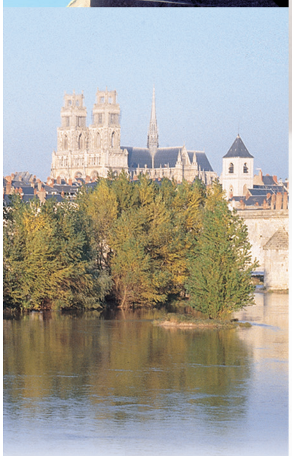

ENGINE

ENhanced Geothermal Innovative Network for Europe

Launching Conference

12-15 February 2006

BRGM - Orléans - France

Conference Abstracts

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Edited by: Patrick Ledru & Albert Genter

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Geoscience for a sustainable Earth

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Thumbnail lower top: Orléans Cathedral and the Loire River, Orléans, France, by M. Templier.
Background: EGS pilot plant, Soultz-sous-Forêts, France, by BRGM.

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ABSTRACT SUMMARY

OPENING SESSION

Geothermal energy and strategies to reduce greenhouse gas emissions

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The evolution of the CO_2 concentration in the atmosphere is now widely acknowledged as a major concern for the future of the Earth climate.

In order to stabilize the CO_2 content below 500ppm$_v$ several strategies will have to be employed during the 21st century.

Energy efficiency, CO_2 capture and storage, nuclear energy and renewable energies will share the overall efforts, to a different extend.

Among all renewable, geothermal energy is now ranked 3rd after hydropower, biomass and wind energy. Interestingly, geothermal can produce either heat or power on a continuous basis. Despite this interesting situation, the growth rate of geothermal installed capacity is not so high than the ones of wind energy or biomass. This is probably due to the fact that the thermal and permeability properties of underground geological structures are difficult to assess leading to somewhat high capital risk of many geothermal projects. Even if this knowledge could be greatly improved, the spatial distribution of high grade (good temperature, good permeability) geothermal resources is rather scarce.

This is the reason why the development of Engineered Geothermal Systems (EGS) is so important to allow a rapid growth of heat and power production in a large percentage of the continents.

The most important gaps to be fulfilled before achieving this growth are probably linked with the reduction of drilling costs and with the complete mastering of the creation and the maintenance of the underground heat exchanger.

The ENGINE Coordination Action will allow European research organizations to share their expertise with industries and public entities. Many crucial aspects of the development of EGS will be presented during this launching conference.

EC support to geothermal energy research and demonstration

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Collaborative energy research at the European level is essential to support Europe's transition to a more sustainable energy policy, the fight against global climate change and air pollution, ensure security and diversity of Europe's energy supply, and improve industrial competitiveness.

Commission support for geothermal energy research has been part of all six framework programmes. EU co-ordinated research in the field of Enhanced Geothermal Systems (EGS) started in FP3.

EGS technology could permit significant levels of electricity generation in many countries that are not currently considered as geothermal, though continued technological research is required before pilot plants can provide convincing demonstration of the practical and economic aspects of EGS systems. EGS technology has been developed to a large extent in the EU co-funded EGS Project at Soultz-sous-Forêts, and Europe is presently the world leader in this technology. The verification of the technical feasibility and cost-effectiveness of electricity production from EGS is one of the strategically important research areas in the medium to longer term part of the Sustainable Energy Work Programme of the current (6^{th}) Framework Programme. In addition, international co-operation takes place through the Commission participation in the IEA Geothermal Implementing Agreement. The Commission is committed to supporting research into geothermal technologies in the 7^{th} Framework Programme.

Policies and strategies for the development of geothermal energy

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An increased use of renewable energy within the European energy system is on the political agenda already since decades. The reasons therefore are manifold; *e.g.* beside an increasing independency from fossil fuel energy to be imported to Europe from politically unstable regions an improvement of the environmental situation concerning unwanted local effects on nature as well as a reduction in greenhouse gas emissions to reduce the impact on global climate is strived for.

This is basically true for all options for the provision of useful energy from renewable sources of energy as outlined within the White Paper on Renewable Energy published by the European Commission some years ago. But from all possibilities to provide useful energy from renewables some options are characterised by considerable advantages compared to others. This is *e.g.* true for biomass and geothermal energy because these two options can cover the actual given energy demand easily (in comparison to *e.g.* wind and solar energy). And the existing potential of biomass and geothermal energy in Europe is huge and the technology needed for the provision of useful energy is already available to some extend. These are some of the reasons why the market introduction of biomass and geothermal energy is strongly supported by the European Commission as well as various member states.

On this background the aim of this paper is it to discuss various policies and strategies for the increased use of geothermal energy exemplarily for several member states of the European Union. This is realised for the use of geothermal energy for electricity provision only because the provision of heat from shallow geothermal energy (*i.e.* heat pump application) as well as from deep geothermal resources is market mature where the geological conditions are promising (like in the Paris basin or in the North German basin) and the conditions on the demand side are well developed (*i.e.* where district heating systems exist).

The introduction of a new energy technology within the energy system can be promoted by the government based on measures in two areas. On the one hand side research and development (R&D) activities are carried out mainly to improve the performance of the conversion technology and to reduce the costs. On the other hand market introduction measures are put into force to overcome market introduction barriers typically existing for new energy technologies. Ideally activities in both areas should be linked closely to form an overall strategy.

Within the European Union R&D-activities concerning geothermal electricity generation are performed very broadly in countries where the geological conditions within the underground are more or less promising. Often these R&D-activities are realised by base funded research institutes mainly dedicated to cost intensive basic research and research programmes where universities, research institutes, research companies and other companies can apply for; the latter are in most cases dedicated to applied research. These R&D-activities realised in some EU member states on the national level are supported by the European Commission providing additional funds especially for multinational research projects with a focus on basic research as well as applied research. Such R&D-measures usually ends when demonstration plants are operated successfully.

To bring such a new energy technology into the market beside these R&D-activities market introduction measures are needed; therefore in recent years the integration of each new energy technology into the national energy system has been strongly supported by political measures. Therefore market introduction measures are put in force in several member states of the European Union. By analysing these measures one can basically distinguish between measures reducing the investment costs and measures to support the operation of plants; often one can find combinations (*e.g.* the construction of a geothermal power plant is supported by an investment subsidy and the operation by a defined feed-in tariff). Additionally supporting measures can be introduced *e.g.* to reduce the risks connected with the development of *e.g.* geothermal power plants (*i.e.* insurance packages covering the geological risk which are supported by the government).

The measures outlined above are mostly part of an overall market introduction policy. Within member states of the European Union one can find basically two different approaches: the quota model and the reimbursement model. The former defines a quota of *e.g.* electricity from renewables to be fulfilled within a certain period of time and the latter a guaranteed feed-in tariff covering basically the electricity generation costs. Both approaches – also in combinations and with various supporting measures – can be found in Europe; but the feed-in reimbursement model prevails in Europe due to certain advantages.

Additionally the market introduction of geothermal electricity generation can be promoted by so called supporting measures. This type of support from public bodies includes *e.g.* PR activities to a wider public, conferences for project developer, guide books for the development of projects for electricity generation based on the use of geothermal energy, and the provision of geological data. These type of activities are carried out mainly based on public money spend from regional or national governments as well as from the European Union. But also non-governmental organisations as well as federations financed by industry might realise such measures striving often for very specific aspects.

To sum up various policies and strategies can be found within the European Union to support an increased use of geothermal energy for the provision of electricity. They are spread over the overall range from basic research via applied research and various market introduction measures covering a wide variety from investment support measures to information campaigns. Based on this and the different geological conditions in different member states of the European Commission one can find very different strategies based on quite varying combinations of these different measures. These strategies on the national level are supported by additional measures on the European level. But due to very different geological conditions and varying energy policies on a national level the overall frame conditions for the further development of a geothermal electricity production are very different in different member states of the European Union.

Enhanced Geothermal Systems: challenges and problems ahead

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Enhanced Geothermal Systems (EGS) present a unique challenge for a future energy source: they could provide CO_2-free cogeneration. Theoretically, cooling down a 1km^3 rock volume at 200°C by 20°C corresponds to an electric power generating capacity of 10MWe over 20 years. EGS power potential estimates for Germany yield 300,000TWh, equivalent to 600 times the annual power consumption. Numerical simulations show that sustainable production is achievable over many decades.

Operational numbers, necessary for a technically feasible and economically viable EGS system call for heat exchange surfaces >2.106m² in a volume >2.108m^3 and production flow-rates of 50-100l/s with 150-200°C, at flow impedance <0.1MPa/l/s, water losses <10%. So far, such numbers have not yet been demonstrated; presently there is no power generation from EGS systems.

Here it should be noted that power generation can already be achieved, albeit at lower conversion efficiency, with fluid temperatures of 120-150°C. Attempts to produce this, from shallower depths, could be less risky. In other words there is still room for optimisation of the approach.

Numerous problems must be solved to reach the goals and many unknowns need to be clarified: irregularities of the temperature field at depth, favourable stress field conditions, long-term effects of rock-water interaction, possible short-circuiting, environmental impacts like man made-seismicity, to name only a few.

A key issue is the creation, characterization and management of the central (and crucial) system component: an extended, sufficiently permeable fracture network at several km depth, with suitable heat exchange surfaces. To achieve this, no direct observation/ manipulation is possible; it must be accomplished by a kind of remote-sensing and control. Promising developments to provide the tools needed here are underway (*e.g.* the HEX-B and HEX-S software of GEOWATT).

What will really be needed is the planning and establishment of successful EGS systems in several contrasting geological settings. Joining forces by a broad, internationally based interdisciplinary effort like ENGINE is an important step towards the ambitious goals. The EGS adventure resembles an Alpine tour: the difficulties and struggles underway are numerous and major, the prospect however ("the view from the top") is rewarding.

Why a co-ordination action about Enhanced Geothermal System?

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The work programme of the priority thematic area 1.6 "Sustainable energy systems" of the 6th framework defines a priority on innovative concepts for cost-effective investigation, assessment development and management of potentially exploitable Unconventional Geothermal Resources. The main potential impact expected from the Co-ordination Action is to re-establish the institutional and political support that is currently lacking to ensure that geothermal energy reaches its full efficiency and profitability thresholds at European scale. This reestablishment requires a mobilisation throughout the entire geothermal-energy community.

It is first of all necessary to structure the geothermal-energy community towards the definition of innovative research projects. The expected impact is the mobilisation of a large scientific and industrial community that will concentrate on the problem of “Heat exchange with the Earth’s thermal Engine”, taking into account the European policy for renewable energies and the targets defined by the circulars.

