GEOELEC

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Manual

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for the *First Training Course on Geothermal Electricity*, 5–9 November, in Strasbourg, France, organized in the framework of the GEOELEC project.

The GEOELEC project is a pan-European project on geothermal electricity, supported by the *Intelligent Energy Europe programme* of the EU. The objective of the GEOELEC project is to convince decision-makers about the potential of geothermal electricity in Europe, to stimulate banks and investors in financing geothermal power installations and finally, to attract key potential investors such as oil and gas companies, and electrical utilities to invest in geothermal power. One key element will be to present them the huge geothermal potential in Europe (http://www.geoelec.eu).

GEOELEC Partners

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Keywords: Geothermal electricity, market aspects, legal/environmental and financial aspects, Enhanced Geothermal Systems (EGS); geothermal exploitation/exploration, resource assessment, EGS technology, geothermal well drilling, reservoir Exploitation assessment, flash steam and binary technology, plant operation, energy supply and grid integration

Content

Session I: Market aspects

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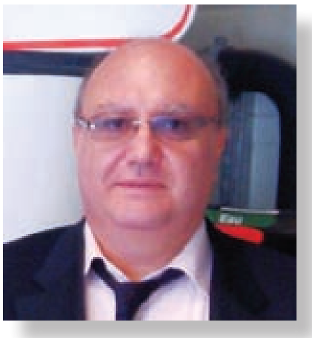
Presenter



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Curriculum vitae

Constantine Karytsas has a PhD degree in Geology-Energy from Pennsylvania State University (PSU) USA -1992, and a MSc degree in Environmental Geochemistry from the University of Newcastle Upon Tyne (UK) (1984) is a Geothermal Application Specialist with over 20 years professional experience in fuel science in geothermal as well as solar thermal applications. Recent work amongst others includes the fields of Seawater Desalination, ORC Binary Cycle Power Production, Geothermal Direct Heat Applications, Geothermal Heat Pump Research and Demonstration, and innovative COMBI system Solar Energy Applica-tions. Participation in 80 research and application/demonstration projects (coordinator in 20 of them) funded by the E.U., the European Industry, the Greek State and the Government of the United States (Departments of Energy and Environment). Dr. C. Karytsas is the author or co-author of more than 18 peer reviewed journal articles and 60 announcements in the pro-ceedings-abstracts of international conferences.
Served as: Deputy director of RES division, CRES (2010 – today); Head of the Geothermal Department of CRES (1989-2010); Lecturer on Geothermal Applications at Technical University of Crete (since 1994) and National Technical University of Athens – NTUA (2004).

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Abstract

Geothermal resources of Europe can contribute to the EU targets of 20% less greenhouse gas emissions, 20% RES share and 20% more energy efficiency by 2020. The session provides an overview of the present status and future prospects of global geothermal electricity market niche, including market size (turnover, capacities, energy yields), near term growth, quality of resources, technologies employed, key players, investment and electricity generation costs, market barriers and incentives.

Keywords: geothermal, power plants, resources, market, development, costs

International Geothermal Market overview

Geothermal energy is the heat of the earth. Depending on the geological environment they are encountered in, geothermal resources are characterized as magmatic/volcanic systems, thermal aquifers, geopressured basins and crustal heat. A global geothermal resource estimate of above categories, in comparison to fossil fuel reserves, is presented in Table 1.

Table 1. World geothermal resources compared to global fossil fuel reserves

Geothermal resources	billion TOE	Fossil fuel reserves (end 2010)	billion TOE
Crustal heat	10.775.600	Coal	422
Magmatic/Volcanic	327.360	Oil	208
Geopressured	55.924	Natural gas	168
Aquifers, thermal	18		

Geothermal exploitation technology requires drilling one or more production wells delivering subsurface hot fluids to the surface, which after feeding a geothermal power plant, are injected back to their origin formations through reinjection wells. In that case, e.g. when deep hot fluids are available, the geothermal resource is termed as a hydrothermal system. Almost all geothermal power plants today are located in such hydrothermal systems, which are encountered mainly at the boundaries of tectonic plates and at geological hot spots, where hot magma is rising towards a thin earth crust. Location of geothermal power plants is shown in Figure 1.

The geothermal plant at Soulz, proved that the exploitation of other parts of the earth crust, where deep hot formations do not naturally deliver the necessary amounts of fluids, is also technically feasible. In these geologic conditions, the hot rocks are artificially fractured by hydraulic fracturing, acidizing, propelants, etc., in order to engineer a man made reservoir, through which surface water is circulated serving as the heat transfer media. These are termed as enhanced geothermal systems (EGS). At present only a few EGS plants are in operation or under development around the globe, but future large scale exploitation of geothermal energy lies in this technology.

Figure 1. Power plants around the globe (yellow); the larger the cycle, the higher the installed plant capacity.

Depending on the temperature and permeability of the geothermal resource, production wells can deliver to the surface, either dry steam, or two phase mixture of steam and liquid water, or only liquid water.

Only a handful of dry steam resources are encountered around the globe. The most important are the geothermal fields of Larderello, Italy, Geysers, California, and Kamojang, Indonesia. In such fields, the steam from the production wells is directly conveyed to a steam turbine in order to generate electricity. This is termed as a dry steam plant.

In most cases, production wells deliver a mixture of steam and liquid water, which is flashed in order to separate the steam and the liquid (flash plant); the steam is conveyed to a turbine to generate electricity and the separated liquid can be further utilized for power generation or for its heat (cogeneration plant) and then reinjected to its origin reservoir. A flash plant is economically feasible if the production wells deliver more than 150˚C.

In cases where resource temperature is lower than 150˚C, production wells deliver liquid water with the aid of a submersible or line shaft pump, which feeds a binary power plant. In such a plant, the hot water deliveres its heat to a closed loop of secondary fluid, which vaporizes, drives a turbine and condenses in a closed cycle (organic rankine or kalina).

In general, eploitation of hydrothermal resources down to 3-4 km depth is a mature commercial technology done by:

- Binary plants for T=100-180˚C
- Flash plants for T>180˚C
- Dry steam at favorable locations

EGS from 3-6 km depth is a new technology, while supercritical plants (T>350˚C) from 5-10 km depth will be a future technology.

The geothermal power market in terms of historical evolution, present status and future projection of installed plants is summarized in Table 2 (world) and Table 3 (EU). Prediction of future installations was based on projects which are at present under development (2015) or anounced (2020). The market is dominated by mostly dedicated geothermal field operators and lesser by diversified power utilities, with presence of oil and gas companies, mainly in Indonesia. The six major geothermal field owners and plant operators control >6.5 GWe or 60% of installed capacity.

Table 2. World geothermal power plant capacity

MWe	historical evolution					present	forecast	
Country	**1990**	**1995**	**2000**	**2005**	**2010**	**2012**	**2015**	**2020**
USA	2.775	2.817	2.228	2.544	3.093	3.187	4.136	5.148
Philippines	891	1.227	1.909	1.931	1.904	1.972	2.112	3.447
Indonesia	145	310	590	797	1.197	1.200	2.325	3.451
Mexico	700	753	755	953	958	990	1.050	1.140
EU	552	641	805	822	896	941	1.137	1.499
New Zealand	283	286	437	435	628	747	1.350	1.599
Iceland	45	50	170	322	575	665	890	1.285
Japan	215	414	547	535	536	537	568	1.807
El Salvador	95	105	161	151	204	204	287	290
Kenya	45	45	45	127	167	209	402	535
Costa Rica	0	55	143	163	166	163	201	201
Nicaragua	35	70	70	77	88	107	209	240
Turkey	21	20	20	20	82	99	206	715
Russia	11	11	23	79	82	82	190	194
Papua NG	0	0	0	39	56	56	75	75
Guatemala	0	33	33	33	52	52	120	141
China	19	29	29	28	24	24	60	64
Ethiopia	0	0	9	7	7	7	45	70
Australia	0	0	0	0	1	1	40	70
Thailand	0	0	0	0	0	0	1	1
Chili	0	0	0	0	0	0	40	160
Honduras	0	0	0	0	0	0	35	35
Nevis	0	0	0	0	0	0	35	35
Argentina	1	1	0	0	0	0	30	300
Canada	0	0	0	0	0	0	20	493
Tanzania	0	0	0	0	0	0	0	20
	5.832	**6.867**	**7.974**	**9.064**	**10.717**	**11.242**	**15.564**	**23.013**

Table 3. Geothermal power plant capacity in EU

MWe	historical evolution					present	forecast	
Country	**1990**	**1995**	**2000**	**2005**	**2010**	**2012**	**2015**	**2020**
Italy	545	632	785	790	843	883	923	1.019
Portugal	3	5	16	16	29	29	33	60
France	4	4	4	15	16	16	21	42
Germany	0	0	0	0	7	12	69	161
other	0	0	0	1	1	1	91	217
	552	**641**	**805**	**822**	**896**	**941**	**1.137**	**1.499**

At global level, market growth which was 3% during the past 20 years, is expected to exceed 10% in the next years, resulting in more than double installed geothermal capacity from 11,2 GW today to 2,3 GW by 2020. At EU level, market growth patterns are expected to increase from 2% to 6% during the next years, due to wider geothermal development, as EU member states try to reach their 2020 targets for 20% renewable energy share, resulting in installed capacity to increase from less than 1 GW today to 1,5 GW in 2020.

The different types of installed geothermal power plants today, are presented in Table 4, while the corresponding manufacturers and their market position in Table 5. Average plant sizes are 5 MWe binary, 30 MWe flash and 45 MWe dry steam, with maximum at around 100-130 MWe. Six major turbine manufacturers account for 95% of total installed capacity.

Table 4. Types of geothermal power plants installed today

Geothermal plant type	installed MWe
Flash, condensing	6.904,3
Dry steam	2.862,0
Binary	1.303,0
Flash, back Pressure	146,6

Table 5. Geothermal power plant manufacturers with their corresponding installed capacity

Manufacturer	Steam MWe	Binary MWe	total MWe
Mitsubishi	2.729		2.729
Toshiba	2.505	25	2.530
Fuji	2.315		2.315
Ormat		1.159	1.159
Ansaldo	1.158		1.158
General Electric	532		532
Alstom	155		155
Assoc. Elec. Ind.	90		90
Kaluga	72	10	82
British Thomson Houston	82		82
Mafi Trench		72	72
Qingdao Jieneng	21		21
UTC Turboden		19	19
Kawasaki	16		16
Westinghouse	14		14
Eliot	12		12
Harbin	11		11
Enex		11	11
Turbine air system	8		8
Parsons	5		5
Siemens		4	4
misc.		4	4

The investment costs of geothermal power plants depend on the depth, temperature and chemistry of the resource, as well as the delivery flow rates of the wells. The dry steam, flash and binary plants in operation today exploit the most favorable resources usually from 2-3 km depth, going down to 4-5 km for EGS plants. Investment and levelized electricity generation costs in recent projects are shown in Table 6. Investment costs include exploration, field development and power plant.

In order to estimate the electricity generation costs presented in Table 6, typical operation costs of 0,011-0,020 €/kWh were assumed, an investment discount factor of 8% for 20 years, as well load factors relevant to the installed country: 95% for Germany, 90% for USA, 75% for EU and Turkey and 80% elsewhere.

The main aspects of global and EU geothermal power markets are summarized in Table 7.

Table 6. Economic aspects of geothermal power generation

recent projects	Investment, €/MWe			Energy production costs, €/kWh		
	Flash	Binary	EGS	Flash	Binary	EGS
USA	2.700.000	3.100.000	6.200.000	0,055	0,060	0,100
Indonesia, New Zealand, Philippines	2.300.000			0,044		
Central America	1.900.000			0,042		
EU		4.500.000	11.600.000		0,090	0,200
Chile	3.600.000			0,072		
Germany		6.500.000			0,100	
Turkey	2.750.000			0,063		

Table 7. Global and EU market size and growth

	2012			2012-2020	
	installed capacity MWe	annual sales		annual growth	
		electricity GWh	value billion €	capacity MWe	investments billion €
World	11.242	70.500	7,05	1.450	3,75
EU	941	6.150	1,20	65	0,43

Table 8. Indicative incentives to geothermal development in USA (non exhaustive)

Jurisdiction	Statute	Incentive Title	Tax	Type	Taxpayer	yrs	Amount	Max	Expire
Federal	§45	Renewable Electr. Prod.	Income	Credit	Producer	10	$0.022/Kwh	-	2013
	§48	Investment Energy Prprty	Income	Credit	Owner	5	10%	-	2016
	§168(e)3	Certain Energy Property	Income	Deduction	Owner	5	200% DB	-	2016
	§54C	New Clean RE Bonds	Income	Credit	Holder	-	0 interest	-	Limit
Alabama	§40-18-	Altern. Energy Prod. Faclt.	Income	Credit	Utility	20	5%	-	2015
	§40-9B-4	Altern. Energy Prod. Faclt.	Property	Abatement	Utility	-	100%		2018
Delaware	§2040	Clean Energy Mfg Jobs	Income	Credit	Manufacturer	-	$750/J & $100k	$500k	-
Florida	196.175	RES Devices	Property	Exemption	Owner	10	100%	-	-
	220.193	Renewable Energy Prod.	Income	Credit	Producer	-	$0.01/kWh	$1mio	2016
Maryland	§10-720	RE Production	Income	Credit	Producer	5	$0.0085/kWh	$2.5mio	2015
N. Jersey	§54:10A	Altern. Energy Tech. Co.	Income	Credit	Investor	3	30%	$500k	-
	§54:4-3.	RE Systems	Property	Exemption	Owner	-	100%		

Main market barriers hindering geothermal deployment are lengthy permitting procedures, lack of regulations, high risk in finding & identifying geothermal resources and associated finance availability, as well as know how and competent personnel to few companies only.

In USA, geothermal development is driven by federal and state incentives available to energy producers, manufacturers and utilities, which are summarized in Table 8. They include renewable portfolio standards, tax exemptions, investment subsidies and access to grid.

Table 9. Feed in tariffs in developed countries

country	€/kWh	country	€/kWh	country	€/kWh	country	€/kWh
Japan<15MW	0,4077	Slovenia	0,1525	Greece	0,0995	Spain	0,0692
Japan>15MW	0,2692	Belgium	0,1423	Hungary	0,0950	Malta	0,6990
Germany	0,3000	Indonesia max	0,1308	Poland	0,0940	Sweden	0,6876
Switzerland	0,2000	France overs.	0,1300	Romania	0,0918	Estonia	0,0518
Italy	0,2000	Finland	0,1289	Indonesia min	0,0833		
France cont.	0,2000	Slovakia	0,1214	Slovenia	0,0800		
Czech Rep.	0,1733	UK	0,1078	Austria	0,0729		

Table 10. Developers of new geothermal power projects

Company	Location	Core Business	operating, MWe	new projects, MWe
Gradient resources	USA	Geothermal	0	1025
Pertamina	Indonesia	Oil & gas	642	710
Oski Energy	USA	Geothermal	0,8	655
Ram Power	USA, global	Geothermal	40	610
Enel	Italy, global	Power utility	955	505
Contact Energy	New Zealand	Power utility	336	490
Landvirksjun	Iceland	Geothermal	63	480
CallEnergy	USA	Power utility	329	470
Calpine	USA	Power producer	1309	420
Idatherm	USA	Geothermal	0	400
Ormat	USA, global	Geothermal	777	350
US Geothermal	USA	Geothermal	54	350
Itochu	Japan, Indonesia	Trade & investments	0	330
EDC	Philippines	Geothermal	756	305
Altera	USA, global	Power producer	198	280
Zorlu	Turkey	Power producer	15	185
Terra-Gen	USA	Power utility	392	180
GDC	Kenya	Geothermal	0	140
			total:	7885

In EU geothermal development is supported by feed in tariffs, with the tendency to be replaced by feed in premiums in the future. Following the successful example of Germany, Indonesia and Japan have recently introduced aggressive feed in tarrif schemes, in order to stimulate large scale geothermal power development in their teritorry. A list of available feed in tariffs is presented in Table 9.

