

DEVELOPMENT OF HOT DRY ROCK TECHNOLOGY

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INTRODUCTION

Hot-Dry-Rock (HDR) for a long time has been a synonym for heat, extracted from deep hot crystalline rock (> 5,000 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 widely 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 at 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 if discontinuities are 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 possible use of geothermal energy from so-called "Man - Made - Geothermal -Energy - Systems" (MAGES) on the basis of available experiences. Objectives of the study was a first systematic analysis of all single components of such a complex system, identify the problems, suggest possible solutions, and to evaluate the economics for using HDR geothermal energy. The database was increased by experiences from several HDR- projects during the last 25 years. The technology was adapted to the conditions underground.

Geology and natural conditions are becoming more important and should be taken into consideration in 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); Jung, et al. (1997) and Baumgärtner & Jung (1998). The following compilation is based on these publications.

THE HDR CONCEPT

The first Hot Dry Rock concept was 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 hydrothermal systems, the fluid circulation is performed in a closed loop where the fluid

pressure is maintained at such a level to prevent boiling. Steam for electric energy production is only produced in the secondary loop at low pressure or by using a secondary fluid with low boiling temperature. Originally electric energy production was the main objective, which only can be achieved economically at temperatures above 140°C. 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 be economical. 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, economics limit the operation pressure. 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 conceives the crystalline rock of the deep underground as a homogeneous impermeable block. The idea was to connect two boreholes by artificially created fractures. This fracture system was to be created by hydraulic fracturing which would lead to approximately planar vertical fractures evoked by strain processes. The heat would be extracted in a closed loop system: water pumped from an injection borehole to a production borehole, and the required pressure keeping the fracture surfaces open.

The concept of the Camborne School of Mines (Cornwall), which was proposed some years later emphasizes the fracture network in the underground: the existing joints preventing 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.

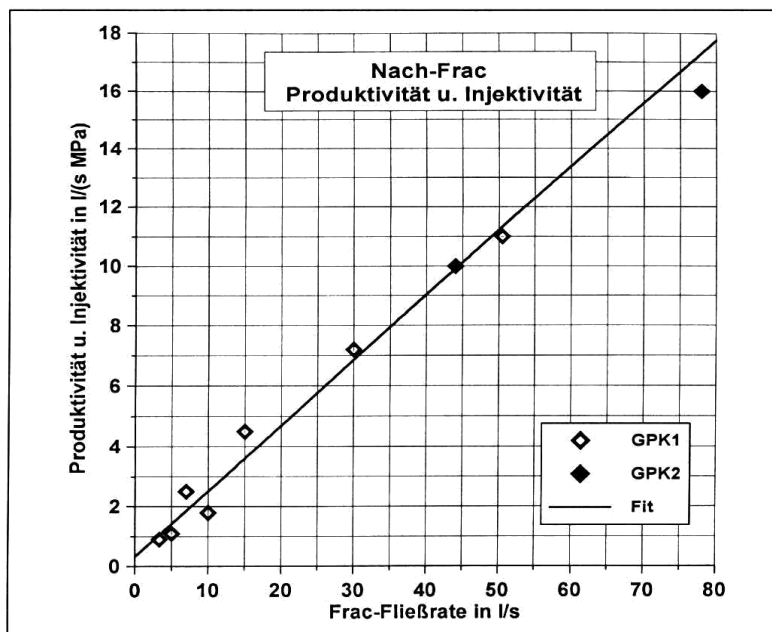


Figure 1. Conceptual models of HDR systems.

The recent concept of the European Research Project Soultz 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 drill holes 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 an extensive circulation systems can be created. Such a system, which normally is peripherally open, cannot be operated with an over-pressure, because this would result in a large 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.

Due to good results from experience 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 the system to run with submersible pumps using the natural fracture network after massive hydraulic stimulation. This avoids/reduces the water losses from high injection pressure during circulation.

GENERATION OF FRACS BY HYDRAULIC STIMULATION

The aim of a HDR system is to create a 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 have 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 in the case of crystalline rocks, water can be used as stimulation fluid to enhance rock mass permeability. The use of proppants is not necessary.

IMAGE TOOLS FOR FRACTURE DETECTION

The development of borehole logging tools allows measuring the orientation of single fractures on the borehole wall and determining the fracture network in the rock mass.