- Earth-science professionals must pay attention to applications of the knowledge recently acquired on the structure of the Earth’s crust, particularly in Europe, for societal needs. How is heat partitioned at depth, what are the driving forces and what are the links between present-day stress fields and fluid circulation at the scale of a basin or that of a basement-cover interface? Answers to such questions would constrain the localisation at depth of potential heat-exchange reservoirs and thus have a high scientific impact.
- Geophysical methods and exploration techniques (3D and 4D seismic, drilling and microdrilling methods…) used by the oil and gas industry have been improved and adapted to allow investigation and production in new basins, for example deep water, sub-salt, etc. Successful application of this technology will reduce the geological uncertainty and hence lower the risk of drilling unsuccessful wells. It will also have a profound impact on the geothermal investigation methodologies used to identify and prove up geothermal reserves.
- The geothermal reservoir engineers must define the range of heat source parameters (nature, depth, physical) for which exploitation tools are either available or need to be developed at the short, medium or long term. They will then be in a position to define generic reservoir systems that geologists, geophysicists and geochemists will be able to translate into favourable geological settings. This type of coupled technological and scientific approach will enable the development of integrated projects and have a high impact on the European Energy Policy.
- Geothermal field operators and industrial enterprises involved in geothermal energy conversion and use must seek ways to drastically reduce both capital and operating costs and improve overall conversion efficiency. As existing equipment is tailor made for

hydrothermal systems, they need to be adapted for use with enhanced unconventional geothermal systems such as hot dry rock.

- A permanent link will be established with other projects concerning geothermal energy. This will be the case with the Hot Dry Rocks Soultz experiment, the new I-GET STREP project that concerns the use of geophysical methods of investigation for assessment of geothermal reservoirs, the projects concerning the development of Larderello, Bouillante and Iceland geothermal field and in particular with the Deep Drilling project from Iceland.

The first condition for the emergence of such integrated projects is a capitalisation of the knowledge of the different actors currently playing in the "geothermal field", which implies sharing experiences, exchanging best practices and clearly identifying the gaps and barriers. These are the objectives of the Co-ordination Action. The expected impact of this Co-ordination Action is that a large scientific research community will be mobilised that is able to promote such spin-off projects with industrial partners.

The Co-ordination Action intends to play a "transmission role" and constitute an exchange platform. It will provide an opportunity to integrate and synthesise all information about know how, practices, innovations and barriers at the level of the Steering Committee and Expert Groups. This will be particularly helpful during discussions with Executive Directors of international funding agencies or National Policy makers.

Session 1

CURRENT AND PLANNED GEOTHERMAL ACTIVITY IN EUROPE

Current status of the EGS Soultz project: main achievements, results and targets

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Objectives of the project

The Soultz project is a long-term research project aiming to develop a new kind of geothermal energy. It is an ambitious project, not only in scientific and industrial terms but also in terms of its organisation. The numerous stages and partners involved mean that it is a fairly complex programme spread over a long period of time.

The EGS (Enhanced Geothermal Systems) principle also called HFR (Hot Fractured Rocks) aims to extract the heat contained in deep-seated rock (between 3,000 and 6,000m) by circulating water through a large capacity natural heat exchanger. This can be created by hydraulic and/or chemical stimulation of the permeability of natural fractures in hydrothermally active regions where deep rocks are permeable enough for the temperature to increase more quickly with depth than normal due to regional convective loops (200°C at about 5,000m deep at Soultz). The search for deep hot fractured massif led to the selection of a site in the Rhine Valley which corresponds, from the geological point of view, to a graben zone. The region chosen was Soultz, 50 km north-west of Strasbourg, a zone already well-known for its thermal springs and with a well-established geology because of oil extraction in the past (it is close to Pechelbronn oil field).

The objective of the current works is to build a pilot plant aiming to demonstrate that it is possible, using an experimental loop, to develop an extraction process which:

- is a net energy producer, *i.e.* producing much more than what is consumed by the auxiliaries;
- is stable over a long period (several years);
- constitutes a technical system free from gaps which has no prohibitive impact on the environment;
- is designed so that the technology will be rapidly standardised and cost-effective.

The results obtained today: drilling of the three deep wells and preliminary underground hydraulic tests. After five years of progresses, the construction of the underground part of the pilot is now almost finished.

Drilling works, which ended in April 2004, made possible to verify the geotechnical conditions, particularly the resistance of the wells to breakouts. In order to limit risks of hydraulic "short-circuits", the extremities of the wells are, as planned, 650m to 700m apart, but because directional drilling was used, the well heads are only 6m apart.

Works for the connections of the wells on the surrounding massif, together with the development of the inter-well exchange zone, have progressed enough for the start of medium-term circulation tests (5 months) to be engaged in July 2005. These provided a first evaluation of the inter-wells exchanger(s) and of the surrounding natural reservoir's behaviour particularly with regard to the evaluation of the future improvements required for efficient pumping and the likely kinetics of cooling the environment.

During the medium term tests performed in 2005 some 165,000m^3 and 40,000m^3 of brine were produced respectively from GPK2 and GPK4 using buoyancy effect, keeping # 8 bars well head pressure in order to avoid scaling risk. Consequently about 210,000m^3 were reinjected in the central well GPK3.

During the vast majority of time:

- GPK2 produced F2 # 12l/s with ∆P2#12bars (Productivity index # 1l/s/bar);
- GPK4 produced F4 # 3l/s with ∆P4#9bars (Productivity index # 0.35l/s/bar);
- F3=(F2+F4), i.e. # 15l/s, was re-injected in GPK3 with a bottom hole overpressure #60 bar (Injectivity index # 0.25l/s/bar) which generated some minor micro-seismic activity.

A tracer test shown that after about 5 months of circulation, some 25% of the fluorescein injected in GPK3 was recovered in the production of GPK2 and only # 1.8% in the one of GPK4.

Targets for future: Short term

From the tests performed in 2005, it appears today that the distribution of natural permeabilities in the deep fractured system at Soultz is the leading factor for the wells productivities/injectivities. Consequently the quality of the connections developed between the wells and the far field network of natural permeable fractures is of major interest. The main targets being both to produce maximum flow rates with minimum pumping power and to get the most possible stable production temperatures it will be necessary to carefully consider the future role which could be devoted to the inter-wells heat exchanger for EGS operations in the context of "Soultz type" systems.

During the next months this will lead us to try to develop for the best the connections between GPK4 and the far field natural reservoir. Then, depending from the results of some planned investigations, we will try to address the question of the poor injectivity of GPK3 (and associated risk of micro-seismic nuisances) with an appropriate strategy towards a general optimisation of the future conditions of exploitation.

Targets for future: Medium term

The main objective of the next step is the construction of a pilot plant producing electricity.

Particular attention is already focused on the following points:

- Pumps and power required for production and reinjection;
- Possible adverse environmental effects;
- Predictive maintenance of facilities;
- Cooling system;
- Hydraulic and thermal performances of the system;
- Thermodynamic conversion cycles.

A preliminary evaluation of the results will be made, before validation of the decision to build a first electrical conversion unit aiming to produce early 2007 some 1.5MW then to extend that production towards its optimal value.

Targets for future: Long term

Industrial test phase (industrial prototype) – by 2010

If the technical and economic hypotheses investigated in the preceding phase are validated, the objective will be to construct a first prototype module, on an industrial scale in terms of size and structure, then to test it, before to improve performances and arrange for large-scale production of standard modules; the power would be in a ratio of four to five with that of the pilot (25MWe).

Industrial development and distribution phase – by 2015 and after …

This will consist, at each production site, of combinations of modules suitable for adaptation to the best local conditions of exploitation. Substantial price reductions will be achieved by standardising the modules and plant management as it has already been demonstrated at standard geothermal extraction sites (for example in Italy and Indonesia).

Geothermal exploration in the Upper Rhine valley in Germany

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The Renewable Energy Sources Act (EEG) in Germany was mainly introduced to facilitate sustainable development of energy supply in the interest of managing global warming, conserving nature and protecting the environment. In the summer of 2004 the program was amended with new conditions of funding, increasing the rate for geothermal power from 0.089€/kWh to 0.15€/kWh for power production of up to 5MWe. This created a much better economic opportunity for further study and utilization of the geothermal power resources in Germany.

The potential for geothermal power production in Germany was investigated by GGA on behalf of the "Office of Technology Assessment at the German Parliament (TAB)" funded by the German parliament. The study shows that the resources for geothermal power production in Germany amount to about 10^{21}J, while three types of reservoirs were considered: hot water aquifers, faults and crystalline rocks (Jung *et al.*, 2002).

Several geothermal projects aiming at the exploration of these three types of reservoirs have been launched in the Upper Rhine valley. The high density of faults, the crystalline basement and the hot water aquifers, limestone and buntsandstone, in the graben area are attractive mainly because of their high temperatures at relatively shallow depths. Since knowledge and experience in this area is limited, each project is developing its own concept for achieving this goal.

Exploration work has been started for the hydrothermal projects in Bruchsal, Speyer, Offenbach, Landau and Bellheim. First wells have been completed and tested in Speyer, Offenbach and Landau. Further projects like Karlsruhe, Riedstadt, Ettenheim, Kehl are still in the planning and early preparation phase.

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The Swiss Deep Heat Mining programme: activities and perspectives

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Theoretical research and development work had already been under way in Switzerland for 20 years in what was at that time still referred to as Hot Dry Rock geothermal energy technology, when at the end of 1995 the Federal Office of Energy expressed their interest in it as a potential component of a future new energy mix.

The result was the creation of the DHMA and subsequently the formulation of the Deep Heat Mining programme. DHMA were further charged with managing the programme. In the ten years since 1995 the necessary studies and investigations have been undertaken, resulting in a positive verdict on the feasibility and on the potential usefulness of implementing EGS technology in the Swiss context.

Multi-parametric data analysis, including socio-political aspects, led to the selection of the city of Basle for a first pilot plant, with Geneva as the reserve choice. For the necessary pre-studies the Office of Energy provided seeding money, with the understanding that the pilot plant itself would have to be financed by local / private organisations.

A plant has been conceived, sited within the area of the city of Basle, which at the present state of the art, can only be designed in final detail upon completion of the reservoir stimulation and generation and testing of the underground heat exchanger. The target is a co-generation plant contributing heat to the district-heating network and power to the electrical supply. A wide range of technical solutions have been examined, one of which uses a hybrid (gas turbine plus ORC cycle) system for energy conversion.

The choice of site, the concept of co-generation and the decision to operate under commercial pressures are parts of a concept to give the EGS hot fractured rock technology the best chance of success.

During the past two years the financing of the new plant and the structure of GEOPOWER BASEL AG have been worked out by the investors. In parallel, much effort has been put into project preparation tasks and building up the structure of a project team. All permissions to prepare and drill on the main site having been received in the course of 2005, the site preparation, including power supply, water supply, drainage and water return systems, have been undertaken. By the end of 2005 four monitoring wells were ready for the installation of micro-seismic instruments. Two additional wells will be ready by mid February. The operational and logistic planning, and the design for the first deep well are largely completed. Drilling is now programmed to start at the end of April of the current year.

Current status of the EGS Gross Schönebeck project within the North German basin: main achievements and perspectives

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The Rotliegend of the North German basin is the target reservoir of an interdisciplinary investigation program to develop a technology for the generation of geothermal electricity from low-enthalpy reservoirs. An *in-situ* downhole laboratory was established in the 4,3km deep well Groß Schönebeck with the purpose of developing appropriate stimulation methods to increase permeability of deep aquifers by enhancing or creating secondary porosity and flow paths. The goal is to learn how to enhance the inflow performance of a well from a variety of rock types in low permeable geothermal reservoirs.

A series of stimulation experiments with different fracturing concepts were carried out. In a first attempt open hole hydraulic proppant-gel fracturing treatments were conducted in two pre-selected sedimentary reservoir zones in Rotliegend sandstones in about 4km depth. They proved to be on the one hand technically demanding and on the other hand less successful than expected due to a suboptimal design.