In developing countries support to geothermal projects is limited to world bank loans and carbon certificates.

Global geothermal market development is done by ambitious new-coming companies, the most important of which correspond to 67% of total power plant capacity under development worldwide and are presented in Table 10.

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Session II: Financial aspects

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Presenter

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Curriculum vitae

Gerd Wolter is CEO of a Chartered Accountant firm in Hannover, Germany, specializing in consultancy together with Dr. Thomas Reif, lawyer and MBA in economics, regarding clients investing in the Geothermal Business.

Gerd Wolter is 60 years of age, since 30 years in the Audit, Tax and Consultant Business working for the Big Four and medium sized accountant and law firm as partner.

Abstract

GGSC Treuhand is working closely together with the law firm Gaßner Groth Siederer & Collegues, Berlin and Augsburg. The Augsburg Branch is dealing for over eight years in that business offering Due Diligences (financial, legal, tax and environmental), feasibility studies on financial issues and consulting in company law in the bavarian region of the Molasse Becken.

GGSC belongs to a network of professionals of the Geothermal Business covering the geological, drilling and technical aspects. The broaden knowledge enables GGSC profound studies in a standard setting art.

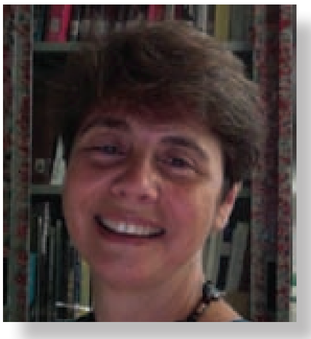
The upcoming Geothermal Business in the northern part of Germany (Norddeutsches Becken), which differs geologically from the south and south western parts of Germany, is a challenge not only for the geologists but also for true economical statements in financial feasibility studies evaluating the bunch of risks in a fair manner.

Beside the national sector GGSC is focussing in the domains of geothermal energy comprising high enthalpy systems.

Session III – Geothermal exploration and resource assessment

Adele Manzella, Pierre Durst and Jan-Diederik van Wees

Presenter



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Adele Manzella, Senior Research Scientist, worked in seismology, numerical modeling for seismic and electromagnetism. Working since 1990 as a geophysicist in geothermal exploration to conduct field and theoretical investigations of geothermal systems in Italy and abroad, in particular using the magnetotelluric method. On 2006 obtained the G.W. Hohmann Award for Teaching and Research in Applied Electrical Geophysics, SEG Foundation, for "outstanding application of electrical and electromagnetic methods to the study of geothermal resources".
Responsible for over 20 projects related to geothermal, crustal and volcanology exploration using geophysical methods, lectured at the annual International School of Geothermics of Pisa and at short courses on geothermal exploration in Chile, North Korea, Ecuador, Ethiopia, Uruguay and Italy, authored about 40 articles in peer-reviewed journals with geothermal-related subjects, and over 100 presentations at international symposia and congresses.
She is the scientific coordinator of the two main CNR projects (VIGOR and ATLAS) of geothermal assessment of southern Italy.

Pierre Durst is a Research Scientist, who did his PhD on geochemical modelling on the Soultz-sous-Forêts geothermal project. He worked five years on geochemical and reservoir modelling related to CO_2 storage, then four years on hydrogeological modelling related to water resources management and geothermal resources assessment. Currently he is working on geothermal resources assessment as well as on potential risks and impacts related to geothermal exploitation.

Relevant Publication

Oskooi, B., Pedersen, L.B., Smirnov, M., Árnason, K., Eysteinsson, H., Manzella, A., and the DGP Working Group: The deep geothermal structure of the Mid-Atlantic Ridge deduced from MT data in SW Iceland. Phys. Earth Planet. Int., 150, 183-195, 2005.

Spichak V., and Manzella A.: Electromagnetic sounding of geothermal zones, Journal of Applied Geophysics, 68, 459–478, 2009. doi: 10.1016/j.jappgeo.2008.05.007

Abstract

Geothermal exploration is aimed at detecting the geothermal resource at depth, defining its physical and chemical features. Geothermal resources can be analysed on different scales and for various purposes, following a step-by-step procedure and zooming from regional, local and reservoir scales. Following the general overview of the previous session, Session IV will analyze in detail how to locate a potential geothermal reservoir, defining its geometry, size and the heat content, and then retrieve information regarding productive zones or areas where stress condition are suitable for EGS development by enhancement of natural permeability. Different tools and approaches can be used to investigate geothermal resources, which depend on the geological context of the site, from sedimentary to volcanic to crystalline reservoirs, and on the nature of the resource, both for natural system and EGS perspectives. The course will provide an overview of the most common geological, geophysical, geochemical methodologies and the collected information, and will explain how to integrate the different data and provide the conceptual model of the resource to be used for locating the exploratory drilling.

With the help of case studies, the presenter will exemplify the exploration procedure and will show what are the main parameters of a conceptual geothermal model, how to compile a body of basic data against which the results of future monitoring can be viewed, and to determine pre-exploitation values of environmentally sensitive parameters.

Keywords: Geothermal assessment, exploration methods, geology, geophysics, geochemistry, monitoring parameters, environment

Geothermal assessment and exploration: an overview

The objectives of geothermal exploration are:

- To identify geothermal phenomena.
- To ascertain that a useful geothermal production field exists.
- To estimate the size of the resource.
- To determine the type of geothermal field.
- To locate productive zones.
- To determine the heat content of the fluids that will be discharged by the wells in the geothermal field.
- To compile a body of basic data against which the results of future monitoring can be viewed.
- To determine the pre-exploitation values of environmentally sensitive parameters.
- To acquire knowledge of any characteristics that might cause problems during field development.

The relative importance of each objective depends on a number of factors, most of which are tied to the resource itself. These include anticipated utilization, technology available, economics, as well as situation, location and time, all of which affect the exploration programme.

Before attempting an exploration program, it is important to define the main features of a geothermal system and therefore the exploration targets.

A conventional geothermal system is made up of four main elements: a heat source, a reservoir, a fluid, which is the carrier that transfers the heat, and a recharge area. The heat source is generally a shallow magmatic body, usually cooling and often still partially molten. The volume of rocks from which heat can be extracted is called the geothermal reservoir, which contains hot fluids, a summary term describing hot water, vapour and gases. A geothermal reservoir is usually surrounded by colder rocks that are hydraulically connected with the reservoir. Hence water may move from colder rocks outside the reservoir (recharge) towards the reservoir, where hot fluids move under the influence of buoyancy forces towards a discharge area.

The mechanism underlying geothermal systems is by and large governed by fluid convection. Convection occurs because of the heating and consequent thermal expansion of fluids in a gravity field; heat, which is supplied at the base of the circulation system, is the energy that drives the system. Heated fluid of lower density tends to rise and to be replaced by colder fluid of high density, coming from the margins of the system. Convection, by its nature, tends to increase temperatures in the upper part of a system as temperatures in the lower part decrease.

One aspect of a conventional geothermal system is that it must contain great volumes of fluid at high temperatures or a reservoir that can be recharged with fluids that are heated by contact with the rock. A geothermal reservoir should lie at depths that can be reached by drilling. It is unreasonable to expect to find a hidden hydrothermal system at depths of less than 1 km; at the present time it is not economic to search for geothermal reservoirs that lie at depths of more than 5 km, although actual technology allows reaching depth up to 10 km. In order to be productive, a well must penetrate permeable zones, usually fractures, which can support a high rate of flow. When this requirement is no met, actual technological development is attempting to enhance the natural permeability (EGS). Enhancing a geothermal system generally involves drilling along deviated well paths and with large diameters, drilling with formation damage mitigating technologies, stimulating the reservoir by hydraulic fracturing, and/or targeting fault zones that will produce with high flow rates, which are usually higher than those in hydrocarbon production. Thus, one of the key geological issues, especially critical for EGS development, is knowledge of the stress field and an understanding of geomechanics in the subsurface. The geological characterization must therefore also include various methods that constrain the stress field of a reservoir and elucidate the stress states along faults slated for stimulation. Specific stress conditions are then required, and they should be defined during exploration.

The geological setting in which a geothermal reservoir is to be found can vary widely. The largest geothermal fields currently under exploitation occur in rocks that range from limestone to shale, volcanic rock and granite. Volcanic rocks are probably the most common single rock type in which reservoirs occur. Rather than being identified with a specific lithology, geothermal reservoirs are more closely associated with heat flow systems. As far as geology is concerned, therefore, the important factors in identifying a geothermal reservoir are not rock units, but rather the existence of tectonic elements such as fracturing, and the presence of high heat flow.

The high heat flow conditions that give rise to geothermal systems commonly occur in rift zones, subduction zones and mantle plumes, where large quantities of heat are transported from the mantle to the crust of the earth. Geothermal energy can, however, also occur in areas where thick blankets of thermally insulating sediment cover basement rock that has a relatively normal heat flow. Geothermal systems based on the thermal blanket model are generally of lower grade than those of volcanic origin.

The different elements of a geothermal system represent targets for the application of geological, geophysical and geochemical prospecting techniques. Because of the high temperatures involved, both in the geothermal reservoir and in the source of the geothermal system, we can expect major changes to have taken place in the physical, chemical and geological characteristics of the rock, all of which can be used in the exploration project.

Heat is not easily confined in small volumes of rock. Rather, heat diffuses readily, and a large volume of a rock around a geothermal system will have its properties altered. The rock volume in which anomalies in properties are to be expected will, therefore, generally be large. Exploration techniques need not offer a high level of resolution. Indeed, in geothermal exploration we prefer an approach that is capable of providing a high level of confidence that geothermal fluids will be recovered on drilling.

A geothermal assessment program is generally combined with comprehensive assessment of the geologic setting, especially of the tectonic and structural framework. Thus, fruitful exploration strategies typically involve the following:

- Assessment of the geologic and geodynamic setting
- Geochemistry including fluid and rock isotope chemistry
- Structural analysis of faults, fractures, and folds
- Determination of the regional stress field
- Potential methods, mainly gravity and magnetic surveys
- Electrical and electromagnetic methods
- Seismic methods, both active and passive

A typical procedure in a geothermal project foresees exploration to follow a down-scale workflow, summarized in Fig. 1.

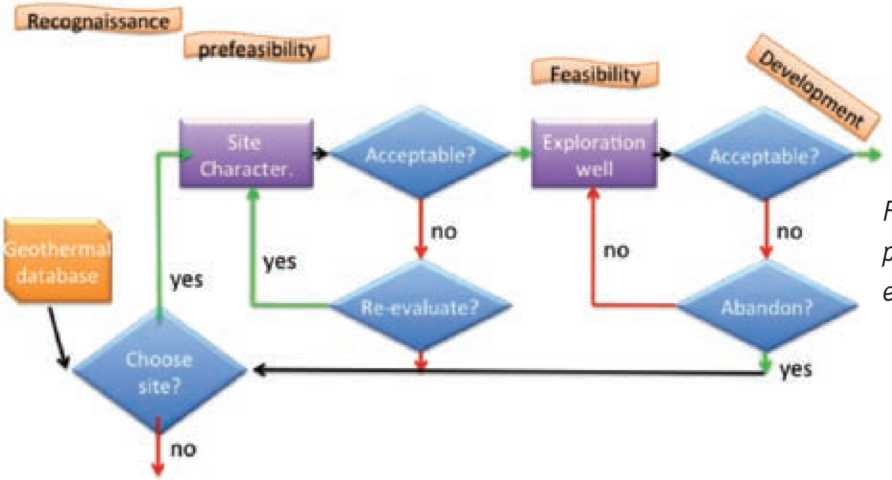

Figure 1. The three phases of a geothermal project development that incorporate exploration.

The assessment programme on a regional basis will begin with a review and coordination of the existing data (reconnaissance phase). All heat flow data acquired previously will have to be re-evaluated, re-gridded, smoothed, averaged and plotted out in a variety of forms in an attempt to identify areas with higher than normal average heat flow. Similarly, the volumes of rocks with ages younger than 106 years should be tabulated in a similar way to provide a longer-range estimate of anomalous heat flow from the crust. Because fracturing is important, levels of seismicity should be analysed, averaged and presented in a uniform format. All information on thermal springs and warm springs should be quantified in some form and plotted in the same format. Comparison of these four sets of data, which relate directly to the characteristics of the basic geothermal model described above, will produce a pattern that will indicate whether the area possesses the conditions favourable for the occurrence of specific geothermal reservoirs. These areas should then be tested further, by applying some or all of the many geophysical, geological and geochemical techniques designed to locate specific reservoirs from which fluids can be produced. Surface manifestation may also be detected by remote sensing techniques, which may be able to map superficial thermal anomalies and topographic changes associated to shallow geothermal anomalies.

The objective of the more detailed studies is to identify the existence of a productive reservoir at attractive temperatures and depths. Detailed geophysical, geological and geochemical studies will be needed in order to identify drilling locations once a prospect area has been defined from reconnaissance.

Geochemical surveys provide the most reliable indications of reservoir temperatures if the thermal fluids emerge at the surface. In any event, all springs and other sources of groundwater should be sampled and various geothermometer calculations carried out. Some prospect areas will probably show much more positive geochemical indicators than others. This could merely reflect the difference in the amount of leakage from subsurface reservoirs, but it does provide a basis for setting priorities for further testing; the geothermal reservoirs that show the most positive indications from geochemical thermometry should be the ones that are investigated first by other geophysical techniques.

Geophysical methods play a key role in geothermal exploration since many objectives of geothermal exploration can be achieved by these methods. The geophysical surveys are directed at obtaining indirectly, from the surface or from shallow depth, the physical parameters of the geothermal systems. A geothermal system generally causes inhomogeneities in the physical properties of the subsurface, which can be observed to varying degrees as anomalies measurable from the surface. These physical parameters include temperature (thermal survey), electrical conductivity (electrical and electromagnetic methods), elastic properties influencing the propagation velocity of elastic waves (seismic survey), density (gravity survey) and magnetic susceptibility (magnetic survey). Most of these methods can provide valuable information on the shape, size, and depth of the deep geological structures constituting a geothermal reservoir, and sometimes of the heat source.

