismic observation hole
- 1994-1995** Phase III of the Soultz project: Drilling of the second main hole to a depth of 3876 m (170°C)
Production tests, first steam production in Middle Europe from crystalline rocks
Massive stimulation and circulation tests with seismic monitoring, development of the heat exchanger stage I, thermal power of 8 MW was achieved.
- 1991-1996** Phase III of the Urach Project. Extension of the drillhole to a depth of 4445 m (172°C) and intense borehole measurement programme
- 1996-1997** Development of the

downhole heat exchanger by massive hydraulic testing, worldwide the largest HDR system was created. Hydraulic longterm 4 month circulation test, thermal power of 11 MW was achieved.

- 1998-2000** Extension of the second main hole at Soultz to a depth of 5060 m (201°C) Hydraulic stimulation and seismic monitoring
- 2001** Planning and preparation of a first scientific HDR pilot plant at Soultz sous Forêts Planning and preparation of a first HDR research pilot plant at Urach

Examples of various HDR projects: milestones of HDR development

The first HDR project

Los Alamos Scientific Laboratory (LASL), USA

The first proposal to use geothermal energy from deep hot rocks of the crystalline basement came from physicists at the LASL in 1970. The active phase started in 1973, at certain times about 110 scientists and engineers were employed. The total financial expenditure until 1990 is estimated at DM 300 million. Germany and Japan contributed to the project financially and personnel with an amount of about DM 60 million.

Fenton Hill is located east of a Caldera about 40 kilometers west of Los Alamos on the west side of the Rio Grande Graben in New Mexico. Due to volcanism the thermal heat flow is about 250 milliwatts per squaremeter or about three times the average heat flow at the Earth's surface.

During the first phase of the project (1973 - 1979) LASL tested the basic HDR concept: connecting 2 boreholes by a single fracture at a depth of 3 kilometers in granodiorite rock at a bottom hole temperature of 195 centigrades. The fracture was generated in the first drillhole (GT-2) by hydraulic fracturing, and was identified by seismic-acoustic measurements. The subsurface flow path system consisted of several natural fractures in addition to the induced hydrofrac.

The distance between inlet and outlet was about 90 meters. Circulation experiments were carried out over a total period of 100 days and demonstrated rather low water losses and low flow resistance of the system. This first result was beyond previous expectations and also showed that proppants are not required to keep fractures open in crystalline rock. This propping effect due to rough and uneven fracture surfaces is of great significance for HDR technique.

The mean thermal capacity of this first small circulation system was about 3 megawatts. Based on the data from the circulation experiment the effective subsurface heat exchange area was estimated as only 8.000 squaremeters, an area much smaller than the induced or stimulated fracture area. During the experiments a geothermal energy of 5 gigawatthours was extracted from the rock mass, an amount to cover the yearly energy consumption of several hundred households.

After these first promising tests, the two boreholes were connected by a large fracture over a distance of 300 meters. A one year circulation test phase follows which, however, only yielded a production rate of 6.4 liters per second due to much higher flow resistance. A rather poor result, although the water loss again was small. The effective heat exchange area was estimated as 50.000 square meters, confirming the previous result that the effective flow path is limited to the direct connection between the two boreholes. It is interesting to mention that a part of the thermal capacity of 2.3 megawatt was used to drive a 50 kilowatt turbine generator and to produce electric energy.

The second phase of the LASL- HDR project started in 1980. Objective of this project is to test the multistage HDR concept. The system consists of two 4.500 meter deep boreholes, which are deviated on the last 1.000 meters to an angle of 30 degrees with respect to the vertical. The bottom hole temperature is 327°C. This high temperature in the vicinity of the Valles Caldera, however, induced various problems for drilling and borehole measurements and hydraulic

tests. A hydraulic connection between the two boreholes could not be achieved in the deeper part. Therefore, it was decided to fill this part of the boreholes with sand, and to carry out hydraulic fracturing experiments at a depth of 3.600 meters. This test was the largest hydrofrac operation ever conducted in the U.S., but failed with respect to connect both boreholes hydraulically. The spatial distribution of microseismic events monitored during the injection test shows that a large complex fracture system was stimulated over an extension of 800 meters and with a thickness of about 150 meters. Instead of being vertical the system is inclined by about 30 degrees. According to this information the second borehole was directionally deviated to penetrate this fracture zone. Thus, in 1986 - seven years after the start of the project phase - the second HDR circulation system could be completed. A one month circulation test indicates that the system may be characterized by rather favorable hydraulic properties. The thermal system capacity is in the range of 10 megawatts