Nevertheless, the main inflow zones could be clearly identified. In a second step the concept of zonal selection and proppant application was abandoned and massive waterfrac treatments were applied over the entire open hole interval of the well below 3,874m to the final depth at 4,294m. Evidence of the creation and properties of vertical fractures were retrieved from pressure response analyses and demonstrated a bilinear flow regime in the reservoir. Therefore, the stimulation effect in terms of a productivity increase can be determined for the described concepts and improvements can be recommended for similar field experiments.

The GeneSys- and Prometheus-Projects: concepts for the extraction of heat from deep and tight sedimentary rock

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The GeneSys- and Prometheus-Projects are linked by an ambitious goal; while HDR-research efforts have until recently been limited to settings where crystalline rocks prevail, these projects now tackle the challenge to transfer major ideas and concepts to sedimentary rocks. This is an important step to make, since for a substantial fraction of potential sites sedimentary rocks will be found at the target depth for geothermal energy extraction.

For both projects porosity and permeability of the rocks at target depth are low, and hydrothermal use is consequently not feasible. Also direct use of geothermal energy is the common objective of both projects. Still, the projects do not just duplicate ideas, instead they follow different concepts.

The Prometheus-Project of the Bochum Ruhr-University daughter company "rubitec" is aiming to install a two well HDR-system at a depth of approximately 4km. Anticipated operation figures are a production flow rate of 30l/s and well head temperatures of at least 110°C to deliver a thermal power output of 7MW. So far, a detailed feasibility study has been carried out. Knowledge of the geological situation to a depth of approx. 2km is very good as a consequence of coal mining. As no deep wells are present in the vicinity a deep exploration well is mandatory for further planning of the underground heat exchanger. Due to the geological situation the production and injection well will have to be drilled as deviated wells into the Upper Carbonian sandstones/quartzites. The concept and detailed planning of the stimulation of the underground heat exchanger will be based on the results of drilling, logging and hydraulic testing within the exploration well. Drilling and testing is anticipated to start in 2006.

In contrast to the classical HDR-systems, one-well concepts, where one well is simultaneously used for the production of hot water and reinjection of the cooled water, are in the focus of the GeneSys-project. These concepts will in particular be attractive for sites where a thermal power in the range of few MW is required. The GeneSys project started in 2003 as a joint project of the 'German Federal Institute for Natural Resources and Geosciences' (BGR) and the 'Leibniz Institute for Geosciences', both located in Hannover, Germany. The project aims to finally provide geothermal energy for space heating of the building complex of the institutes. In preparation of the project at the Hannover site, an extensive test program has been carried out in the abandoned gas exploration well Horstberg Z1 (final depth: 4,100m) which is operated as a research well by BGR. It was shown that in sedimentary rocks large hydraulic fractures can be propagated by waterfrac technique and, that a residual hydraulic transmissivity of the fracture is kept even if no proppants are added. Also the feasibility of three different innovative one-well concepts were successfully tested. Encouraged by the positive results the realisation of the project at the Hannover site started in 2005. Currently the drilling of a 3,800m well is prepared. Beyond, concepts and methods will be further developed by hydraulic tests at the Horstberg site.

Current status of the high enthalpy conventional geothermal fields in Europe and the potential perspectives for their exploitation in terms of EGS

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The electrical energy production from geothermal power plants in Europe comes almost entirely from Iceland, Italy, Russia (Kamtchatka and Kurili islands), France (Guadeloupe, French West Indies), Portugal (Azores) and Turkey. Installed generating capacity are respectively 202, 790, 79, 15, 16 and 20.4MWe. The temperatures are 190-320ºC, 150-350ºC, 200-300ºC, 250ºC, 250ºC and 140-240ºC, respectively. The percentage with respect to their National Energy is 16.6% for Iceland, 1,9% for Italy, 9% for France (only referred to Guadeloupe Island), 25% for Portugal (only referred to San Miguel Island), while it is ranked negligible for Russia and Turkey.

Exploited reservoir depths range from shallow in Guadeloupe, Azores (0.3-1.1km) to medium in Iceland, Russia and Turkey (1-2km) to deep in Italy (1.5-4km). In most cases the permeability is defined by fractures and faults, which are difficult to locate prior drilling.

Although some of these geothermal areas are among the most important in the world, they are probably not used at their maximum efficiency. EGS technology may enhance production from conventional high enthalpy fields, and is used only to a certain extent in some of these areas.

EGS methods that could be applied are various. Well stimulation methods to improve permeability of poor-producer wells; tracer tests and improved geophysical imaging to determine the extent of faulted reservoirs and prevent strong interference between wells; complete reservoir modelling; efficient scale inhibitors to prevent scaling in wells and surface pipes. All these are examples of goals that should be addressed in high enthalpy systems in the near future, in order to increase the contribution of geothermal power generation in Europe.

A review of the main characteristics of these geothermal areas will be given, as well as a discussion of their EGS potentiality.

Session 2

WHAT NEEDS FOR SUCCESSFUL INVESTIGATION OF ENHANCED GEOTHERMAL SYSTEMS?

A review of the results presented in WGC 2005 concerning the investigations of enhanced geothermal systems

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During the World Geothermal Congress 2005 (WGC2005) held last April in Antalya (Turkey) the papers presented concerning geothermal geophysical surveys were as follows:

Exploration

20 papers concerning resistivity survey, of which:

- 5 papers concerned Schlumberger resistivity or similar (two on 1-D inversion concerning Egypt and Japan; and three on 3-D inversion concerning Mexico and Indonesia);
- 16 papers concerned MT (six on 1-D inversion concerning Ukraine, Japan, Philippines, Iceland; five on 2-D inversion concerning Ukraine, Japan, Mexico, Iran, Turkey; three on 3-D inversion concerning Russia, Japan, Indonesia, Korea, USA; one on 1D-inversion CSMT);
- 1 paper concerned resistivity measured from cores (Iceland). 10 papers concerned heat flow surveys, of which:
- 2 papers concerned flow manifestations measurements (Japan, New Zealand);
- 4 papers concerned borehole temperature surveys (Ukraine, Russia, USA);
- 2 papers concerned aerial gamma ray/magnetic (Egypt);
- 2 papers concerned earthquake surveying (Japan, Iceland);
- 2 papers concerned gravity measurements (Japan, Indonesia);
- 2 papers concerned reflection seismics (by ENEL, Italy);
- 2 papers concerned porosity measurements (Russia, Iceland).

Reservoir monitoring during exploitation

5 papers concerned micro-gravity transients (Philippines, Japan, Indonesia) and 4 papers micro-seismic activity evolution (Russia, Indonesia, Japan). These methods seem to be the main geophysical surveys monitoring geothermal production. In addition, one paper each on SP transients, changes in magnetic field and changes in borehole temperature (Japan) were presented.

Philippines

It is worth focusing on the case of Philippines, as they are the second geothermal power in the world with approximately 2,000MWe of installed geothermal power and the highest growth rate. There, before 1995 the key method to geothermal exploration was the Schumberger Resistivity. This was used to delineate geothermal resources, well sitting and estimation of the plant size. They have been successful with approximately 1,000MWe installed at that time. After 1995 they shifted to MT with 1-D inversion, due to its simplicity, easy to use, and its ability to provide reliable earth imaging at greater depths, down to 2km. Imaging quality of MT method for depths deeper than 2-3km was in question, due to intense noise at frequencies below 2Hz from surface sources. The result was to identify deeper hydrothermal resources and at greater aerial extent, which resulted in another 1,000MWe to be installed within the next 10 years. Schumberger resistivity was only able to identify shallow smectite zones of high alteration, which form the cap of the deeper geothermal reservoir. On the other hand, MT method was able to directly locate the actual deeper drilling target of intermediate resistivity, as well as several enhanced geothermal zones of high resistivity, which at present are not exploration targets but may become in the future. Controlled source MT have been used in low enthalpy groundwater systems, based on US experience for water surveys.

Italy

Although with only two papers, both on reflection seismics, they are worth to be mentioned, as ENEL has successfully applied reflection seismics in order to locate deep fault zones as drilling targets at depths 3-4km. Faults tend to bring fluid from depth and create high permeability.

MT, 3-D inversion

Papers here concerned mainly basic research. 3-D inverted MT data are theoretically more accurate than 1-D and 3-D inversion can provide a better starting point to the earth scientist to define the resistivity substructure. However, its use in the field has been limited by its complexity and the need for sophisticated computing equipment. More research is needed in inversion algorithms, elimination of noise which hinders its accuracy at lower frequencies, and especially correlation with field data from deep wells.

Evaluation of the different geophysical exploration methods through analysis of experiences in Europe and overseas

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This presentation aims at describing a state of the art of the existing and/or promising geophysical methods for geothermal exploration and recognition of geological structures and specific physical properties at depth. It makes a brief review of the geophysical methods applied in the past 20 years in Europe and, in particular, to five selected sites in different geological contexts: volcanic (Hengill, Iceland, and Bouillante, France), metamorphic (Larderello, Italy), deep sediments (Groß Schönebeck, Germany), plus the European HDR of Soultz-sous-Forêts, where geophysical methods were focused on recognition of deep fractured reservoirs.

Three aspects are pointed out: efficiency, precision and uncertainty of the results, and innovation. It is concluded that the methods used up to now, allow building a preliminary conceptual model of the reservoir in conjunction with exploration wells data. Nevertheless, the improvement of this conceptual model to decrease the drilling risk of the exploitation wells needs more integration between different methods, advanced 3 D modelling coupled with thermo-hydrodynamic modelling and rock physics measurements. This will be one of the objectives of the I-GET project, funded by the FP6.

Magnetotelluric in combination with seismic data for geothermal exploration

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A key matter for the exploration of geothermal systems is the geophysical detection and monitoring of reservoirs at several kilometers depth. In the past decade there has been a tremendous increase in time-lapse reservoir monitoring and development of seismic methods like repeated 3D surface seismic, surface-to-borehole vertical seismic profiling and borehole-to-borehole cross well seismic. At the same time electromagnetic methods, and particularly magnetotelluric (MT) sounding have been extensively used to detect fluid circulation at depth, since resistivity is very sensitive to the presence of brines. Thanks to improved methodology and software, MT is now very affordable in terms of costs and field logistic, and has gained a lot in popularity.

Seismic imaging, whilst being a powerful geological mapping tool, has not always resulted in a significantly improved understanding of the nature and composition of the deep structure of geothermal systems. In order to make advances and reduce the cost of geothermal exploration and monitoring, resistivity needs to be included in the interpretation. An integrate approach may help to go beyond the limits of seismic and MT data. Various examples are provided regarding limits of both methodologies and improvement in the interpretation when the two are integrated.

Rising open questions on investigation of Enhanced Geothermal Systems, as addressed by the I-GET project

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One of the major economic risks in the exploitation of geothermal reservoirs is the cost of exploration and drilling combined with the uncertainty of success.

Exploration methods employed have largely been developed for the hydrocarbon industry, where drilling costs do not constitute such a high proportion of the budget compared to that of geothermal reservoirs. In addition, geothermal reservoirs differ from those of oil and gas in several ways, such that exploration methods cannot be transferred one to one.