In summary, geothermal exploration for conventional and EGS means, on the one hand, that a reservoir should be understood as a part of a complex geosystem and, on the other hand, it is part of a complex mechanical rock response in the subsurface reacting – either positive or negative – to all manipulations that need to be done from exploration over reservoir access to exploitation. Consequently, geothermal exploration should encompass a broad palette of approaches, which are summarized in Figure 2, from geosystem analysis to reservoir characterization to reservoir geomechanics.

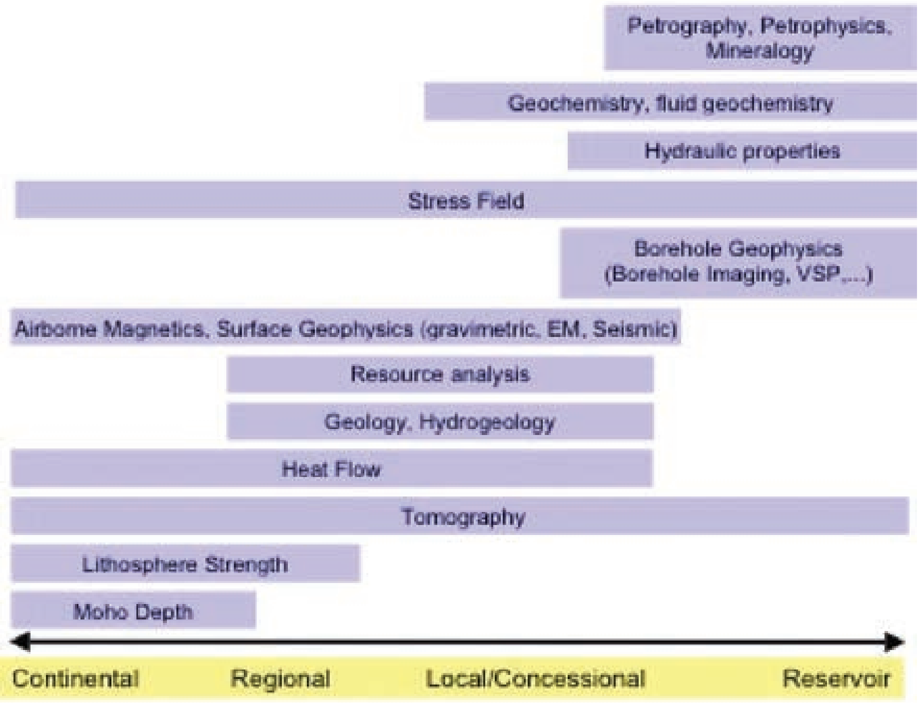

Figure 2. Different information and knowledge available on regional, local/concessional and reservoir scales, to be integrated for site-screening and exploration.

Session IV: EGS technology

Jan-Diederik van Wees, Chrystel Dezayes and Günther Zimmermann

Presenter

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Prof. Dr. Jan-Diederik van Wees is principal scientist of geothermal research at TNO, and is extra-ordinary professor at Utrecht University on tectonics and geothermal energy. He has published over 60 papers in leading international journals on tectonics, resource assessment, reservoir engineering, and techno-economic models. His current research expertise focuses towards enhanced geothermal systems (EGS) and direct use applications in Europe. Van Wees serves in various co-ordinating roles in major European and national geothermal research projects, including sub-program management (resource assessment) in the Joint Program on Geothermal Energy of the European Energy Research Alliance. Under his leadership, TNO has developed various state-of-the-art geothermal information systems and performance assessment methodologies, including thermoGIS for geothermal aquifers in the Netherlands and a decision support system for the performance assessment of enhanced geothermal systems. Further TNO is active in the EU project GEISER focused towards in depth understanding and mitigation of induced seismicity at geothermal operations.

Relevant Publication

Cloetingh, S., Van Wees, J.D., Ziegler, P.,Lenkey, L., Beekman, F., Tesauro, M., Forster, A., Norden, B., Kaban, M., Hardebol, N., Bonte, D., Genter, A., Guillou-Frottier, L., Voorde, M.T., Sokoutis, D., Willingshofer, E., Cornu, T., Worum, G., 2010. Lithosphere tectonics and thermo-mechanical properties: an integrated modelling approach for Enhanced Geothermal Systems exploration in Europe. Earth-Science Reviews 102, 159-206.

Bruhn, D., Huenges, E, Agustsson, K, Zang, A, , Rachez, X., Wiemer, S., Van Wees,.J,D..Calcagno, P., , 2011. Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs - The European GEISER Project. GRC transactions, 39.

Wassing, B., Van Wees, J.D., Fokker, P., 2012. , Coupled Continuum Modeling of Fracture Reactivation and Induced Seismicity During Enhanced Geothermal Operations. ARMA paper 12-400

Abstract

This session provides an insight into subsurface technology of Engineered Geothermal Systems (EGS), in particular the process of hydraulic fracturing and induced seismicity in EGS projects. Basic concepts of geomechanics and hydraulic fraccing, results of hydraulic stimulation and induced seismicity in EGS projects will be covered by lessons learned from the GEISER FP7 project.

The setup of this session is as follows

Part 1 theoretical background:

- *Basics of Rock mechanics, tectonic faulting and seismicity*
- *Hydraulic stimulation : best practice from oil and gas, objectives and physical principles*

Part 2: EGS case studies

- *Enhancing flow rates*
- *Induced seismicity*

Part 3: outlook

- *Mitigation strategies*
- *Best practice guidelines*

Keywords: enhanced geothermal systems, hydraulic stimulation, induced seismicity

Introduction

The development of renewable energies is more urgent than ever. Geothermal energy systems have a strong undeveloped potential in continental Europe that is estimated to be between 10,000 and 50,000 MW. But only in the European magmatic areas in Italy, Iceland and Portugal, production of high temperature heat (>200˚C) has been harnessed for the generation of electricity (>1,400 MW). Technological development of site-independent technologies to extract high temperatures at very deep levels and independent from natural hot water resources would allow production of geothermal energy in areas which are not marked by magmatism. There, the key is to use open fractures in high-temperature rock so that water and steam circulating into them can rapidly transfer heat to the Earth’s surface. Where fractures are not naturally abundant, one needs to create new fractures or to reactivate existing ones to increase the permeability. This can be carried out by hydraulic stimulation, hydraulic fracturing or acidization, which all consists of injecting fluids at high pressures in the underground. Such so-called enhanced geothermal systems (EGS) hold the key to future growth of geothermal energy but more experience is required to successfully develop these systems.

Theoretical background

Tectonic stress and geomechanical properties of rocks explain jointly the process of natural seismicity as well as the process of breaking rock by fluid injection. Natural fault motions are characterized by shear failure resulting in earthquakes. The spatial distribution and nature of earthquakes is strongly controlled by tectonics, the natural deformation of the earth. Hydraulic fraccing relies on the stress state of the rock and its geomechanical properties.

Since decades tensile fraccing, marked by hardly any shear failure, is used routinely in oil and gas to improve the performance of wells. For shale gas and EGS operations hydraulic stimulation often involves the generating of shear fractures in order to connect wells with permeable fractures over large distances.

EGS case studies

Most EGS projects require drilling to several kilometers depth to reach adequate temperatures (about 120°C). In Europe, a few EGS pilots have been performed (Figure 1). These stimulations are often accompanied by vast amounts of induced seismicity, which can be used to characterize the reservoir, but which is also of major concern when it releases sufficient energy to cause possible surface damage or to be felt by the population.

In this session we present in detail the results from Soultz-sous-Forêts and Groß Schönebeck.

Soultz-sous-Forêts was Initiated in 1986, and the project has now a long history which is broadly documented) and benefits from a vast amount of field observations in numerous domains (geology, geochemistry, geophysics, petrophysics, hydrogeology, etc.) gathered during the exploration, drilling, stimulation, circulation, production phases. Today, 1.5 MWe net power can be delivered to the French electrical network.

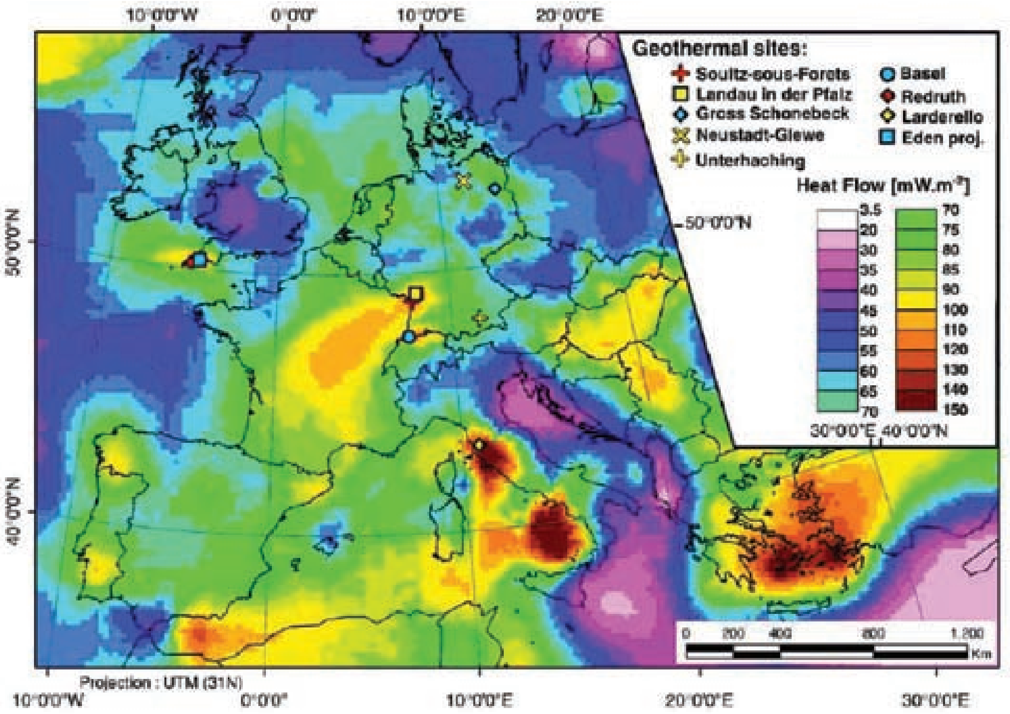

Figure 1. Heat flow map of Europe and geothermal projects.

Over the development of the EGS, four wells have been drilled and stimulated to create the heat exchanger prior to production. The bottoms of the holes are aligned in a N170°E direction consistent with the horizontal principal stress direction.

At the current stage, Soultz is producing from a reservoir at around 5000m depth, at T=190°C, with stimulations after the year 2000 in the wells GPK2, GPK3 and GPK4, circulation tests since 2005 and the longest circulation test in 2010. From logging measurements, it has been noticed that the reservoir consists of strongly altered granite with hydrothermally altered and fractured zones. The hydraulic exchanger of the current Soultz reservoir is dominated by such an altered fracture zone, which extends on large scale as a planer structure linking GPK2 and GPK3 in the deeper reservoir.

Groß Schönebeck is developed from a reopened oil and gas well which was deepened to 4294 m depth to serve as an in-situ geothermal laboratory. Nine months after reopening, the bottom hole temperature was 149 °C at 4285 m depth. The reservoir of interest is composed of sandstones, conglomerates and underlying andesitic volcanic rocks. The sandstones constitute the principal targeted reservoir. They are well-sorted, middle to fine grained, with 8 to 10 % porosity and in-situ permeability of 10 – 100 mD. In contrast to the Dethlingen sandstone formation, the permeability of the volcanic rock is rather high due to connected fractures. Several stimulation operations were carried out in this well at the reservoir level to enhance water productivity and they are discussed in the next section in parallel with the induced seismicity. To complete the doublet system of this EGS site, the production well was drilled in 2007 down to the volcanic rocks. The stress magnitudes in the Dethlingen sandstone at 4.1 km depth were determined to be S_V=78 - 100 MPa from density logs, S_H=98 MPa (at N18E) estimated from transitional form of stress regime from normal faulting to strike slip faulting, and S_h=55 MPa from leak-off tests in both wells. In the volcanic section, mainly the minimal principal horizontal stress is different and is equal to S_h=72 MPa.

During stimulation, the strongest microearthquakes (with $M_w \leq -1$) occurred on a pre-existing fault, which theoretically was relatively critically stressed. The strike and dip of this fracture plane are 17°±10° and 52°±10° SE respectively.

In Soultz, Groß Schönebeck, and other pilot sites, the observed induced seismicity, spatially lines up in relatively large and planar fault and fracture zones. Mechanical models for seismic rupture clearly demonstrate that the geometrical and rheological alignment of these fractures, in interaction with the pre-existing and perturbed stress field due to hydraulic stimulation is key to induced seismicity. Connecting to critically stressed crustal scale faults, can -in theory- trigger relatively large events.

Outlook

The predicted contribution of EGS in the worldwide geothermal energy production portfolio is significant for 2050. Widespread growth of EGS is anticipated after 2020 since, at that point, easy accessible hydrothermal systems are becoming scarce. Moreover, research and development will enable EGS to be ready for large scale deployment, both in terms of securing public acceptance and environmental safety with regards to induced seismicity and in terms of reducing levelized (the levelized cost of a given energy is the ratio between the sum of all costs necessary to produce this energy over time and the production duration) costs of energy (IEA, 2011).

In Australia and in the USA, generous funding of EGS projects provides the opportunity for these countries to develop EGS technology. In Europe, to face these challenges, the European Energy Research Alliance (EERA) Joint Program on Geothermal Energy (JPGE) aims at providing an outstanding contribution bringing together 20 leading European geothermal research institutions in a single strategically oriented joint research and development program. The EU funds research activities partly under the umbrella of the JPGE which includes for instance the EU project GEISER (2010-2013) that investigates geothermal engineering integrating mitigation of induced seismicity in geothermal reservoirs.

With an emphasis on expanding the geothermal resource base by including potential sites for enhanced geothermal systems (EGS), engineering concepts need to be developed for a variety of geological settings that are not normally accessed for geothermal electricity production. As the enhancement of a geothermal reservoir involves fracturing of the reservoir rocks, the risks of this process needs to be understood in detail to both increase the probability of creating the enhanced flow paths for fluid circulation to make exploitation of the reservoir economically viable and to reduce the risk of triggering earthquakes that can be felt at the surface, disturb the public and cause damages to buildings.

It is clear that we need a more sound theoretical understanding complemented by hands on experience in pilot projects. For these pilot projects we need guidelines for safe and reliable EGS operations. The EU project GEISER will provide these. Key is a dynamic –forewarning- traffic light system. The reliability of the dynamic model comes from physics and probabilistic based underpinning for seismicity forecasting, calibrated to geological subsurface information and real-time monitoring data. This approach allows adjusting operational conditions to mitigate unsolicited effects and to improve system performance.

Further the guidelines will propose a strategy to enhance public support to EGS projects, based on lessons learned from past projects. A cost-benefit balance for the stakeholders throughout the entire exploration and production workflow is important, capable of identifying and proper addressing different interests and (perceived) risks regarding a specific EGS project. In view of the latter, nuisance and trivial damage should be addressed with care and considered as a significant project risk. For structural damage a procedure is needed to evaluate and compensate the costs involved.

