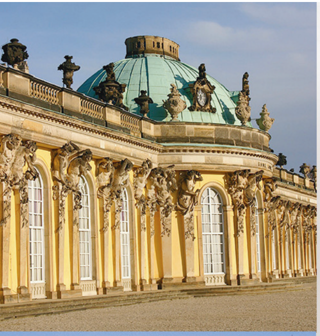

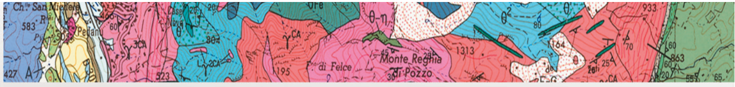

ENGINE

ENhanced Geothermal Innovative Network for Europe

Mid-Term Conference

9-12 January 2007

GeoForschungsZentrum - Potsdam - Germany

Conference Contributions

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Edited by: Ernst Huenges (GFZ Potsdam) and Patrick Ledru (BRGM)

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Thumbnail upper top: Potsdam, Germany, Schloss Sanssouci by Dana Pavel.
Thumbnail lower top: GeoForschungsZentrum Potsdam, Germany, by Kemal Erbas, GFZ Potsdam.
Background: Prototype of the GFZ drilling rig “InnovaRig” (under development) by Herrenknecht Vertical GmbH

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Table of Contents

OPENING SESSION 7

Reinforcing the role of EGS in the future energy mix 9

Geothermal Energy R&D in the 7th Framework Programme 10

ENhanced Geothermal Innovative Network for Europe: the state of the art 11

SESSION 1: GLOBAL DEVELOPMENTS 15

Enhanced Geothermal Resources in the United States Resource Base and Location 17

Economics of Developing EGS Systems and Potential for Market Penetration 18

Central America Geothermal Development and EGS perspectives 20

The Current State of Geothermal Energy Development in the Philippines and Southeast Asia 21

Possible Applications of Geothermal Energy in Oil Sand Mining 22

Volcanic Systems and Thermal Regimes: A major theme of the ICDP 23

Europe, from a pioneering role to the leading edge of R&D with a global perspective for the future of geothermal energy 24

SESSION 2: EXPLOITATION, ECONOMIC, ENVIRONMENTAL AND SOCIAL IMPACTS 25

Electricity generation from Enhanced Geothermal Systems, Summary of the Workshop 5, 14-16 September 2006, Strasbourg (France) 27

Renewable Energies in the German Energy System – Promotion and Development of Renewable and Geothermal Energy 31

Low temperature cycles – concepts and prospects 32

Optimized geothermal binary power cycles 33

Economic approach of geothermal energy generation 34

Probabilistic and decision tree approach to geothermal techno economic performance 35

Environmental impacts by the use of geothermal energy 36

Non Technical Barriers in Developing Geothermal District Heating in the Paris Basin 37

Non technical barriers in Tuscany (Italy) 38

Power Extraction from Hot Dry Rocks 39

SESSION 3: DRILLING, STIMULATION AND RESERVOIR ASSESSMENT 41

Stimulation of reservoir and microseismicity- Summary of the Ittingen workshop June 2006 43

Developments in Geothermal Drilling 47

Drilling of Hot and Fractured Granite at Soultz-sous-Forêts 48

Drilling a geothermal well into a deep sedimentary geothermal reservoir – case study on the Groß Schoenebeck wells 49

Hydraulic stimulation and microseismic fracture monitoring within the deep granite holes at the Soultz-sous-forêts geothermal site 50

Hydraulic fracturing in the hydrocarbon industry 51

Stimulation of geothermal wells in basaltic rock in Iceland 52

Development of conceptual and numerical reservoir models for the Hengill high-temperature resource, Iceland 53

Nuclear techniques for the in-situ detection of mineral scale in geothermal systems 54

Hydraulic stimulation in the light of single-well tracer tests 55

SESSION 4: INVESTIGATION OF UNCONVENTIONAL GEOTHERMAL RESOURCES AND IN PARTICULAR ENHANCED GEOTHERMAL SYSTEMS.... 58

Defining, exploring, imaging and assessing reservoirs for potential heat exchange" Summary of the Workshop 5, 6th to 8th November 2006 Potsdam 60

Reactive transport model of silicification at the Mount Isa Copper deposit, Australia 62

Recent progress in Discrete Fracture Network modelling for EGS development in tight fractured rocks 63

How geology can contribute to improve the knowledge of EGS fields in Europe? 64

Geophysical methods for EGS investigation: an overview of actual and future perspectives. 65

How Can Petrophysics Support Geothermal Exploration? 66

Geochemical methods in geothermal exploration and exploitation 67

Modelling of Geothermal reservoirs - an overview 68

Tectonic models for geothermal exploration and production 69

A new crustal model as input for the European strength map 70

SESSION 5: DISSEMINATION AND INFORMATION 72

The ENGINE information system birthday 74

Capacity building through training by research in geothermal activity: an experience from Mexico and Latin America 75

ISS - A Successful Trial for Internationalization of Specialized Education and Training 76

Dissemination of Geothermal knowledge at ISOR 77

Geothermal Education in Europe and other Continents 78

AUTHORS' INDEX 80

Opening Session

Wednesday, 10 January 2007
11:00 – 12:30

Reinforcing the role of EGS in the future energy mix

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In spite of all the efforts that are already planned in the developed countries to promote energy efficiency, the world energy consumption will grow very importantly in the 21st century due to the combination of world population and PIB increase. The ultimate production potential from renewable energy sources is extremely high. Unfortunately, the rate at which this potential could substitute the use of fossil based energy production remains very low. This predominance of fossil fuel electricity production now provokes a serious threat on climate change. It is therefore indispensable to speed up the development of renewable. Among all these new sources, geothermal energy has several interesting characteristics: it can give base load production and it is less sensible than hydro power to climate evolution. Among all, the geothermal power production schemes, heat and power production from EGS are the only way to access geothermal resources in an appreciable percentage of the continents. Consequently, the European efforts to fill the research gaps that are still preventing today the full deployment of EGS exploitation are extremely important for our common future.

Geothermal Energy R&D in the 7th Framework Programme

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EGS technology has been developed to a large extent in the EU co-funded EGS Project at Soultz-la-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 7th Framework Programme. Reductions in the category of capital expenditures hold the greatest potential for reducing the overall costs of EGS power plants. However, the lack of public acceptance can be a show stopper, and block further EGS development. The avoidance or mitigation of induced seismicity related to EGS development and operation is crucial for the wider uptake of EGS in densely populated areas like the EU. Several years of successful operation without negative environmental side-effects will be required before utilities and consumers could be expected to develop confidence in the systems. Continued technological research is required before pilot plants can provide convincing demonstration of the practical and economic aspects of EGS systems. In the 7th Framework Programme, research into geothermal technologies will be facilitated under the headers "Renewable Electricity Production" and "Renewables for Heating and Cooling". For geothermal electricity production, research and development should aim to develop enabling technologies for the exploitation of high-temperature resources, and to prove the feasibility and sustainability of EGS technology in representative EU sites. The estimated current cost of electricity generation from the first-generation prototype plants is of the order of € 0.08 0.15/kWh. Demonstration projects should aim at improving geothermal reservoir detection technology, increasing the performance of fluid production systems (corrosion and scaling), and increasing the efficiency of electricity generating systems. A continued reduction in cost through innovative developments, learning curve effects and co-generation of heat and power should lead to an electricity cost from enhanced geothermal systems of around 0.05 €/kWh in 2020. In the field of geothermal heating and cooling, the focus will be on improving the performance of geothermal specific heat pumps and on improving the reliability and ease of maintenance of the underground components of the heat pumps.

ENhanced Geothermal Innovative Network for Europe: the state of the art

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The main objective of the ENGINE Co-ordination Action (ENhanced Geothermal Innovative Network for Europe) is to co-ordinate present research and development initiatives for Enhanced Geothermal Systems, ranging from the resource investigation and assessment stage through to exploitation monitoring. From the very beginning, the focus has been on the quality of the organisation of the meetings. By mid-term, the project has organised 2 conferences and 3 specialised workshops, following what was defined in the work plan. CD-Roms and Newsletters have disseminated information resulting from each meeting and the web site has had a constant growth of visits. Several points have been emphasized, such as the interest of partners to share their knowledge and practices, the progressive broadening of the community participating to these meetings and the definition of R&D's stakes for developing unconventional geothermal resources. The close and frequent relationship and exchanges between partners belonging to the conventional geothermal community and partner representing European EGS pioneers was also a major element of success for the meetings hold during the first year of ENGINE. The settlement of a stakeholder committee is a next step in order to enhance links between R&D teams and stakeholders by providing strategic guidance to the Executive Group and to Contractors in general. This will coincide with the official start of the expert groups in charge of defining the best practices and priorities for research investment. As an introduction to the main sessions of the conference, work package leaders will present the main outcomes of the meetings and specialised workshops and from some elaborated synthesis. These documents already provide a framework for some of the R&D issues that will result from the ENGINE project. Concerning investigation of Unconventional Geothermal Resources and Enhanced Geothermal Systems, the synergy with the IGET STREP dedicated to Integrated Geophysical Exploration Technology proved to be fruitful since the kick off meetings. This project aims at testing geophysical methods that can be deployed for defining targets, characterising reservoirs and optimising investigation methodologies. Thus the ENGINE coordination has dedicated a workshop in Potsdam in November 2006 to the identification of the parameters that are needed before exploration drilling within potential geothermal reservoirs It was agreed that structural geology, temperature distribution, stress and fluid pathways, as well as the chemical and mineralogical composition of the rocks hosting the geothermal system, constitute key elements that can be considered as priorities in terms of research needs. Structural Geology is fundamental for imaging potential geothermal reservoirs. Geophysical methods are suitable for determining the architecture, geometry, and quality of the target intervals. However, existing methods must be improved and used in combination with different, highly sensitive techniques (passive and active seismics, MT, etc.) in order to meet the specific requirements of modern geophysical exploration for geothermal purposes. A significant effort has to be made in the interpretation of geophysical features that must be supported and validated by both petrophysical laboratory and borehole measurements, as well as by modelling. Finding heat at depth is a second challenge of the investigation phase.

The extension of large-wavelength heat-flow anomalies at depth is often inaccurate due to insufficient knowledge of the causes of the heat-flow anomaly and of the thermal properties of the main lithologies. Several physical parameters are coupled with temperature and can be imaged by different geological, geophysical and geochemical methods. Thus, the definition of possible targets for EGS could be improved by the use of a 3D modelling platform, in which all solutions from geological, geochemical and geophysical modelling, direct and inverse, could be combined and analysed. The knowledge of the stress field is another parameter crucial for understanding and stimulating fluid circulation. Evidence exists that demonstrates the influence of the stress field on hydro-fracturing while the mechanisms of rupture and propagation of an existing fault system and related displacement remain debated as well as the actual permeability associated with.The ability of the fault and fracture systems to channel fluids is directly dependent on the stress field (orientation and intensity). Favorable and unfavorable conditions exist depending on the tectonic setting and the geological environment. This debate has of course its natural continuation within the workpackage in charge of the evaluation of the different stimulation methods. In conclusion, defining integrated conceptual models is a next step for defining the necessary starting conditions for the development/stimulation of an EGS. There is a need to refer to conceptual models of the main geothermal sites, ranging from extended active geothermal sites through to EGS for which heat distribution and permeability networks are available for modelling pathways for fluid circulation, gas-water-rock interaction processes and heat exchange. A significant improvement of knowledge is expected from natural analogues on which hypotheses could be tested, for example circulation of fluids in relation to seismicity and lithology heterogeneity, or the thermal imprint of fluid circulation. The links with other investigation programmes, such as nuclear waste storage, capture and geological storage of CO_2 and oil and gas field development, could be also developed as a way to benefit from existing installations and experiences. About drilling, stimulation and reservoir assessment, the main focus has been on the enhancement methods during the first year. Enhancing or engineering the reservoir is a key issue for EGS and mechanical and chemical stimulations are commonly used to enhance their hydraulic properties. Moreover, induced microseismicity, geochemical tracing and thermal evolution of the system is an exceptional opportunity to characterize the reservoir and its dynamics. In the framework of ENGINE, the experience of experts who have been active on many case studies has been largely illustrated and debated during the Orléans launching conference and Ittingen workshop. It has been concluded that nowadays the success of these experiences is still a matter of trial and error, depending on the variety of geological contexts and site conditions. More detailed reviews have been planned about some stimulation methods, and exchanges with hydrocarbon industry and underground nuclear waste and CO_2 storage platforms are encouraged. As it is already partly expressed in the FP7 work program, researches should (a) define conceptual models for irreversible enhancement of permeability of the reservoirs (relationships between stress field and strain mechanisms, fluid-rock interaction, fluid pressure development…), (b) analyse the distribution in time and space of the magnitude of seismic events in order to improve the 3D imaging of the fracture system and stress field (interaction between tectonic, lithostatic and fluid pressure), (c) set requirements for seismic monitoring (modelling and metrology) and recommend management strategies for prolonged field operation, and (d) provide a methodology for the estimation of site-specific seismic hazard prior to development of potential sites for EGS. Finally, the induced earthquake in Basel on the 8th December reveals the urgent necessity to fill the gap in knowledge about this matter. The definition of an area thermally suitable for the development of an EGS is clearly depending on the solutions we will be able to find for these problems of exploration and assessment of reservoirs. It is also highly depending of the exploitation and business plan including an evaluation of the economic, environmental and social impacts. One of the

R&D perspectives related to this aspect is to analyse and assess possibilities and limitations of the currently available power plant technology using the energy retrieved from low enthalpy geothermal sources. To get an overall view, representatives of research and industry as well as project operators and planners have been brought together during the Strasbourg workshop in September 2006. Besides some partly controversially conducted discussions, the basis for fruitful exchange of information and experiences was thus created. The available know-how from existing geothermal power plants shows that electricity production from low enthalpy resources in Europe is still a fairly young technology which lacks wide experience. This is the case for the development of geothermal resources as well as power plant systems. Nevertheless there are quite a lot of projects planned and considerably more experience will be available in the years to come. Several lessons learned from this workshop are summarized. The discussion about the pros and cons of ORC vs. Kalina cycle, of air vs. water cooling, of fancy vs. proven technology and of power vs. Combined Heat Power is of no interest in terms of a further development of geothermal energy use. The main task of project developers is considered to be the identification of the optimisation potential in terms of the design of the working fluid, the cycle and turbine designs as well as the cooling systems. New and innovative technology is always connected with technical and financial risks. With an increasing technical effort and innovative ideas, the efficiency of a power plant cycle can be improved. Before being able to break into the market these technologies need to be tested, which is generally not possible on a purely commercial basis. Here the governments, national agencies and Europe are asked to support the market access of such new and innovative technologies which are definitely needed for further establishing geothermal electricity production in Europe. It seems that both these concepts developed during the workshop of identification of the optimisation potential and choice of an innovative technology, have been directly applied by choosing a Turboden-Cryostar binary power plant for the Soultz-sous-Forêts experiment. Another approach to promote geothermal electricity production from low enthalpy resources was stated as a combination with other sources of energy. New concepts of combining different energy options supplying heat on different temperature levels can result in a higher overall efficiency and thus profitability and hence be decisive for realising geothermal based electricity production.