The main need for a reduction of the mining risk is therefore a geophysical method that is cost-effective and tailored to the specific needs of geothermal exploration and the geological situation of a reservoir.

The EU project IGET is funded to investigate and develop such a method by integrating several geophysical methods that are commonly used independently. In the field, seismic 2-D lines with 3-component geophones record seismic waves in 3 orientations, such that anisotropic structures can be deduced. The same profile is used for magnetotelluric recordings, complementing the structural information with that of water content. The combined interpretation and the joint inversion of these measurements has the potential to provide more information than the sum of the two used independently.

The anisotropy of the structures is investigated by AVO, with the potential to detect fluid-filled cracks.

Another major question for high-enthalpy geothermal reservoirs is the physical signal of the liquid-steam transition, as the position of that transition is of great economic interest. This question is first addressed by laboratory experiments at *in-situ* conditions, using core samples from wells in the areas investigated by IGET.

These areas comprise one reservoir in a metamorphic geological environment, (Larderello/Travale, Italy), where rock porosity is low and the reservoir permeability is provided by cracks and fault zones, one in a volcanic environment (Hengill, Iceland), and one in a deep sedimentary basin (Groß Schönebeck, Germany) as well as one in shallower sedimentary rocks (Skierniewice, Poland), where initial rock porosity is relatively high.

The information provided by field measurements, well-logging and laboratory experiments will be used to develop numerical models of the reservoirs in 3D in order to produce a static image of the reservoirs and calculate the fluid-dynamic behaviour of the fracture systems.

How EGS is investigated in the case of the Larderello geothermal field?

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Larderello is the oldest geothermal field in operation worldwide. The first experiment for electricity production was carried out in 1904, and this field has represented the sole example in the world of intensive geothermal energy exploitation up to the end of 50's, when geothermal power plants were commissioned and started up in New Zealand and then in USA.

After a first period of intensive field development and electricity generation increase, in the mid 70's serious problems of production decline became evident and new R&D programs were implemented to sustain/increase the steam production.

A deep exploration program was implemented and it made possible to verify the presence of productive layers up to depths of 3,000-4,000m, with an increase of temperature and pressure with depth. On the basis of the positive results several deep wells have been drilled and a reassessment of the geothermal resource was carried out, in terms volumes of rocks characterized by thermal anomaly and heat in place.

In the same period a program of experiments related to low permeability wells stimulation and reinjection was implemented with the specific aim of developing a "heat mining strategy", that is the same strategy for EGS.

The results of both the programs have been very successful and have made it possible to sustain/increase the steam production of the area.

More in particular on the basis of the positive results of well stimulation and water injection activities, new exploitation strategies have been adopted for the Larderello field, aimed at the resource sustainability. In these recent years the exploitation strategies have been therefore moved from those typical of hydrothermal systems to those related to Enhanced Geothermal Systems.

Geothermal reservoir characterisation of clastic sedimentary targets – needs and gaps

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The influence of depositional architecture of clastic sedimentary environments on reservoir properties is well known. 3D-seismic attribute analysis is an established technique for mapping this distribution of facies bodies in hydrocarbon exploration.

One aim of this talk is to compare results and quality of 3D and reprocessed 2D-seismic data and the implementation of sedimentary datasets in reservoir models. One of the most common problems in reservoir characterisation is the scaling of rock properties from seismic imaging down to the grain scale. Reservoir properties are extremely influenced by horizontal and vertical permeability distributions within the reservoir rocks. The lithologic control on petrophysical property variability has to be known for an accurate prediction of productivity and as input parameter for thermal-hydraulic modelling of the pay zones. The irreducible water content of reservoir sandstones as an often undervalued factor in geothermal reservoir characterisation will also be discussed.

Session 3

WHERE SHALL WE FIND NEW GEOTHERMAL RESOURCES AT DEPTH AT THE SCALE OF EUROPE?

EGS prospects in Hungary

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The BRGM report (Genter *et al.*, 2004) identified the Pannonian basin in general, and its part situated in Hungary in particular, as the most promising region in Europe for EGS systems. A follow-up study ("European HDR/EGS resources: Future potential development in Hungary", WP10, European Hot Dry Rock Project Soultz, 2005) provided further clarifications about the geologic-geothermal conditions as well as about the relevant legal, institutional, regulatory, market and social matters.

The following necessary prerequisites for EGS siting have been defined and evaluated: sufficiently high *in-situ* rock temperatures, favorable seismo-tectonic settings, suitable lithologies. In parallel, a suite of legal and market issues has been clarified. The project work was then been performed and the report completed by a Swiss/Hungarian team.

The geoscientific results are based on the most recent knowledge available in Hungary. The geothermal conditions at depth have been evaluated and presented in various maps (heat flow, geoisotherms); the geologic conditions as well (depth to the Pre-Tertiary basement; abundance and distribution of crystalline rock types in the basement). Granitoid rock types have been identified as the most promising candidates for EGS reservoir development. Special attention was given to the recent stress field and seismicity. To this end, the now available information has been assembled and presented in two new maps.

The EGS evaluations boil down to the identification of numerous geographic areas with pronounced attributes for hosting future EGS sites: the most promising regions for EGS realizations in Hungary are located in the south-southeastern part of the country, on the flanks of deep subbasins (*i.e.* Dráva, Makó, Békés, Nagykunság and Derecske subbasins) or at the top of basement highs between those, in crystalline (preferable granitoid) basement at ~4,000m depth. The present study has thus identified several new, potential EGS sites in addition to those already identified in the BRGM (2004) study (Dráva, Békés).

Reference

Genter A. *et al.* (2004) - Typologie des systèmes géothermiques HDR-HFR en Europe – Rapport final, Open file report, BRGM/RP-53452-FR.

EGS resource in France and Europe

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EGS resource accessible by drilling is mainly dependent of the deep-seated geology to minimum depths ranging between 1 and 5km. The main favorable geological conditions in France and Europe correspond to the hottest geothermal areas, *e.g.* first order anomalies, characterized by recent volcanic activity or magmatic intrusion, deep sedimentary basins, deep fractured basement or granites having high heat production derived from natural radioactive elements.

Based on the litho-tectonic characteristics observed on the EGS Soultz site (Rhine graben, France), a first classification of the EGS types in France and in Western Europe was carried out. The prerequisite conditions for an EGS system site are related to sufficient *in-situ* temperatures, favorable seismo-tectonic conditions and adequate hard rock lithologies. For temperature higher than 180°C, an estimation of the EGS potential of Europe was calculated with a simple volumetric method based on temperature extrapolated at 5km depth.

In France and in Western Europe, two main types of EGS system have been evidenced according to their geodynamical context: (1) the western European rift system which contains the Upper Rhine graben and then the Soultz and the Basel sites, and (2) some complex back-arc basins located inside the Alpine belt and related to subduction process (Pannonian basin, Tuscany). As a result, the hottest zones matching with the Tertiary graben location represent a minimum area of about 30,000km² in France. Other promising EGS types occurred in Europe and correspond mainly to deep sedimentary basins and their underlying Paleozoic basement. New areas corresponding to second order geothermal anomalies or hidden potential geothermal structures were also investigated in terms of deep seated geology based on geophysical data mainly. For example highly populated areas located in the central part of the Paris basin in France were studied through gravity and magnetic data combined with deep borehole information. A series of both non magnetic and low density zones was delineated below the Mesozoic and the Cenozoic sediments of the Paris basin. These large-scale basement areas could mainly correspond to deep Paleozoic granites, gneiss or migmatites potentially able to produce heat.

Lithosphere temperatures and geothermal energy

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In this presentation we explore the effects of intrinsic uncertainties in large-scale properties of continental lithosphere on thermal regime in sedimentary basins. Specifically, we quantify the effect of steady state and transient processes connected to basement heat flow and its consequences for geothermal energy.

In many basins calibration date are available such as BHT (Bottom Hole Temperature) data or surface heat flow measurements. Lithosphere scale modeling shows that inversion of geotherms and their thermal characteristics, including heat flow and conductivity, does not convey a unique solution, resulting in a considerable uncertainty range for geothermal energy purposes. This is even the case if basin calibration data are available such as BHT-data or surface heat flow measurements. Therefore, a strong need exists to better constrain uncertainties in lithospheric thermal evolution through an independent comparison with different data sets on, for example, both lithospheric and basin structures. This approach is illustrated for a number of case studies of European basins.

Temperature profiles in geothermal systems

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Anomalous hot temperatures at shallow depths can be due to several distinct causes, such as the presence of a shallow magmatic reservoir, or a thick insulating sedimentary cover, or a high heat-producing plutonic body, or a maintained circulation of hot water within shallow fractures, etc. A combination of some (or all) of these causes may explain famous geothermal sites. For example, the Soultz-sous-Forêts geothermal anomaly (France) can be explained by both regional and local factors. Locally, measurements of thermal properties have shown that conductivity contrasts alone cannot explain the high temperature gradients, and that the underlying granite exhibit high values for heat production rates (up to 6microW/m^3).

At the Bouillante geothermal site (Guadeloupe, French West Indies), interbedded lavas and tuffs in the 300 first meters probably result in a bulk thermally insulating layer, overlying the active hydrothermal system. In both cases, as well in others, vertical temperature profiles can be separated in three parts, typical of those describing convective systems: a high temperature gradient in the upper part, then a regularly decreasing temperature gradient yielding, at depth, a thick zone of nearly constant temperatures.

These typical temperature profiles can be easily reproduced by simple one-dimensional theoretical models, with sometimes unknown parameters. Transient cooling of a magmatic body, as well as upwelling of hydrothermal fluids can explain similar curvatures in temperature profiles. Such models however prevent any prediction for geometry of the underlying geothermal system. On the opposite, the use of neighbouring temperature profiles – when available – may help in the reservoir characterization, provided that thermal properties of representative local lithologies are measured. Examples of such neighbouring profiles at Soultz and Bouillante will be discussed.

3D strength and thermal model of intraplate Europe

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The construction of the first 3D strength cube of the European lithosphere has lead to an improved understanding of the dynamics of intra-lithospheric deformation processes. The 3D strength model is constructed using a first order 3D geometrical model of Europe's lithosphere and consists of several regions, representing areas of different composition, tectonic and/or thermal history. The depths of the different interfaces of the layers are distinguished on the base of deep seismic reflection and refraction or surface wave dispersion studies. The base of the crust is detected using a recently compiled European Moho map. Further constraints on the thermal lithospheric structure are obtained from heat flow studies and upper mantle seismic tomography.

The first results show that the European lithosphere is characterized by major spatial mechanical strength variations, with a pronounced contrast between the strong lithosphere of the East-European Platform east of the Tesseyre-Tornquist line and the relatively weak lithosphere of Western Europe. Within the Alpine foreland, pronounced north-west-southeast trending weak zones are recognized that coincide with major structures, such as the Rhine Rift System and the North Danish-Polish Trough, that are separated by the high strength North German Basin.

Moreover, a broad zone of weak lithosphere characterizes the Massif Central and surrounding areas. A pronounced contrast in strength can also be noticed between the strong Adriatic indenter and the weak Pannonian Basin area and between the Fennoscandia, characterized by a relatively high strength, and the North Sea rift system corresponding to a zone of weakened lithosphere.