Session V – Geothermal well drilling

Miklos Antics and Pierre Ungemach

Presenter

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Pierre Ungemach, presently Chairman of GPC IP, a geothermal engineering and service company he founded in 1989. Holds Masters degrees in Physics and Applied Maths and a post graduate degree in Geophysical Engineering. His wide professional experience covers the areas of physics of the Earth interior, geophysical prospecting, reservoir engineering and simulation, well testing and log analysis, geothermal engineering and servicing. Pierre Ungemach served successively, among other appointments, as ground water consultant (Ital Consult, Italy), research engineer (French School of Mines, French Geological Survey, BRGM), R&D Programme Manager in geothermal energy(European Commission, DGXII). Served two terms (1995-2001) as IGA BoD member. Currently Board member of the IGA European Branch Forum and of EGEC (European Geothermal Energy Council) and member of the GRC (Geothermal Resources council). Authored and co-authored over seventy technical/scientific papers, including six books and conference proceedings. Holds six patents in drilling/completion and production processes.

Miklos Antics, presently Managing Director of GPC IP, is a graduate and post graduate reservoir engineer of the Ploïesti (Romania) School of Petrol. Holds a PHD in well testing, multiphase flow and reservoir simulation. Miklos Antics has gained a wide experience in resevoir engineering, simulation, well testing/logging and drilling/production in teaching, field practice and operation management areas. He served as Secretary of the Romanian Geothermal Association and is currently secretary of EGEC (European Geothermal Energy Council), member of the IGA BoD, Chairman of the Programme and Planning Committee, and Chairman of the IGA European Branch Forum. He authored/co-authored over 35 technical papers and four textbooks.

Abstract

The formation and reservoir conditions that characterise geothermal systems require the adoption of drilling practices that differ from those utilised in conventional oil, gas, and water well drilling operations. Temperature, Geology, and Geochemistry are the principal areas of difference.

This paper outlines typical geothermal drilling conditions, and the drilling practices that have been developed to optimise the drilling processes in these conditions.

Acknowledgment

The first part of this paper was authored by Hagen Hole and was borrowed from the Lecture Notes of SC1: Drilling completion of geothermal wells held at WGC2010, Bali, Indonesia

Keywords: geothermal, drilling

Introduction

Although heat from geothermal sources has been used by mankind from the earliest days – for cooking and bathing, for instance - its major development has taken place during the past 30 years. This has occurred in parallel with the significant advances made in deep drilling practices, and it's importance has risen dramatically during the last few years as the price of petroleum has soared, and awareness of the importance of 'renewable energy' has developed.

The equipment and techniques used in the drilling of geothermal wells have many similarities with those used in exploring and exploiting petroleum reservoirs. However, the elevated temperatures encountered; the often highly fractured, faulted, and permeable volcanic and sedimentary rocks which must be drilled; and the geothermal fluids which may contain varying concentrations of dissolved solids and gases have required the introduction of specialised drilling practices and techniques.

Temperature

The temperature of the earth's crust increases gradually with depth with a thermal gradient that usually ranges from 5° to 70° per kilometre. In anomalous regions, the local heat flux and geothermal gradients may be significantly higher than these average figures. Such anomalous zones are typically associated with edges of the continental plates where weakness in the earth's crust allow magma to approach the surface, and are associated with geologically recent volcanism and earthquakes. It is in such settings that the majority of geothermal resources are found and that the majority of geothermal wells have been drilled.

While a few wells have been drilled into temperature conditions that approach the critical point of water (374°C) and a number of fields produce dry and superheated steam, the majority of higher enthalpy resources are two phase - either vapour or water dominated, with temperature and pressure conditions controlled by the saturated steam / water relationship - "boiling point for depth".For design purposes, where downhole pressures and temperatures are not known, 'boiling point for depth' (BPD) conditions are assumed from ground level as indicated in Figure 1.

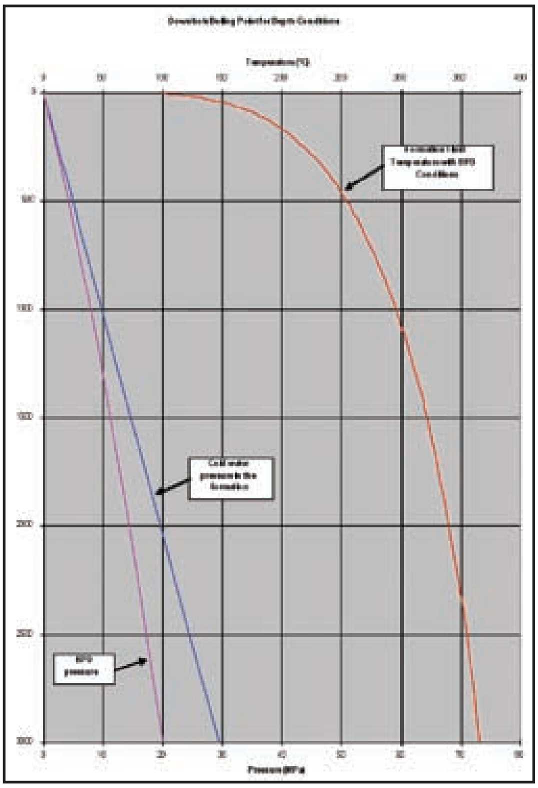

Figure 1. Downhole fluid conditions - BPD.

Saturated steam has a maximum enthalpy at 235˚C and consequently many geothermal fields are found to exist at temperatures approximating this value (dissolved solids and gases change this value somewhat). Such elevated formation temperatures reduce drill bit and drilling jar performance and often precludes the use of mud motors and directional MWD instrumentation equipment; it adversely effects drilling fluid and cementing slurry properties; and reduces the performance of blow out prevention equipment. In addition it significantly increases the potential for reservoir fluid flashing to steam resulting in flowback or blowout from shallow depths.

The well, the downhole well components and the near well formations are subject to large temperature changes both during the drilling process and at the completion of drilling. The circulation or injection of large volumes of drilling fluid cools the well and the near well formation, but as soon as fluid circulation is ceased, rapid re-heating occurs. These large temperature differentials require special precautions to be taken:-

- to avoid entrapment of liquids between casing strings – which can exert extreme pressure when heated resulting in collapsed casing.
- to ensure casing grade and weight, and connection type is adequate for the extreme compressive forces caused by thermal expansion.
- to ensure the casings are completely cemented such that thermal stress are uniformly distributed.
- to ensure casing cement slurry is designed to allow for adequate setting times and to prevent thermal degradation.

Geology

Geothermal fields occur in a wide variety of geological environments and rock types. The hot water geothermal fields about the Pacific basin are predominantly rhyolitic or andesitic volcanism, whereas the widespread hydrothermal activity in Iceland occurs in extensively fractured and predominantly basaltic rocks. In contrast the Larderello steam fields in Italy are in a region of metamorphic rocks, and the Geysers steamfield in California is largely in fractured greywacke.

The one common denominator of all of these fields is the highly permeable, fractured and faulted nature of the formations in which the reservoirs reside. This high permeability is one of the fundamental and requisite components for any geothermal system to exist.

Typically, the permeable nature of the formations is not limited to the geothermal reservoir structure alone, but occurs in much of the shallower and overlying material as well.

In addition, a characteristic of most of these geothermal systems is that the static reservoir fluid pressures are less than those exerted by a column of cold water from the surface – the systems are "under-pressured". The high temperatures of the systems result in reservoir fluid densities which are less than that of cold water, and the majority of geothermal systems are located in mountainous and elevated situations – resulting in static water levels often hundreds of metres below the surface.

Drilling into and through these permeable and "under-pressured" zones is characterised by frequent and most often total loss of drilling fluid circulation.

Particularly in the volcanic geothermal systems, many of the shallow formations comprise low bulk density materials such as ashes, tuffs and breccias, which as well as being permeable, are often unconsolidated and friable, and exhibit a low fracture gradient, and thus provide low resistance to blowouts.

Geochemistry

Geothermal fluids contain varying concentrations of dissolved solids and gases. The dissolved solids and gases often provide highly acidic and corrosive fluids and may induce scaling during well operations. Dissolved gases are normally dominated by CO_2 but can also contain significant quantities of H_2S, both of which can provide a high risk to personnel and induce failure in drilling tools, casings and wellhead equipment.

The presence of these dissolved solids and gases in the formation and reservoir fluids imposes specific design constraints on casing materials, wellhead equipment and casing cement slurry designs.

Drilling practices

In general, the drilling processes and equipment utilised to drill deep geothermal wells are substantially similar to those developed for petroleum and water well rotary drilling. However, the downhole conditions experienced in geothermal systems, as described above, require some significantly different practices to be adopted. Some of these differences are outlined below.

Well design

The thermal efficiency of converting geothermal steam/water to electricity is not particularly high (±20%), therefore large mass flows and therefore volume flowrates are required, particularly in vapour dominated systems. These large volume flowrate requirements necessitate large diameter production casings and liners.

Typically a "standard" sized well will utilize standard API 9 5/8" diameter casing as production casing and either 7" or 7 5/8" diameter slotted liner in an 8½" diameter open hole section.

A “Large” diameter well will typically utilise standard API $13^{3}/_{8}$” diameter casing as the production casing, with either $9^{5}/_{8}$” or $10^{3}/_{8}$” diameter slotted liner in a $12^{1}/_{4}$” diameter open hole.

Casing sizes utilised for the Anchor, Intermediate, Surface and Conductor casings will be determined by geological and thermal conditions.

Figure 2 illustrates schematically the casing strings and liner of a typical geothermal well.

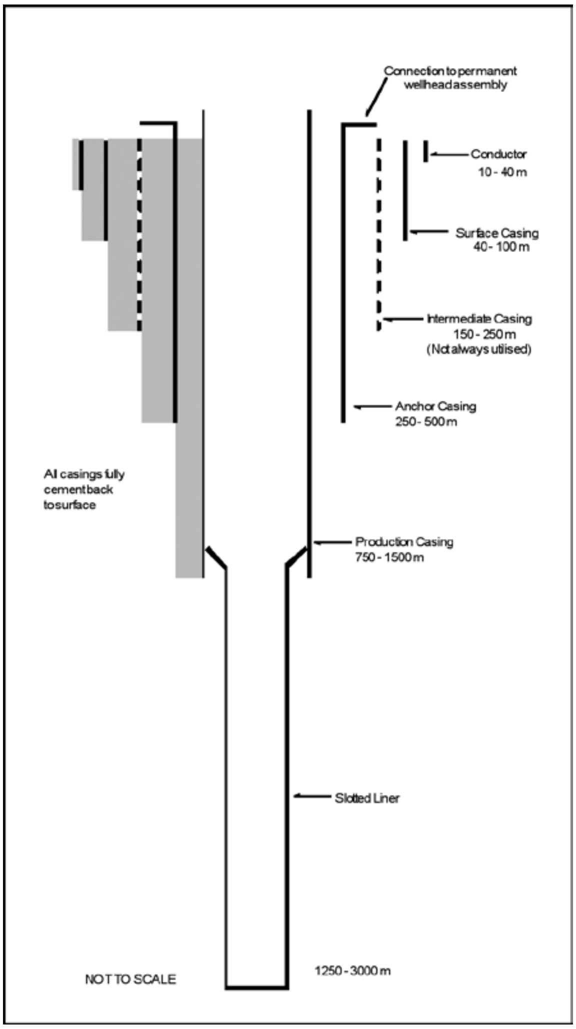

Figure 2. Casing strings and liner for a typical well.

Casing depths

The depths of all cemented casing strings and liners is determined such that the casings can safely contain all well conditions resulting from surface operations and from the characteristics of the formations and fluids encountered as drilling proceeds.

Casing shoe depths are determined by analysis of data from adjacent wells which will include rock characteristics, temperatures, fluid types and compositions and pressures. In particular fracture gradient data gathered from nearby wells. At any time the depth of open hole below a particular casing shoe should be limited to avoid exposure of the formations immediately below the casing to pressures which could exceed the fracture gradient at that depth and hence lead to a blowout. It is usual to assume worst case scenario’s such as exposing the previous casing shoe to the saturation steam pressure at the total drilled depth of that section. Figure 3 illustrates how the shoe depths may be chosen using a somewhat simplistic and theoretical model with boiling point for depth fluid pressure condition from a nominal water level at 200 m depth; and a uniform formation fracture gradient from the surface to the total depth of 2400 m.

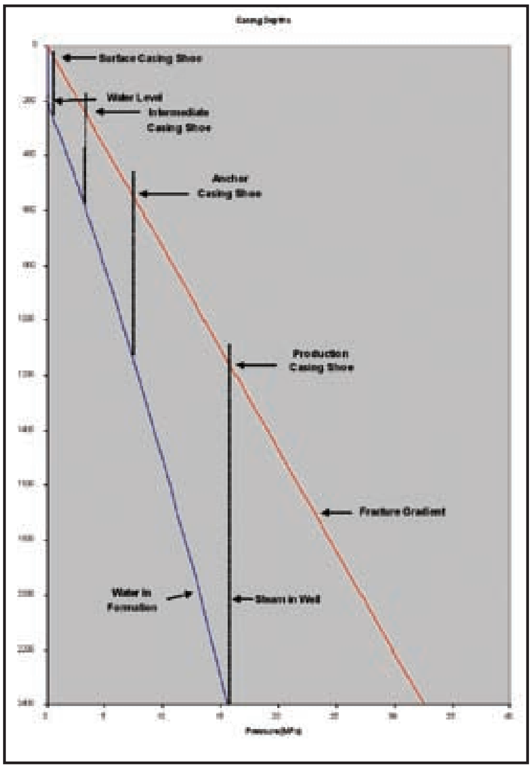

Figure 3. Casing Shoe Depths

This simplistic model suggests that the production casing shoe would need to be set no shallower than 1100m; the anchor casing shoe at approximately 550 m; an intermediate casing set at 250 m depth; and a surface casing set at around 40 m depth.
It is likely that with real data that this casing programme would be somewhat simplified, the production and other casings shoes somewhat shallower, and the intermediate casing eliminated.

Casing diameters

Casing diameters will be dictated by the desired open hole production diameter - typically either 8½" or 12¼". Slotted or perforated liners run into these open hole sections should be the largest diameter that will allow clear running - there is an obvious advantage to utilise "extreme line" casing connections from a diameter point of view, however this is often offset by reduced connection strength of this type of casing connection.
Casing internal diameters should not be less than 50 mm larger than the outside diameter of connection collars and accessories, to allow satisfactory cementing.

A typical well design would include:-

- Conductor:– 30" set at a depth of 24 metres, either driven or drilled and set with a piling augur.
- Surface Casing:- 20" casing set in 26" diameter hole drilled to 80 metres depth.
- Anchor Casing:- 13 3/8"casing set in a 17½" hole drilled to 270 metres depth.
- Production Casing:- 9 5/8" casing set in a 12¼" hole drilled to 800 metres depth.
- Open Hole - 7" perforated liner set in 8½" hole drilled to 2400 m - Total Depth.

Casing materials

Steel casing selected from the petroleum industry standard API Spec. 5CT or 5L.
In general the lowest tensile strength steel grades are utilised to minimise the possibilities of failure by hydrogen embrittlement or by sulphide stress corrosion. The preferred API steels are: Spec 5CT Grades H-40, J-55 and K-55, C-75 and L-80; Spec 5L grades A, B and X42.
In cases where special conditions are encountered, such as severely corrosive fluids, use of other specialised materials may be warranted.