Session 1: Global developments

Wednesday, 10 January 2007
13:30 – 16:30

Enhanced Geothermal Resources in the United States Resource Base and Location

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The USDOE has just completed and is about to publish an assessment of the potential contribution of geothermal resources to the electrical power production of the United States over the next 50 years. The topics range from the resource base to financial aspects. This paper briefly presents the resource aspects of the report. In this study the definition of Enhanced Geothermal Systems (EGS) was expanded to include all non hydrothermal geothermal development. Additional categories of resources considered were coproduced (waste heat) resources associated with oil and gas development, and geopressured geothermal resources (also associated with oil and gas development). Maps were produced of the temperature at 1 km depth intervals from 3 to 10 km for the conterminous US. Heat in place was calculated for 1 km depth intervals over the same depth intervals. The heat-in-place calculations were made on a country wide and state by state basis.

The resource base is estimated at 13,3000,000 ExaJoules (1EJ = 10^{18} J). This value is about 130,000 times the current annual consumption of primary energy in the US. If only 2% of the resource base were developed the electrical power production would still be about 26,000 times the annual consumption. The large surplus suggests that geothermal energy could be developed in a sustainable way. The resource is widely distributed throughout the US although there are several large areas (> 100 km^2) of special interest to EGS development due to the presence of high temperature at shallow depth, favorable conditions, etc. described on the report. These large areas include The Geysers/Clear Lake area in California, parts of the Basin and Range Province, the Southern Rocky Mountains and the Salton Trough. About 100,000 EJ of the true EGS resource is estimated to lie in sedimentary formations. These resources may represent the most direct path to large scale EGS development as the reservoir uncertainty is minimal and extensive drilling and fracturing in tight gas sands is already commonplace.

Unconventional resources include in addition to these already mentioned of 71,000 to 170,000 EJ in geopressured resources and .1 to .5 EJ in coproduced fluid resources.
Unconventional developments include 500 kW installed on a 74°C (165°F) resource in Alaska and a 1 MW development in progress at a large oil field in Wyoming with fluid temperatures of about 93°C (200°F).

The complete report can be downloaded in pdf format (one file for each chapter, the front matter, and appendix) from the following websites:
http://geothermal.inel.gov
http://www1.eere.energy.gov/geothermal/egs_technology.html

Economics of Developing EGS Systems and Potential for Market Penetration

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A comprehensive assessment of enhanced, or engineered, geothermal systems was carried out by a 12-member panel assembled by the Massachusetts Institute of Technology (MIT) to evaluate the potential of geothermal energy becoming a major energy source for the United States. Geothermal resources span a wide range of heat sources from the Earth, including not only the more easily developed, currently economic hydrothermal resources; but also the Earth's deeper, stored thermal energy, which is available almost anywhere. Although conventional hydrothermal resources are used effectively for both electric and nonelectric applications in the United States, they are somewhat limited in their location and ultimate potential for supplying electricity. Beyond these conventional resources are EGS resources with enormous potential for primary energy recovery using heat-mining technology, which is designed to extract and utilize the earth's stored thermal energy. EGS methods have been tested at a number of sites around the world and have been improving steadily. Because EGS resources have a such large potential for the long term, we focused our efforts on evaluating what it would take for EGS to provide 100,000 MWe of base-load electric-generating capacity by 2050. This study performs a traditional benefits analysis using the National Energy Modeling Systems (NEMS) to assess the competitiveness of geothermal electricity generation in the mid-term (up to 2030). This analysis incorporates input data and assumptions different from past geothermal analyses, including recently available updated geothermal resource supply for hydrothermal geothermal energy and also for EGS energy completed as part of the MIT study of EGS resource supply and costs. This analysis, consistent in approach with the preliminary Government Progress and Results Act FY2008 (GPRA08) analysis conducted for the Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy EERE portfolio of technology programs included in the FY2008 budget request, indicates a significant increase in overall geothermal penetration and in incremental capacity and generation benefits over past analyses. A stand alone case that incorporates the estimated cost-reduction impact of potential technology improvement results in 50 GW of capacity in 2030. Implementation of a carbon policy that increases the price of fossil fuels based on their carbon content increases penetration over the stand alone case by 30 GW. Supply in non-Western regions plays a significant role in national penetration through the development of co-produced fluids from existing oil and gas wells. Hydrothermal resources provide the bulk of capacity additions in Western regions. Enhanced Geothermal System (EGS) resources play a small but significant penetration role in the next 25 years unless significant technology improvement is allowed. The Updated Supply representation features significantly lower development costs for hydrothermal resources, although somewhat higher EGS costs than used previously. The inclusion of a significant amount of relatively low cost co-produced resource further accentuates the hydrothermal cost difference and contributes to a significant increase in the amount of geothermal resource that is likely to be technologically and economically accessible in the near through mid-term period. While this Updated Supply representation is the primary supply-related input to NEMS, there are several other key inputs, including industry learning, program improvement, and annual builds limits, that either impact the capital cost component of the supply representation through time or place limits on how much supply can be absorbed. Comparison of specific case results suggests that penetration is most sensitive to the supply representation and annual build limits inputs. The significant increases in both overall and incremental penetration compared to previous results are likely attributable to differences in these two key inputs. Given the assumptions used in the analysis, these forecast results

should be treated more as the maximum possible, rather than the most likely or probable, level of absorption of geothermal capacity by the electricity market. Other factors such as market forces, government regulation changes to geothermal leasing laws, state renewable portfolio standards and availability of venture capital for resource exploration and development will control the actual rate of absorption. Several limitations in the current NEMS treatment of geothermal modeling are overcome in this analysis.

Summary

This report documents the approach taken to characterize and represent an updated assessment of geothermal supply for use in forecasting the penetration of geothermal electrical generation in the National Energy Modeling System (NEMS). The resulting supply is compared to a dated representation, which relies in part on resource characterizations and a cost estimation tools from the mid-1980s, used in earlier analyses.
This updated supply assessment is made possible by recent studies that examine the supply potential of geothermal power accessible through advanced technologies such as co-produced fluids and Enhanced Geothermal Systems (EGS), and the recent release of a new geothermal cost analysis tool.

Approach

The approach has two main components:

1. Characterization. Resource characteristics and potential electrical output are identified from existing databases and source publications. These attributes are then used to calculate development and operating costs for specific physical volumes in the subsurface using a batch processing approach with the Program's Geothermal Electric Technology Evaluation Model (GETEM), a techno-economic systems analysis tool for evaluating and comparing geothermal project cases.
2. Representation. Output capacities and costs are then regionally aggregated and generalized in a manner suitable for input into NEMS using the Geothermal-Electric Sub-module (GES) input file format.

The supply representation incorporates five specific resource types: hydrothermal flash, hydrothermal binary, geothermal fluids co-produced with oil and gas, and two types of Enhanced Geothermal Systems (EGS) resource – convective EGS associated with hydrothermal resources at depths less than three kilometers, and conductive EGS potential for depths between three and ten kilometers. The representation extends supply beyond the traditional three Western regions (NWP, RA, CAL) by including cost and capacity estimates for three mid-continent regions (ERCOT, SPP, SERC).

Results

This new Updated Supply representation comprises 126 GW of resource potential nationally: 89 GW across all resource types in the Western regions and 37 GW mostly from co-produced potential in the non-Western regions (Table E1). The total represented capacity is nearly the same for the Western regions as used in previous recent Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Government Performance and Results Act (GPRA) benefits assessments, referred to as GPRA06 Supply, however the mix among specific types of resources is different.

In comparison to the earlier representation, the Updated Supply features significantly lower levelized costs (LCOEs) for hydrothermal resources and somewhat lower LCOEs for EGS resources (Figure E1). The significant amount of relatively low cost co-produced resource is unique to the new representation. In aggregate, the Updated Supply has a lower levelized cost than GPRA06 Supply throughout the range of cumulative capacity addition. The difference is particularly pronounced in the first 20 GW of potential additions.

Central America Geothermal Development and EGS perspectives

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The Central America region has tectonic activity that produce an extensive volcanic chain along the pacific rim. The first geothermal development was the Ahuachapán field where a geothermal reservoir was discovered in 1968. The commercial exploitation started in 1975 when two condensing units went on line, the actual install capacity is 95 MW and the field still producing steam to run the units. Another geothermal field in the area are Miravalles in Costa Rica (1994), Momotombo in Nicaragua (1983) and Zunil in Guatemala went (1999). In the region, the total install capacity is 8,890 MW with a maximum available capacity of 7,300 MW, The peak load is 5,170 MW, with an average power growth rate of 6%/year. The annual generation in 2005 was 34,272 GWh, with 2,500 GWh (7.3%) coming from geothermal power plants. Given the accelerated growth rate of electricity demand and the oil price the region faces difficult options to increase the supply of electricity in a near future. Most of the countries in the region is considering as a national strategy the development of indigenous sources of electricity like the geothermal. In 2003, LaGeo and Shell did a hydraulic stimulations test in well TR-8 in the Berlin Geothermal field as part of a project to explore the feasibility of commercial hot fractured rock energy generation. During the pumping period the level of the seismicity was much lower than anticipated and the pressure growth as a function of the injected flow rate, the final injection capacity of the well improve from 5 kg/s(24.5 bar) to 25 kg/s (18 bar). In 2005 LaGeo decided to repeat the test for a long period of time (3 months/24 hours per day), the results indicate that is possible to improve the injection capacity for long term period using permanent high pressure (50 bar) pumping system

The Current State of Geothermal Energy Development in the Philippines and Southeast Asia

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The rapid economic growth in many Southeast Asian countries results in an increase in demand for electricity which is projected to grow at the rate of 5-15 percent per annum. The target of these countries to attain energy security and to sustain their economic growth is central to their energy policy. It is a key driver in their development of renewable and indigenous sources of energy as alternate to their fossil-based fuel requirements. Two of these countries, the Philippines and Indonesia, are both ideally situated along the stretch of Pacific Ring of Fire, and as such are largely endowed with geothermal resources. Geothermal development in the Philippines is now in its mature stage, where most of the geothermal fields have been operating for 10-30 years. On the other hand, Indonesia, with its 20,000 MW potential reserves, has been held back in its geothermal development. While the Philippines currently ranked second to the US with 1,931 MW installed geothermal capacity, Indonesia has installed only 807 MW, approximately 4 percent of its total potential. There are minor geothermal activities in Thailand, Vietnam and Malaysia utilizing their low temperature resources mainly for direct heat application. This paper presents the current state, problems and key components of region's geothermal development. A brief discussion on possible candidate fields for Enhanced Geothermal Systems (EGS) in the Philippines is included.

Possible Applications of Geothermal Energy in Oil Sand Mining

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In the oil sand mines in Alberta, Canada, geothermal energy provides the opportunity to reduce CO_2 emissions from the heat-intensive process of extracting the oil. To separate 1 m^3 of oil from the sand, 5 m^3 of heated water are required. The energy to heat this water is generated by burning natural gas. To generate 1 MWth, 2300 m^3 of natural gas have to be burned (theoretically), resulting in 4.4 T of CO_2 emissions and costs of 600 US$ every day. For the same power output from geothermal energy, (theoretically) 50 borehole heat exchanger (BHE) - heat pump (HP) systems with 400 m depth, or 6 BHE/HP systems with 2000 m depth are necessary.

In the Athabasca Oil Sands area, granitic basement is relative shallow (200-800 m), making EGS an alternative option. Temperature gradients in the sediments range from 20-40 K/km, and heat flow is 30-60 mW/m^2. The industry consortium GeoPOS plans to drill an appraisal well 500 m into the granitic basement to study the thermal and hydraulic conditions in the granite. If conditions are favourable the well can be the first step to develop an EGS system. The aim would not be to produce electricity but direct heating of separation water. If conditions are not favourable for EGS, the well will be used for a BHE/HP system.

Shell will invest 1.4 bln US$ to double daily production from the oil sand mines until 2010, other operators have similar plans. Besides water usage, gas consumption (commercial) and CO_2 emissions (environmental) become major issues that need to be addressed for these expansions. This situation provides an ideal opportunity for geothermal energy applications where they are needed and not where subsurface conditions are favourable because initial profitability is of secondary importance and any level of heat supply is a success.