The next approach to realize a 3D European strength map consists of a refinement of the previous thermal model in order to obtain more detailed temperature distributions, which will be subsequently used as input parameter in the calculation of the integrated strength.

The new model under development consists of one 3D block limited on the top by the topography reconstructed using GTOPO30 data and on the bottom by the lithosphere-astenosphere boundary, defined using tomography data. This 3D block is divided in a number of layers depending on the number of discontinuities detected in the crust and mantle lithosphere by seismic reflection and tomography data. Two main layers are defined in every part of the model (crust and lithospheric mantle layer), while the others (*e.g.* sedimentary and lower crust layer) are only specified in the areas where they are observed. In order to generate the temperature distribution in our model we used the steady state conditions to solve the heat conduction equation. In tectonically active regions, affected by uplift and erosion, the velocity of the rocks inside the crust with respect to top free surface is taken in account. The model is constrained at the top by surface temperatures corrected for latitude and altitude effects and at the bottom by temperatures obtained by the inversion of tomography data. Sensitivity tests will be made to check the influence on the model of the approach chosen to calculate the heat production, density and thermal conductivity variation and of the boundary conditions used.

The geothermal use of HHP granites: the recycling of an old concept

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Granite plutons of high heat production (HHP) form “hot” anomalies that can be easily identified against the background heat-flow field of the Earth. These zones of higher than average heat flow are perspective sites for encountering high temperatures at shallow depth, shallow enough to favor exploitation of geothermal energy. Thus, it is not surprising that high heat-production granites, from a thermal point of view, are potential geothermal resources that might someday be harnessed with developing heat-extraction technologies based on an EGS concept. HHP granites occur throughout Europe, though in different frequency and volume. Most HHP granites formed during the Variscan orogeny such as those from SW England, the French Massif Central, and the Erzgebirge of Germany and the Czech Republic. They also occur in older terranes as in the Scottish Caledonides and the Proterozoic shields of Fennoscandia, Baltica, and the Ukraine.

The nature of geothermal energy in HHP granites has been well investigated as part of academic research throughout the last three decades. Thus, a wealth of earth-science information is available that can be used for selecting the most promising sites for developing a technological system to harness this type of geothermal energy.

This information includes (1) surface geophysical data that assess the lateral and vertical extent of the granite intrusions and (2) well-logs and drillcore data that include mechanical and thermal properties of granites and host rocks (geothermal gradient, thermal conductivity/diffusivity, fracture density, fracture mineralization etc.) and their chemical and petrological features, and (3) large-scale injection experiment data to learn about the artificial stimulation of granites or their metamorphic country rocks.

Other research, conducted especially for the purpose of nuclear-waste disposal, dealt particularly with the issue of fluid flow and fluid pathways through granite bodies. Thus, it is time to recycle all this important knowledge and channel an initiative for the promotion of research and development of this geothermal resource.

Development of Polish Geothermics in relationship to heat flow data

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Development of Geothermics has almost 25 years of tradition in Poland. First experimental Geothermal plant commenced their activity in 1992 in Podhale (South of Poland). It took next 4 years to open first geothermal plant in Pyrzyce (NW Poland). Currently there are 6 plants in Poland however they are mainly focused on heating then electricity production. There are also almost 30 spa using geothermal waters for recreation and heath treatment.

Widespread opinion that almost 80% of Polish territory meet criteria for geothermal energy development is overestimated. Looking for perspective area one uses heat flow data to evaluate the temperature. Estimation of temperature model is critically dependant on high-quality surface boundary values of heat flow. A terrestrial heat flow (HFD) could be strongly influenced by paleoclimatic factor (Bailing, 2002; Kukkonen and Joeleht, 2003; Szewczyk 2001; Szewczyk and Gientka, 2004) taking into consideration the grate number of HF data bases on shallow holes. A majority of HFD maps not only for Europe were performed without this factor consideration.

The next very critical factors influencing all values of HFD determinations are the insufficient knowledge of depth distribution of the thermal conductivity (K). Based on our investigation the heat flow densities for deep boreholes in Polish Lowlands for uppermost part (<2,000m) are not in equilibrium. The lower parts of profiles are still in thermal regime of the Weichselian glaciation. Interglacial warmings were quickly forgotten by underground space. Changes of Paleoclimatic ground surface temperature (GST) in last 100ka are a major factor causing vertical variation of terrestrial heat flow density (HFD). From geothermal point of view the information of "normal" glacial HFD is more interesting.

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Session 4

WHAT LESSONS FROM THE OIL AND GEOTHERMAL FIELD EXPLOITATION FOR THE STIMULATION OF THE RESERVOIR?

Drilling, stimulation and reservoir assessment for EGS and UGR projects

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The ENGINE work-package 4 "Drilling, stimulation and reservoir assessment" is investigating the current stage of development of these three key technologies relating to Enhanced Geothermal Systems (EGS) and Unconventional Geothermal Resources (UGR). Several research projects have been carried out over the past 30 years at widely different geological conditions and others are being planned. Economic development of such geothermal resources depends very much on improving the output of wells by stimulation and drilling techniques and also by lowering the cost of drilling. The results obtained are incorporated into the reservoir assessment together with the available geoscientific information. Recent technological advances in these areas will be examined and ways to integrate them into “Best Practices”. Two ENGINE workshops are planned to this end and it is hoped that the partners to ENGINE will contribute their experience and ideas and thereby further the development of these resources and geothermal utilization in general.

Out of several worldwide EGS (including HDR) projects only a small number of projects are still under development. One of the main reasons in the long development time is the learning curve that can be tracked by the evolution of different expressions for the geothermal subsurface heat exchanger. Originally, the HDR (hot dry rock) concept started with the Los Alamos project, some 30 years ago with the idea of targeting the heat exchanger in unfractured rock and improving the low permeability only by mechanical stimulation of a penny-shaped crack. It was anticipated that an artificial fracture with sufficient large surface area (roughly 2 km^2) would be created and expected that the stress components (orientation and magnitude) as well as the rock mechanical parameters describing fracture propagation were most significant for the successful development of a reservoir. However, after having effectively created the fracture system, the final hydraulic link between the injection and production holes did not reveal the necessary flow impedance of $< 0.2 GPa/(m^3/s)$.

Especially under the light of the Japanese projects, the significance of the natural subsurface flow field was discovered, leading to the acronym HWR (Hot Wet Rock). Existing fracture systems around the boreholes attributed a positive effect to the reservoir, however tended to create unwanted consequences: Large fluid losses were encountered.

In contrast, the European project in Soultz-sous-Forêts targeted on a well-pronounced heat anomaly in the Upper-Rhine Graben was successfully conducting a long-term flow circulation in 1997 without any fluid losses. The natural flow field was providing the necessary fluid from large neighboring fault systems. In parallel, conventional geothermal systems mainly in the U.S. started re-injecting the produced steam or balancing the water budget. With this development the initial difference between HDR and conventional systems started diminishing since of the latter one were already operating in highly convective subsurface. As such, the acronym EGS (Enhanced Geothermal Systems) now stands for geothermal projects in a hydrothermal environment that requires stimulation procedures to circulate fluid across the deep heat exchanger.

It is now generally agreed that an EGS resource assessment has to focus on those locations that have optimum hydraulic and stress settings. Clearly, can the site evaluation under central European conditions be optimized, however, experience has shown that the thermal target parameter (*i.e.* ~200°C) is only exceptionally encountered at depths below 5km. Rarely the hydraulic permeability in the undisturbed target rock will be sufficient for hydraulic circulation at economic operation conditions.

At EGS, the host rock generally needs to be stimulated by appropriate measures. Today, chemical and mechanical stimulations are commonly used. Depending on their chemical reaction behavior, individual minerals clogging fracture walls can be dissolved by chemical treatment. The injection of acids is performed with modest flow rate creating pressure levels below values needed for mechanical stimulation.

Acidization is used for the removal of skin damage associated with drilling operations and to increase formation permeability in undamaged wells. The operation of matrix acidizing has not changed in the last 30 years and is composed of three main steps (André & Vuataz, 2005): 1) preflush, usually with hydrochloric acid, 2) mainflush usually with a hydrochloric – hydrofluoric acid mixture, and 3) postflush/overflush usually with soft HCl acid solutions or with KCl, NH_4Cl solutions and freshwater. An improvement of the well conditions is generally observed, however with largely varying success rates.

Also for mechanical stimulation the success of improvement cannot be anticipated. There are two main mechanisms that act during injection of massive flow injection. Mechanical fracturing of intact rock or induced shearing events. Depending on the stress regime, the downhole overpressure may not always reach the magnitude of the minimum stress (P ~ Smin) in case of induced shearing. Recently, numerical simulations of complex fracture geometries have been performed that relate the shearing slippage to located microseismic events. This leads us to a more integrated understanding of the complex interplay between the mechanical and the hydraulic processes. Kohl & Mégel (2005) have demonstrated that slippage events are likely to occur as function of pressure development in adjacent fractures.

With increasing numerical capabilities, the stimulation behavior may become more predictable. In the near future there is the prospect that designing stimulation measures beforehand, without having created irreparable damage to the host rock.

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Needs and requirements for high temperature instrumentation in extreme geothermal environment

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It is believed that substantial power enhancement can be obtained by utilizing superheated steam from unconventional supercritical wells drilled in high temperature geothermal regions. The realization of such utilization can only be achieved by using and developing the most recent and advanced technological know-how and experience in high temperature geothermal exploration.

There is a growing need for more advanced highly tolerant instrumentation to aid in the evaluation of unconventional geothermal wells. To meet the instrumental requirements, groups of experienced instrumentation developers, university researchers and users were brought together in an attempt to develop, produce and test new high temperature instrumentation.

The tests would be preformed in actual deep supercritical or near supercritical wells being drilled in an international project called the Iceland Deep Drilling Project (IDDP). The application was named HITI and was submitted as a STREP to EC in December 2004. It was marginally rejected but may be revived under the EC 7th framework. A brief description of the plans in the proposal will be discussed along with recent developments.

Microseismics and reservoir engineering: What can we learn and what is the price?

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Microseismic mapping was recognised as an key tool for mapping porosity/permeability creation and enhancement in EGS systems undergoing stimulation in the first project at Fenton Hill, and it largely within the EGS context that the technique has been most intensively developed. Microseismicity is probably the only practical way we have of learning about what happens in an EGS reservoir undergoing stimulation.

Microseismic waveforms, if acquired on a sufficient number of suitably-placed sensors, allow the geological structures activated by the pressurised fluid, to be imaged, and the scale an magnitude of shearing on the internal fractures within the parent structures to be constrained. In this talk I will show by example what can be accomplished given even a realistically sparse array of sensors, and how the information extracted from the waveforms can be relevant for reservoir engineering.

Microseismicity developments during hydraulic stimulations at Soultz-sous-Forêts

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During the last five years, four hydraulic stimulations were carried out at the geothermal site of Soultz-sous-Forêts (France). In order to monitor the seismic activity induced by these massive injections of fluid, a surface seismological network composed at least by 13 seismological short period and one broad-band stations have been installed during each stimulation in complement of the 4 down-hole accelerometers or velocimeters. Every hydraulic experiment generated several thousands of seismic events among which more than 5,000 (September 2004 and February 2005 taken together) were located automatically by the surface network.