In 2001 the U.S. Department of Energy (DOE) has closed its Fenton Hill Hot-Dry-Rock project. In order to be more responsive to US industry, DOE now has the Enhanced Geothermal Systems (EGS) program that will provide near term benefit to the geothermal electric power generation industry, and a long term benefit to the nation's electric power consumers. Initial focus of the EGS program is on transiting from a national lab-based R&D Program (HDR), to a highly industry-responsive program. Short term objectives will seek to increase steam production from a commercially developed hydrothermal field, while longer term objectives will seek to create a man-made reservoir that can produce steam, and electrical power, at competitive rates. The knowledge achieved from the Fenton hill experiments should now be transferred to the geysirs.

The HDR project at the Camborne School of Mines (CSM), UK

The second large HDR research project

was carried out by the Camborne School of Mines in Cornwall. First experiments in shallow boreholes drilled to a depth of 300 meters started in 1977. Since 1980 experiments have been conducted at a depth of 2.000 meters, at a rock temperature of 80 centigrades. The objective within this project phase was, first, to solve HDR - related drilling, hydraulic and rockmechanical problems, before attacking the problem of rock temperatures by drilling to great depth during a third project phase scheduled for 1992.

The location is the Rosemanowes quarry near Penryn in Cornwall, in the middle of the Carmenellis granite massif which is characterized by the highest heat flow in England (120 milliwatt per squaremeter). The average geothermal gradient is about 35 degrees Celsius per kilometer depth.

The English scientists intended to create a multifracture system by stimulating the network of existing fractures both by blasting and hydraulically. Since natural fractures are essentially vertical, boreholes were planned as inclined holes at depth in order to intersect as many as possible.

In 1980, two 2.000 meter deep boreholes were drilled with the inclined sections 300 meters apart. During the subsequent circulation test over a period of half a year only a poor hydraulic connection between the two boreholes could be achieved. Therefore, a third borehole was drilled to a depth below the other boreholes. In 1984 the borehole drilled by directional drilling technology reached the target area with high precision. Hydraulic connection with the existing borehole could only be created by a massive hydraulic fracturing stimulation test - the largest ever conducted in Europe. Over the following 3 1/2 years the 3 - borehole system was intensively investigated by hydraulic circulation tests from one borehole (injection hole). After about three years circulation in one of the flow path a thermal short circuit occurred, i.e. the circulating water was not heated any more along this flow path. Although only 20 per cent of the total flow passed through this channel, it resulted in a drastic reduction of

the water temperature at the outlet. Presently, this short circuit is explained by assuming channel flow instead of water flow over a wide heat exchange area. This is a problem which must be generally considered in future HDR system planning.

HDR research in France

After first preliminary investigations in the Massif Central since 1978, from 1984 to 1986 more fundamental investigations related to the HDR concept were carried out at a granite location near the village Le Mayet de Montagne in the Massif Central. The project was funded by the European Community, the Agence France pour la Maitrise de l'Energy and the Centre National de la Recherche Scientifique. Besides several shallow boreholes for seismo-acoustic observations, two 800 meters deep vertical boreholes were drilled. Different in comparison with other HDR drilling projects where borehole sections of several hundred meter length were stimulated, in Le Mayet single existing fractures were selected and then hydraulically opened and propagated by the use of borehole packers. During circulation tests over a period of several months the hydraulic properties of the fracture system and the heat exchanger were investigated. An important technical innovation was the development of an electrical borehole imaging device which allows to observe the generation of fractures during hydraulic fracturing in the pressurized borehole interval.

HDR activities in Japan

In Japan the development of HDR systems is systematically pushed ahead since 1970. At present, four HDR projects exist; field experiments are essentially carried out in the following three projects:

Hijiori - Project (Yamagata Province):

Since about 1980 the Ministry of International Trade and Industry (MITI) supports a technical feasibility study of the

HDR principle in four boreholes of about 2000 –2200 meter depth and rock temperatures of about 250 centigrades at Hijiori. A multi well system was developed. Short term hydraulic tests were performed in 1991, 1995 and 1996. Two reservoirs at 1800 and 2200 m in the hot granite basement were created. In 1991 a three-month circulation test was conducted in the upper reservoir. End of 2000 a longterm (2 year) circulation test started in the lower reservoir. The main objective is to investigate the lifetime of the artificial reservoir. Unexpected high impedance of injection at the beginning was observed. A higher recovery and a very low pressure of the shallow reservoir were determined.