Volcanic Systems and Thermal Regimes: A major theme of the ICDP

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The International Continental Scientific Drilling Program, ICDP aims with its efforts on topics of high scientific priority and its drilling projects are conducted at locations of global geological significance. The program focuses on challenging themes of both geoscientific and socio-economic relevance such as Earth history and climate, natural hazards, impact structures and mass extinctions, deep biosphere, and also volcanic systems and thermal regimes. The latter is presently being addressed though the Icelandic Deep Drilling Project, in which supercritical fluids will be investigated in situ. Previously supported drilling projects with a major volcanological and geothermal component comprise the Long Valley Exploration Well in California, the Hawaii Deep Drilling Project, and the Unzen Volcano Drilling in Japan. Currently, the Campi Flegrei Caldera in Italy and the Mutnovsky Volcano in Kamchtka, Russia are being developed as new project proposals within the ICDP. On the one hand, ICDP funds drilling operations and drilling-related activities with international financial contributions paid from the annual membership fees of the currently 13 ICDP member countries. On the other hand, ICDP provides scientific-technical assistance through its Operational Support Group (OSG) and offers access to the ICDP equipment pool and operational expertise.

Europe, from a pioneering role to the leading edge of R&D with a global perspective for the future of geothermal energy

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Europe's pioneering role for the development of geothermal energy The development of the Earth's thermal resources, especially in Europe, relies on the sound scientific and technical knowledge that has been acquired during the 20th Century. This knowledge spans from the first production of electricity in Italy, to the exploitation of shallow aquifers in the Paris basin, through the booming sector of geothermal heat pumps, to the Soultz-sous-Forêts Enhanced Geothermal System (EGS) experiment in France. Conventional geothermal energy is still benefiting from ongoing technological improvements in heat conversion and distribution and should, therefore, become increasingly cost-effective due to the inevitable rise in energy prices and growing environmental constraints. Thus, geothermal energy must be considered in the global debate on greenhouse effect and energy supply. It is in such a context that the European Union's contribution to R&D projects must be assessed, with a budget of € 20 million dedicated to geothermal energy as part of the 6th FP for a total budget of about € 50 million over four years. The contribution of geothermal energy to Europe's strategy for renewable energy, as defined in 1997 in the White Book, was a doubling of electricity capacity from 500 to 1,000 MWE and an increase in heat production capacity from 750 to 25,000 MWt by 2010. These targets have already been achieved for electricity capacity, which has reached 1,179 MWE, whereas in terms of heat production 13,626 MWt have been installed for geothermal direct use capacity. The technology is now available for heating/cooling and power generation for both medium-to-high enthalpy fields and for low-to-very-low enthalpy fields (geothermal heat pumps), and this is shared by many countries. The diversity of developments worldwide, many of them referring to the European experience, is also a very strong advantage, as it provides numerous case histories that can be used for attracting investors. Gaining/Maintaining the leading edge There is a need for long-term collaborative research within international projects in order to develop EGSs. The community is aware that the development of geothermal energy requires, in addition to short-term projects, medium-to-long-term projects involving EGSs, including extensive active geothermal systems and geothermal recovery from existing oil and gas operations having a wide application and a relatively low risk. EGS development requires the mobilisation of the international community. The Soultz experiment is considered as the international reference by Australian investors and by American scientists, for whom EGS is one of the few renewable energies that can provide continuous base-load power. Furthermore, the extension of existing geothermal fields in Italy, Mexico, Costa Rica and El Salvador is considered a priority issue by these countries. The co-ordination of such short- and long-term projects requires a well organised scientific community at international level. The development of geothermal energy and the regaining of political support require the enhancement of existing knowledge and know-how and the definition of ambitious projects. This conviction, which is shared by a broad scientific community, the ENGINE co-ordination action, as well as other initiatives such as the working groups of the European Commission, IEA-GIA, MIT, the International Geothermal Association (IGA), and the European Geothermal Energy Council (EGEC), strives to increase the audience and impact of geothermal energy. Thus, one of ENGINE's major objectives is now to contribute to the construction of an international strategy for promoting geothermal energy by consolidating the available information systems and proposing spin-off projects that will receive the support of stakeholders, decision makers and private investors.

Session 2: Exploitation, economic, environmental and social impacts

Thursday, 11 January 2007
8:30 – 12:30

Electricity generation from Enhanced Geothermal Systems, Summary of the Workshop 5, 14-16 September 2006, Strasbourg (France)

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Introduction

Presently the overall capacity of electricity generation systems based on geothermal energy installed within European countries is 1.13 GW (EU 0.8 GW). These geothermal power plants contribute with approx. 7.1 TWh/a (EU 6.0 TWh/a) to the European electricity supply. The by far biggest share of this electricity generation (about 98 %) results from high enthalpy fields which can only be exploited at specific locations with promising geological conditions. Only to a very small extend low enthalpy resources are presently used. But these low enthalpy resources have by far the biggest electricity generation potential throughout Europe and worldwide. However, techniques for exploiting low enthalpy resources for the production of electricity are currently only partially established. Firstly there is the challenge to lock up the deep underground to achieve flow rates at temperatures high enough to realise an economic viable project. Secondly the surface technology (i.e. power plant technology) needs to be further developed and optimised in order to achieve high efficiency rates with low investment costs and thus low electricity generation costs. In the past, different technical approaches to convert low temperature heat into electricity have been developed. Some systems are available on the market, others are still in a demonstration phase and others only exist as system studies (i.e. on paper) so far. The overall goal of these development efforts was and is to achieve the highest possible efficiency rates taking the given thermodynamic constraints into consideration. Therefore for the use of low enthalpy resources mostly binary cycles are chosen. These cycles have on one hand the advantage of the turbine not getting in touch with the brine in case of e.g. too aggressive brines; on the other hand – and even more important – binary cycles are able to convert low temperature heat (i.e. even temperatures below 100 °C) into electricity. However, a simple conclusion about the most promising binary cycle respectively power plant technology can not be drawn based only on the criteria “efficiency”. Additionally a wide range of further aspects has to be taken into consideration. In general thermodynamic aspects need to be seen together with technical feasibility and availability as well as economic, environmental and social aspects related to the site specific conditions. On this background the aim of the EU-funded ENGINE-workshop was to analyse and assess possibilities and limitations of the currently available power plant technology using the energy retrieved from low enthalpy geothermal sources. To get an overall view representatives of research and industry as well as project operators and planners have been brought together and presented their individual view. Besides some partly controversial conducted discussions, the basis for fruitful exchange of information and experiences was thus created. The slides of the presentations are available under http://engine.brgm.fr/. Besides the R&E-needs irrespective of a specific cycle or power plant (e.g. material selection for sealing, turbine parts, heat exchangers etc., optimising of the working fluids) the main findings and discussion results of the workshop can be summarised as follows to give an impression of the overall picture.

ORC or Kalina Cycle?

Geothermal electricity generation from low enthalpy resources is realised in binary plants. Thereby the heat of the brine is transferred via heat exchanger to a working fluid, which evaporates already at low temperatures (e.g. organic substances). Currently two types of binary cycles suitable for the frame conditions given in geothermal power plants for low enthalpy resources are available on the market: the Organic Rankine Cycle (ORC) (i.e. a conventional Rankine cycle running with a specific working fluid evaporating below 100 °C) and the Kalina cycle (i.e. also basically a Rankine cycle being fed with a working fluid consisting of a mixture of two substances like e.g. ammonia and water). To use of such a mixture as working fluid has the advantage that the heat can be transferred more efficiently between the brine and the power plant cycle; this reduces possible losses. Therefore the Kalina cycle promises higher efficiency rates within a certain temperature window and hence might be advantageous at temperatures below 130 to 140 °C. But the use of a mixture of two substances with a varying mixing ratio within the working fluid streams is only possible with a more ambitious and expensive technology compared to the use of only one substance. This is one of the reasons why there is only one Kalina cycle in operation within a geothermal power plant so far. In contrast there are numerous Organic Rankine Cycles under operation worldwide. Apart from these differences between the two cycles "ORC" and "Kalina cycle" these cycles do have more in common than being contrary. Each cycle has for a certain application at a specific spot specific pros and cons. But both cycles also show a significant optimisation potential in terms of the design of the working fluid, the cycle and turbine designs as well as the cooling system. Therefore the question is not to choose an ORC or a Kalina cycle. Rather the optimisation task is to find the right cycle for the reservoir characteristics and the other project specific demands given at a certain site.

Axial or radial turbines?

The turbine used within an ORC or a Kalina cycle is in most cases an axial inflow type. This is derived from the conventional water steam turbine industry where axial turbines are state of technology due to their promising performance within the respective application (i.e. for the use in big e.g. coal fired power plants). The design parameters of the turbine however within cycles driven by low enthalpy resources can vary decisively compared to a "classic" turbine used within a water steam cycle (e.g. enthalpy drop, stream and rotor velocity). Therefore investigations have shown that radial inflow turbines can lead under specific conditions to higher efficiencies. Considering the importance of optimising the efficiency of such cycles under the conditions defined by the geothermal reservoir without raising the overall complexity of a cycle radial turbines could be a promising opportunity. Therefore the question is not to use axial or radial turbines. The point is to choose the turbine type promising the highest efficiencies at lowest risks – without any ideology and predefined opinions.

Air or water cooling?

The working fluid of the ORC or Kalina cycle could be cooled down with cooling systems driven by air or water. Air cooled plants have the disadvantage to face seasonal changes in cooling temperatures. Therefore such systems can often not guarantee maximum power from the plant throughout the year. Additionally the running fans need electricity and space; also noise emissions need to be considered at a location close to populated areas. In contrast water cooled plants in most cases can realise lower and over the year more constant condensation temperatures and pressures. They therefore allow for a larger enthalpy drop in the turbine and thus slightly higher efficiencies. However the mass flow of water in the demanded quality required by the water based cooling system needs to be provided considering legal obligations e.g. of the temperature level and the available amount. This can also culminate in high provision costs due to power demand for pumps and e.g. water conditioning systems. Therefore - at a certain location - the question about air or water cooling is not really the most important one because in most cases a location specific compromise has to be found anyway. If e.g. enough water is cost efficient available in most cases a water cooling system will be implemented due to economic reasons. But often this is not the case. Then there is only the chance to go for an air cooling system or even a combined system.

Fancy or proven technology?

Fancy ("high efficiency – high risk") or proven ("low efficiency – low risk") technology is a matter of the viewpoint respectively of the philosophy. Aiming for low risks one can get good and reliable power plant technology on the market characterised often by relatively low efficiencies; this is e.g. the case for a standard power plant based on an ORC. Accepting a slightly higher risk one will find on the market cycles which promise considerably higher overall efficiencies with the disadvantage that these cycles do exist so far maybe only as a demonstration plant or even only on paper. Therefore the question is not to go for fancy or proven technology. The question is what technological risk a project can / will accept for the profit the project strives for. This question is in most cases not answered by the project developer; rather the bank or the investor providing the credits decides what risk might be taken. Due the fact that the risk finding the reservoir conditions needed for an economic viable project is in most cases quite high most projects go for a proven and well known power plant technology with a high availability in order to minimise the existing risk. This attitude makes it very difficult for new and innovative technologies to break into the market. Therefore fund raising of public money for demonstration projects is often an important step in order to prove technical feasibility of new technologies to allow them the market access.

Power or CHP?

Converting low enthalpy resources to electricity produces considerable amounts of waste heat because of necessarily low thermal efficiencies due to the – according to Carnot – given thermodynamic constraints. The logical consequence – regarding the relatively high investments of geothermal power production from low enthalpy resources – is therefore to try to additionally sell this heat on the local heat market and realise combined heat and power (CHP) projects like i.e. in Húsavik, Iceland, or in Neustadt-Glewe, Germany. In order to further optimise this economic win-win-situation under the given economic and political frame conditions it might be even more promising to run a geothermal CHP plant heat leaded instead of aiming for the highest power output. In Unterhaching, Germany, for example, running the system with the overall installed electrical capacity for maximising the electricity output is the strategy for the summer, whereas during the winter supplying the demanded heat - even by reducing the electricity generation - has priority. Therefore the goal should always be to find a way to sell the heat locally respectively to identify a location where a heat demand is given to improve the economic performance of a geothermal power plant especially for low enthalpy resources.

Lessons learned

The available know-how from existing geothermal power plants – regardless if with ORC or Kalina cycle, with axial or radial turbine, with water or air cooled, if power or CHP, with fancy or proven technology – shows that electricity production from low enthalpy resources in Europe is still a fairly young technology which lacks further experience. This is the case for the development of geothermal resources (i.e. the underground part) as well as power plant systems (i.e. the part on the surface). Nevertheless there are quite a lot of projects planned and considerably more experience will be available in the years to come. On this background the lessons learned so far can be summarised as follows. • Optimisation was mainly thought to be a question of thermodynamics. But regarding geothermal projects this is only one part of the whole picture, in which technical and economic aspects as well as the site specific frame conditions need to be included in order to provide high availability and economic feasible power plants. Therefore the simple discussion about the pros and cons of ORC vs. Kalina cycle, of air vs. water cooling, of fancy vs. proven technology and of power vs. CHP in terms of a further development of geothermal energy use will not lead to any results. The main task of project developers instead is to identify the site specific conditions and clarify the perception of risks which can be taken. Thereupon the project as total needs to be optimised aiming for economic feasibility free of predefined opinions. • New and innovative technology is always connected with technical and financial risks ("No risk, no fun!"). This is also the case for systems generating electricity from geothermal resources in general and for low temperature power plants in particular. But with an increasing technical effort (and higher costs) and innovative ideas the efficiency (and thus the income) of a power plant cycle can be improved. Before being able to break into the market these technologies need to be proved which is generally not possible on a purely commercial basis. Here the government is asked to support the market access of such new and innovative technologies which are definitely needed for further establishing geothermal electricity production in Europe. • Another approach to promote geothermal electricity production from low enthalpy resources – and also evidence that promoting geothermal energy use needs open minded project developing – was stated as a combination with other sources of energy (like e.g. biogas plants). New concepts of combining different energy options supplying heat on different temperature levels can result in a higher overall efficiency and thus profitability and hence be decisive for realising geothermal based electricity production. Low enthalpy resources for geothermal energy production show the potential to contribute substantially within the energy system (i.e. within the heat and electricity market) throughout Europe. Thereby it is necessary to develop this technology to contribute for a more sustainable energy system in the future. On this background the goal is to successfully develop (i.e. technologically promising, economically viable, environmentally benign and socially acceptable) geothermal power plants. Project development and optimisation is hence a task of having a look on the overall picture.