Casing connections

The compressive stress imposed on a casing strings undergoing heating after well completion is extreme. As an example, an 800 metre length of casing undergoing heating from the cement setup temperature of around 60˚C to the final formation temperature of 210˚C (a change of 150˚C), would freely expand 1.44 m. If uniformly constrained over the full length, the compressive strength induced would be 360 MPa; the minimum yield strength of Grade K-55 casing steel is 379 MPa. As this illustrates, axial strength is critical and it is therefore important that the casing connection exhibits a compressive (and tensile) strength at least equivalent to that of the casing body.
It is usual that a square section thread form is chosen, and this is typically the API Buttress threaded connection.

Cementation of casings

Unlike oil and gas wells, all of the casings down to the reservoir are usually run back to the surface, and are fully cemented back to the surface. The high thermal stresses imposed on the casings demand uniform cementation over the full casing length, such that the stress is distributed over the length of the casing as uniformly as is possible and such that stress concentration is avoided.

The objective of any casing cementing programme is to ensure that the total length of annulus (both casing to open hole annulus, and casing to casing annulus) is completely filled with sound cement that can withstand long term exposure to geothermal fluids and temperatures.

Of course, as suggested above, the permeable and under-pressured nature of the formations into which these casings are being cemented means that circulating a high density cement slurry with S.G.'s ranging from 1.7 to 1.9, inevitably result in loss of circulation during the cementing procedure.

The traditional method of mitigating this problem was to attempt to seal all permeability with cement plugs as drilling proceeded, however, this is usually an extremely time consuming process, and more often than not, circulation is still lost during the casing cementing process.

Many approaches to overcome this problem have been tried, and include:-

- Low density cement slurry additives – pozzalan, perlite, spherical hollow silicate balls
- Sodium silicate based sealing preflush
- Foamed cement
- Stage cementing
- Tie back casing strings – the casing is run and cemented in two separate operations.

Many of these options were tried but generally none have proven totally successful nor economic.

To date, in the experience of the author, the most successful procedure has been to utilise the most simple high density cement slurry blend, and to concentrate on the techniques of placing the cement such that a full return to the surface without fluid inclusions can be achieved. This nearly always involves a primary cement job carried out through the casing, and in the event of a poor or no return and immediate annulus flushing procedure, which is then followed by an initial backfill cement job through the casing to casing annulus, with sometimes repeated top-up cement jobs. Particular care must be taken to avoid entrapment of any water within the casing to casing annulus.

Perforated and slotted liner

Unlike the cemented casings discussed above, it is usual to run a liner within the production section of the well. This liner is usually perforated or slotted, typically, with the perforation or slots making up around 6% of the pipe surface area. As it is extremely difficult to determine exactly where the permeable zones within the production section lie, it is usual that the entire liner is made up of perforated pipe.

The liner is not cemented, but either hung from within the previous cemented production casing, or simply sat upon the bottom of the hole with the top of the liner some 20 to 40 metres inside the cemented production casing shoe, leaving the top of the liner free to move with expansion and contraction.

Drilling rig and associated equipment

The drilling rig and associated equipment are typically the same as is utilised for oil and gas well drilling, however a few special provision are required.

- Because of the large diameter holes and casings utilised in the surface and intermediate (if used) casing strings, it is important that the rotary table is as large as practicable - typically a 27½″ diameter rotary table is utilised, and even 37½″ is sometimes seen.
- Again, due to the large hole diameters drilled in the upper sections, large diameter Blow Out Preventers (BOP's) are required, however only moderate pressure rated units are necessary – a typical set of BOP stacks would include:-

  - 30″ (or 29½″) 500/1000 psi annular diverter and associated large diameter hydraulically controlled diversion valve.

  - 21¼″ 2000 psi BOP stack including blind and pipe ram BOP's and an annular BOP.

  - $13^5/_8$″ 3000 psi BOP stack including blind and pipe ram BOP's and an annular BOP.

  (comparatively – oil and gas rigs would usually have 5000 psi and 10000 psi rated BOP's)

  For aerated drilling 21¼″ and $13^5/_8$″ rotating heads and a $13^5/_8$″ 'Banjo box' is required.
- The use of a 'choke manifold' is not mandatory in geothermal operations; usually an inner and outer choke valve is sufficient.
- As the BOP stacks are relatively large and occupy a significant height above the ground level (in particular if aerated drilling is to be used) it is necessary that rigs are equipped with an 'extra' height sub structure – a clear height of at least 6 metres is necessary.
- All of the elastomeric parts of the BOP's must be high temperature rated.
- It is preferable, although not mandatory, that rigs are fitted with top drive units – allowing for drilling with a double or triple stand of drill pipe; for easy connection and circulation while tripping the drill string in or out of the hole; and for back reaming.
- Rig mud pumps – (usually tri-plex) must be capable of pumping 2000 to 3000 lpm on a continuous basis. Pressure rating is not as important as pumped volume; pumps must be fitted with large diameter liners (usually 7″ diameter).

- Rig mud pumps must be piped to the rig such that fluid can be pumped to both the rig standpipe and to the kill line (annulus) at the same time. It is important that the pump sizes or quantity of pumps is such that sufficient fluid can be pumped for drilling purposes, while a secondary volume – say 1000 lpm can be simultaneously pumped to the kill line.
- The drilling fluid circulating system requires a fluid cooling unit – often a forced draft direct contact cooling tower, or chilling unit.
- Drilling water supply must be capable of providing a continuous supply of at least 2000 lpm and preferable 3000 lpm - backup pumps and often dual pipelines are utilised.
- Drillpipe should be lower tensile strength material to avoid hydrogen embrittlement and sulphide stress corrosion – usually API Grade E or G105. Drillpipe is now usually supplied with a plastic internal lining, it is important that this lining has a high temperature rating.
- A high temperature rated float valve, (non return valve), is always fitted immediately above the drill bit in the drill string to prevent backflow into the drill string which often results in blocking of the drill bit jets.
- Drill bits – usually tri-cone drill bits are utilised however the elastomeric parts of the bearing seals and the lubrication chamber pressure compensation diaphragm are particularly heat sensitive. It is important that while tripping the drill string into the hole, that the bit is periodically cooled by circulating through the drill string.
- PDC – polycrystalline diamond compact drill bits are now being used more often - initially they were found to be totally unsuitable for hard fractured rock drilling – improvements in materials are now making this type of bit a real option. With no moving parts, bearings and seals they are essentially impervious to temperature.
- Drilling tools – the high downhole temperatures limit use of mud motors and MWD instrumentation tools to the upper cooler sections of the hole.

Drilling fluids

The upper sections of a well are usually drilled with simple water based bentonite mud treated with caustic soda to maintain pH. As drilling proceeds and temperatures increase, the viscosity of the mud is controlled with the addition of simple dispersants. If permeability is encountered above the production casing shoe depth, attempts will be made to seal these losses with ‘Loss of Circulation Materials’ (LCM), and cement plugs. If the losses cannot be controlled easily, then the drilling fluid is switched to either water ‘blind’ – that is drilling with water with no circulation back to the surface, or to aerated water.

Once the production casing shoe has been run and cemented, and drilling into the production part of the well commences, mud is no longer use as drilling fluid as it has the potential to irreparably damage the permeability and thus the production potential of the well.

Once permeability is encountered in the production section of a geothermal well, drilling was traditionally continued with water, 'blind' – with no return of the drilling fluid to the surface. The drill cuttings are washed into the formation, and periodic 'sweeps' with either mud or polymer assists in keeping the hole cleared of cuttings.

While this method alleviates the impractical and uneconomic loss of large volumes of mud, and the associated mud damage to the formation, the build up of cuttings within the hole often results in stuck drill strings, and the washing of cuttings into the formation causes damage to the permeability, although not on the same scale as bentonite mud.

Aerated water is now more commonly utilised for drilling this section of the well. To enable circulation of drilling fluids to be continued despite the presence of permeability and 'under pressured' reservoir conditions, the density of the drilling fluid must be reduced. The addition air to the circulating water allows a 'balanced' downhole pressure condition to be established, and the return and circulation of the drilling water and cuttings back to the surface.

Well control

Perhaps one of the most crucial differences between geothermal and oil and gas drilling operations is the nature of the formation fluids and how they can be controlled.

A geothermal well has the potential of being filled with a column of water at boiling point – even the slightest reduction in pressure on that column can cause part of, or the entire column to boil and flash to steam. This process can occur almost instantaneously. The potential for 'steam kick' is always there and requires special drilling crew training and attention.

Whilst the likelihood of a well kicking at any time is real, the method of controlling such a kick is simple and effective. Steam is condensable, so by simply shutting in the BOP's and pumping cold water into the well – both down the drilling and down the annulus, the well can be quickly controlled. The pressures involved are not high, as they are controlled by the steam / water saturation conditions.

During such a 'steam kick' it is normal that some volume of non-condensable gas (predominantly CO_2) will be evolved. After the steam fraction has been quenched and cooled, it is usual that this usually small volume of non-condensable gas be bled from the well through the choke line. Some H_2S gas may be present, usually in small quantities, so precautions are required.

Running the open-hole liner

One of the final tasks in completing the drilling of a geothermal well is the running and landing of the perforated or slotted liner. At this stage the drilling operations have been completed and hopefully permeability and a productive resource has been encountered. This operation is potentially critical as while a string of perforated or slotted liner (casing) is through the BOP stack, the functionality of the BOP stack is disabled. It is critical that a significant volume of quenching water is pumped to the well prior to and throughout the entire process.

In the event that a kick occurs in this condition, there are only two options available. A capped blank joint of pipe must be readily available so that it may be screwed in and run into the BOP stack so the well may be closed and then quenched. The alternative is that the liner is released and dropped through the BOP stack allowing it to then be closed and the well then quenched. Neither option a very satisfactory situation – it is crucial that a full understanding of the behaviour of the reservoir and the necessary quench volumes that are required to maintain the well in a fully controlled state.

The reliability of the water supply system for this process is of paramount importance.

Geothermal district heating and cooling: typical well designs and drilling/completion programs

Contrary to current oil and gas practice, drilling and completion of high enthalpy, dry and flashed steam, wells address non sedimentary volcano-tectonic settings and hard and abrasive rock environments, often exhibiting massive circulation losses. Such is not the case of low to medium enthalpy geothermal wells which, in most instances, are completed in sedimentary reservoirs, therefore applying straightforwardly standard petroleum drilling technology. However, completion designs should differ; as a matter of fact geothermal completions aim at maximizing fullbore well delivery, whereas hydrocarbon production, at least one order of magnitude lower than its geothermal counterpart , is in general completed inside the wellbore via a tubing-packer-safety valve- perforated casing/cement suite.

Current low to medium enthalpy geothermal drilling/completion technology will be illustrated through selected examples focused on (i) deep district heating and cooling wells drilled in carbonate and sandstone reservoirs, (ii) design of injection wells in fine grained clastics alternating sand, clay, sandstone depositional sequences, (iii) medium depth dual completion wells exploiting tepid aquifers in conjunction with water/water heat pumps, and, last but not least, (iv) an anti-corrosion well concept combining steel casings and fiberglass liners.

Geothermal district heating and cooling wells

Deep wells

The standard design of a geothermal district heating and cooling (GDHC) system is described in Fig. 1 (geothermal loop features).

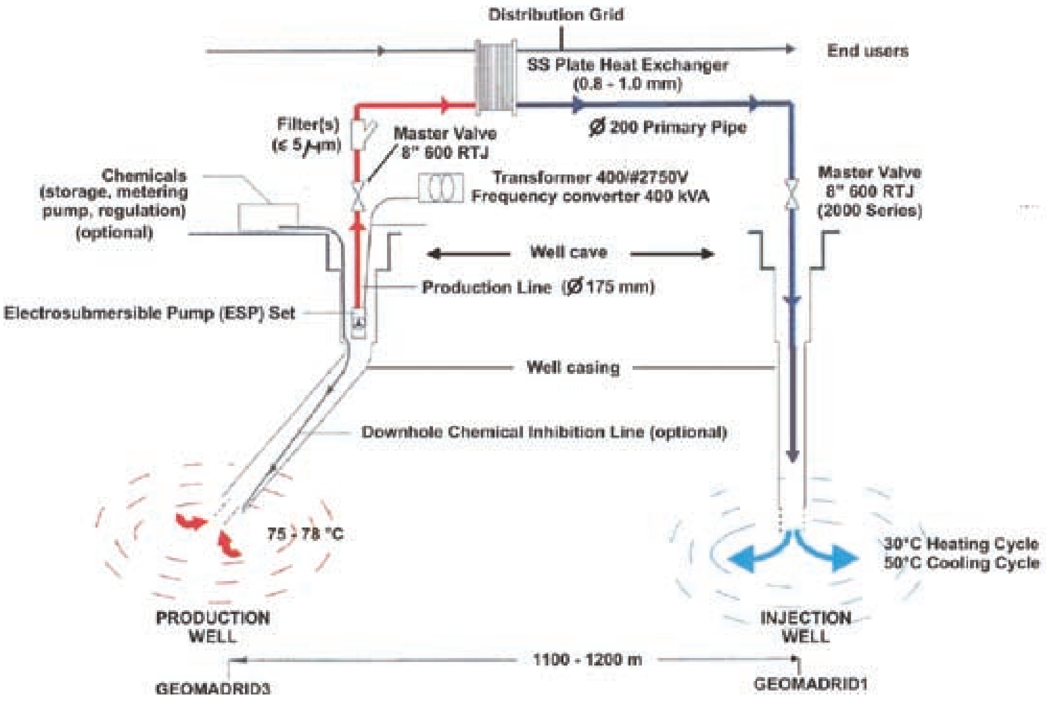

Figure 4. Geothermal District Heating & Cooling – Primary Loop Schematic

The system for waste disposal, pressure maintenance and heat recovery considerations is based on the geothermal doublet concept of heat extraction depicted in Fig.2 and 3 with respect to carbonate reservoir environment and either a casual steel cased or combined steel cased/fiber glass lined well completion.

The impact of two standard GDHC production casing programs [pumping chamber x production casing] on well losses can be visualised in Fig. 4.

Fig. 5 addresses the design of a well producing from a thick sandstone hot water aquifer, complying with the programme summarised in Table 1 and in Fig. 6 time-depth chart.