Most common high resolution tools are the Acoustic Borehole Televiewer (BHTV) and the Formation Imager

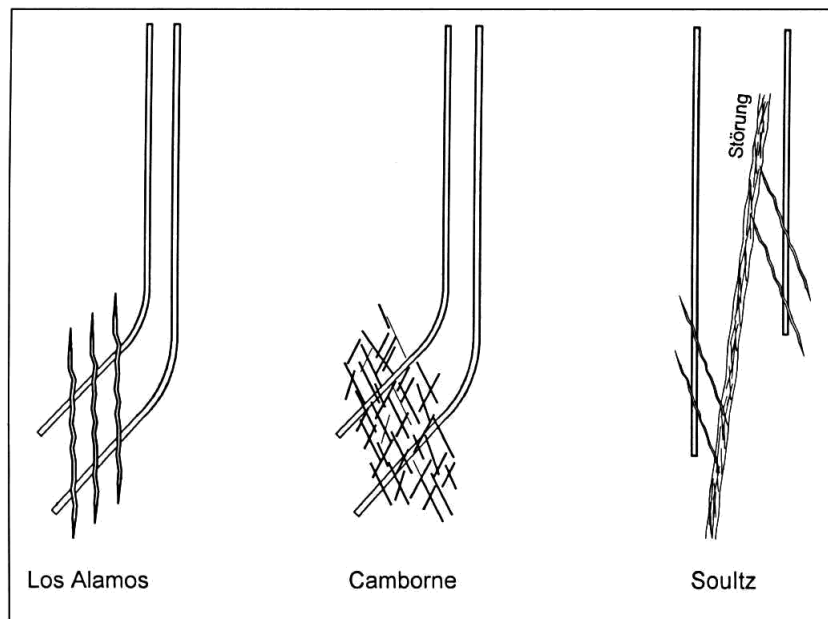


Figure 2. Seismic cloud.

(FMI). The BHTV produces an acoustic image of the entire 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 four 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 ($>200^{\circ}\text{C}$) is needed.

SEISMIC MONITORING

A comprehensive understanding of the fracture distribution and hydro geomechanical 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 the 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 micro-earthquakes. 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 improved 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 a 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 the volume of rock with seismic activity is experiencing critically elevated pressures during stimulation from each well (intersection) as shown in Figure 2.

Additionally seismic waveforms from active seismic sources are used extensively for seismic imaging. The reflection method and multi-component signal processing were 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 make quantitative predictions about the relation between seismic events and reservoir performance.

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, 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 I 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 Germany and Japan in the LASL - HDR project.	1991-1996	Phase III of the Urach Project. Extension of the drillhole to a depth of 4,445 m (172°C) and intense borehole measurement program.
1974-1977	HDR feasibility studies in Japan.		
1975	Start of preparations for the Urach research drillhole (Germany).	1996-1997	Development of the downhole heat exchanger by massive hydraulic testing ; worldwide the largest HDR system was created. Hydraulic long-term four month circulation test; thermal power of 11 MW was achieved.
since 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 program.	1998-2000	Extension of the second main hole at Soultz to a depth of 5,060 m (201°C). Hydraulic stimulation and seismic monitoring.
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.	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.
1977-1981	HDR studies in the former German Democratic Republic at Mellin, Altmark.	EXAMPLES OF VARIOUS HDR PROJECTS: MILESTONES OF HDR DEVELOPMENT	
1980	Deepening of the Cornwall drill holes to 2.6 km depth (80°C).	The First HDR Project -Los Alamos Scientific Laboratory (LASL), USA	
1980-1986	Deepening of the Urach borehole to 3,488 km (147°C) in Phase III and hydraulic testing program (single borehole system).	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 (US\$150 million). Germany and Japan contributed to the project financially and personnel with an amount of about DM 60 million (US\$30 million).	
1984-1989	Fundamental investigations in the Le Mayet de Montagne - project in France at a depth of 800 meters (University of Paris).	Fenton Hill project 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.	
1986	Start of the German - French HDR project at Soultz - sous - Forêts in Northern Alsace (F).	During the first phase of the project (1973 - 1979) LASL tested the basic HDR concept: connecting two boreholes by a single fracture at a depth of 3 kilometers in granodiorite rock at a bottom hole temperature of 195°C . The fracture was generated in the first drillhole (GT-2) by hydraulic fracturing, and was identified by seismo-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 propants 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.	
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.	The mean thermal capacity of this first small circulation system was about 3 megawatts. Based on the data from the circulation experiment, the effective sub-surface 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 gigawatt hours was extracted from the rock mass, an amount to cover the yearly energy consumption of several hundred households.	
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. Formation of an industrial consortium to organize planing and technical operation of an European HDR - project.		
1990-1993	Phase II of the Soultz project: drilling a second 2-km deep drillhole 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 3,876 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.		