Renewable Energies in the German Energy System – Promotion and Development of Renewable and Geothermal Energy

Uwe Büsgen, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

How to combine energy security, competitiveness and environmental protection, in particular the need to reduce CO2-Emissions by 80% by 2050? The paper discusses:

- The role of geothermal energy in Germany
- The promotion of renewable energies in Germany
- The promotion and R&D activities in the field of geothermal energy
- The development of renewable energy in Germany
- The development of geothermal energy in Germany and future perspectives

Low temperature cycles – concepts and prospects

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Low-enthalpy geothermal resources are typical finite heat capacity sources, while the environment which acts as heat sink may be regarded infinite. Therefore the temperature-enthalpy curves of heat source and heat sink have an almost triangular shape. Applicability, advantages and disadvantages of different ideal power cycles in such a setting, like the Carnot cycle, the Lorentz cycle and a cycle with triangular shape, are discussed. Different optimisation criteria like thermal efficiency, power output and resource utilization may be applied to improve the design of the plants. Every criterion would result in a different design. A couple of power plant concepts were developed to get close to the ideal cycle. The most prominent like the organic Rankine cycle (ORC) and the Kalina cycle will be presented, including suitable optimisation approaches. Cold production competes fairly well and will be addressed also. Since combined generation of heat and power, or heat, power and cooling, is expected to significantly improve the economics plant, promising methods of coupling of the processes will be discussed briefly.

Optimized geothermal binary power cycles

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This study has been carried out for the LOW-BIN (Efficient Low Temperature Geothermal Binary Power) project, which is supported by the European Commission FP6 program. Its aim is to study and recommend optimal Rankine cycles using Isobutane (R600a) and R134a as working fluids for two geothermal binary power machines. The first one (System A) should be able to generate electricity from low temperature geothermal resources, with profitable operation down to 65°C. The second one (System B) should be able to cogenerate both heat and power by heat recovery from the cooling water circuit, corresponding to geothermal fluids of 120-150ºC and cooling water supplying a district heating system at 60/80ºC. The main Rankine Cycle parameters and components are modelled, such as the shell and tube condenser and the geothermal plate heat exchanger. The objectives of the optimization are maximizing overall conversion efficiency and minimizing the cost of the plant, which is represented as minimizing the exchangers' surface. Through this study, a set of optimal solutions for Systems A and B are obtained, that combine maximum plant's efficiency (6.7-7.4 %) and minimum cost. Each optimal solution corresponds to an optimal Rankine Cycle and every parameter of the cycle is defined.

Economic approach of geothermal energy generation

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The direct use of geothermal heat is in Europe already widely competitive due to the high oil and gas prices. Geothermal electricity production however faces in most countries huge financial challenges as far as low enthalpy fields are exploited. Besides the use of high enthalpy fields - whose use has partly a long tradition - low enthalpy resources have the larger and area-wider potential but are comparatively only scarcely exploited so far. Apart from technical challenges which power production from geothermal low enthalpy fields are facing, also economic barriers hinder the wider use of geothermal energy within Europe. Therefore the power production costs of geothermal low enthalpy fields will be analysed in case studies in order to identify the crucial cost factors and to point out which measures could result in a widely economic feasible geothermal power production in Europe.

Probabilistic and decision tree approach to geothermal techno economic performance

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Decision and risk management of geothermal assets requires a thorough quantitative understanding of the effects of techno-economic uncertainties on geothermal energy performance. These uncertainties can be considerably large especially in the initial stages of exploration and design. Optimum design under such uncertainties can benefit considerably from best practice and probabilistic decision and risk management tools which are have been developed in the Oil and gas industry. In this presentation we give a description of best practices for probabilistic techno-economic integration of uncertainties all along the workflow. Combined with use of decision trees and parameters sensitivity analysis, this allows to find critical uncertainties in parameters and optimum scenarios for design.

The practical implementation of such best practices, is illustrated through an application in performance assesment of re-use of deep boreholes drilled by oil and gas industry for a deep Borehole Heat Exchanger (DBHE). A DBHE is based on the principle of a fluid migrating through a coaxial pipe in the subsurface, heated gradually by migrating downwards in the outer pipe, whereas the inner pipe acts as the return path for the heated fluid. The inner tube is isolated for the total length of the DBHE, in order to prevent the producing water from cooling down. The upper part of the injection tube can be isolated from the surrounding rock up till the depth at which the geotherm equals the temperature of the injected fluid.

The energy performance of the DBHE is proportional to the temperature difference between injected and produced water multiplied by the injection rate (m3/h). In this study we focus on the effects of various natural uncertainties in the subsurface geology (heat flow, sediment conductivity), preceding use of the well (e.g. production heating the surrounding of the well) and specific design parameters for geothermal energy production.

Preceding production can have a significant effect at the heating of the surrounding of a well, resulting in substantial increase in geothermal energy, especially when production has taken place over a long period of time.

Environmental impacts by the use of geothermal energy

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Geothermal energy is a promising energy source. Not only due to its large and area-wide potential but also because of its base load ability geothermal plants can contribute to energy supply. However, a contribution to a sustainable heat and electricity provision is only reasonable if its use – compared to given alternatives - results in general benefits for the environment. This is true for the environmental impacts connected with the whole life cycle, i. e. life cycle assessment regarding construction, operation and deconstruction as well as the therewith combined process chains, but also for the effects on the natural environment, which are primarily site specific and regional. On this background a survey of local environmental impacts by using geothermal high and low enthalpy fields will be given and a case study of a life cycle assessment presented.

Non Technical Barriers in Developing Geothermal District Heating in the Paris Basin

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The Paris suburban areas enjoy an almost unique setting, characterised by the combination of reliable heat source - a dependable geothermal reservoir of regional extent -and a large heat market – large concentrations of social dwelling eligible to district heating.
It led to the launching by the State of a vast development scheme, which peaked, in the mid 1980s, with the implementation of 55 geothermal district heating (GDH) doublets and a yearly production nearing 2,000 GWht. As of year 2006, 34 GDH doublets, cumulating a ca 1,000 GWht, remain online, a score regarded positive, given many obstacles which, from the infantile disease to entrepreneurial maturity stages, somewhat jammed the learning curve of this energy route.
Among these obstacles, non technical barriers, not totally overcome yet, took an important share. Those analysed and discussed in this paper, address the following headings:

1. structural. Lack of expertise from, the often unskilled, operators in managing industrial installations and energy processes with a strong mining impact.
2. administrative and managerial. Unclear definition of the duties and commitments of concerned intervening parties (operators, engineering bureaus, heating companies, consultants…) and relevant exploitation/service contracts and/or concession/farming agreements, inefficient marketing and negotiation of heat sales and customer subscription contracts;
3. economic and financial. Severe competition from conventional fossil fuels (heavy fuel oil, natural gas) penalising heat sales and revenues, persistent low energy prices in the aftermath of the second oil shock adding to a debt nearing 85 to 90% of total investment costs, in a capital intensive (ca 10 M€) low equity, high interest rates (12 to 16%!) environment. This clearly placed most operators in a typically third world situations;
4. fiscal. A 19.6% VAT rate applied to GDH grid subscription contracts whereas energy producing utilities (power, natural gas) benefit from a 5.5% rate, applicable also to maintenance/repair works in collective buildings and individual residences;
5. image. Geothermal energy, particularly direct use of low grade heat has a structural image problem with respect to social acceptance and public awareness. The heat recovery remains somewhat mysterious or esoteric as opposed to obvious, visible competing solar, wind and (bio/fossil) fuel sources. In the early days of GDH (the so-called infancy stage) it was regarded as a poorly reliable and costly, occasionally hazardous technology an impact widely exploited by the “antis” lobbies.

Non technical barriers in Tuscany (Italy)

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The utilization of geothermal resources for industrial purposes began in Larderello with boric salts production in the early 1800's, with the first experiment of electric energy generation in 1904 and the installation of the first 250 kW unit in 1913. This makes of Tuscany the birth-place of geothermal activities. At present, the Italian geothermal power plants are located in 3 areas (Larderello, Travale and Amiata) with different for development history and installed capacity.

After the 2nd world war electricity generation is continuously increased (about 5200 GWh in 2006) and a significant increase has been planned for the next few years (5600-6000 GWh in 2012), as the result of new specific projects or development of resources located by previous deep exploration programs. However an uncertainty about the feasibility of these projects exists and is strictly linked to the non-technical barriers that are mainly represented by "Economical Sustainability", "Environmental Aspects" and "Political Contest". Economical Sustainability is an important issue since geothermal exploitation needs high investment costs to locate the resource (mining investment) and to build gathering systems and power plants. Without financial incentives there are no possibilities to realize a geothermal project, but in Italy there are two favorable circumstances: Enel experience in the exploration allows the reduction of mining risk, hence of the required investment, furthermore Italian laws provide incentives that increase the economical sustainability. Environmental Aspects can play a prevalent role as non-technical barrier. Usually, in the world, geothermal generation is developed in areas where the landscape is not affected by geothermal activities, but in Tuscany geothermal development involves a region characterized by high population density and historical and artistic peculiarities. This put the environment at the centre of the general interest and the main real worries are related to land use and visual impact, to the noise coming from power plants and wells during drilling and production tests, to the air quality especially for the smell nuisance due to H_2S emissions. Moreover many worries are also induced by statements of some "scientists" in cases like the induced seismicity ("Geothermal activities increase the local macro-seismicity"), the hydrogeology ("Geothermal exploitation impoverishes the drinking water reserves") and the effects on health. Induced worries feed an hostile political contest more than the real ones and local committees, as well as political parties, are often against any level of geothermal development.

Enel is seriously engaged in managing these non-technical barriers with technical approach. In particular, to reduce the environmental impact Enel developed and designed an innovative technology (AMIS) for the Hg and H_2S abatement that will be installed on 16 power plants in 2007, with an investment of about 40M€, and approved a budget of more than 30 M€ for land recovery and new architectural solutions both for power plants and gathering system. Furthermore, Enel is also engaged in increasing the social acceptance of the geothermal development by mean of cooperation and relationships with local communities, agreement with the Tuscan Council requirements about environmental issues and knowledge diffusion. Not always technical and political approaches are sufficient because the weight of psychological aspects is prevailing. To contrast not real worries of the population is necessary an action involving not only the industrial operator, but all the stakeholders.

In this effort the scientific community can help geothermal industry, supporting knowledge spreading, assuming unambiguous positions to avoid unjustified population fears about negative effects coming from the presence of geothermal plants on their lands, emphasizing the uncertainties of geo-scientific interpretations in order to avoid their incorrect use or ill-exploitation.

Power Extraction from Hot Dry Rocks

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The heat content of hot dry rocks (HDR) down to depths 5 to 10 km is enormous. To extract this heat it is necessary to create an underground water circulation system using the HDR as a heat exchanger. To maintain the underground flow a system of natural or artificial fractures between injection and recovery wells shall exist. The water is injected from above, heated in the underground heat exchanger and recovered at elevated temperature. The water pressure throughout the flow between the two wells should be some higher than the saturation pressure at the water exit temperature to prevent boiling, which can hamper the flow and the heat exchange process. Hence the specific of HDR systems is that the geothermal heat will appear as a pressurized water flow at elevated temperature. To produce power the heated water transfers its heat in a counter-flow heat exchanger to a working media circulating in a thermodynamic cycle.

Usually defined are the water temperatures T_1 at the recovery well mouth and T_0 at the exit of the power production unit. Thus defined is the specific thermal power carried over by 1kg/s of the water: $N_{th} = 1 \cdot c_{pw}(T_1 - T_0)$, where c_{pw} is the water heat capacity assumed constant in the mentioned temperature interval.

Designing the power plant it is useful to calculate the theoretical maximum specific electrical power N_{max}, which can be produced using the available thermal power N_{th}. Assuming that the geothermal water is cooled down in the power plant heat exchanger at a constant pressure N_{max} can be calculated as an integral of works produced in a sequence of elementary Carnot cycles operating between current water temperatures T and T_0:

$$N_{\max} = N_{th}[(1 - x\ln(1 + \frac{1}{x})],$$

$x = T_0/(T_1 - T_0)$

To approach the theoretical limit it is necessary to choose a thermodynamic cycle with a heat admission curve as close as possible to the water cooling down isobar, and with a heat removal curve as close as possible to the T_0 isotherm. These conditions can be to a certain extent satisfied by a supercritical Rankine cycle.

Selecting the thermodynamic cycle one can define the work l, which can be produced by 1 kg of the working media. The installation power N is a product $l \cdot w$, where w is the specific flow rate of the working media. Hence to maximize N we need to define the maximum w, which can be carried over through the counter-flow heat exchanger under the stipulation that this flow rate is compatible with the selected thermodynamic cycle. If along the heat admission isobar of the cycle the working media heat capacity c_{pwm} would be constant, the maximum w could be calculated as

$w_{max} = 1 \cdot c_{pw}/c_{pwm}$

However in reality the working media heat capacity is not constant making the definition of the maximum working media flow rate more complicated. This issue can be clearly demonstrated for an undercritical Rankine cycle. In this case the heat admission curve has an isothermal evaporation section where the heat capacity is infinite. For the counter-flow heat exchanger defined are the inlet temperatures of the hot water T_1 and of the condensed working media T_{wm}. Both outlet temperatures T_0 and T are functions of the flow rate w. When w is quite small $T_0 \approx T_1$ and $T = T_1$. With increasing w the temperature T_0

decreases however T remains equal to T_1. It means that the selected cycle remains intact. This is valid until w reaches the value w_{pinch}, where in some section of the heat exchanger the water temperature becomes equal to the saturation temperature of the working media. At $w > w_{pinch}$ the working media outlet temperature becomes gradually less than T_1. It means that the thermodynamic cycle will change and in particular its thermal efficiency η_{th} will decrease.