In the second year active controll of the shallow reservoir is planned.

The scientific responsibility is with the New Energy and Industrial Technology Development Organization (NEDO) and with the National Research Institute for Pollution and Resources (NRIPR).

Yunomori Experimental Field (Iwate Province):

Following the more fundamental - oriented Gamma - project at the Tohoku University the so-called Hot - Wet - Rock (HWR) project was started with an experimental field in Yunomori in 1988. Objective of the project is to study the water rock - interaction at a depth of 1.5 kilometers at a rock temperature of 200 °C. The project is funded by the Ministry of Education and by several private institutions.

At Yunomori also the in-situ experiments of the TIGER project are carried out scientifically operated by NEDO and funded by MITI.

Ogachi - Project:

The Ogachi project is supported by the electric power industry and is operated by the Central Research Institute of Electric Power Industry (CRIEPI). Subsequently to numerous fundamental research works in the

Akinomiya experimental field between 1986 and 1988 (Phase I) circulation tests in shallow depth were performed. The reservoir in about 1000 m depth was developed with two new bore holes between 1990 and 1992. Large scale hydraulic fracturing and circulation test has been conducted since 1990 in Phase II at temperatures of 228 °C. In Phase III 1993 a circulation test of 22 days was conducted. In the following year of 1993 a 5 month circulation test was performed and in 1995 a 1 month circulation test followed. A production temperature of 160 °C and a fluid recovery of 25 % were achieved. Acoustic emission monitoring and tracer tests were carried out.

In addition to its own HDR research activities Japan also participated in the HDR project of the Los Alamos Scientific Laboratory in the US. During 1980 to 1986. Also a scientific cooperation with the European projects is in progress.

Summarizing it may be concluded that in Japan HDR technology and its related scientific and technical research is supported on a large scale financial basis. In addition to governmental funding the development of HDR technology is either partially funded by the electric power industry, or directly carried ahead like in the Ogachi project. In the so-called TIGER project all HDR research groups collaborated with industry. Japan also seeks exchange of know-how with European HDR research groups.

Australian HDR activities

A large potential for HDR geothermal energy exists in Australia. Investigations started around 1995. A commercial company was formed in 2000 "Geodynamics Limited". The mission of the company is to develop Australia's unique potential for the profitable generation of clean and renewable geothermal energy from known Hot Dry Rock resources.

Several regions in the central, southern and eastern part of Australia will be investigated. In significant parts the estimated subsurface temperature at 5 km depth is >

250°C. This was extrapolated from a database of temperatures recorded on 3291 wells. The deepest well is 5594 m while the average is 1669 m.

Studies started to investigate some potential sites. An excellent economic potential was estimated -.. operating costs of 1c-2c /kwh and total costs of 6c-8c/kWh. A Study of a 360 MW (electric) power plant with 25 injection wells an 36 production wells is under work.

HDR - activities in Germany

Several German researchers were actively involved in the first HDR activities at Los Alamos since 1972. Such associations automatically resulted in the formulation of own concepts and contributions related to HDR research:

- the **Falkenberg Frac Project** had the objective to investigate hydraulic fracturing in a tectonically rather intact crystalline rock at shallow depth (boreholes to 500 meters depth);
- the **Urach Geothermal - Project** intended to explore the geothermal anomaly Urach by a borehole drilled to 3.500 meters depth and to test the possibility of geothermal energy extraction by one borehole only;
- participation in the **HDR - Project of the Los Alamos Scientific Laboratory** (1980-1986);
- participation in the German - French **HDR - Project at Soultz - sous - Forets** in the French Alsace since 1986;
- conducting the **MAGES - study** for the International Energy Agency (IEA) during 1978 to 1980.

In the following only the projects conducted at Falkenberg and Urach are presented in more detail.