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 followed; which however, only yielded a production rate of 6.4 liters per second due to a much higher flow resistance. This was 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 to produce electric energy.

The second phase of the LASL- HDR project started in 1980. The objective of this project was to test the multifrac HDR concept. The system consists of two 4,500 meter deep boreholes, which were deviated on the last 1,000 meters to an angle of 30 degrees with respect to the vertical. The bottom hole temperature was 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 connecting 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 can be characterized by rather favorable hydraulic properties. The thermal system capacity was in the range of 10 megawatts

In 2001, the U.S. Department of Energy (DOE) closed its Fenton Hill Hot-Dry-Rock project. In order to be more responsive to U.S. 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 transitioning 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 Geysers field in northern California.

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. The 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°C. The objective within this project phase was, first, to solve HDR - related drilling, hydraulic and rock mechanical problems, before attacking the problem of rock temperatures, by drilling to great depth during a third project phase scheduled for 1992.

The location was 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 square meter). The average geothermal gradient is about 35°C per kilometer.

The English scientists intended to create a multi-fracture 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-m 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 ½ years, the three-borehole system was intensively investigated by hydraulic circulation tests from one borehole (injection hole). After about three years of 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 the 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-m-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 observation of the generation of fractures during hydraulic fracturing in the pressurized borehole interval.

HDR Activities in Japan

In Japan, the development of HDR systems has been systematically pushed ahead since 1970. At present, four HDR projects exist; with field experiments 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 2,000–2,200 meter depth and rock temperatures of about 250°C at Hijiori. A multi-well system was developed. Short-term hydraulic tests were performed in 1991, 1995 and 1996. Two reservoirs at 1,800 and 2,200 m in the hot granite basement were created. In 1991, a three-month circulation test was conducted in the upper reservoir. At the end of 2000, a long-term (two-year) circulation test was 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 control 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 at

shallow depth were performed. The reservoir at about 1,000 m depth was developed with two new bore holes between 1990 and 1992. A large-scale hydraulic fracturing and circulation test has been conducted since 1990 in Phase II at temperatures of 228°C. In Phase III in 1993, a circulation test of 22 days was conducted. In the following year of 1993, a five-month circulation test was performed and in 1995, a one-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 U.S. during 1980-1986. Also, 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 called “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 3,291 wells. The deepest well is 5,594 m, while the average is 1,669 m.

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

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 their 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-Forêts** 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 (US\$7.5 million) by the German Federal Ministry of Research and Technology and--to some extent--by the European Community.

The test site was about two kilometers west of the village of Falkenberg in the northern part of the Falkenberg granite 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-m 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 square meters was induced which also connected all seven boreholes over a distance of about 70 meters.

Numerous hydraulic and rock mechanical 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-m depth. Subsequently its hydraulic behavior was tested. These tests demonstrated that the actual fracture surface had to be several square kilometers 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 drill hole. A depth of 3,334 m within a metamorphic gneiss rock was achieved. An extension of the drill hole to 3,488 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 behavior 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 3,488 m to higher depths, where the required rock temperature of >170°C was expected. The final depth was reached in a third phase, at 4,445 m. The bottom hole temperature at true vertical depth of 4,394 m, 72 m was determined at 170°C. It can be proved that the temperature gradient is constant with 2.9°K/100 m depth. Temperatures expected at 4,500 m depth are in the range of 175°C. As main lithological units, meta-morphic rocks such as biotite-gneiss, anatexite and diatexite were determined in the extended drill hole. The different crystalline units are effected by brittle deformation. The resulting fracture system is sealed by hydrothermal products (clays, carbonates, sulphates). The aperture of the fractures is in the range of some tenth to ten millimeters. Sub-vertical sinistral strike-slip shears and faults which correspond to the most intense cataclastic structures, strike N 170° E. Televiewer 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 at N 170° E. Wireline Hydrofrac stress measurements at 3,352 m depth yields values of $S_{h_{min}}$ between 41-50 MPa. Estimated stress magnitudes of Anelastic Strain Recovery (ASR) measurements on cores from around 4,425 m depth yields values of $S_h = 63$ MPa. In a study (1990-1996), local boundary conditions, infrastructure, user potential and a preliminary utilization 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°C per kilometer or nearly 100°C 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 two-km deep well penetrating the subsurface granite to a depth of 2,000 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 the planned HDR experiments. The rock temperature is 120°C at a depth of 1,000 meters, but increases much less at greater depth. At 2,000 m depth, the temperature is only 141°C. This is less than the 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/m²) and quasi normal in the granite basement (2.8°C/100 m²; 82 mW/m²).