The same considerations are valid for supercritical Rankine cycles. A supercritical isobar in the critical point vicinity has a bend point, where the heat capacity becomes maximum providing for formation of a pinch similar to an undercritical isobar.

Calculations of the maximum installation power N were carried out for undercritical and supercritical thermodynamic Rankine cycles with hydrocarbon working media using the TRNSYS software. When a supercritical cycle was selected the geothermal water temperature T_1 was assumed higher than the working media critical temperature. The calculations demonstrate that N is slightly higher for supercritical Rankine cycles. In both cases maximum N is obtained at working media flow rates higher than w_{pinch}.

It is concluded that for each geothermal water temperature a proper supercritical Rankine cycle should be selected and for this cycle an optimum specific flow rate calculated providing for maximum installation efficiency.

Session 3: Drilling, stimulation and reservoir assessment

Thursday, 11 January 2007
13:30 – 17:55

Stimulation of reservoir and microseismicity- Summary of the Ittingen workshop June 2006

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Introduction

Enhancing or engineering the reservoir Enhanced (or engineered) geothermal systems (EGS) are engineered reservoirs that have been created to extract economical amounts of heat from low permeability and/or porosity geothermal resources. This includes all geothermal resources that are currently not in commercial production and require stimulation or enhancement. Mechanical and chemical stimulations are commonly used in order to enhance hydraulic properties of EGS systems. To the present day, the success of permeability improvement by massive hydraulic injections ("mechanical stimulation") is still a matter of trial and error and the success depends on the experiences made in geothermal and hydrocarbon reservoirs. Two main mechanisms for the success of permeability enhancement are to be considered: shear fracturing (or faulting) and jointing (tensile fracture). Both methods increase the pore pressure in the rock, however at different levels. A common view is that the shearing of natural fractures tends to produce dilation of the fracture walls and the opening of tubes at jogs in the fracture trace. The generation of microseismicity and the permanent nature of the transmissivity increases in both cases with different effects. The application of chemical acids generally improves conditions in the reservoir, however with largely varying success rates.

Creating artificial heat exchanger The concept of HDR-systems (ancient term, that are EGS without dominated natural water) foresaw the creation of an artificial heat exchanger at depth. The view nowadays is focused on the reservoir scale (i.e. a volume of several km³ around the wells located between 1.5 and 6 km depth). A heterogeneous natural geothermal reservoir is mostly dominated by a network of fracture clusters oriented close to the main horizontal stress direction. They are separated by distances of few hundred meters and crossing each other within distances of some kilometres forming a kind of 3D network of complex "aquifer" layers. The homogeneity of the geothermal water composition independent of sampling depth and the observed natural pressure distribution demonstrated that none of these clusters can be considered as being a totally closed system.

Improve inflow conditions In water bearing systems hydraulic fracture treatments have the goal either to bypass damaged permeability close to the well, or to create additional contact area between the reservoir and the well. While for the first goal the key is to maximize the fracture conductivity and thus the fracture width in the vicinity of the wellbore, the second goal requires large fractures, preferably connecting to an already existing network of natural fractures. Typically, such massive hydraulic fractures are placed in low-permeability reservoirs.

Stimulation techniques

Hydraulic fracturing – waterfrac The basic idea of hydraulic fracturing using the waterfrac technique is quite common –high rate injections pressurize the reservoir, leading to the creation of new fractures or to the enhancement of the permeability of pre-existing ones. The enhancement of permeability near the well is carried out to reduce the friction losses between the well and the formation. This is of particular importance for production wells, as experience has shown that the permeability of the injector will always improve during the circulation due to thermal contraction and the higher pressure. On the other hand improvement of permeability between the wells over larger distances (~1km) has always been a problem until recently, when this was successfully achieved at Soultz. The

enhancement of permeability near a wellbore can be increased by applying high pressure for a short period. Pressure can reach above the minimum earths stress and this helps to shear all joints from critically aligned to the direction of maximum earths stress. Methods used for achieving this varies from using low viscosity fluid such as fresh water to high viscosity gels.
Hydraulic fracturing – proppant frac The open hole hydraulic proppant fracture treatments can be applied successfully to deep sedimentary wells. Propped fractures are created and the inflow performance of the well can be enhanced. The successful placement of a propped hydraulic fracture depends critically on the quality of the design based on input data. Such data contain knowledge about the in-situ stresses, the reservoir permeability, the elastic parameters, and the fracture propagation criteria.
Geochemical stimulation Acid treatments have been successfully applied in many cases to increase or to recover geothermal wells production rates to commercial levels. Chemical stimulation techniques were originally developed to address similar problems in oil and gas production wells. The applicability of these stimulation techniques to a hot and fractured reservoir is less well known. High temperatures increase the acid-rock reaction rate. The development of Enhanced Geothermal Systems (EGS) depends on the creation of permeable and connected fractures. Acid stimulation jobs intend to clean (pre-existing) fractures by dissolving filling materials (secondary minerals or drilling mud) and mobilizing them for an efficient removal by flow transport. If, for example. a geothermal reservoir contains fractures partially filled with secondary carbonates (calcite and dolomite). In order to dissolve these carbonates and to enhance the productivity around the well, the borehole can be successfully treated with various amounts of hydrochloric acid. It is important to consider for chemical treatments, that the high reactivity prevents the penetration of acid in the far field between the wells. This high reactivity also involves the risk of creating wormholes, able to increase the porosity but not always the permeability of the fractured medium.
Thermal stimulation Intermittent cold water injection, with periods of thermal recovery in-between injection periods is one of the most common methods used for high-temperature well stimulation in Iceland. This method is aimed at causing cracking through thermal shocking.

Reservoir characterization during stimulation

Monitoring of injection-induced microseismicity as a method to image the stimulation effect During massive hydraulic stimulations large amounts of fluid are injected into the formation using drilled wells. Such water injections usually trigger considerable amounts of microseismic events that can be recorded by adequate seismic networks. The analysis of such data sets allows to estimate the orientation, i.e. dip and strike, of the (re-)activated fracture system. The deduced fracture orientation together with results from in-situ stress measurements are then used to describe the critical condition of fracture sliding. As a result one then can estimate the pore pressure at the location of the sliding fracture and at the time when the sliding (microseismicity) occurs. The generation of microseismicity can explained by the shearing of existing joints when the pore is increased until the normal stress goes to zero causing the joint to fail. Although the generation of microseismicity can only be associated with pressure increase in joints, there are ample observations that indicate that flow channels do exist within the seismic clouds.

Case studies

Soultz sous Forets The results observed during the past twenty years at Soultz demonstrated that “usual” hydraulic stimulation techniques when applied in such a hydrothermal / tectonic context can provide both real, but unfortunately limited, improvements of the well’s hydraulic performances and real, but fortunately up to now limited, microseismic nuisances. Seven major hydraulic stimulation tests performed at Soultz generated always large “microseismic clouds” but quite variable improvement of the wells hydraulic performances. The 5-km depth EGS reservoir of Soultz-sous-Forêts, France, has been developed using essentially fresh water and heavy brine injections. Thanks to these operations, connection could be achieved between two wells GPK2 and GPK3, the connection with the last well being problematic for the moment. The volume of injected acid in the first soft acidizing test on GPK4 had only an impact on the first 4 metres around the injection well. With these rather small acid amounts, the impact on the reservoir properties seems to be limited, although the porosity increases in the close vicinity of the wells due to carbonates dissolution.

Deep sediments (HC, Genesys, or Groß Schönebeck) Development of a technology to stimulate deep geothermal reservoirs in sedimentary basins is the purpose of installing the downhole geothermal laboratory in the former gas exploration well in Groß Schönebeck 3/90. The results of several reservoir treatments at site reflect the learning curve. These experiments are major steps towards developing a procedure to increase the thermal water productivity from a prior low permeability sedimentary reservoir. Open hole hydraulic proppant fracture treatments were successful applied at the geothermal research well Gross Schoenebeck 3/90. Propped fractures were created and the inflow performance of the well was enhanced. A still higher improvement was achieved using the waterfrac technique. For “engineering” this kind of reservoir type a method is recommended of massive waterfrac wth a proppant treatment at the end to ensure 1) connection to the reservoir by generating long fractures and increasing overall transmissibility 2) tie-back of generated fracture system to the well 3) sustaining fracture conductivity by proppant placement. Within the Genesys-experiments, an extensive test program including massive waterfrac tests and Geophysical fracture monitoring has been carried out in the last years. Waterfrac tests were performed using un-treated freshwater. Injection rates went up to 50 l/s at wellhead pressures of 330 bar during fracture propagation. Test analysis shows that the tensile fracture that was created covers an area on the order of 100.000 m² and has a vertical extension of approximately 200 m. Microseismicity was not observed in Groß Schönebeck, and only very few low magnitude events within the Genesys experiments.

Basaltic rocks in Iceland Stimulation of high-temperature production wells through cyclic cooling and thermal shocking/fracturing has proven to be effective for basaltic rocks, especially when the stimulation period can be extended for several weeks after the drill rig has been removed. Seismic monitoring should be more commonly applied during long stimulation- and injection operations, since it may provide highly valuable reservoir information. In addition, the application of reservoir monitoring, such as interference monitoring is recommended.

Lessons learned

Review HC-Stimulation and EGS-development and others implicate:

- More exchange between hydrocarbon industry and geothermal industry
- to consider the combination of geothermal experiments and CO2-sequestration
- the exchange with nuclear industry /hydrogeology - to extend the application of gel injection

Understanding Many parameters play a role in the failure mechanism that is expected:

- Fluid pressure development in the reservoirs, that depends on:
    - injection rate, time, and length
    - the setup of the test in the well
    - fluid type (water, heavy brine, gel of various viscosity, presence of proppants)
    - fluid temperature reservoir
- Stress field, that is different for each EGS site
    - Rock and fractures parameters, like cohesion and Mohr angle, may highly influence results obtained, and could be modified by the use of proppant agents or acid treatments

- Shearing represents the relaxation of the natural shear stresses within the rock mass triggered by the weakening of the fracture by the elevated fluid pressure.
- The pore pressure increase required to initiate shear failure on favourably oriented fractures is often very small.

This reflects the tendency for the Earth's crust to be close to failure, a state which is referred to as being critically stressed. As such, the vast majority of the mechanical work of permeability/porosity creation is done by the natural stresses. The stress state thus determines which fractures shear and thus has a major influence of the geometry of the stimulated volume and flow paths that develop therein. It follows that knowledge of the stress state is essential if the process of reservoir creation is to be understood and modelled, which is a step towards developing the means to control it. The confident determination of the complete stress tensor is at best difficult and often not practical. Fortunately, limited knowledge of the stress tensor suffices for reservoir engineering purposes, but complete knowledge is needed for modelling. Understanding the fracturing performance is helped by close monitoring. The pressure will always be recorded and a post-mortem analysis gives insight in the fracturing process. Monitoring during the fracturing process can also be done using tiltmeters and microseismic mapping.
To improve the basics it is recommended:

- to focus on understanding stimulation and to work on the predictability of stimulation
- to extend the knowledge about stress, artificial fractures, structures, fabrics (fracture propagation)
- to focus on understanding self propping
- to take proppant crushing into account
- to visualise stimulation in different geological environments
- to investigate scale dependence of fracture propagation
- and the validation of acidification treatments

The needs are:

- Long-term circulation tests
- Developping modelling tools (microseismicity)
- and technical tools (seismic anisotropy)
- to go again to shallow borehole experiments
- Geology 3D (impact of geology on success of EGS/HDR)

Public acceptance
Geothermal energy can be one of the future energy sources for base load power and heat provision. This way of environmental and sustainable energy supply is almost accepted. However, using the instruments for exploring, accessing (drilling into) and engineering the reservoir needs to be explained to the public to hold the acceptance on a high level. Exspecially explosion seismic (as done in Groß Schönebeck) and not least high rate stimulation (as done in Soultz and Basel) with recognisable seismological events must be prepared in a reliable publication management ensuring that every potential affected person is reached. In cases of violation of set thresholds the procedure most be stopped by the geothermal developper. This is much better than being stopped be local authorities.

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Developments in Geothermal Drilling

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There have been considerable advances in high-temperature geothermal drilling technology and improving the output of wells over the past decade. The main interest is in technology that can lower the cost of geothermal wells both for exploration and production. This goal is a worthy one and at the present time two international efforts, ENGINE and IEA GIA, are under way to explore the possibilities. Actual well costs have, however, over the past few years not gone down, but increased rapidly mainly due to price increases and the cost of new technology. Drilling costs have also gone up because more challenging wells are being drilled going deeper and deviating from the vertical ("directional drilling"). The other way to lower the overall cost of geothermal development is to drill very productive wells. Considerable progress has been made in this respect. Once several wells have been drilled in the same geothermal field the results become more predictable and also how to deal with the drilling problems. Standardization of well designs and a more developed market for drilling services is likely to lower the cost. Contracts structured with incentives will also lead to greater efficiency. Nevertheless one must remember that geothermal wells are remarkably different, even inside the same field. The new technology adds to the costs but in balance it is hoped that the overall cost of geothermal development can come down in time and lead to more reproducible results. The ENGINE workshop 4 "Drilling cost effectiveness and feasibility of high-temperature drilling" in late June 2007 will explore these things further. Active participation from the ENGINE partners is thus sought.

Drilling of Hot and Fractured Granite at Soultz-sous-Forêts

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Since its beginning in 1987, the Soultz Project was designed to validate a modified HDR / EGS concept associating an attractive geothermal gradient with the natural permeabilities and formation fluids expected at depth in a Graben setting. In such a geological setting a dense fracture network intersected by major tectonic features can be expected. The results of a drilling operation are reported here which involved reaming and drilling of hot and fractured granites using a low cost clear brine water mud. Highly permeable zones were temporarily (to be available later for scientific investigations) sealed spotting pills of loss circulation material (LCM). Experience in Soultz indicated that the effectiveness of LCM pills under geothermal conditions (bottom hole temperatures 200 °C) can be increased considerably by giving the heat sufficient time to act on the mixture before resuming drilling. The well was completed with an uncemented 9 ⅝" internal casing (0 4546 m) which is only supported at the bottom by open hole casing packers and a short cementation. Thermal expansion and contraction, of the otherwise self-supporting pipes (during injection and production experiments), are compensated in the well head assembly. To our knowledge, the well reported here (GPK3) was the first directional well with such a completion. Drilling operations were finished after 142 days, some 16 days ahead of schedule.

