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Proceedings Swissphotonics-Workshop

Photonics for Deep Geothermal Energy Harvesting

Neuchâtel, Switzerland

7.11.2012

Editors: Christian Bommer, Niklaus Waldvogel, Paul Hardegger
HSR University of Applied Sciences Rapperswil, Switzerland

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HSR HOCHSCHULE FÜR TECHNIK RAPPERSWIL
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Proceedings of the Swissphotonics-Workshop: Photonics for Deep Geothermal Energy Harvesting

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Supported by the Commission for Technology and Innovation CTI

Swissphotonics-Workshop: Photonics for Deep Geothermal Energy Harvesting

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1 Preface

The future energy supply in Switzerland faces an enormous challenge, mainly due to the decision of a stepwise exit of the nuclear energy, recently taken by the Swiss Federal Convention, as a consequence of Fukushima. The implementation of the aspired energy change shall be mastered by the ”Energy Strategy 2050”[1]. The unsustainable nuclear and fossil energies, which amount to 75% of the total consumption today, are supposed to be replaced by sustainable and renewable energies.

This ambitious turnaround will succeed at its best by the concurrent deployment of all renewable primary energies, namely the wind-, hydro-, solar-, biomass- and geoenergy. For a sustainable, thus safe energy supply, the geothermal energy is considered as prior, according to several studies, see the ”Weissbuch zur Energiewende”[2]. Power production requires ”deep geothermal energy”, 5 - 10 km depth. The decisive assets of deep geothermal energy production are its autonomy, no resource cost, negligible maximum credible accident, no dangerous emissions and its availability (year-round). The crucial point of deep geothermal energy is both its accessibility and exploitation. Its limitation is the economic feasibility, due to the excessive cost with increasing depth of rotary drilling, the only industrially deep drilling procedure approved. Therefore, the Swissphotonics-workshop was organized to present alternative and promising, cost breaking technologies for deep drilling, as for example by photonics.

1.1 Interests and Capabilities of IBU

The Institute for Civil-Engineering and Environment IBU at the University of Applied Science, Rapperswil HSR has gathered knowledge and scientific experience in geothermal energy harvesting over the last years. The IBU is interested to support industrial partners referring to scientific challenges created by non-abrasive drilling with large diameters and great depths (> 5 km), concerning both civil-engineering and environment, such as the identification and handling of physical rock properties, optimized hydraulics in tubes, assessment of environmental impact and added values. Therefore, the IBU plans to contribute decisively to the aspired competence centers according to the action schedule ”coordinated energy research” of the Swiss Federal Council and the energy strategy 2050.

Christian Bommer
IBU / HSR

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2 Introduction

The workshop was organized by the Swiss Photonics and Laser Network (Swissphotonics) in collaboration with the École Polytechnique Fédérale de Lausanne (EPFL), Optics & Photonics Technology Lab and the Centre for Hydrogeology and Geothermics at the University of Neuchâtel. It took place at the University of Neuchâtel in Switzerland at November 7th, 2012. Subsequent to the welcome address of Hans Peter Herzig, professor at EPFL - Optics & Photonics Technology Lab, Neuchâtel, Christoph Harder held the introduction to the Swissphotonics-Workshop Photonics for Deep Geothermal Energy Harvesting. Dr. Harder is the current president of the Swissphotonics.

One of the Swissphotonics initiatives is to explore new energy sources, which can replace existing nuclear and fossil power generation. With the workshop in Neuchâtel, Swissphotonics continues its workshops on understanding what photonics can do in exploring alternative energy sources, after photovoltaics and photosynthesis now also deep geothermal energy.

The first talk was given by Berthold Schmidt, Expert of the Commission for Technology and Innovation (CTI) in Switzerland, providing a short overview of central activities funded by CTI, in order to strengthen the cooperation of applied research with the Swiss economy. Dr. Schmidt addressed both the importance of the national development efforts for alternative energy sources and the motivation of this workshop.

The thematic talks, composing the Swissphotonics-workshop, are presented herein at length. Each one is summarized by an extended abstract, by the slides of the presentation and, if applicable, by the detailed answers to ten standardized questions characterizing the different drilling methods. The summarized replies about the different drilling methods of the speakers involved are compared and illustrated on the following two pages.

3 Comparison of Drilling Methods

Questions/ Drilling Methods	Hydrothermal Spallation Drilling HSD	Laser Foro Energy Inc.
Max. bore hole depth (m)	undisclosed, 335 m so far (Browning et al.)	undisclosed
bore hole diameter (cm), max./min. or optimal	undisclosed, 45 cm for spallation drilling at ambient conditions (Los Alamos Laboratory, USA, 1985)	standard industry bore hole diameters
Volume capacity of rock excavation at the bore hole bottom (cm^3/s)	175 cm^3/s (Browning et al.)	2-4 times the rate of mechanical-only drilling
Mode of operation of rock excavation at the bore hole bottom	spalling by heat shock (flame)	spalling by heat shock (laser), combined with rotary drilling
Transport/disposal of cuttings to the surface	upward stream of drilling fluid	gas or fluid under pressure (oilfield standard)
Environmental conditions during drilling (air, water, mud…) at the bore hole bottom	water and/or water-based drilling fluid	transparent fluid or gas (oilfield standard)
Main risks of the drilling method	fast cool down of the jet due to entrainment of drilling; rock behavior under massive stresses unknown; lowered drilling performance in sedimentary rock formations; development of a sensor system not yet realized	in line or lower to conventional oilfield technology
Drilling cost at depth of 100 m, of 1’000 m, and of 5’000 m	undisclosed	undisclosed
Status of development, publication of the previous R&D results	basic investigations already published or in preparation	ongoing industry partner colaborations, no publications so far
Main advantage/disadvantage of the drilling method	**adv:** heat shocks instead of mechanical forces; nearly “contact-free”; wear and tear of the drilling head is minimized; enhanced drilling velocities in hard rock formations	**adv:** improved drilling rates, less weight on bit and torque, longer bit life **dis:** power loss in fiber; optical components cause problems
Field experience	none so far	none so far