Falkenberg in North East Bavaria

Considering the enormous technical expenditures for deep drilling at high temperature convinced some of the German research groups to conduct a common HDR research project at shallow depth to study

some principal problems of fracture growth in a natural jointed rock mass and fluid transport in hydraulically induced fractures in shallow experiments. The Falkenberg project was conducted during 1977 to 1986 and was funded with about 15 million marks by the German Federal Ministry of Research and Technology and - to some extent - by the European Community.

The test site was about 2 kilometers west of the village of Falkenberg in the northern part of the Falkenberg granit massif in northeast Bavaria. The test site seemed to be suitable due to a low density joint network and due to rock homogeneity. Seven boreholes were drilled on 100 by 100 meter surface area and gave an excellent opportunity to conduct a subsurface investigation of the joint network by geophysical borehole explorations prior to a generation of a large artificial fracture. In comparison to massive hydrofrac operations for oil exploitations and also used in other deep HDR projects, the Falkenberg fracture stimulation work was limited to small injection rates and only small fluid injection volumes. In spite of this an artificial fracture plane of an area of 15.000 squaremeters was induced which also connected all the seven boreholes over a distance of about 70 meters.

Numerous hydraulic and rockmechanical tests were conducted on this fracture. For the first time the relation between fracture width and fluid pressure within the fracture was systematically investigated. The measurements demonstrated that fractures can be kept open without the use of proppants due to their natural unevenness. The fracture was intersected by several boreholes drilled to 450 meters depth. Subsequently its hydraulic behavior was tested. These tests demonstrated that the actual fracture surface had to be several squarekilometers and its transmissivity was much larger than required for an HDR system. This result demonstrated that crystalline basement rock may contain large natural fracture zones suitable for extraction of geothermal energy.

Research work at Urach Spa

The first phase of the Hot Dry Rock (HDR) Project in Urach Spa began in 1977/78 with the Urach 3 drilling hole. A depth of 3334 m within a metamorphic gneiss rock was achieved. An extension of the drill hole to 3488 m depth followed in a second phase in the year 1982/83, where a temperature of 147° C was attained. A single hole circulation system was tested.

Basic results concerning the temperature field, joint system, stress field and hydraulic behaviour of the rock were achieved. Due to high flow impedance the concept was turned back to a doublet system. To reach higher temperatures for realizing a HDR pilot plant, further investigations had to be obtained. The Urach 3 drill-hole had to be extended from 3488 m to higher depths, where the required rock temperature of > 170°C was expected. The final depth was reached in a third phase, at 4445 m. The bottom hole temperature at true vertical depth of 4394,72 m was determined with 170°C. It can be proved that the temperature gradient is constant with 2.9 °K/100 m depth. Temperatures expected at 4500 m depth are in the range of 175°C. As main lithological units, metamorphic rocks such as biotite-gneiss, anatectite and diatexite were determined in the extended drill hole. The different crystalline units are affected by brittle deformation. The resulting fracture system is sealed by hydrothermal products (clays, carbonates, sulphates). The aperture of fractures is in the range of some tenth to ten millimeters. Subvertical sinistral strike-slip shears and faults which correspond to the most intense cataclastic structures, strike N 170° E. Televue and FMI logs show a general North-South orientated joint system and borehole breakouts around N 80-120° E. The orientation of maximum horizontal stress direction was determined with N 170° E. Wireline Hydrofrac stress measurements at 3352 m depth yields values of S_{hmin} between 41-50 MPa. Estimated stress magnitudes of Anelastic Strain Recovery (ASR) measurements on cores from around 4425 m depth yields values of $S_{\text{h}} = 63$ MPa. Within

a carried out study (1990-1996), local boundary conditions, infrastructure, user potential and a preliminary utilisation concept (3 MWe, 17 MWth) were evaluated. Due to the results of the investigations, it is proposed that the Urach site located in a widespread tectonic horizontal strike-slip system is suitable for a HDR demonstration project. The results can be applied in Southern German and Northern Swiss regions and in other areas of Europe. Many potential consumers of geothermal energy produced by the HDR concept are situated close around the Urach 3 drill site. In 2001 it is planned to continue the research work and to develop a research pilot plant.

The European HDR research project at Soultz-sous-Forêts, Alsace (F)

In 1986 some of the German and French research groups conducting HDR research joined to concentrate on an HDR research project in the Upper Rhine Graben.