Drilling a geothermal well into a deep sedimentary geothermal reservoir – case study on the Groß Schoenebeck wells

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The Rotliegend of the North German basin is the target of an interdisciplinary investigation program to develop a technology for the generation of geothermal electricity from low-enthalpy reservoirs in deep sediments. An in-situ downhole laboratory was established in the 4,3 km 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 research the in situ laboratory is now concentrated to drill the second well into the EGS in the low permeable Rotliegend formation. The stepwise strategic approach is aimed to establish and improve the practical experience to drill into deep sedimentary geothermal reservoirs and to recover data knowledge via • the reopening of an abandoned gas exploration well, • tests and comprehensivestimulation experiments, • drilling of an production well and stimulating that well, • a circulation test of the system and • the installation and operation of a demonstration power plant. The drilling of the second well is ongoing and the design considered • the deep static water table of the reservoir and the respective withdrawal during production, • the option for an additional protecting casing in the top hole region (housing for the submersible pump), • the distance between the two wells of the doublet in the target horizon by using the directional drilling techniques, • a drilling mud concept, which enables a protecting penetration through the reservoir, • the opportunities of increasing the inflow conditions by an inclined well and later by implementation of multiple fracs, and • the geological conditions known from the analysis of previous wells in the vicinity of the Groß Schoenebeck site. Spotlights of the 9 months lasting drilling operations will be given with the focus on the specific conditions of the drilling rig, the applicability of available drilling performance data with respect to a significant larger hole diameter, and the encountered drilling difficulties ranging from circulation loss during cementation via collapsing of casings within the Permian salt up to the occurrence of natural gas indications during drilling the very last borehole section. A summary of the lessons which had to be learned is given and some future research tasks are addressed.

Hydraulic stimulation and microseismic fracture monitoring within the deep granite holes at the Soultz-sous-forêts geothermal site

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The aim of the HDR project Soultz is geothermal power production based on an artificially created heat exchanger at 5000 m depth. During the years 1999-2004 three wells were drilled down to 5000 m, one injection (GPK3) and two production (GPK2 and GPK4) wells. After drilling each of the well was stimulated individually by massive water injection. Water volumes up to 30000 m^3 were injected with a flow rate of 30 - 50 l/s. A downhole seismic network has been operated to monitor the spatial development of the stimulated or artificially created fractures. The spatial orientation and the spatial density of the seismic events vary significantly for the different stimulation operations performed in Soultz. For GPK2 the seismic events are clearly aligned along a strike direction of NW-SE (140°-150°) and the spatial density is very high. In contrast, for GPK3 almost no preferential orientation could be observed. For GPK4 a high spatial density of the seismic events was found again but the strike direction shows a tendency towards N-S. The high density of seismic events during stimulation of GPK2 and GPK4 indicate effective stimulation operations here whereas for GPK3 a large portion of the injected volume seems to be lost by diffusion into natural fractures without significant stimulation. Hydraulic observations i.e. the characteristics of the stimulation pressure curves support these statements. After the stimulation operations injection tests with significant lower rates were performed to determine the injectivity (productivity) of the wells. For all three wells a good agreement was obtained between the injectivity during stimulation and after stimulation. Obviously, the stimulated flow pathes retain their hydraulic conductivity completely after stimulation. It is very important to notice that this correlation between injectivity during stimulation and after stimulation allows the prediction of the productivity enhancement due to the massive water injections.

Hydraulic fracturing in the hydrocarbon industry

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This paper gives some of the issues present in the hydraulic fracturing design, application and evaluation procedures in the hydrocarbon industry. Depending on the reservoir, hydraulic fracture treatments have as a goal either to bypass damaged permeability close to the well, or to create additional contact area between the reservoir and the well. While for the first goal the key is to maximize the fracture conductivity and thus the fracture width in the vicinity of the wellbore, the second goal requires large fractures, preferably connecting to an already existing network of natural fractures. Typically, such massive hydraulic fractures are placed in low-permeability reservoir. The successful placement of a propped hydraulic fracture depends critically on the quality of the design input data. Such data contain knowledge about the in- situ stresses, the reservoir permeability, the elastic parameters, and the fracture propagation criteria. Minifrac tests are designed to disclose such parameters. To this end, the time-dependent behaviour of the pressure after a short injection test above the fracture pressure is analysed with specially designed software. Further important knowledge is the containing capacity of different layers in the subsurface, as these determine the height / length ratio of the fracture. A profile of the parameters, required to assess this, however, is often difficult to obtain. Even with good design input data and a properly operated fracturing treatment, the results are not always in line with the predictions. Knowledge is usually built up in specific areas during subsequent hydraulic fracturing treatments and their careful evaluation. Method that can help considerably in this evaluation are tiltmeter mapping and microseismic monitoring, by which the dimensions of the created fracture can be estimated. Microseismic monitoring has proven particularly helpful in deep, low-permeability fractured reservoir, where the main goal of the fracturing campaigns was to connect the well to an already existing fracture network. The experience with hydraulic fracuring in Geothermal applications like the one on the drillsite in Gross Schönebeck and the GeneSys project in Hannover will be put in the context of hydraulic fracturing in the oil and gas industry.

Stimulation of geothermal wells in basaltic rock in Iceland

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Stimulation operations are an integral part of the completion programs of geothermal wells drilled in the basaltic environment of Iceland, for high- enthalpy as well as low-enthalpy wells. These are most commonly applied for a few hours to a few days, while the drill rig is still on location, although much longer stimulation operations have also been conducted. The purpose of the operations is to enhance the output of the wells either by improving near-well permeability that has been reduced by the drilling operation itself or to open up hydrological connections to permeable zones not intersected by the well in question. The method most often applied to low-enthalpy wells involves applying massive high-pressure water injection, often through inflatable open- hole packers. This method is not as commonly applied as was the case 2-3 decades ago, partly because air-lift aided drilling has reduced the need for such stimulations. This method still has great potential in particular cases, however. The method most often applied to high-temperature production wells involves cyclic cooling and heating, through intermittent cold water injection, aimed at thermal shocking and fracturing. This method has proven to be effective; especially when the stimulation period can be extended for several weeks after the drill rig has been removed. The stimulation of wells through acidizing is not commonly applied in geothermal wells in Iceland, however. The stimulation operations often result in well injectivity/productivity being improved by a factor of 2-3, while in some instances no improvement is observed. Emphasis is placed on careful reservoir monitoring during stimulation operations in Iceland.

Development of conceptual and numerical reservoir models for the Hengill high-temperature resource, Iceland

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The large Hengill volcano complex is currently up for intensive development by Orkuveita Reykjavikur (Reykjavik Energy). Around 60 full size high-temperature wells are already drilled in the region, sustaining geothermal power plants in the Nesjavellir and Hellisheid sectors of the greater Hengill area. Geosciences have had a priority in the field development, resulting in a wide range of surface and subsurface exploration activities. A major task of geothermal reservoir engineers has been to integrate all field data into conceptual reservoir models, which later on serve as basis for multi-phase, non-isothermal, distributed parameter numerical reservoir models. Modeling activities date back to 1985 and these are currently an important tool in the resource management. Geothermal activity in the region appears closely related with ocean plate rifting, massive upflow of magma under the Hengill summit and frequent lateral intusions to the north, towards Nesjavellir, as well as to the south in Hellisheidi. Geothermal reservoirs are hosted within the rift graben, typically at 700-2500 meter depth. Temperatures ranging from 200 to more than 380 °C have been encountered. Conceptual reservoir model assumes only 1 upflow zone under the Hengill summit and lateral flow of hot fluids to the north and the south. Thermal alteration plays important role in permeability, seen as low permeability cap on top of the high-temperature reservoirs. There are three documented cases of intense microseismicity accompanying cold water injection to deep wells, possibly reflecting a stress field of very low minimum horizontal stress as seen by normal faulting on surface. New wells indicate, however, that the S-Iceland transverse seismic zone is counteracting with the normal faulting, resulting in more complex fracturing to the south of the Hengill summit.

Nuclear techniques for the in-situ detection of mineral scale in geothermal systems

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The production, utilization and/or reinfection of brine found in geothermal reservoirs are often hampered by serious and very unique scale problems. Some of these scale problems are so severe that entire field operations are endangered. Effective scale management requires on-line monitoring of scaling tendencies as well as detection and identification of scale deposits. Laboratory determinations of real-time scale deposition were recently reported using a radiotracer technique, an attenuated total reflection sensor, a rotating disk electrode technique, tapered optical fibers, a piezoelectric sensor and an ultrasonic technique. In addition, various nuclear attenuation techniques for the in-situ detection of mineral scale in actual production systems have been also reported recently. In particular, a handled device was developed to detect the presence of scale in surface piping by measuring the nuclear attenuation across the pipe diameter and two field cases were presented in which a dual-energy-venturi multiphase flow meter was used to detect and characterize scale according to the attenuation of the nuclear spectrum. A gamma-ray attenuation method, based on continuous triple-energy gamma-ray attenuation measurements, for the detection of scale deposition in real-time in oilfield production tubulars has also been presented recently. The last method was actually an extension of previous work that had been applied to several field cases of surface pipe scale detected by dual-energy attenuation measurements. The method enables a simple monitoring device to detect and characterize scale in its earliest stages of formation. The objective of this work is to present the state-of-the-art in detecting mineral scaling in geothermal operations using various nuclear techniques. In that respect, a gamma transmission (attenuation) technique and a gamma emission (radiotracer) technique were designed and evaluated in the lab for the real-time measurements of scale formation under flow conditions.

Hydraulic stimulation in the light of single-well tracer tests

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Tracer tests provide information on transport properties essential for heat exchange in geothermal reservoirs - fluid residence times and fluid-rock contact surface areas or fracture densities, which are not properly determined by hydraulic or geophysical methods. Even when only one borehole is available, either push-pull or flow-path tracings (or both) can be conducted in a single- well setting. Injected fluids can be spiked at different times (with different flushing volumes) in order to characterize flow and heat transport during different regimes (or at different spatial scales) of a reservoir. Under certain conditions, temperature signals in produced fluids can complement the solute tracer information.

- First example: stimulation of deep crystalline reservoir -

At the German ICDP site, known as the KTB (Kontinentale Tiefbohrung), comprising two boreholes - pilot hole, main hole - in the crystalline basement, both solute and heat push-pull tests could be performed at the pilot hole in the depleted (2004), the stimulated (2005-a), the early post-stimulation (2005-b) and the late post-stimulation, still weakly pressurized (2006) states. The change in fracture densities, derived from measured heat and solute push-pull signals, indicates that the prevailing effect of long-term, moderate-rate, cold-fluid injection was to enlarge pre-existing fractures, rather than creating new ones, despite some expectations as to a prevailance of cooling-induced cracking. A long-term production test is intended at the main hole as of 2007/2008; tracer levels in the produced fluid could reveal the (least) size of the reservoir accessed between the two holes. The existence, location and geometry of a fracture system connecting the two holes is not known beforehand.

- Second example: stimulation in deep sedimentary, supra-salinary formation -

At the Horstberg site in the Northern-German sedimentary basin, a former gas exploration borehole is available for geothermal research and for testing various heat extraction schemes in supra-salinary horizons. Using the hydro-frac technique, a large-area fault was created between two sandstone horizons in ~3.8 km depth. Assuming that the induced fault will maintain sufficient permeability over time (without the need for proppants), and that the same result can be achieved at many similar formations in the Northern-German sedimentary basin, a low-cost single-well, two-layer circulation scheme is endeavoured for heat extraction by the Leibniz Institute of Applied Geosciences (GGA) and the Federal Institute for Geosciences and Natural Resources (BGR), Hannover. In order to better characterize flow in the induced fault, it was our task to conduct a single-well flow-path tracing, by spiking the fluid injected at the lower horizon and sampling the fluid produced from the upper horizon (tracer dilution in divergent flow field). After a 1.5-year shut-in phase, short outflow phases from both the production and the former injection horizon yielded further information, of both flow-path and push-pull type. Extrapolated tracer recoveries show that up to 12% of the (more or less radially divergent) flow field is focused to the production screen.

- Third example: stimulation in deep sedimentary, sub-salinary formations -

At the GroßSchönebeck site in the NE German sedimentary basin, with two boreholes reaching down to sub-salinary formations, a sequence of short-term, high-rate fracings in ~4 km deep layers (of at least two different kinds of rock), followed by short- and mid-term flow-back tests, and by a long-term, moderate-rate production test is planned as of 2007 by the Geoscientific Research Centre (GFZ) Potsdam. Our task was to design and dimension several spikings at both boreholes, such that each individual spiking yields measurable signals during each of the subsequent outflow or abstraction phases. One borehole is to be used for hydro-fracing, injectivity and sequential flow-back tests (with 4 spikings), whilst the other borehole is to be used for fluid disposal (reinjection, with 1 spiking). Forward simulations and sensitivity analyses (based on a simplified flow and transport model for the induced fracs) were undertaken as an aid in dimensioning the tracer slugs and sampling phases. From these analyses, tracer signals from flow-back (push-pull) tests at the one borehole appear to be more sensitive to effective aperture and specific contact-surface area (within the volume accessed by each test phase), than to the total reservoir size, whilst tracer signals at this same borehole but originating from reinjection at the other borehole appear to be very sensitive to the total reservoir size, and also to dispersion and surface/exchange parameters (fluid-rock contact-surface area, im/mobile exchange rates or alike).

In all cases described, tracer tests are conducted in parallel with hydraulic tests, stimulation or hydro-fracturing experiments, without noticeable additional effort.