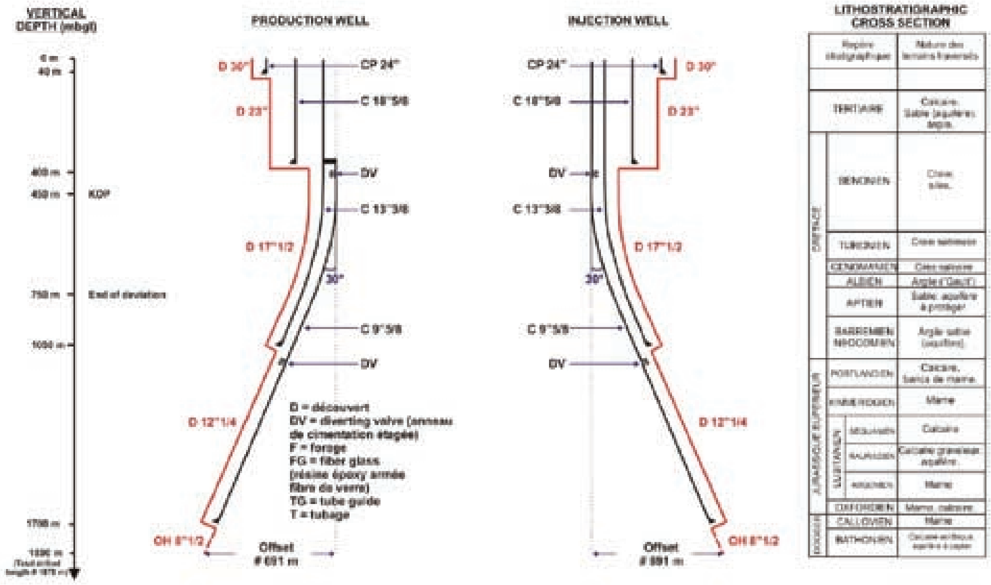

Figure 2. Conventional (steel cased) GDH doublet design

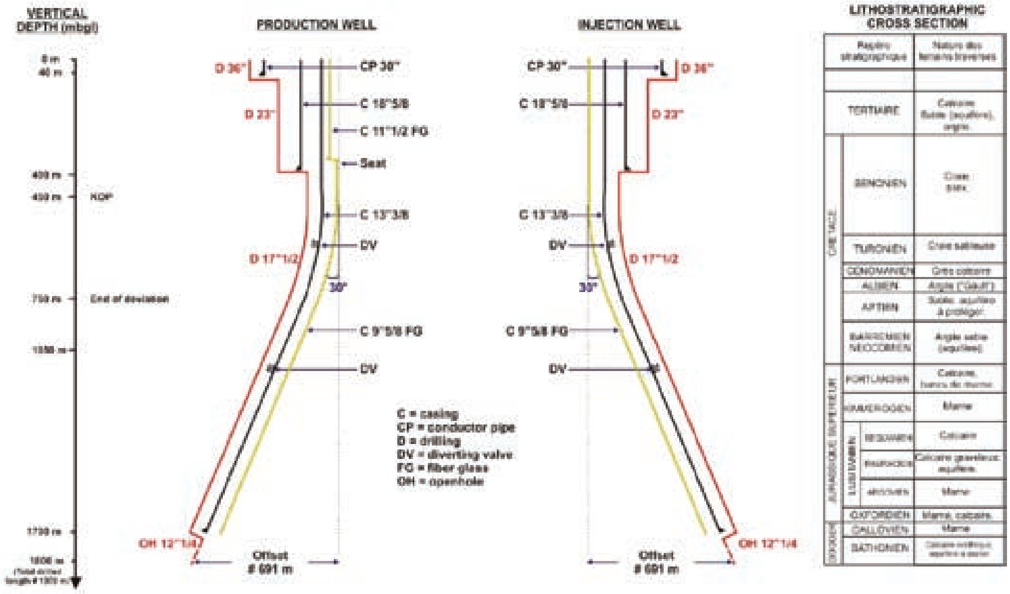

Figure 5. GDH doublet completion combining steel casing and fiber glass liners

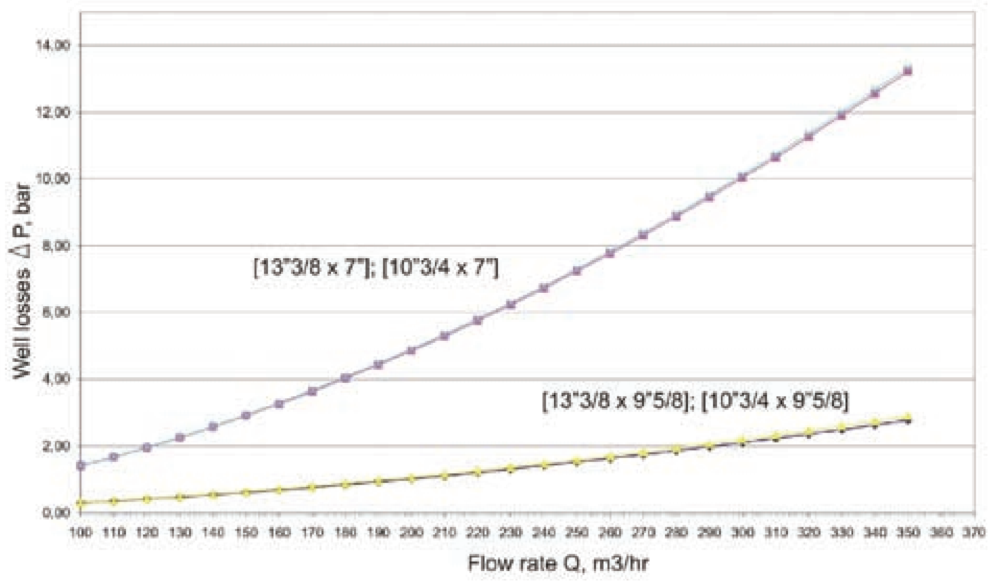

Figure 6. Friction losses as a function of production casing programmes

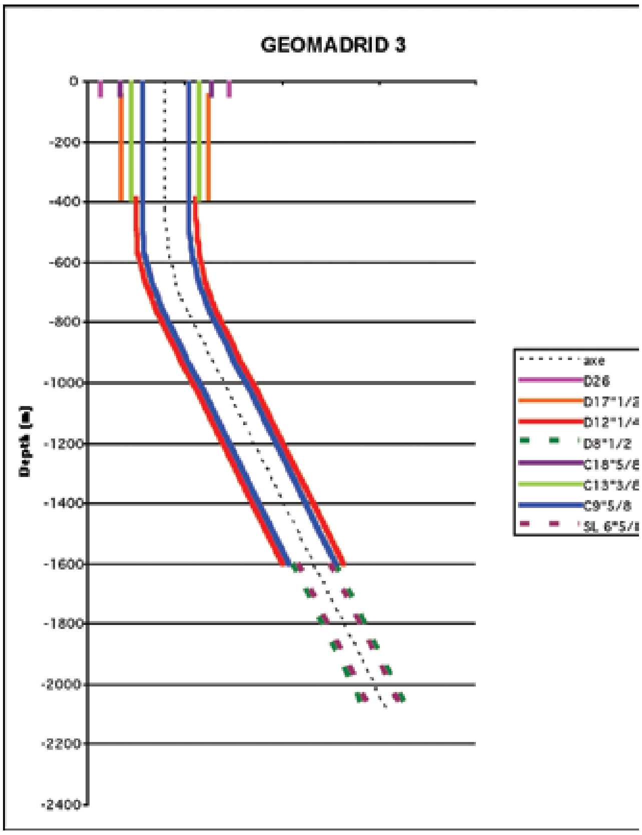

Figure 7. Production well profile. Consolidated sandstone reservoir

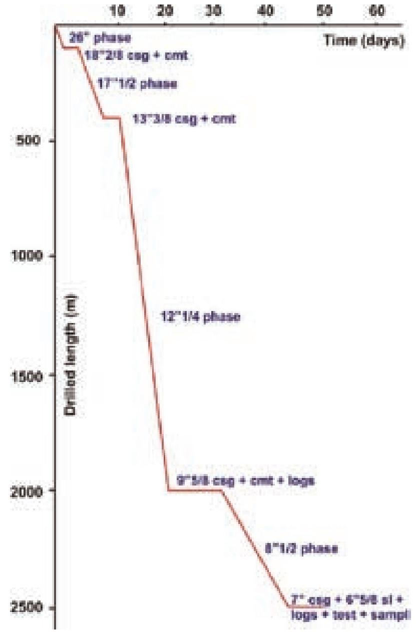

Figure 8. Projected drilling/completion/testing time vs depth diagram

Medium depth wells

Fig.9 is an illustration of a water/water heat pump assisted GDHC doublet based on a dual aquifer completion scheme in a sandy formation context, casual in petroleum production but unusual in geothermal and groundwater projects.

Note incidentally that Fig. 7 design may accommodate the operation of two submersible pump sets.

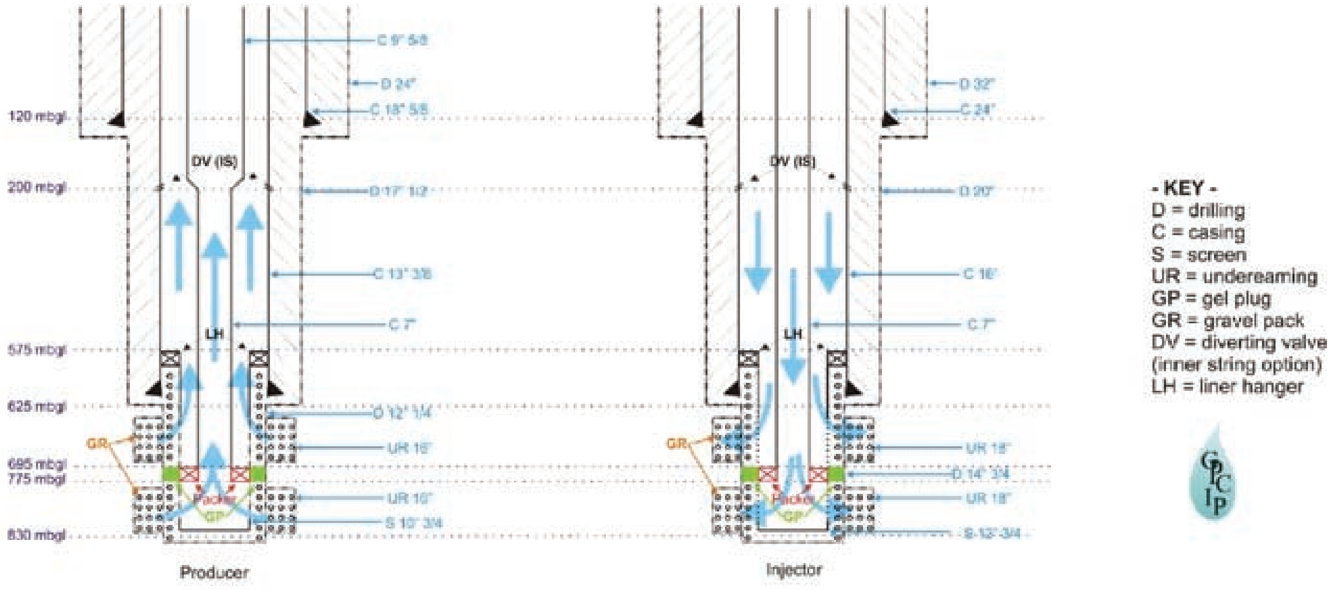

Figure 9. Dual, heat pump oriented, water well completions. Note that the producer well can be equipped with two submersible pump sets.

Water injection in fine grained reservoir clastics

Injection wells are known to undergo severe injectivity losses further to near wellbore permeability impairment and subsequent formation damage, a topic further discussed in section 6.5.

Given the produced, heat depleted, brine is injected into the source reservoir, no water incompatibilities are to be feared. Therefore, matrix plugging by fine, preferably external, particles is the prevailing damaging mechanism. To be defeated or at least mitigated it requires, in addition to surface filtration facilities, careful completion design regarding casing diameters, undereaming and gravel pack grain size and placement, screen selection among others. Based on field experience the foregoing should lead to sandface velocities lower than the 1cm/s critical threshold.

A typical well completion designed to secure 150m3/h injection flowrates in the Great Hungarian Plain (Pannonian basin), fulfilling the aforementioned requirements, is attached in Fig. 8.

Projected well/reservoir performance	
Top reservoir depth	1,500 m
Static WHP	-5 bars
Total pay	400 m
Net pay (h)	110 m
Effective porosity ($_e$)	0.2
Permeability (k)	100 mD
Skin factor (S)	-2
Formation temperature	90 ˚C
Mean injection temperature	35 ˚C
Fluid (eq. NaCl) salinity	2.5 g/l
Fluid dynamic viscosity (production) (µp)	0.32 cp
Fluid dynamic viscosity (injection) (µi)	0.73 cp
Total compressibility factor (c_c)	10^{-4} bars^{-1}
Fluid density (ρp) at 90 ˚C	965.34 kg/m^3
Fluid density (pi) at 35 ˚C	994.06 kg/m^3
Target injection rate (Q)	150 m^3/hr
WHP (150 m^3/hr, 35 ˚C)	20.5 bars
Sandface velocity (v_{sf})	0.23 cm/s
Velocity at completion outlet (v_c)	0.61 cm/s

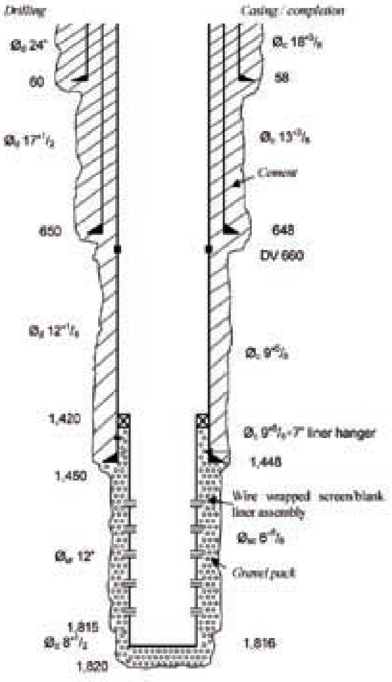

Figure 10. Water injection in a clastic sedimentary environment. Typical well completion design [Ungemach, 2003]

Anti-corrosion well concept

The design, depicted in Fig. 9, is a material response to corrosion damage. It has been successfully implemented on a Paris Basin self flowing well in early 1995 and since then the well has been operating, at a constant 200 m^3/h discharge, without any workover nor even light well head servicing recorded whatsoever, contrary to his steel cased GDHC companions which undergo at least one heavy duty workover every ten years or so.

The well combines steel propping casings, providing the required mechanical strength, with a fiberglass production/

injection column, chemically inert vis-à-vis any geothermal corrosive fluid environment. The annulus is kept free in order (i) to circulate (or simply fill) corrosion inhibitors, preserving steel casing integrities, and (ii) to remove the fiberglass string whenever damaged (wheap destructuring) and replace it by a new one thus achieving long well life. Fiberglass integrity is assumed to last 25 to 30 years.

Operating temperatures are limited by the glass vitreous transition temperature, the practical limit being set at ca 90°C. Well inclination should not exceed 35°C. The production well architecture, displayed in Fig.9, requires (i) a larger diameter fiberglass column, to accommodate an ESP placed in compression on a fiber glass coated seat at the (18"5/8 x 13"3/8) casing transition, and (ii) a slimmer liner, freely suspended under its own weight below the seat. Both liners are centralised via fiberglass coated centralisers so that there is no contact other than with fiberglass materials. Thermomechanical effects are compensated at well head by an *ad hoc* expansion spool.