The location of the hypocenters is obtained through the classical Hypoinvers routine adapted to the specific case of the network and with a variable Vp/Vs ratio or via a simultaneous inversion together with the velocity structures. In this last case, the uncertainty on the locations is 50 meters or less in every direction while it is the double in the first. The magnitudes are deduced from the coda duration T following the relation Ml = aLog T + b in which a and b were established from a set of events whose magnitudes of moment have been obtained from the spectral analysis of the broad-band records. The focal mechanisms are built from the polarities of P wave first arrivals. It was always possible to built a double couple solution contrarily at what is currently observed in regions where natural fluid circulation is present. That doesn't mean that a non-double couple component is totally absent, but it is always moderate.

The main features of the seismic activity will be presented and then we will focus on the largest microseismic events, in the magnitude range 1.4 to 2.9, 1.4 is the magnitude of the smallest events felt by the population and 2.9 is the magnitude of the largest event ever produced during the hydraulic experiments in Soultz. For these events, the arrival times of the P and S-waves recorded at the surface have been manually picked and merged to the data from the downhole stations.

The main conclusions are:

1 - the non-overlapping of the seismic clouds induced by the successive stimulations;
2 - most of the mechanisms show normal faulting to strike-slip faulting in a stress field compatible with the regional one deduced from *in-situ* measurements and focal mechanisms;
3 - the “large” earthquakes underline the role of the large structures on the circulation of the fluid within the reservoir;
4 - the relative amount of large events increases after the shut-in.

Hydraulic stimulation of EGS: A comparison of the HDR-project Soultz and the GeneSys project

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A comparison of hydraulic stimulation experiments in the HDR-Soultz project, France and in the GeneSys-project, Germany will be presented. Similar stimulation concepts have been applied in both projects but for completely different rock types.

In the well known Soultz-project massive hydraulic fracturing experiments (waterfracs) have been performed in granite rock. Typically, water volumes of more than 10,000 m^3 have been injected in order to stimulate large fracture areas and to form hydraulic links between the three wells at a depth of 5,000m.

The stress field in Soultz is characterised by a great difference between the maximum vertical stress and the minimal horizontal stress component. Therefore, the stress field favours shearing as the significant stimulation process. The observed high intensity of microseismic events and the pressure curves during stimulation indicate shearing too. On the other hand hydraulic tests after stimulation suggest the existence of high or infinite conductive fractures around the wells. Further, the wellbore storage is high (in the order of 1m^3/bar) even for a low pressure.

Both properties: the large wellbore storage and the infinite conductive fracture can not easily be explained by shearing of natural pre-existing fractures. A special pull apart mechanism seems to be likely that keeps the fracture "wide" open in the vicinity of the wells. Such a mechanism could be the development of a tensile fracture within a fault zone. Due to the shearing of the boundaries of the fault zone the tensile fracture inside remains open and causes the observed high wellbore storage.

The GeneSys-Project of BGR/GGA in Hannover is directed to the development of single well concepts for direct use of geothermal energy. In a test well about 80km NE of Hannover stimulation experiments in a tight sandstone layer (formation "Bunter") were performed. The stress field here is much more isotropic than in Soultz. At the target depth of about 3,8km the minimal horizontal stress component accounts for approximately 80% of the overburden. But the minimal horizontal stress changes significantly between the different layers at similar depth (clay stone, sandstone).

The main stimulation operation was performed by injecting 20,000 m^3 of fresh water with an injection rate up to 50l/s. Almost no seismic events could be recorded from the surface seismic network during this operation indicating only weak seismic events ($M < 0.5$). Extended pressure oscillations and a very weak pressure decline after Shut in gave evidence for a huge wellbore storage (≈ 100m^3/bar), much higher than ever observed in Soultz.

All the observations during the stimulation indicate that a huge tensile fracture was created here. Surprisingly, the conductivity of the tensile fracture was very high (“infinite”) even for a pressure much lower than the frac extension pressure. This behaviour is contradictory to the expected one. In general it is assumed that the hydraulic conductivity of fractures is low if no shearing occurs.

The explanation of the infinite conductive fracture has to take into account the geological structure of alternating layers with different minimal stress. Likely, the fracture extension pressure was controlled by the minimal stress not of the sandstone layer itself but by ambient claystone layers. The fracture extension pressure is much higher than the minimal stress in the target sandstone leading to an inelastic deformation inside the sandstone layer.

Hydro-mechanical modeling of fractured crystalline reservoirs hydraulically stimulated

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The understanding of the main mechanisms taking place in a hydraulic stimulation of a fracture network is a fundamental point to improve our ability to define stimulation strategy in fractured geothermal reservoir. Since several years, various modeling studies at various scales have been undertaken on the base of the results of the hydraulic stimulation tests performed on the site of Soultz-sous-Forêts (France).

A study, started several years ago, aimed to construct a 3D hydro-mechanical model of the stimulation of the fracture network around each well at Soultz-sous-Forêts. A numerical approach is developed in order to understand and to explain the physical mechanisms which are at the origin of the hydraulic behavior observed during the stimulation tests conducted in the various wells. The model is designed to reproduce the observed behavior in terms of pressure-flow curves as well as in terms of flow rate flowing into each fracture constituting the network.

The numerical model used for the simulations is the 3DEC software (Itasca, 2003). It is employed to make the coupled hydro-mechanical calculations that allow us to simulate interactions between the mechanical process (deformations, stresses,…) and hydraulic process (pressures, apertures, …) in a solid cut by discrete discontinuities corresponding to a realistic geometry of the fracture network intersecting the blocks. These blocks are considered to be deformable and impermeable. Fluid flow occurs exclusively through the fracture network and obeys a cubic law. The modification of the pressure field results in a modification of the actual stresses applied to the surrounding formations, which may themselves cause changes in the openings of the fractures and hence of the pressure field.

Based on the various studies performed over several years by geologists, the conceptual model of the site used for this modeling is the following: a homogeneous impermeable granitic mass crossed by a network of discontinuities constituted by hydrothermalized fractured zones formed by the tectonic and hydrothermal history of the site (Dezayes *et al.*, 2004). The location and the orientation of the fractures are more or less constrained according to the quality of the basic data.

The modeling approach has been first developed on the upper part of the reservoir where a maximum of data are available in the two wells constituting the geothermal doublet at a depth of around 3,500m. Considering the satisfactory results of the first application, the hydro-mechanical model has been extended to the lower part of the reservoir at depth between 4,500m and 5,000m where the three deepest geothermal wells have been drilled.

The various modeled cases show the role played by some main parameters on the results of the modeling such as orientation of the main permeable fractures, the intersection between them and their hydro-mechanical properties. The results obtained by the 3-dimensional models show that the permeability increase is highly associated with shearing on some fracture planes. These results also show a significant correlation between the orientations of the permeable fractures in relationship with the orientation of the *in situ* stresses. In conclusion, these models point out the importance of the knowledge of the geological structural and tectonic context of the site and the role of shearing mechanisms in the stimulated fracture planes.

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Overview of chemical stimulations of EGS and non EGS reservoirs

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Resources exploitation of gas, oil and heat from deep reservoirs needs sometimes the development of the permeability around the production wells to ensure an efficient production. Different techniques can be used to enhance the reservoir productivity but the main ones are the hydraulic fracturation and the chemical treatment. This presentation will be focused on the methods of chemical stimulation.

This technology, developed for more than one century by the oil industry for the stimulation of oil and gas wells, is also used in geothermal wells. The aim of this technology is to enhance the well productivity and to reduce the skin factor by removing near-wellbore damage and by dissolving scales in natural fractures. It consists to pump into the reservoir reactants such as strong acids (hydrochloric acid, HCl-HF mixture), organic acids (acetic acid, chloroacetic acid, formic acid, sulfamic acid) or chelatants (EDTA). These reactants can be pumped into the reservoir according to two procedures: below the fracturing flow rate and pressure of the reservoir (matrix acidizing) or above the fracturing flow rate and pressure (fracture acidizing). The matrix acidizing allows the reaction of acids with minerals present in existing pores and natural fractures.

Normally used for the removal of skin damage associated with work-over, well killing or fluids injection in damaged wells, matrix acidizing is also used to increase the formation permeability in undamaged wells. It is performed in three steps: firstly, an adequate preflush with HCl to dissolve associated carbonates, secondly, a mainflush with a correct HCl-HF mixture formulation depending on the rock composition and at last, an overflush with weak HCl or freshwater.

This technique is one of the mostly used for oil and gas wells but also for geothermal reservoirs. It was performed with success for damage removing from geothermal wells in Philippines, where in some cases the boreholes productivity increased by a factor 3 to 10 before and after treatment. The fracture acidizing method, also called acid fraccing, consists to inject first a viscous fluid at a rate higher than the reservoir matrix can accept, opening new fractures and then, to inject HCl acid reacting all along the created fractures.

This technology provides well stimulation and not just damage removal. In numerous cases, acid treatments have shown their high efficiency for near-wellbore damage removing. Nevertheless, it should be noted that, most often, the high reactivity of chemical agents prevents a deep penetration into the formation, creating wormholes which increase the porosity around the well but not necessary its productivity. Even if this drawback can be limited by retardants, many studies demonstrate that the influence radius of acid treatments in a homogeneous system does not exceed some metres around the injection well (maximum 2 to 5 metres).

The major disadvantage of acid treatments is linked to the corrosion risks of the casing in particular with strong acids. Nevertheless, this risk can be reduced by using less-corrosive agents as chelatants or by addition of corrosion inhibitors, but their use increases the treatment cost. In the field of EGS, few chemical treatments have been applied to stimulate reservoirs. In November 1976, at Los Alamos Scientific Laboratory (USA), 190,000l of 1 N carbonate sodium base solution was used to dissolve quartz from the formation and to reduce the impedance of the existing system. About 1,000kg of silica were dissolved and removed from the reservoir but without impedance reduction. In 1988, a matrix acidizing was performed on the Fjällbacka reservoir (Sweden): major and minor fractures of the granitic reservoir were filled with calcite, chlorite and clay minerals. About 2,000l of HCl-HF acid were injected in Fjb3 to leach fracture filling. Returning rock particles showed some efficiency of this acid injection. Recently acid treatments on EGS were performed at Soultz-sous-Forêts (France). This deep granitic reservoir contains fractures partially filled with secondary carbonates (calcite and dolomite). In order to dissolve these carbonates and to enhance the productivity around the wells, each of the three boreholes (GPK2, 3 and 4) were treated with different amounts of hydrochloric acid. If GPK2 and GPK3 have shown weak variations of their productivity, GPK4 presented a real increase of its productivity after treatment: the wellhead pressure was reduced by about 40% due to the acidification treatment and a decrease of the reservoir impedance of a factor 2 (0.2 to 0.4l/s/bar) has been estimated.

A comparison of hydraulic stimulation approaches within EGS and conventional geothermal reservoirs with examples from Soultz, France and Coso, California

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Developers of conventional geothermal systems have a long history of successful management of geothermal reservoirs where natural productivity is high, but lack knowledge and experience in reservoir stimulation. In contrast, Developers of Engineered Geothermal Systems have experience in reservoir stimulation techniques, but often lack experience in long-term reservoir management. Better communication and improved technology transfer between the two disciplines would benefit each. This paper examines approaches for breaking down the barriers in order that improved communication might be achieved. It also provides examples of hydraulic stimulation approaches recently practiced at an EGS reservoir and at a conventional geothermal reservoir.