Session 4: Investigation of Unconventional Geothermal Resources and in particular Enhanced Geothermal Systems

Friday, 12 January 2007
8:30 - 11:35

Defining, exploring, imaging and assessing reservoirs for potential heat exchange” Summary of the Workshop 5, 6th to 8th November 2006 Potsdam

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The goal of the workshop was to discuss all parameters that should be known before drilling for exploitation of potential geothermal reservoirs. The workshop was strongly focused on debates about the definition of targets, characterization of reservoirs and optimisation of investigation methodology for EGS. To achieve this focus, four thematic sessions were defined (Signatures of temperature field for defining and exploring potential geothermal reservoirs, Signatures of fluid transport in Earth's crust, State of the Art in the exploration of potential geothermal reservoirs, Processes in geothermal reservoirs). Definition of targets, characterization of reservoirs and optimisation of investigation methodology for EGS require, among other topics, a significant improvement of the imaging and modelling of fault and fracture systems, of the knowledge of the paleostress field as well as of the heat flow and temperature distribution at depth. Following the workshop, it is stated that heat, temperature, stress and pathways as well as chemical and mineralogical composition of rocks hosting the geothermal system are besides the structural inventory of the subsurface the key elements that could be put as priority for research needs.
Four main research target were defined, and the main conclusions can be summarized as follows:

Structural Geology: imaging potential geothermal reservoirs

Geothermal reservoirs are sections at drillable depths containing enough heat for geothermal utilisation. Geophysical methods are suitable to determine the architecture, geometry, and quality of target intervals. However improvement of existing methods and in particular reasonable combination of different, most sensitive techniques (passive and active seismic, MT, and others) are needed to meet the requirements of modern geophysical exploration. The interpretation of geophysical features must be supported and validated by petrophysical laboratory and borehole measurements, as well as modelling. Experiences made in hydrocarbon exploration must be modified for EGS. EGS requires usually more knowledge about fracture and fault systems with respect to their role as potential water conduits. The reservoir imaging strategy should include large scale approaches supplemented by high-resolution experiments. Further benefit should come from adapted processing techniques.

Heat: finding heat at depth

The extension of large-wavelength heat flow anomalies at depth is often inaccurate due to the improper knowledge of the causes of the heat-flow anomaly. The existence of convective and advective cells, such as those well characterized at Soultz and in the Rhine graben area, hinder a temperature extrapolation to greater depth and can lead to wrong evaluation of thermal gradients. Consequently advective cells have to be properly identified and characterized through detailed geochemical studies comprising definition of water chemistry, application of suitable geothermometric techniques (hydrochemical and gas geothermometers), mapping of CO_2 fluxes from soils, etc. Maps of the heat flow distribution at surface and at the crust-mantle boundary provide far-field conditions for any definition of possible targets for EGS. However, such maps require a basic knowledge of the main lithologies and their thermal properties. In order to properly define temperature and heat distribution for an EGS database thermal conductivity and the radiogenic heat production are now feasible for better constrained modelling. Several physical parameters (density, wave velocity, electrical resistivity…), as well as chemical and mineralogical properties are coupled with temperature and can be imaged by different geological, geophysical and geochemical methods. Thus, the definition of possible targets for EGS could be improved by the use of a 3D modelling platform, in which all solutions from geological, geochemical and geophysical modelling, direct and inverse, could be combined and analysed.

Stress: understanding and stimulating fluid circulation
Evidences exist and show the influence of the stress field on hydro fracturing (ref workshop Ittingen). The knowledge of spatial stress distribution (map and depth) on a local as well as on a regional scale is thus fundamental for any future experiment. Mechanisms of rupture and propagation of an existing fault system and related displacement remain debated, especially in connection with the circulation of fluids and success rate of improving sustainable permeability. The circulation and accumulation of fluids in the crust are fundamentally controlled by the geometry of the fault and fracture systems. The ability of these systems for the channelling of fluids is directly dependant on the stress field (orientation and intensity). Favourable and unfavourable conditions exist depending of the tectonic context and geological environment. However, hydro-fracturing is not the only option to enhance the permeability of reservoir rocks. Selective dissolution should also be taken into account (as a technique to increase *effective* porosity and permeability) as it could be more effective than fracturing, provided that it is applied to suitable lithological frameworks (e.g., sandstones made up of quartz and silicate minerals but also containing relevant amounts of fast-dissolving carbonate minerals) and under carefully selected conditions.

Pathways: defining integrated conceptual models
What starting conditions are necessary to develop/stimulate an EGS? What are the conditions classifying a thermally suited area for the development of an EGS? There is a need to refer to conceptual models of the main geothermal sites, from extended active geothermal sites to EGS for which heat distribution and permeability networks are available for modelling pathways for fluid circulation, gas-water-rock interaction processes (and their effects on *effective* porosity and permeability) and heat exchange. The cradle of such models should be the geometry of geology. They could be built by integrating the most significant datasets and their interpretation on reference key areas, like Larderello, Bouillante, Soultz, Groß Schönebeck. Such models must be updated as soon as new data or new experiences and results are available. A significant improvement of the knowledge is expected from natural analogues on which hypotheses could be tested about, for example, circulation of fluids in relation with seismicity and heterogeneity of the lithologies, thermal imprint of fluid circulation. The links with other investigation programmes such as nuclear waste storage, capture and storage of CO_2 and oil and gas field development will be developed to take advantage of existing installations and experiences. Workflows encompassing fault interpretation from 3D seismics and geostatistic tools, 3D retro-deformation and fracture interpretation from well data should be further developed to give a base for possible pathway interpretation through time. Palaeostress maps may also help in distinguishing between open or closed pathways. Technological platforms could be promoted to develop new methods and tools, test hypotheses in situ or the accuracy of conceptual models.

Investigation for EGS is of strategic importance for reduction of costs and increase of efficiency in the development of geothermal projects, and Workshop 1 of the ENGINE project has certainly made an important contribution.

Reactive transport model of silicification at the Mount Isa Copper deposit, Australia

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A distinct feature of the world-class Mount Isa copper system is the presence of a massive silica body enveloping the chalcopyrite ore body in the Urquhart shale. Because silicification may be genetically linked to the copper mineralization, it is important to understand its formation. It can be shown by numerical simulations of reactive transport processes that both hydraulic head and buoyancy driven flow are capable of generating silicification patterns similar to the field example. Considering the physical conditions required to form the observed patterns we suggest, however, that head-driven flow rather than free thermal convection produced the silica body. Free convection requires very special conditions and only one of several possible scenarios reproduces the observed silicification whereas any of the tested forced flux scenario is capable of doing so.

Recent progress in Discrete Fracture Network modelling for EGS development in tight fractured rocks

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The paper addresses the modeling of geomechanical effects induced by both reservoir development and production phases and their influence on the overall fluid flow pattern. The geological context is that of heterogeneous fractured rock masses, somehow compartmentalized, with a low natural permeability at large scale. A stress dependent DFN simulator is used to discuss some of the remaining unanswered questions raised by the european EGS project under operation at Soultz-sous-Forêts.

How geology can contribute to improve the knowledge of EGS fields in Europe?

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Geological investigations are extensively used in all phases of exploration of EGS fields. At large scale, geological key elements for the geothermal resource evaluation include temperature data distribution, field geology, geological mapping, seismic profile interpretation, structural analysis of large-scale faults or volcano-tectonic structures. During the drilling exploration phase, a lot of geological data are acquired in order to characterize the deep lithology, the fracture system organisation, and some information about the present-day stress field. The knowledge of the reservoir composition (lithology, mineralogy) is derived from drilling data such as core samples, cuttings, and various geophysical loggings. The detailed chemical and mineralogical composition of the hosted rocks and hydrothermal alteration is investigated from petrographical studies (thin sections, X-ray, dating). The knowledge of the fracture system during the phase of drilling reconnaissance is mainly based on core data and borehole imagery logs. Additional information about the fracture system could derive from classical geophysical logs. Moreover, the fluid flow characterisation of the permeable fractures is deduced from temperature and flow logs. Compilation and interpretation of geological and geophysical data obtained in the different phases of the EGS exploration conduct to conceptual models which could be modelled in 3D for a better understanding of fluid flow circulation and heat exchange. Based on the Soultz experience, the main needs identified are related to the lack of information about the fracture extension in 3D and the difficulty for characterizing crystalline altered rocks at great depth. In order to fill these gaps, fracture mapping on well-exposed analogues, geophysical methods such as vertical seismic profiles (VSP) or new high resolution geophysical logging techniques run in the boreholes could improve significantly the image of EGS reservoirs.

Geophysical methods for EGS investigation: an overview of actual and future perspectives.

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Heat, temperature, stress and pathways as well as chemical and mineralogical composition of rocks hosting geothermal systems are, besides the structural inventory of the subsurface, the key elements that could be put as priority for research needs in geothermal investigation for EGS. Several physical parameters of roks, e.g., density, wave velocity, electrical resistivity, are coupled with temperature and can be imaged by various geophysical methods. Geophysics may also help in the reconstruction of stress distribution at depth, which is known to influence hydrofracturing. Moreover, the presence of fluids and pathways produce a sensible anomaly of different physical properties, with the limitations of depths of penetration and resolution. Geophysical methods are suitable to determine the architecture, geometry, and quality of target intervals. However, improvement of existing methods and in particular reasonable combination of different, most sensitive techniques are needed to meet the requirements of modern geophysical exploration. Experiences made in hydrocarbon exploration, as well as in volcanology, nuclear waste disposal or CO_2 sequestration must be modified for EGS, and coupled with the existing knowledge in geology and geochemistry in order to develop an integrated interpretation of different physical parameters.

How Can Petrophysics Support Geothermal Exploration?

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The overall goal of petrophysical work is the development of interpretation methods that allow the transformation of measurable physical properties of the subsurface as they can be delivered by geophysical surface and borehole methods into information relevant for exploitation and reservoir management. The first step in this process is the identification of that type of information which is relevant for the exploitation and may be hidden in the data gathered with geophysical methods. The second step is the design of a lab-experiment which simulates the conditions and processes in nature with close control of all relevant parameters. Such lab-experiments provide the basis to study how the interesting parameter or information influences the physical properties, which are directly measurable with geophysical methods. The discovered interdependencies between the parameters of interest and the measurable physical properties can then be used to formulate interpretation algorithms which still may require calibration for different rock types. However, the first step, like no other, requires the communication between the different scientific branches involved, from the field geophysicist to the reservoir engineer. With respect to petrophysics for geothermal exploration and exploitation there are still technical limitations due to the high temperatures we have to deal with. However, taking advantage of the achievements of material- and other technical sciences we have many more options nowadays. Using high performance polymers it is now possible to perform petrophysical experiments on drill cores (4-electrode-resistivity; p- and s-wave velocities, permeability) with controlled pore pressure up to 300°C in oil pressure chambers. The investigation of rocks at higher temperatures is possible in gas pressure systems but requires a much higher experimental and financial effort, therefore, these experiments can not be performed on a routine basis yet. This presentation will give an overview about the recent scientific and technical developments in experimental petrophysics that could be useful for geothermal exploration.

Geochemical methods in geothermal exploration and exploitation

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Geothermal exploration is often been divided into several phases due to the many uncertainties involved. This is done in order to minimize cost and maximize information and makes it possible to decide at the end of each phase whether to continue into the next phase or not. Geochemical techniques are extensively used in all phases. In the exploratory phase the main purpose of geochemical surveys are to predict subsurface temperatures and to obtain knowledge of the origin and flow directions of the geothermal fluid. The basic philosophy behind this type of prospecting is that geothermal fluids on the surface reflect physico-chemical and thermal conditions at depth. Subsurface temperatures are estimated with different geothermometers which are probably the most important geochemical tool used in geothermal exploration and development. They are often classified into three groups: Water geothermometers; steam or gas geothermometers; isotope geothermometers. Isotopic techniques are used to identify the origin of the geothermal fluids and flow directions. In the exploration drilling phase geochemical methods play a role in providing information on e.g. the ratio of water to steam in the reservoir; the quality of water and steam in relation to the intended use; scaling and corrosion tendencies. This information is relevant to the preliminary power plant design. Geothermal reservoirs are dynamic in nature and will respond to production and change with time from there initial conditions. The changes are basically associated with pressure drop which will increase boiling and recharge of new water to the reservoir. Therefore geochemical monitoring focus largely on changes in well fluid composition in order to e.g. identify recharge, changes in steam and water quality, scaling tendencies and to revise conceptual models of the reservoir. Geochemical methods are applied to problems which may be linked to injection of geothermal fluids into the reservoir to minimize the environmental impact of geothermal utilization and to slow down the pressure drop. This will increase the lifetime of individual wells and the reservoir as a whole.

Modelling of Geothermal reservoirs - an overview

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The larger the interpretation of geophysical and hydrogeological measurements in a geothermal reservoir, the more the complexity of the mass transport in a reservoir becomes visible. Moreover, the non-linearity of hydraulic, thermal, mechanical or chemical processes is often only visible for especially designed experiments. Theoretically, geothermal modelling offers the possibility of an overall system evaluation however mostly only conceptual models are derived that allow for the quantitative description of individual aspects. The focus of this overview is to present the state of individual approaches for the evaluation of various geothermal reservoirs. Herein, the bandwidth from low-enthalpy, porous media simulators up to high enthalpy multi phase flow models in fractured environment will be covered.

Tectonic models for geothermal exploration and production

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For geothermal exploration and production (EGS) knowlegde of the thermo-mechanical signature of the lithosphere and crust is important to obtain critical constraints for the crustal stress field and basement temperatures. The stress and temperature field in Europe is subject to strong spatial variations which can be linked to Polyphase extensional and compressional reactivation of the lithosphere, in different modes of deformation.