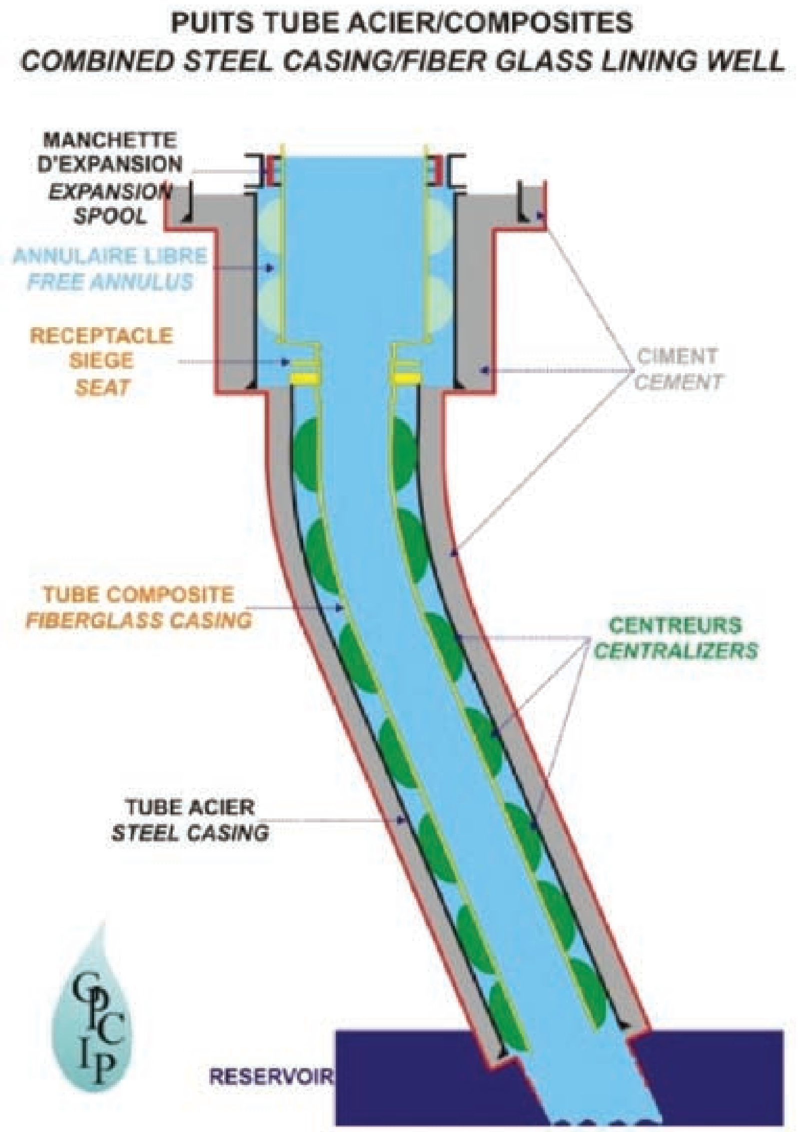

Figure 11. Combined steel casing/fiber glass lining well (GPC)

Table 1. Drilling/completion/testing programme

DRILLED DEPTH INTERVAL (mbgl)	PHASE DESCRIPTION	REMARKS
0 – 50	Drill ϕ 26”, tricone roller bit, WOB # 12-25 t ; 800-200 rpm ; >3500 l/min ; penetration rate 5 m/hr. Bentonite base mud: d = 1.10 – 1.15; V # 30 – 50 M. Run 182/5/8 casing. Inner string cementing = CP55 Cement slurry, d = 1.80	Possible meterage change owing to completion of a large diameter, 0 – 20 m, foreshaft
50 – 400	Drill “ 17”1/2, tricone roller bit, WOB # 15-20 t ; 80-200 rpm ; >3500 l/min; penetration rate 7-8 m/hr. Bentonite base mud: d = 1.10 – 1.15; V # 35 M. Run 132/3/8 casing. Inner string cementing = CP55 Cement slurry, d = 1.80	Designed as a future pumping chamber withstanding a 150 – 200 m water level drawdown
400 – 1850	Drill “ 12”1/4, PDC bit, WOB # 12 t ; 120 rpm ; 2500-3000 l/min; penetration rate 4-5 m/hr. Bentonite/PAC, PAC+CMC/polymer base mud formulations: d = 1.10 - 1.15; V # 35 M. Start deviation @ KOP=450 m with downhole, steerable, motor, MWD, KMonel, hydraulic jar, assembly; build up gradient = 1˚/10 m; slant angle # 380, azimut = __*. When reaching # mbgl drilling depth continue either with identical motorised, steerable, BHA or, with rotary assembly instead. Run 905/8 casing with either a liner hanger or DV + left hand connection (casing cut) to accommodate the required 13”3/8 pumping chamber space. Conventional stage cementing procedure with cementing head, shoe, float collar and DV placed @ # 1100, above the upper lost circulation horizon, POZZMIX (dry blended puzzolane/class G cement) slurry, d # 1.60. Wireline (OH/CH) logging programme = BGL/GR; SPGR; MRT; STI; CIC; CBL-VDL	The 9”5/8 casing cutting strategy should be selected instead of the liner hanger configuration in order to meet the 13”3/8 pumping chamber space requirements. The left hand connection would enable to recover the DV and ease an eventual further 13”3/8 x 9”5/8 casing lining issue.
1850 – 2485	Drill “ 8”1/4, PDC bit (rotary assembly), WOB # 8t ; 120 rpm ; 1500-2000 l/min; penetration rate 5-7 m/hr. Polymer base mud: d = 1.05; V # 35 - 40 M, 50 m full size 5” sample coring. OH/production logging programme = CNL, SGR, SpeD, BGL, HMI (optional), PLT, T, pressure build-up, BHFS (PVT). Run completion string according to flowmeter identified producing layers: 7” casing x 6”5/8 slotted liner assembly. Liner hanger set @ __** mbgl. Mud acid (HF + HCl) well stimulation (10 -20 m^3 HF 4X + HCl 14X). Bottomhole fluid sampling. Surface suspended particle monitoring. Production/injection well loop circulation test.	Mixed (casing x slotted liner) column designed and run downhole according to flow meter logging survey. Bottomhole fluid sampling aimed at liquid and gas phase analyses at reservoir conditions.

* from reservoir modelling

** from geology

Conclusion

The processes of drilling geothermal wells is very similar to those developed by the oil and gas and water well drilling industries, however the nature of a geothermal reservoir system; the temperature; the geology and the geochemistry require that some quite different practices be followed if the drilling process and the resulting well are to be successful.

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Session VI – Flash steam and binary technology

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Presenter

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Curriculum vitae

Mrs Elín Hallgrímsdóttir is a Mechanical Engineer, MSc, from Danmarks Tekniske Universitet in 1998. Mechanical Engineer, CandSc, from University of Iceland 1996. Mrs Elín Hallgrímsdóttir has experience within thermodynamics and process engineering as well as project management and quality systems. Mrs Hallgrímsdóttir has participated as assistant project manager and senior designer within numerous projects in Mannvit such as in the Nesjavellir and Hellisheidarvirkjun geothermal combined heat and power projects. Mrs Hallgrímsdóttir held the position of Mannvit project manager in a feasibility study for KenGen in Kenya. Mrs Hallgrímsdóttir has further given presentations on geothermal energy for short courses held by Mannvit.

Relevant Publication

Hallgrímsdóttir E., Ballzus C. and Hrólfsson H. (2012); “The Hellisheiði Power Plant, Iceland.” GRC transaction, Volume 36, page 1067 - 1072

Abstract

This is an overview of geothermal power plants with focus on flash and binary thermodynamic cycles, geothermal steam gathering system and mechanical equipment used. Further provided examples highlight special features of utilizing geothermal fluid for power generation. The examples taken are connected to the special conditions encountered in geothermal energy.

Flash steam cycles with single flash and double flash as well as different binary cycles as ORC and Kalina Cycle are introduced and compared. Models for different thermodynamic cycles are used to calculate the same example for visual comparison of the different cycles.

An overview presented of the design process of a geothermal steam gathering system with emphasis on particularities of the geothermal fluid. The presenter goes through a calculated example to show methods used for basic engineering within steam gathering system design.

A presentation will focus on mechanical equipment used in geothermal power plants. Emphasis will be on different design considerations compared to conventional steam plants. A calculated example will show methods used for basic engineering within mechanical equipment design.

Operation and maintenance of geothermal power plants with emphasis on the geothermal part of the plant is introduced. Photographs of extreme conditions are discussed with solutions.

Keywords: Geothermal energy, electricity generation, process flow, binary technology, steam gathering system, operation and maintenance

Process flow and steam gathering system

Geothermal power plants utilize heat energy from the Earth to generate electricity and can also be designed as combined heat and power (CHP). They are cost effective, reliable and environmentally friendly. The specific geothermal power plant configurations must match the heat resource to maximize its potential but should also take into account a variety of other criteria including, local conditions and requirements as well as the needs of a community. Thermodynamic cycles used in geothermal energy production will be reviewed with examples. Flash steam cycles with single flash and double flash as well as different binary cycles as ORC and Kalina Cycle are introduced and compared through both capacity and cost.

An overview of the design process of a geothermal steam gathering system with emphasis on particularities of the geothermal fluid is presented. Models for different thermodynamic cycles will be used to calculate the same example for visual comparison of the different cycles.

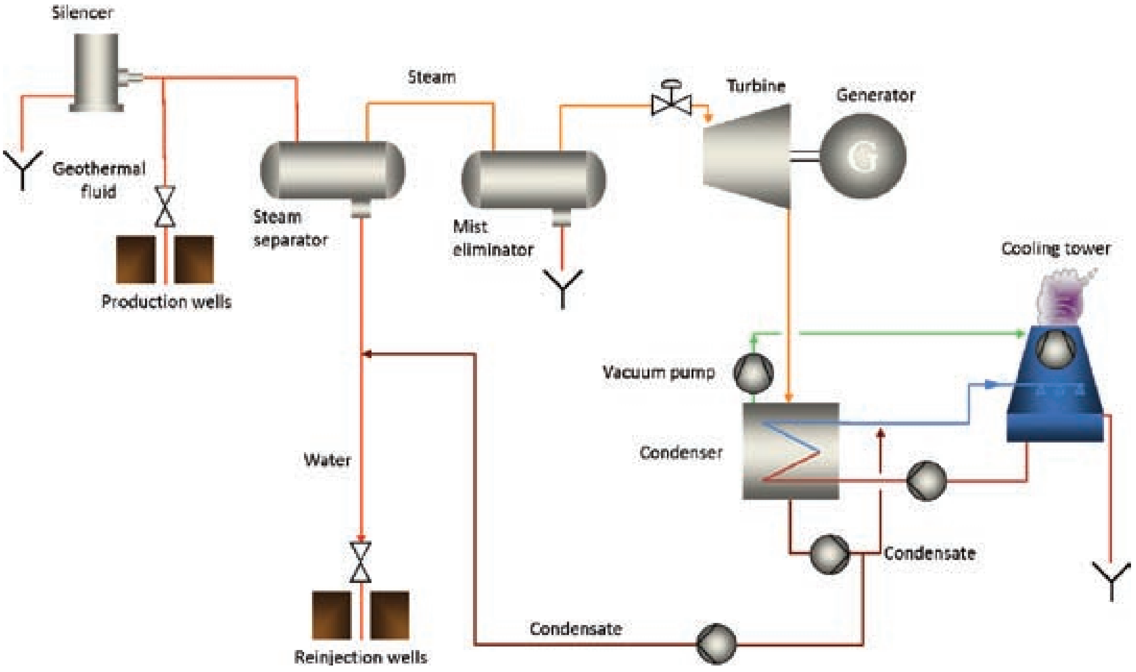


Figure 1. Process Flow Diagram of Steam Power Plant with Condenser

All geothermal fields are unique and the steam gathering system carries the energy from the field to the power plant. To unite multiple wells into one steam gathering system requires for example decision of optimum separator pressure. The presenter will go through a calculated example to show methods used for basic engineering within steam gathering system design. The example taken will be connected to the special conditions encountered in geothermal energy.

Figure 2. Steam field of Hellisheiði Power Plant

The steam field design includes situating wells drilled in groups as appropriate. Wells are preferably situated higher in the landscape than the separator station and power station. If possible the power station should be situated a little lower than the separator station. This is preferred to facilitate natural fluid flow. The distance between separation station and mist separators should be selected long enough for the water droplets to condensate in the pipeline before entering the mist separators.

Mechanical equipment and operation and maintenance

Mechanical equipment used in geothermal power plants are proven traditional equipment adjusted to the geothermal fluids. Emphasis within the course will be on different design considerations compared to conventional steam plants such as geothermal turbine sizes and control solutions at turbine inlet connected to operation of the geothermal steam field. Choice of material for geothermal turbines has to be adjusted to the available steam and is therefore different from material in traditional steam turbines. Non-condensable gases must be considered since they can cause stress corrosion cracking. The steam entering the turbine is saturated and therefore, the steam starts to condense in the turbine. As a result droplets form in the flow and the droplets wear down the turbine blades. To decrease the amount of droplets in the flow, it is important to carefully design lead ways for the condensate in the turbine. Scaling may also occur especially at the first-stage nozzle nearest the turbine inlet leading to reduced generator output. Scaling can impact the effectiveness of the guide vanes. Scaling is removed during regular turbine maintenance.

Figure 3. Machine hall of Hellisheiði Power Plant

The presenter will go through a calculated example to show methods used for basic engineering within mechanical equipment design. The example taken will be connected to the special conditions encountered in geothermal energy.

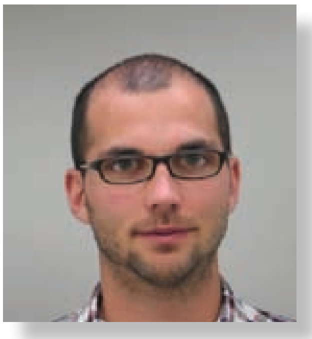
In this session operation and maintenance of geothermal power plants with emphasis on the geothermal part of the plant is introduced. Photographs of extreme conditions will be shown and discussed with solutions.

Figure 4. Scaling and corrosion in turbine casing

Session VII: Plant operation, energy supply and grid integration

Franz Heilemann and Sören Reith

Presenter



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Dr.-Ing Franz Heilemann is experienced in planning, construction and operation of electricity grids on all voltage levels. The development of interdisciplinary smart grid strategies with integration of renewables and customers as well as economic analyses, efficiency benchmarks and regulatory management are part of his work at the network operator EnBW Regional AG.

Sören Reith did his Bachelor at the Baden-Württemberg Cooperative State University Karlsruhe (DHBW), followed by his Master at the Karlsruhe Institute of Technology (KIT), which he finished in 2011. Parallel to his studies he was working in different departments of EnBW. Since 2009 he gathered experience in the research and development.

Abstract

The integration of electricity from geothermal power plants into the electricity grid has to be seen from different perspectives. In the following the legal aspects and the function of the regulated energy market are explained as well as demand for geothermal power and the process, the costs and the legal background of grid integration. This gives the reader a broad understanding of the main foundations for grid integration of geothermal electricity. Based on a regulated energy market different legal system in Europe support the integration of renewable power into the market, which is met by a growing demand for renewable power in general and geothermal power in particular. The growing share of renewable power causes problems in grid stability. That's why besides legal also technical requirements determine the process of grid integration. The costs for grid integration are very site specific and are determined by the network connection point and the installed capacity of the power plant.