Hydraulic stimulation experiments were conducted on tight injection wells at the Soultz-sous-Forets, France and Coso, California geothermal systems. Significant improvements in injectivity were observed at both reservoirs, although lower stimulation pressures and less fluid were required in order to achieve better injectivity for the Coso well. Following the stimulation experiments, circulation tests were conducted and hydraulic communication was confirmed through tracer testing. The tracer data were analyzed in order to compare the tracer-swept pore volume and the relative degree of dispersion within each stimulated reservoir. The tracer data indicate greater dispersion and therefore a possibly more extensive fracture network at Soultz, although the stimulated-fracture-volume at Coso appears to be greater.

Session 5

HOW TO IMPROVE EXPLOITATION AND COST-EFFECTIVENESS OF GEOTHERMAL ENERGY AND MANAGE ENVIRONMENTAL AND SOCIAL IMPACTS?

Requirements for the Development of EGS

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Covering the future energy demand will be increasingly based on new technologies. One of the most promising concepts is the utilisation of the high enthalpy geothermal energy made available by creating Enhanced Geothermal Systems (EGS). For over 35 years a succession of EGS research projects in different countries has led to a broad scientific and technical knowledge. However, there is still no EGS power plant based on an artificially created or improved subsurface heat exchanger in operation worldwide.

The main question arises how we come to the breakthrough of the EGS technology within the next decades. A breakthrough will be based on two aspects: the future energy market prices and the technological feasibility of EGS. It is therefore not predictable whether a technological breakthrough will be accompanied with an economical success. But the development of the technology is a first condition, even if not sufficient. Technological feasibility of a project is finally measured whether the financial risk can be quantified and in a second step also minimised.

Quantifying the financial risk of EGS means first of all that the success of the reservoir creation process and the extent of environmental and social impacts must become predictable to a certain extent.

Minimising the financial risk, and also the capital costs in general, means to develop methods which allow the project team to take the go/no-go decision as early as possible.

A general proposition of required research and development work to reach the technological breakthrough of EGS will be discussed.

The environmental impact of the geothermal industry

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Geothermal systems are classified either as hydrothermal systems (low or high enthalpy), which are encountered in specific locations associated with the presence of fluids and permeability within the Earth, or as enhanced geothermal systems, which can be engineered everywhere. The economics of the latter can be improved if they are located within or close to the boundaries of a hydrothermal system.

The positive environmental impact of all geothermal plants is attributed to foregone CO_2 emissions, had the same quantity of energy been produced by fossil fuels. However, there may be some CO_2 emissions associated with hydrothermal systems, which have been quantified as 15-20 times less than fossil fuels in case of heat production from a low enthalpy geothermal field, or 2.5 times less than natural gas for a typical high enthalpy geothermal field. The latter value can be further reduced by one order of magnitude (10 times or so) in geothermal heat and power cogeneration plants. Zero CO_2 emissions are foreseen for enhanced geothermal systems.

Adverse environmental impact may occur from low enthalpy geothermal utilization, associated with the chemistry of the geothermal fluid, which may include considerable quantities of chloride, small quantities of boron, and traces of arsenic, ammonia, mercury, or heavy metals, making it unsuitable for disposal to the surface. The problem is effectively solved by reinjecting all the produced geothermal fluid to the same deep reservoir it originated from. This practice also has benefits to the water replenishment of the deep system, improving sustainability and the economic life of the plant.

Other impact from long term low enthalpy geothermal utilization may be the dropping of water level of near surface aquifers and the flow reduction or dry-up of nearby springs and shallow water wells. The problem can be solved by effective reservoir engineering and inevitably by donating deep wells to affected water users.

Apart from the above, exploitation of high enthalpy hydrothermal reservoirs, may result in additional effects to local environment, associated with the chemistry of the steam, which may contain non condensable gases, such as CO_2, traces of H_2S and entrained silica or other dissolved solids in the liquid phase. These are effectively alleviated by minimizing the steam losses from the geothermal plant (in fact steam losses should be allowed only at the safety valves), and by conveying the non-condensable gases to the cooling tower draft, where they are diluted by large quantities of air. If these measures fail to limit the H_2S concentration in the air below the smelling threshold, then an H_2S treatment plant should be installed.

Other problems associated with high enthalpy hydrothermal systems are:

- Micro-seismic activity: it is of small magnitude, only registered by the seismographers and does not pose any threat to buildings or structures.
- Soil subsidence: it is of one or more meters magnitude and occurs in the centre of the production zone after many years of exploitation and withdrawal of large quantities of geothermal fluids. During the plant design phase no buildings, pipelines or other structures should be placed there.
- Noise: can be severe. It is encountered by proper plant engineering and by placing noise barriers if necessary.
- Damage to local flora: it occurs every time steam or hot geothermal fluids are released on local plants, trees, etc. Compensations for damaged property should be foreseen.
- Aesthetics: with proper design, the geothermal plant can be transformed to a tourist attraction, rather than an ugly mass of metal.
- Heat pollution: when waste heat is released to local environment. It can be encountered by reinjection, or by geothermal heat and power cogeneration.

Regarding enhanced geothermal systems, none of the above problems is foreseen, as they are engineered by introducing surface water into earth and recycling through the system. However, as mentioned above, it pays to engineer enhanced geothermal systems within or just outside the boundaries of a hydrothermal system in order to benefit from bonuses in temperature, depth and limited natural permeability or fluid presence. In that case some of the environmental consequences mentioned above may occur, but probably in a much lesser extent and magnitude. But we cannot tell for sure what will be the case, as no plants are in operation in such systems at present.

One problem that has been reported during engineering of enhanced geothermal reservoirs, is the occurrence of micro-seismic activity, probably associated with the hydraulic fracturing works. These micro-earthquakes have a magnitude around 2 in the Richter scale and pose no danger to existing buildings or structures.

Whether they will also be present during exploitation, and how they will evolve overtime, remains to be identified in the field, but we anticipate that this micro-seismic activity should not be greater than the one encountered in hydrothermal systems. The reaction of local people to a possible presence of micro-earthquakes remains to be identified and managed.

In any case, in order to a-priori guarantee the success of a geothermal exploitation scheme, close collaboration, cooperation and relations with the local community should be established. That way the local community will maximize their benefit from the geothermal plant, any misunderstanding and possible conflicts will be resolved and the consent of the local community towards geothermal development in their region will be achieved.

Trigeneration with geothermal energy - potentials and pitfalls of combined supply with power, heating, and cooling

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Geothermal energy provides heat at a temperature range from 100 – 200°C. In many installations, this heat is used either for power production or for heat supply.

Cogeneration (Combined Heat and Power CHP) improves the overall efficiency as well as the economics of a geothermal installation. Since the temperature of the heat source might be sufficient for cold production in absorption chillers, trigeneration would be an option, too. Trigeneration, as the name implies, refers to the simultaneous production of three useful energies, and is defined as the simultaneous production of heat and power, just like cogeneration, except trigeneration takes cogeneration one step further by also producing chilled water for air conditioning or process use with the addition of absorption chillers that take the heat to make chilled water for cooling a building.

The main components of these systems would be a power plant, (direct steam or binary), a chiller and heat exchangers of a district heating system. The design of geothermal CHP and trigeneration systems differs from the design of conventional CHP and trigeneration systems. The limited temperature and capacity of the heat source calls for careful consideration of the necessary minimum temperature of each component. Moreover, parallel or serial coupling of the components is an important issue. The talk gives an overview of the possible options including efficiency calculations. The pros and cons of different alternatives as well the differences to conventional trigeneration systems are discussed.

Scale detection in geothermal systems: the use of nuclear monitoring techniques

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Effective scale management requires on-line monitoring of scaling tendencies as well as detection and identification of scale deposits. In that respect, the gamma-ray attenuation technique and the gamma-tracer emission technique are examined in this study for their capability of measuring in real-time the scale formation under field conditions. Calcite formation has been investigated in the lab-scale in absence and presence of scale inhibitors in the course of this work.

A number of runs have been successfully performed where the desired experimental conditions have been evaluated and tested using both techniques. The obtained results are presented here.

Geothermal reservoir management a thirty year practice in the Paris Basin

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The present paper addresses the development and management of large geothermal district heating grids exploiting, since the late 1960s – early 1970s, a dependable carbonate reservoir located in the central part of the Paris Basin, France.

The geothermal reservoir consists of a hot water aquifer, of regional extent, hosted by Dogger pervious oolithic limestones and dolomites, of Mid-Jurassic age, at depths and temperatures ranging from 1,450 to 2,000m and 56 to 80°C respectively.

Development of the resource was boosted in the aftermath of the first and second, so called, oil shocks (mid to late 1970s). It led to the completion of 54 geothermal district heating systems, based on the mass conservative, well doublet concept of heat mining, of which 34 remain online to date.

The paper reviews the main development milestones and related key exploitation and managerial issues which enabled to accumulate a considerable experience with respect to reservoir engineering and maintenance/surveillance of production facilities.

Sustainable development/management problematics are also discussed in the light of geothermal reservoir longevity, innovative (re)designs of mining infrastructures and environmental benefits.

Geothermal development in the volcanic Caribbean islands and EGS perspectives

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Most of the islands in the Caribbean are doted with hydrothermal systems related to their active volcanoes or recent volcanic complexes. They have been surveyed to assess their geothermal potential. To date, only the Bouillante field in Guadeloupe, F.W.I., is currently exploited for electricity generation. It is a conventional high enthalpy system with reservoir temperature around 250°C. Seven deep wells (350-2,500m deep) have been drilled and four are producers, feeding the two small plants (4,5 and 11MWe). Permeability is primary controlled by faulting within the basement made of submarine volcanic formations. The geothermal fluid is a Na-Cl brine with a 20g/l TDS and has a mixed origin between meteoric water and sea water. A stimulation experiment based on cold seawater injection was successfully performed in 1998 in order to improve the permeability of the BO-4 low-producer well.

Two other islands (Dominica, St. Lucia, B.W.I.) are provided with promising high enthalpy geothermal fields. The Sulphur Springs field in St. Lucia has been explored in the 1980's. Two deep exploratory wells have been drilled to 2,200m deep in 1987-88. High temperature conditions (285°C) but adverse fluid chemistry (low pH, high NCG content) and low permeability prevent any development until now. Dominica contains at least two high enthalpy geothermal systems in Wotten Waven and Soufriere areas. No well was still drilled but fluids geochemistry indicates reservoir temperature conditions above 200°C.

The island of Martinique, F.W.I., has been explored in the 1970's and in 2000-01 with 4 exploratory wells drilled in the Lamentin area, South of Fort-de-France. Surface manifestations included hot springs, soil gas anomalies and silica travertine deposits. Unfortunately, the recorded fluid temperature is only 80-90°C. Two other areas with surface manifestations were investigated near the Mont Pelée active volcano and near a 1 My-old volcanic complex in the South-West region. Deep hydrothermal systems with temperature around 180-200°C are expected from fluid geothermometers but there are still large uncertainties about their potential, especially about permeability conditions.