The project was funded by the European Community, the German Ministry of Research and Technology, (followed by the Ministry of Environmental Affairs) and the French Maitrise de l'Energie.

Soultz is located about 50 kilometers north of Strasbourg in the centre of the highest heat flow anomaly of Central Europe. Old oil boreholes indicate a temperature gradient of 60 centigrades per kilometer or nearly 100 centigrades per kilometer at Soultz for the subsurface. The geological conditions are typical for most locations in the Rhine - Graben (e.g. the Landau area).

During the first project phase (1987-1989) the objective was to test the crystalline basement for its suitability for HDR energy extraction. First, a 2 kilometer deep well penetrating the subsurface granite to a depth of 2000 meters was drilled. The borehole was used for numerous geophysical logging and hydraulic tests. Preliminary results demonstrate, that the subsurface granite in spite of the existence of natural fracture systems is suitable for planned HDR experiments. The rock temperature is 120 degrees Celsius at a depth of 1.000 meters,

but increases much less at greater depth. In 2.000 m depth the temperature is only 141 degrees Celsius. This is less than 40 °C expected from extrapolations from the subsurface gradient. This suggests that the geothermal anomaly originates not by a high heat flow from the crystalline basement, but rather from water circulation in the overburden sediments. The temperature gradient and the heat flow values are high in the sedimentary cover (10,5°C / 100m, 176 mW/M3) and quasi normal in the granite basement (2,8°C/100 m; 82 mW/m3).

The hydraulic tests also demonstrate that east - west oriented stresses are extremely low due to the graben tectonics of the Rhine-Graben. The favorable north - south oriented natural joint systems therefore offer good conditions for hydraulic circulation experiments.

In the phase one by stimulation tests a fracture was opened with an area of more than 10.000 squaremeters. Hydraulic tests demonstrated that the induced fracture intersected a natural fracture zone where great water losses occurred and the fracture growth was stopped. This interconnection opened the possibility to produce hot water from this fracture zone at significant rates. Therefore today, the possibility for geothermal heat extraction from such natural fracture systems at graben conditions (like in the Upper Rhine - Graben) becomes possible.

During 1989-1991 a continuous cored well was drilled to 2280 m depth. The well gave useful information on the joint network and mineralogy, and provided the basis for subsequent interpretation of cuttings and geophysical logs.

Main objective of the second project phase starting in 1992-1993 was to deepen the first main hole into a reservoir depth from 2000 m to 3590 m depth with a temperature of about 160 °C.

Large scale hydraulic tests were carried out to characterise the rock mass. Supporting activities during the injection tests included microseismic monitoring, production logging, fluid sampling.

The existing information available was

then used to target a second Well to a depth of 3890 m approximately 450 m south of the first well.

In 1995 and subsequently 1996 this bore hole was stimulated with a maximum flow of 78 l/s to improve the injectivity as a function of flow rate. During the test in 1995 a total of 30,000 m³ of fluid was injected and during the 1996 injection a total of 28,000 m³ of fluid was injected between 3200 and 3600 m in three flow steps (24, 45, and 78 l/s) with a maximum well head pressure of 13 MPa for 78 l/s.