The hydraulic tests also demonstrated 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 1 by stimulation tests, a fracture was opened with an area of more than 10,000 square meters. 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 2,280 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.

The main objective of the second project phase starting in 1992-1993 was to deepen the first main hole into a reservoir depth from 2,000 m to 3,590 m depth with a temperature of about 160°C.

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

The existing information available was then used to target a second well to a depth of 3,890 m approximately 450 m south of the first well.

In 1995 and subsequently 1996, this borehole 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 3,200 and 3,600 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 drill holes 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 attaining 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 simultaneous reinjection.

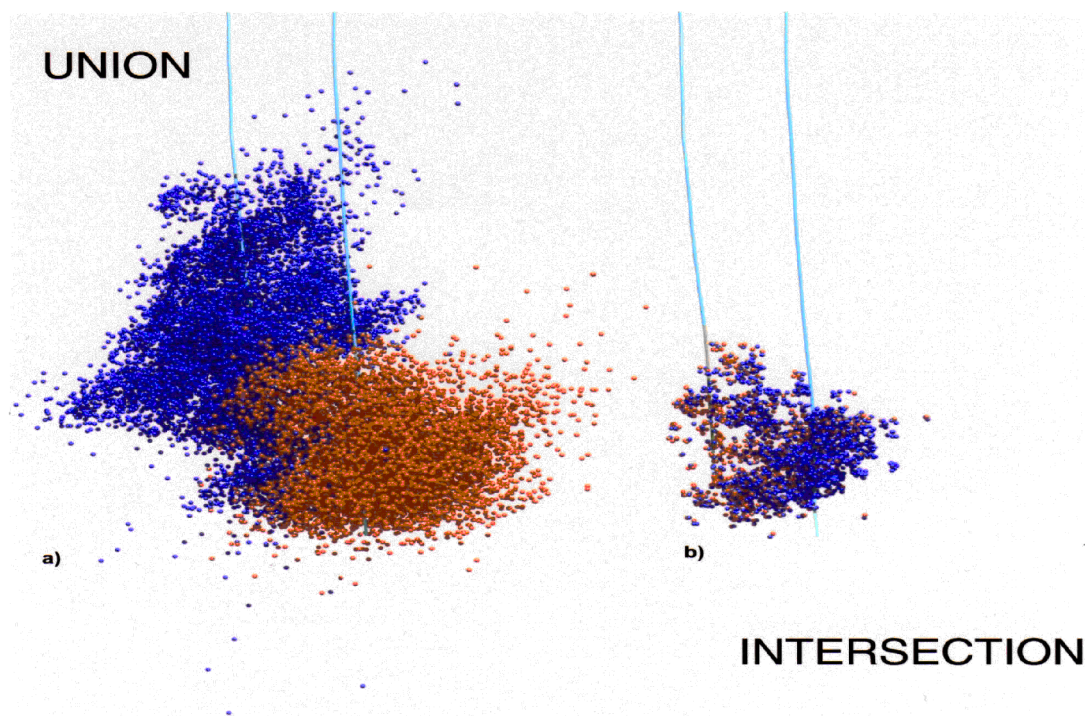


Figure 3. Fracture - production vs. injection.

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

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. A total of 244,000 tonnes of hot brine were produced

In 1999, the second drill hole was extended to 5,060 m depth with temperatures of 201°C. Injection tests and seismic observation indicates that a reservoir independent from the testing zone of 3,200 –3,600 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 the most successful HDR-project worldwide concerning size of fracture system, flowrate, flow impedance and fluid loss. The goal of the next project phase is to construct a HDR-pilot-plant with a thermal power of 30 MW, a final depth of 5,000 m and a rock temperature of 200°C, which seem to be feasible. This project phase will be carried out with a stronger industrial participation especially together with electrical energy supplying companies. According an 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 not been successful. However, not only one HDR method, but several different methods will be realized, 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.

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 realized. 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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