Extension of EGS technologies to the Caribbean geothermal fields could be beneficial in the light of their high temperature conditions at shallow levels. They could be used first to enhance permeability conditions for production/reinjection wells. Others applications could be addressed to the field management. However, the implementation of EGS methods will have to take into account the island remote location and related extra costs, and sometimes the limited financial capacity of local geothermal operators to support them.

State of the art and prospects for geothermal energy development in Russia

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Nowadays the state of the energy industry is determined by depletion of fossil fuel reserves (oil, gas, coal) and permanent growth of fossil fuel cost. Thereupon such developed countries as European countries, the USA, China, etc., try to start utilizing resources of the "Caspian Ellipse" and Russia, where over 80% of oil, 70% of gas are concentrated, as soon as possible and in larger amounts, at the same time developing renewable energy sources (RES).

European countries face the following problem: to replace NPPs (Nuclear Power Plant) and outdated power plants and to meet the increasing electricity consumption, at least 300,000MWe of new installed energy capacities have to be commissioned by 2020 to support just EU-15.

Russia, having large reserves of hydrocarbon fuel and timber, advanced energy technology and electricity-generating facilities, including NPP, and a vast territory, occupies a special position and is self-supporting in respect to heat and electricity. Nevertheless given new open market requirements, Russia should also develop RES, especially for district heating purposes. RES will help putting in place a grid of local, independent, reliable, cheap and environmentally friendly heat and electricity generating facilities accommodating latest achievements of science and technique, also in the field of geothermal heat pumps and binary power plants. The energy potential of geothermal resources of Russia 10-12 times exceeds that of the fossil fuel available in the country.

Latest achievements in design and construction of geothermal power plants in Kamchatka and the Kuril Islands prove that geothermal electricity and heat are always cheaper, more reliable and cleaner than TPP (Thermal Power Plant) produced electricity and even more than that produced by diesel power plants. Kamchatka, the Kuril Islands, Chukotka and partially Magadan region are ready to implement major investment projects on construction and operation of geothermal power and heat plants, since high-potential resources are available here and the price for imported oil is very high.

For example, the production cost of 1KWh at TPP here exceeds 13 cents today, for this production cost should incorporate the fuel cost reaching 10 cents. At the same time, the production cost of 1KWh at Mutnovsky GeoPP (Kamchatka) during EBRD loan repayment period was about 5.5 cents, and when the loan was repaid, reduced and do not exceed now 2.5 cents.

Rich geothermal resources of Russia, latest achievements in the Russian geothermal energy sector and growth of hydrocarbon fuel prices in the world have formed optimal conditions in

Russia for development of new geothermal projects in Northern Caucasus, Kaliningrad region, Kamchatka, the Kuril Islands and Siberia.

12 large geothermal projects are implemented now in Russia. For example, one project envisages 30% production of electricity and heat from RES in Krasnodar region to be started within next 10 years, including development of a geothermal district heating system for cities and settlements of that region (totally up to 1,000MW).

Another project proposing utilization of Hot Dry Rocks of Avachinsky volcano (located 20km away from Petropavlovsk-Kamchatsky City) for heat and electricity supply of the center of Kamchatka region is of special interest for the international cooperation in the field of geothermal energy. The deep chamber of dry rocks with temperatures ranging between 500 and 1,000°C is located at depths between 3-4km at the foot of Avachinsky volcano.

Development of the geothermal energy in Turkey, state of art and perspectives

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Turkey is located on the Alpine-Himalayan orogenic belt, which have high geothermal potential. The first geothermal researches and investigations in Turkey started by MTA in 1960's. MTA discovered 170 geothermal fields where 95% of them are low-medium enthalpy fields and suitable mostly for direct-use applications. In addition about 1,500 hot and mineralized natural springs and wells exist in Turkey. 170 geothermal fields which can be useful at the economic scale and about 1,500 hot and mineral water resources which have the temperatures ranged from 20-242°C (spring discharge and reservoir temperature).

With the existing springs (600MWt) and geothermal wells (2,693MWt), the proven geothermal capacity calculated by MTA is 3,293MWt (discharge temperature is assumed to be 35°C). The geothermal potential, on the other hand, is estimated as 31,500MWt. The installed heat capacity is 1,077MWt for direct-use and 20.4MWe for power production in Turkey with total production of 104.6GWh/yr. A liquid carbon dioxide and dry ice production factory is integrated to the Kizildere power plant with a 40,000 tons/year capacity.

The LOW-BIN project of DG-TREN (efficient low temperature geothermal binary power) aiming in improving EGS exploitation costs

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The LOW-BIN project aims in improving cost-effectiveness, competitiveness and market penetration of geothermal electricity generation schemes, targeting both hydrothermal resources for immediate market penetration and future hot dry rock systems, by:

- Widening market perspectives of geothermal Rankine Cycle power generation by developing a unit that can generate electricity from low temperature geothermal resources, with temperature threshold for profitable operation at 65ºC, compared with 90-100ºC of existing units.
- Developing a Rankine Cycle machine for cogeneration of heat and power by heat recovery from the cooling water circuit. This will lead in cogeneration of heat and power from Rankine Cycle units in present and future geothermal district heating schemes with overall energy efficiency of 98-99%, compared with 7-15% for existing units producing only electricity and for 35-60% of existing geothermal cogeneration schemes.

The project will involve theoretical research, laboratory experimentation, pre-prototype development, technology evaluation of the pre-prototype in terms of technology breakthrough achievement, energy efficiency, electricity generation costs and market potential, manufacturing and demonstration of successful prototypes, monitoring and technology validation, as well as dissemination of the technology and other innovation related activities.

The LOW-BIN project consortium consists of 9 partners from 8 countries: CRES (Greece-Coordinator), TURBODEN (Italy), GFZ-Potsdam (Germany), GEOTEAM (Austria), University of Oradea (Romania), ESTSetubal (Portugal), Politecnico di Milano (Italy), BRGM (France) and ISOR (Iceland). The consortium involves 3 SME partners (TURBODEN, GEOTEAM and ISOR), which represent 62,21% of the budget. The total budget of the LOW-BIN project amounts at 3.935.713 euro, of which 13,70% is devoted to R&D activities, 74,50% for Demonstration and 8,46% to Innovation Related Activities. The EU Funding requested is 1.878.812 euro (47,74%).

Project LOW-BIN addresses short-to-medium term research and complies with the guidelines described in the Thematic Priority 6.1 work-programme as it will deliver results, which will accelerate the market penetration of innovative energy technologies with a particular emphasis on 2010 energy policy objectives. These technologies are Rankine Cycle geothermal power plants, improved by the activities of LOW-BIN project in terms of market opportunities due to broader range of geothermal supply temperature, as well as in terms of improved overall energy efficiency and costs. Market penetration of geothermal power plants will be accelerated by the results of LOW-BIN project as:

- 65-90ºC input temperature allows Rankine Cycle geothermal power plants to target the market segment of hot groundwater, which is widespread beneath the European Continent at economic depths less than 2km;
- the proposed technological solution for the geothermal combined heat and power generation allows dramatic energy efficiency and cost improvements in geothermal power and district heating schemes, facilitating immediate market penetration of geothermal energy utilizing hydrothermal resources of temperature higher than 120ºC (*e.g.* Iceland, Italy, Greece, Romania and elsewhere) and paving the way for the future exploitation of the vast hot dry rock geothermal resources, which abound at depths 3-5 km.

The LOW-BIN project consists mainly of integrated demonstration actions with a typical research component of about 20% and also includes: pre-normative research, energy technology integration, dissemination and technology transfer activities. Apart from technological risks also addresses market and cost issues; the developed prototypes will be manufactured and demonstrated only if all technological, market and cost prospects are positive, as determined by the technology research and market feasibility analysis performed.

The LOW-BIN project will demonstrate, on the one hand costs reductions associated with low temperature geothermal electricity (both prototypes), and on the other, how the integration, under full-scale operating conditions, of innovative technological solutions on geothermal cogeneration of heat and power (2nd prototype), can lead to improving both energy efficiency and costs.

Session 6

HOW TO PROMOTE GEOTHERMAL ENERGY THROUGH DISSEMINATION OF KNOWLEDGE, EDUCATION AND TRAINING?

The information system of the ENGINE co-ordination action

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The aim of the ENGINE project (ENhanced Geothermal Innovative Network for Europe) is to stimulate the institutional and political support for geothermal energy. The co-ordination action proposes to rally the critical mass among the geothermal experts in Europe to produce an overview of the knowledge and methods applied to Unconventional Geothermal Resources. The information system of the ENGINE Co-ordination action intends to be the vector to share and promote the action of the ENGINE community towards institutions, funding agencies and citizens.

The information system of the ENGINE co-ordination action consists in the information, publication and dissemination by:

- organizing the ENGINE conferences and workshops and the publication of their proceedings;
- facilitating the communication among the ENGINE partners;
- defining the publication policy of the ENGINE community;
- compiling the ENGINE partners relevant works on Unconventional Geothermal Resources;
- disseminating general information on Unconventional Geothermal Resources towards media and citizens;
- participating to the training and education objective of the ENGINE project.

A Web site for the ENGINE project (http://engine.brgm.fr) sets out to be the main tool to reach these objectives. A preliminary prototype has been developed and proposed during the ENGINE kick off meeting in Potsdam on 10/11/2005. Its structure, contains and improvements are presented. A section of the Web site is dedicated to the ENGINE conferences and workshops management. A tool called Indico, set up during an European project, has been implemented. It covers the needs of multiple meeting organization: registering, call for abstract, time table, logistics, etc. Indico is tested during the present launching conference and will be used by the ENGINE partners in charge of the other meetings management.

The ENGINE Web site will be refined and completed during the progress of the project. To make possible the success of the whole ENGINE information system, the participation of all the partners will be needed. A great attention will be paid to their knowledge and propositions. Furthermore, the Work Packages results will play a major role to make concrete the information, publication and dissemination objectives of the ENGINE co-ordination action.

Promotion of the geothermal energy through education and training

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After a brief overview on topics related to geothermal taught in some higher education specialisations, the paper presents the known geothermal and training possibilities organised in Europe, including some information on how these are financed.

In the end, the paper identifies some topics which are missing or could be improved in the future to allow for a better promotion and development of the geothermal energy utilisation in the future, with a special focus on enhanced geothermal systems.

Information and dissemination of knowledge in the field of geothermal energy

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Dissemination plays a main role in the integration phase of the Engine Co-ordination Action. It will take the form of sharing information among the partners and stakeholders, toward the definition of the state-of-the-art, and in particular a review of case histories, in order to identify and analyse the best practices to be adopted, the innovative concepts to be applied or developed, as well as the main gaps in knowledge and/or technology. Another important part of dissemination is the promotion of the geothermal energy. The knowledge will be disseminated and made available through the information and publication systems, and should arise the interest of other potential scientific and industrial partners. Scientific and technical know-how and practices is planned to be disseminated through scientific publications and on-line through the Web site. Also general scientific documents are foreseen, as multimedia programmes, articles and information brochures. These less specialised publications aimed at a wider audience will contribute to the promotion of geothermal energy in terms of policy makers and public opinion.

In order to start working on this subject, a review of the geothermal energy dissemination and information available at the moment will be given, as well as a discussion of possible improvements and new ideas.

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