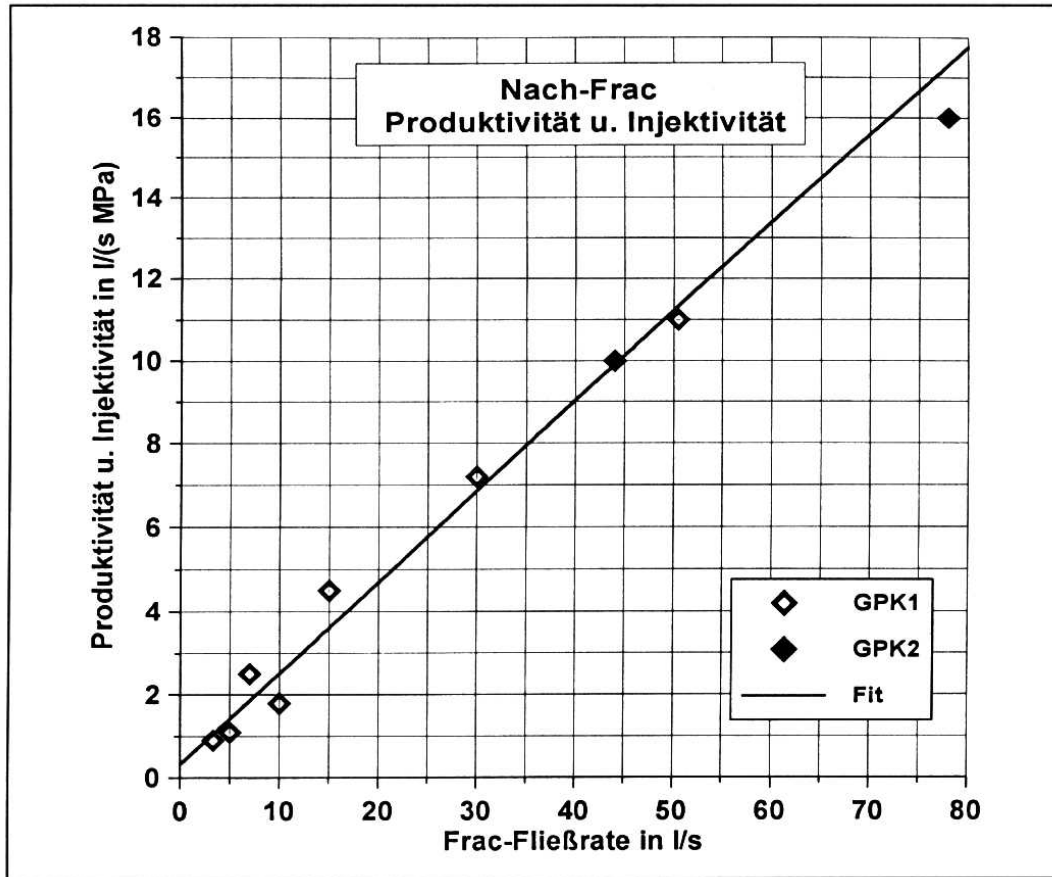
Productivity (and injectivity) of both drillholes is proportional to the applied injection rate during the frac-experiments (Fig. 3). This result is essential especially because it makes the effect of frac-experiments predictable. Despite of turbulent flow in the fracture system the post-frac-productivity was abundant to attain a production rate of more than 10 l/s. This was achieved solely by using a low artesian pressure and buoyancy effect without active production. The production rate could be increased to more than 20 l/s by a downhole pump and a simultaneous reinjection.

During a four month circulation test in 1997 8 MW thermal power were extracted continuously and the general functioning of a HDR could be evidenced.

The circulation test was carried out between the two deep wells at around 25 l/s. The result of the test showed that brine can be circulated through the enhanced fracture rock mass at great depth with a separation in excess of around 450 m, with low power consumption for circulation, no geochemical problems and no water losses. Totally 244,000 tons of hot brine were produced.

In 1999 the second drill hole was extended to 5060 m depth with temperatures of 201 °C. Injection tests and seismic observation indicates that a reservoir independent from the testing zone of 3200 – 3600 m was reached. The first hydraulic tests showed very promising results for the development of a heat exchanger and a scientific pilot plant at depth around 5 km.

Results of the last years made Soultz to the most successful HDR-project worldwide



concerning size of fracture system, flowrate, flow impedance and fluid loss. The goal of the next project phase to construct a HDR-pilot-plant with a thermal power of 30 MW, a final depth of 5000 m and a rock temperature of 200 °C therefore seems to be feasible. This project phase will be carried out with a stronger industrial participation especially together with electrical energy supplying companies. An according agreement has been made.

Outlook

During the last 25 years of worldwide HDR research the initial idea to develop a method for tapping geothermal energy from deep crystalline rocks, which can be used for power generation at any localities, has turned out to be unrealistic. Not only one HDR method but several different methods will be realised, which will use and improve the individual local conditions thus enabling an economic heat production. Scientific tools to achieve this goal were developed

and can be applied in all depth- and temperature-ranges which can be drilled.

An extensive experience of the effectiveness of these methods under varying local conditions is lacking. Therefore in addition to basic research in HDR projects, which has to be continued in the future, HDR-technology should now be realised. Possibilities and demand exist in the marginal high enthalpy storage field and low enthalpy systems as well as in the tapping of hot water from fractured and porous-permeable aquifers that show a deficiency of an adequate flowrate.

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