The development of innovative combinations of numerical and analogue modeling techniques is key to thoroughly understand the spatial and temporal variations in crustal stress and temperature. In this paper we present an overview of our advancement developing and applying analogue and numerical thermo-mechanical models to quantitatively asses the interplay of lithosphere dynamics and basin (de)formation. Field studies of kinematic indicators and numerical modeling of present-day and paleo-stress fields in selected areas have yielded new constraints on the causes and the expression of intraplate stress fields in the lithosphere, driving basin (de)formation.

The actual basin response to intraplate stress is strongly affected by the rheological structure of the underlying lithosphere, the basin geometry, fault dynamics and interplay with surface processes. Integrated basin studies show that rheological layering and strength of the lithosphere plays an important role in the spatial and temporal distribution of stress-induced vertical motions, varying from subtle faulting to basin reactivation and large wavelength patterns of lithospheric folding, demonstrating that sedimentary basins are sensitive recorders to the intraplate stress field. The long lasting memory of the lithosphere, in terms of lithospheric scale weak zones, appears to play a far more important role in basin formation and reactivation than hitherto assumed. A better understanding of the 3-D linkage between basin formation and basin reactivation is, therefore, an essential step in research that aims at linking lithospheric forcing and upper mantle dynamics to crustal vertical motions and stress, and their effect on sedimentary systems and heat flow.

Vertical motions in basins can become strongly enhanced, through coupled processes of surface erosion/sedimentation and lower crustal flow. Furthermore patterns of active thermal attenuation by mantle plumes can cause a significant spatial and modal redistribution of intraplate deformation and stress, as a result of changing patterns in lithospheric strength and rheological layering.

Novel insights from numerical and analogue modeling aid in quantitative assessment of basin and basement histories and shed new light on tectonic interpretation, providing helpful constraints for geothermal exploration and production, including understanding and predicting crustal stress and basin and basement heat flow.

A new crustal model as input for the European strength map

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Tectonic studies made in intraplate Europe have shown that this area is more active than would be expected from its location far away from plate boundaries. Intraplate Europe is characterized by horizontal and vertical motions with deformation rates of the order of 1-2 mm/yr and by diffuse seismicity (Nocquet and Calais, 2003, Tesauro et al., 2005). The first strength map (Cloetingh et al., 2005) has lead to a significant understanding of the dynamics of intra- lithospheric deformation processes. The results have demonstrated that the European lithosphere is characterized by large spatial mechanical strength variations, with a pronounced contrast between the strong lithosphere of the East-European Platform (EEP) east of the Tesseyre-Tornquist Zone (TTZ) and the relatively weak lithosphere of Western Europe. In order to improve the previous results and to extend the strength calculations to the southern and western plate boundaries of Eurasia, we are going to construct a new crustal model, which is a part of a comprehensive lithosphere model. As the first result, we demonstrate the new Moho map of Europe. The Moho depth variations are reconstructed by merging the most recent maps compiled for the European regions (e.g. Ziegler and Dèzes, 2002, Kozlovskaja et al, 2003) and by ourselves using published interpretations of seismic profiles (e.g. in the Vøring and Lofoten basins). Strong differences in the crustal structure are found between the areas east and west of the TTZ, respectively. The eastern region is mostly characterized by thick crust, e.g. over the Baltica region (~42-44 km) with a maximum of over 60 km in the Baltic Shield. By contrast, crustal structure is more heterogeneous to the west from TTZ, being characterized by Variscan crust with an average thickness of 30-35 km, orogens (e.g. the Alps and the Pyrenees), where the crustal thickness is increased up to 45-50 km, and locally by strong extensional deformation, which resulted in a very thin crust in the Pannonian Basin (~25 km) and in the Tyrrhenian Sea (~10 km). Concerning the oceanic domain, the crustal thickness is generally decreased towards the ridge (up to 10 km in the most western part), with local maxima up to 20-25 km (e.g. in the Vøring and Lofoten basins) and up to 35-40 km beneath the islands (e.g. Iceland and Faeroe islands), on account of mantle underplating. We calculated gravity effect of the Moho variations and density variations within the crust (Kaban, 2001) and removed it from the observed gravity field, which gives the residual mantle anomalies (Fig. 4). Since the upper mantle density is supposed to be constant in the reference model (3.35 g/cm^3), the residual anomalies chiefly reflect the effect of mantle density variations (Kaban, 2001, 2002, Kaban et al., 2004). The mantle anomalies are clearly separated into two components possibly accounting for the effects of different factors: (1) A long-wavelength component reflects large-scale structural heterogeneities of the Eurasia lithosphere, supposedly related to its thermal regime. In the study area the TTZ divides EEP, which is characterized by predominantly positive anomalies from Western Europe with mostly negative mantle anomalies. (2) A regional relatively short-wavelength component (L <2000 km) correlates with specific tectonic structures. A chain of negative mantle anomalies (~ -100 mGal) is found west of the TTZ (Pannonian basin; Rhine graben and Massif Central). A very distinctive positive anomaly (>100 mGal) is located over the Carpathians and the Adriatic Sea, supporting the idea about strong lithospheric blocks. The results of deep seismic reflection and refraction and/or receiver function studies will be used to define the depth of the crustal interfaces and P-wave velocity distribution in order to complete the new crustal model. Furthermore, in the next stage, seismic tomography data will be used to get the location of the lithosphere-astenosphere boundary and calculate the temperature distribution. These results, jointly with the new crustal model, will allow us to re-calculate a strength state of the European lithosphere and to construct a new density model.

Session 5: Dissemination and information

Friday, 12 January 2007
11:35 – 13:00

The ENGINE information system birthday

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Partners involved in the Information and Dissemination System of ENGINE (ENhanced Geothermal Innovative Network for Europe) make it the vector for sharing information among the whole ENGINE community and for promoting the works of the Coordination Action towards decision makers and public audience. The tasks to reach this goal consist in facilitating the communication and exchanging good practices, organizing conferences and workshops, compiling and defining a publication policy for the ENGINE community, proposing a road for geothermal education and training in Europe, disseminating general information towards media and citizens. The main information media is the ENGINE Web site (http://engine.brgm.fr) dedicated to the management of the meetings and the dissemination of the coordination action activity. During the first year of ENGINE, 2 conferences and 3 workshops have been organized in Orléans (France), Zurich (Switzerland), Strasbourg (France) and Potsdam (Germany). The publication policy that has been defined allows to produce the meeting material including proceedings on CD. 5 newsletters were issued to keep the ENGINE partners and related informed about the news of the project. Compiling the state of the art of the existing education centres and degree courses in Europe has completed the first step of the education and training task. An overview of the geothermal lighthouse projects in Europe is in progress to facilitate the knowledge dissemination outside the ENGINE community. Before the end of the project, 4 workshops and the final conference will be hold in Volterra (Italy), Reykjavik (Iceland), Milos Island (Greece), Utrecht (Netherlands) and Vilnius (Lithuania). The Web site will progressively host the material produced by the ENGINE workpackages. The Information and Dissemination System partners will make the Web site more and more dedicated to public visitors in order to become a reference in disseminating the European activity on EGS.
J. M. Romo Jones (CICESE). Capacity building through training by research in geothermal activity: an experience from Mexico and Latin America.

Capacity building through training by research in geothermal activity: an experience from Mexico and Latin America

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Centro de Investigación Científica y Educación Superior de Ensenada (CICESE) is an academic institution funded by the Mexican government to conduct scientific research and higher education offering graduate programs in the areas of Earth Sciences, Oceanology, Applied Physics and Experimental Biology. The Earth Sciences Division conducts basic and applied research in Seismology, Applied Geophysics and Geology. We offer a graduate program to students pursuing PhD and MSc degrees, and provide scientific consulting to public and private sectors both, domestic and international. Since it was created, in 1977, the Applied Geophysics Department has been involved in research projects related with geothermal exploration. Graduate students are welcome to join research activities related to geothermics, like application and development of geophysical tools for exploration and monitoring of geothermal fields. The participation of our group in ENGINE consortium will mainly contribute a) to develop expertise in geophysical methods applied to geothermal exploration, and thus for the investigation of unconventional geothermal sources and EGS, b) to the training and dissemination actions of the network.

ISS - A Successful Trial for Internationalization of Specialized Education and Training

Kiril Popovski, isskiril@sonet.com.mk, International Summer School on Direct Application of Geothermal Energy
Sanja Popovska Vasilevska, International Summer School

The lack of organized education of specialists is one of the main constraints for initial geothermal development all over the world. By organization of a specific “movable” international school for organization of short trainings and seminars, accommodated to the needs of country or region in question, IGA successfully fulfilled part of the problematic. Specific methodology of “know-how” transfer, choice of the most renown lectures at world level in combination with local ones on disposal, resulted with a continual process of successful development. 35 courses, workshops and seminars have been organized in Bulgaria, Germany, Greece, Iceland, Macedonia, Poland, Slovenia, Portugal, Romania, Turkey, U.S.A., etc , 30 text-books and proceedings have been published, Over 1000 students from 40 countries all over the world participated some of the events organized by ISS. This year, by the signing of IGA/WB GEF contract, ISS get proper financial background for continuing the activity during the next 5 years, mainly in the East and South East European Region and South West Asia. Up to now, more than 1000 students of more than 40 countries all over the world participated the courses of ISS.

Dissemination of Geothermal knowledge at ISOR

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Dissemination of geothermal knowledge has played a major role in ISOR´s and its forerunners activities for long time. It has contributed considerably to the great success of geothermal energy utilization in Iceland where almost 90% of houses are geothermal heated, about 17% of the electricity and half of the primary energy consumption is from geothermal. Within Iceland, the dissemination activity of Iceland GeoSurvey (ISOR) can be divided into four groups. These are web-based activities, use of mass media and printed material, participation in meetings and teaching activities. The web-based dissemination include at least weekly update of news from ISOR´s activities and how it relates to the society in Iceland. The mass media is aware of the web page so a publication there sometimes leads to further publications in newspapers, radio or TV. The second web based activity includes the geological data viewer named "Gagnavefsja". It is operated in close co- operation with the National Energy Authority (NEA) and contains an open internet access to large parts of NEA´s and ISOR´s data bases on geology and energy issues in Iceland. It is both in Icelandic and English. Publications of printed material, books and newspaper articles and interviews are widely used to make the public aware of the possibilities and importance of geothermal in our society. ISOR and NEA issued last year a comprehensive book of the history, technical aspects and development of the geothermal sector in Iceland. This book was last year appointed to the national price for excellent books. ISOR´s staff participates each year in numerous conferences and open meetings in local societies, clubs and organisations. ISOR also has good relation to universities and high schools were our experts held courses and give lectures. Outside Iceland ISOR participates actively in dissemination of geothermal knowledge through education, development aid, participation in international organizations, meetings and conferences and publication of scientific papers on geothermal energy. In addition ISOR assist our ministries in their dissemination activities abroad. The most important activity is the United Nations University Geothermal Training Programme (UNU-GTP) which has been run in Iceland since 1979. It is financed mainly by our ministry of foreign affairs, run by NEA but about 60% of all the training activities are provided by ISOR. Yearly over 20 geothermal fellows from the developing countries participate in a 6 month intensive geothermal course in Iceland and 6-9 complete also a 2 year MSc studies in geothermal sciences. The UNU-GTP has been extremely successful in world-wide capacity building in the field geothermal. In addition UNU-GTP has recently started geothermal short courses for decision makers in developing counties with geothermal potential. Recently the Icelandic international development aid has started a geothermal dissemination programme in Africa and Central America where ISOR´s experts play significant role. ISOR also participates in international organisations where we use every opportunity to promote geothermal energy. These include IGA, EuroGeoSurvey, IEA geothermal implementing agreement, the ARGEO initiative and participation in the steering committee of the EU´s framework programmes. Furthermore ISOR is active in participations in geothermal conferences and workshops worldwide and last but not least ISOR is a minor shareholder in the Icelandic company Enex Ltd and assist it a lot with its geothermal promotion activities.

Geothermal Education in Europe and other Continents

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The paper presents geothermal education programs offered in different countries, at graduate and postgraduate levels, with as many details as available, such as curricula and course content. This will allow for a comparison between what is currently offered in Europe and on other continents, and a basis for further recommendations on what should be changed in the European countries in the near future in order to have well trained specialists needed for the expected development of the geothermal energy utilization.

Authors' Index

Antics....37
Axelsson....52
Baumgärtner....48
Beekman....70
Behrens....56
Björnsson....53
Blackwell....17
Blaga....79
Brandt....49
Bruel....64
Bruhn....11, 61, 67
Büsgen....31
Calcagno....75
Chatzichristos....54, 55
Cloetingh....70, 71
Dezayes....65
Fabriol....66
Fiordelisi....38
Flovenz....78
Fokker....51
Fouillac....9
Frick....27, 34, 36
Frid....39
Gandy....48
Genter....11, 65
Gessner....63
Ghergut....56
Hardenbol....70
Harms....23
Hettkamp....48
Huenges....11, 43, 49
Jónsdóttir....78
Jung....50
Kaban....71
Kaltschmitt....11, 27, 34, 36
Karytsas....33
Kohl....11, 43, 69
Köhler....32
Kontoleontos....33
Kühn....63
Le Bel....11, 27
Ledru....11, 24
Licha....56
Lodemann....56
Lokhorst....35
Manzella....11, 61, 66
Megel....24
Mendrinos....33
Monterrosa....20
Muller....54, 55
Ólafsson....68
Petty....18
Pfender....50
Popel....39
Popovska Vasilevska....77
Popovski....77
Porro....18
Raab....67
Romagnoli....38
Romo-Jones....76
Rosca....79
Rybach....24
Saadat....49
Sarmiento....21
Sausse....65
Sauter....56
Schuppers....10
Shpilrain....39
Spangenberg....67
Stamatakis....54, 55
Stubos....54, 55
Ter Voorde....70
Tesauro....70, 71
Teza....48
Thompson....22
Thórhallsson....11, 47, 52
Tischner....50, 51
Ungemach....37
Van Wees....35, 70
Wohlgemuth....49
Yang....22
Ziegler....32
Zimmermann....51
Zoethout....35

Notes

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