Keywords: grid integration; costs of grid integration; energy market; electricity grid

Regulation and energy trade

Electricity supply has developed since its beginnings in the late 19th century in monopolistic structures. Because of expensive infrastructure and its associated economic advantages of a monopole, vertically integrated energy suppliers got the task of supplying the public and the industry with electricity.

With the electricity market directive 96/92/EG the European Union has changed this monopolistic market structure. The goal of this directive was free trade and competition on the electricity market (Konstantin, 2007, S. 37). Since then several other EU directives and decisions have brought European wide energy trade and the possibility for every customer to choose its electricity supplier, part of this is the free access to the electricity grid. Several European and national political requirements like for example the so called unbundling, which means the legal separation of production, transport and distribution, shall give every user a fair, transparent and equal access to the electricity network (European Parliament and the Council, 2003, Art. 7-9).

In the liberalised energy markets, electricity became a trade product which is similar to shares or other commodities traded over a stock exchange or in bilateral contracts. Bilateral or the so called over-the-counter trade is a classical contract between two parties, which negotiate price, amount and time of delivered electricity. However, trading over the stock exchange works with standardized products. The products are characterized by the period of supply (hours or time periods) and are offered in €/MWh. As a reference for energy prices the spot-market is used. Here suppliers and buyers of electricity can put their offer and demand requests in an anonymous order book. At 12 o'clock the order book is closed for the following day. Demand and offers are merged in a merit order, where the most expensive power plant which is needed to satisfy the demand sets the price.

Besides this market structure renewable electricity is in many countries supported by different federal programmes. With the Electricity Feed-in Act (StrEG) Germany started 1991 to support renewable energies with feed-in-tariffs and the legal obligation for grid operators to connect renewable capacity to the electricity grid (BRD, 1990). 2000 the "Renewable Energy Act (EEG)"has replaced this act and has introduced geothermal energy into the federal support mechanism. Similar regulations also exist in other European countries for example France. Since 2000 the "Loi n°2000-108" supports renewable energy sources (RES) with feed-in-tariffs, an obligation for the grid connection and special tenders for renewable energies (BMU, 2011).

Electricity Grid

The natural monopole of the electricity grid is strongly regulated. National regulation authorities monitor the discrimination free access and the cost efficient operation of the networks. The operators are paid for their effort by network-use fees. These fees at least have to be made public. In Germany the authority in charge approves them with a benchmark system, which takes among others the geographical differences into account (Konstantin, 2007).

The integrated European electricity grid enables a secure electricity supply in Europe by connecting numerous power plants. This redundancy leads on the one hand to a secure and efficient power supply, on the other hand long distances have to be bridged. The transported power is the key parameter for the network design. The power can be calculated with $P=U*I*\sqrt{3}$, where P is power [W], I is current [A] and U is voltage [V] . As the current is limited by the heat resistance of the wire, the voltage is the only parameter, which can be adapted to the power demand. This fundamental law of electricity transport leads to the insight, that different network levels are necessary for different transport tasks.

The electricity of big power plants (>300 MW) is feed into the extra high voltage grid. This grid level transports the electricity over long distances to consumption centres. The long distances make an extra high voltage of up to 380 kV necessary. Transformer stations transform the electricity to 110 kV (High Voltage). This level is used to distribute electricity to regional consumption centres or large industrial companies. The next step is to transform the electricity to the middle voltage level (10 – 30 kV), which supplies districts, bigger cities and industrial sites. Residential buildings and small businesses are finally connected to the grid by the low voltage level with 400V (Konstantin, 2007, S. 331). Figure 1 gives an overview of the different network levels.

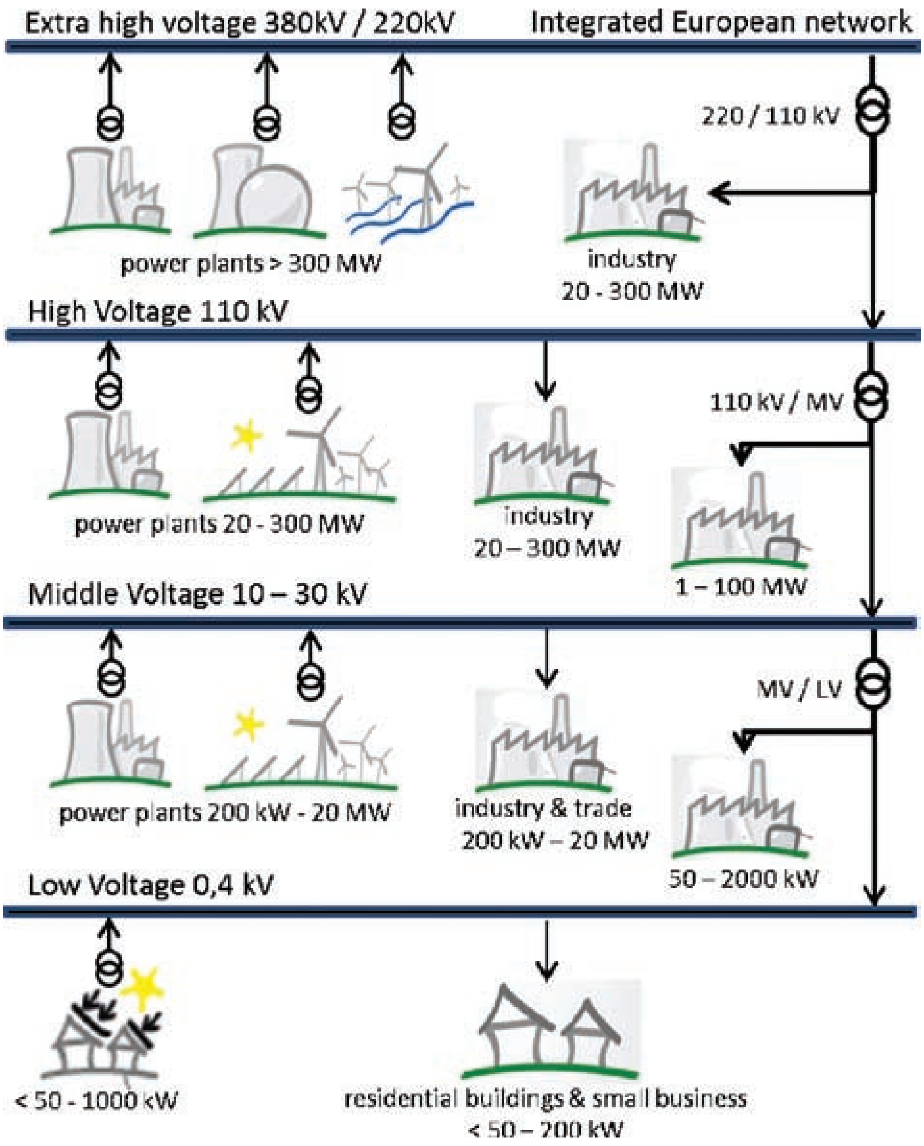

Figure 1. schematic diagram integrated network (own illustration based on Konstantin, 2007, S. 330)

Geothermal power plants (single power plants in a complex) in high enthalpy regions like Italy or Iceland deliver up to 750 MW or more. These power plants usually feed their electricity direct into the high or extra high voltage level. In low enthalpy areas like Germany typical geothermal power plants have an installed capacity of 1 - 5 MW, which means that they are connected to the medium voltage grid.

Demand for geothermal power

Demand for geothermal power arises from different perspectives, which shall be explained in the following.
The European Union has set itself ambitious goals for becoming a high-efficiency, low carbon economy. Until 2020 20% of the energy consumption shall be met with renewable energy. Additionally CO2-emissions shall be cut by 20 % and the energy efficiency shall be increased by 20 % (European Commission, 2012). Geothermal energy is defined under German law as a renewable energy source and is needed to achieve these goals (BRD, 2012, § 3; 3). Geothermal electricity in Germany has a technical potential of nearly 300 TWh/a and can so contribute to renewable energy generation (Paschen, Oertel, & Grünwald, 2003). 300 TWh/a would be ~ 60 % of the annual German electricity demand (based on 2010) (BMWi, 2012). Currently there are 10,7 GWel of geothermal capacity installed worldwide. Germany has with 7,3 MWel only a small share in this capacity. Until 2020 the German government predicts an installed capacity of ~ 200 MWel while the German renewable Energy federation expects up to 470 MWel (Geothermie Bundesverband). The high availability also contributes to the demand for geothermal energy. Geothermal power plants have one of the highest capacity factors (full-load ratio of a power station per annum) of all electricity production technologies. With ~ 90 % geothermal power plants have a capacity factor which is as high as the capacity factor of nuclear power plants (Tidball, Bluestein, Rodriguez, & Knoke, 2010). This makes geothermal power besides hydropower one of the only renewable power plants which are suitable for base load. Beside the electricity production it is possible to use geothermal power as a heat source for district heating. Geothermal power plants can so be used as combined heat and power source. This improves the efficiency of the power plant as well as the economic situation.

Grid integration of an increasing share of renewable power generation – challenges for the network and system operation

The European 20-20-20 energy and climate targets, particularly the enormous increase of renewable generation will have a huge impact on both, the transmission and the distribution network as well. This becomes not only a question of balancing the power according to the equilibrium of generation and consumption and therewith the frequency control from the viewpoint of the Transmission System Operator (TSO), but becomes even more challenging for the Distribution System Operat or (DSO). He has to deal with local and regional reverse load flow conditions, voltage problems and the overloading of lines. This can be summarized in the task of managing the system in a secure and cost efficient manner.
How dramatic the future development could be, illustrates the situation in Germany. Currently the system peak load amounts to nearly 80.000 MW. To reach the intended target of a 35% share of renewables in 2020 the capacity of installed renewables alone will be as high as the maximum peak load. In addition the priority feed-in of RES, the volatility and the intermittent generation will cause substantial problems for system stability in the West European Interconnection (European transmission network) as well as supply problems in the local areas of the DSO where renewables are connected to the grid. To meet these challenges a massive grid expansion and a frequent use of balancing power are necessary, which is associated with considerable costs.
A paradigm shift in the sense that load follows generation is needed. The incorporation of the customer and the development of smart grids with highly complex, real time communication systems to adapt generation and consumption and to realize an optimal use of network assets in a secure and cost efficient manner will be inevitable.

That will lead to additional and new requirements for decentralized power plants based on renewable feeding. For the medium and high voltage levels it will be necessary to implement a load and generation management system to be able to operate the system effectively while keeping the quality standards and to optimize the connection capacity for RES in case of given network assets.

Costs of grid integration

To ensure a secure and reliable network operation network operators have specified requirements for the network connections of RES. An additional boundary condition for the grid connection in Germany is the incentive regulation for DSOs, which was introduced by the Federal Network Agency (BNetzA). DSOs are obligated to connect power plants in total (costs for DSO and power plant operator (PPO)) as cost efficient as possible. The most important point in the question of cost allocation is the network connection point (NCP). Objectives and transparent criteria to determine the NCP are given by law and regulations. This point marks the border of property, the responsibility for assets and defines the cost allocation between the PPO and the DSO.

The costs for the grid integration of a power plant depend on the chosen NCP and the integrated power. The NCP is needed to define the length of the wire, the needed assets like transformation stations and other side conditions, while the integrated power defines the voltage level and the needed type of wire. A general forecast for the costs of grid integration is therefore not reliable.

Process of grid integration

Basis for the determination of an appropriate NCP for the connection of the power plant is the information provided by the PPO. Criteria are the maximum real power Pmax and the apparent power Smax of the plant as well as its location and the request for connection. This enables the DSO by means of network calculations to determine the appropriate NCP.

Usually the local network operator provides checklists, requirements, technical regulation and conditions for the connection and commissioning of the decentralized generation units. In this process the metering concept and the telecommunication devices also need to be specified. Construction and commissioning are rounding up the implementation. The PPO has to provide the conformity declaration to all these specifications. Figure 2 shows the process of grid integration in a flow diagram (BDEW, 2008; VDN, 2004).

In the process of grid connection, the PPO has to choose a model of remuneration. According to the law and regulations in Germany, PPOs can choose between three main models within the Renewable Energy Act (EEG).

1. “Normal” EEG remuneration (currently 25 Ct/kWh for geothermal power, according to §28 EEG).
2. Remuneration according to “Direct Marketing + Market Premium”
3. “Direct Marketing + Avoided Network Charges” model.

For the PPO the different models lead on the one hand to different income possibilities, which have to be calculated for every power plant individually. On the other hand the model selection leads to different contract partners. While in model one the remuneration is completely paid by the DSO, in model two and three the PPO sells its electricity on the free market (direct marketing) and gets an addition from the DSO. The DSO itself finances this support for renewable energy by a levy for the electricity customer. The system is flexible and can be freely selected by the PPO each month if required (BRD, 2012).

In case of the limitation of the production due to the network operator's constraints and system stability requirements, the plant operator is compensated by the DSO for the remuneration losses (BDEW, 2012; BNetzA, 2011).

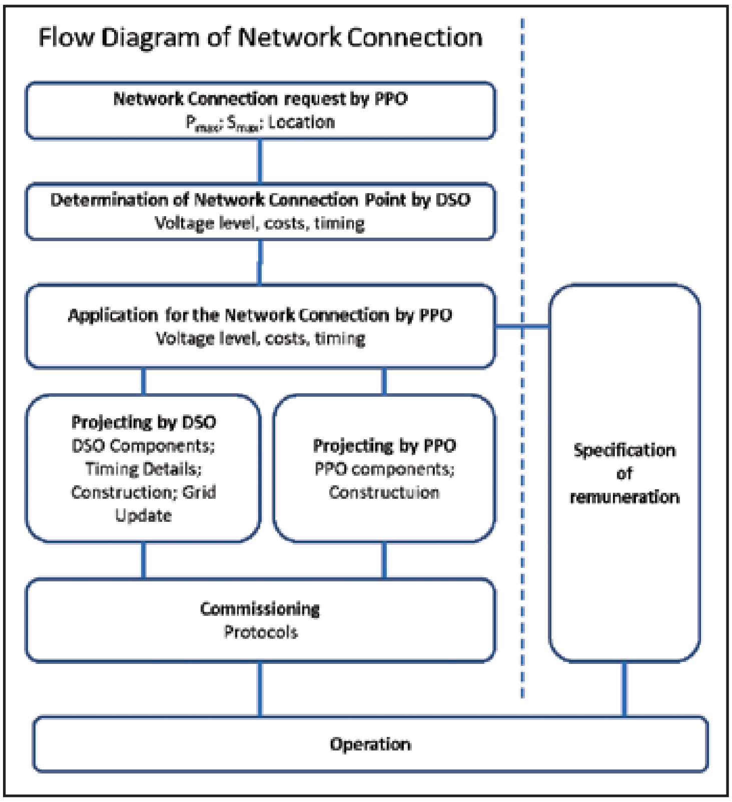

Figure 5. flow diagram of grid integration (own illustration)

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