Laser Trumpf Inc.	**SuperDeep-FusionDrilling**	**Electro Pulse Boring EPB**
determined by drilling concept	10’000-20’000 m	10’000 m
determined by drilling concept	**min:** 500 mm; **max:** 2 m	**min:** 200 mm; **max:** 1 m and bigger
determined by drilling concept and available laser power	4000 cm^3/s	2506 cm^3/s in laboratory; 200 cm^3/s in field
spalling by heat shock (laser)	electrical melting	instantaneous breakage by plasma in matrix between electrodes
determined by drilling concept	rock-melt injection into well-wall by Litho-Fracturing	annular fluid circulation/hose return
assist gas (nitrogen, compressed air, helium or argon)	melted rock	high resistivity fluid
transport many tens of kilowatt of laser power over long distances	fluid-free cracks; conventional exploratory drilling needed in karst areas	usual drilling risks
undisclosed	€3300/m	€100/m, independent of depth
not available	technology and material available in the market	technology platform established, ready for application’s development
not available	**adv:** strong steel-casing; fast (up to 500 m/day); no transport to surface needed; without abrasion; high efficiency	**adv:** unsurpassed volume excavation capacity and energy efficiency **dis:** current systems must be renewed
none so far	tests performed in quarry, see slides	many holes up to 200 m in crystalline

4 Electricity from Deep Geothermal Resources in Switzerland: a Challenge for 2050

François-David Vuataz, Laboratory for Geothermics (CREGE), University of Neuchâtel, Switzerland

4.1 Abstract

Worldwide geothermal energy development is strongly linked to the price of oil, the energy policy and overall economic circumstances. In Switzerland, shallow geothermal resources coupled with heat pumps are widely used, mostly for the heating of private houses, with a very high ranking in terms of density of installations per inhabitant or per square kilometer. However, below the Molasse basin, deep geothermal resources are poorly known, due to the lack of national or regional exploration programs. Only 10 boreholes reach a depth of more than 3 km, and only one of them was drilled for geothermal energy (Deep Heat mining project in Basel).

If geothermal electricity should reach a significant part of the Swiss energy mix in 2050, very strong efforts on applied research and pilot plants in the near future have to be built and exploited. In regions with a normal geothermal gradient like Switzerland and most of the continental Europe (30-35°C/km), the development of deep geothermal energy resources should go through the technology of the Enhanced geothermal Systems (EGS). Indeed, the deep aquifers are limited either in their size, or their temperature for electricity conversion or their permeability for an economic production, what seems to prevent a large development, such in the cases of the Paris basin or of the Munich basin. On the other hand, new concepts of unconventional ultra deep geothermal systems are exciting and should be studied, but many technological barriers will probably limit their industrial development until 2050.

Presently, all the segments to be used for EGS technology have been experimented and improved during the last 30 years. However, the assemblage of the necessary techniques has to progress rapidly in the following domains: directional drilling (up to horizontal) into granitic rocks at depths of 5 to 6 km, size-controlled stimulation of fractured rocks by hydraulic methods, strict control of the induced seismicity, long-term pumping and re-injection the deep hot fluid, efficiency of electricity conversion with binary cycle plants, and finally, upscaling of the geothermal-based power plants from prototype to industrial size.

To reach these goals, R&D needs are striking in the following fields: lowering cost of deep drilling, new drilling methods, development of indirect exploration methods for the granitic basement, multi-parameters monitoring in high temperature and high pressure boreholes and enhancement of the permeability in fractured geothermal reservoirs. For solving several problems linked to these techniques, photonics could definitely help.

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Photonics for Deep Geothermal Energy Harvesting
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Electricity from deep geothermal resources in Switzerland: a challenge for 2030

Dr. François-D. Vuataz
Laboratory for Geothermics - CREGE
Neuchâtel

Centre for Hydrogeology and Geothermics - CHYN

Content

- Geothermal activities at the University of Neuchâtel
- Geothermal conditions in Switzerland
- Geothermal power from hydrothermal systems
- Technology of the Enhanced Geothermal Systems (EGS)
- International situation of EGS projects
- Technology improvements needed for EGS
- Photonics and geothermal development
- Outlook

GEOTHERMAL ACTIVITIES AT THE UNIVERSITY OF NEUCHÂTEL

UNIVERSITÉ DE NEUCHÂTEL

Milestones

1990 : Formation of the *Geothermal Group* of the CHYN (Dr. F.-D. Vuataz with MSc and PhD students): various studies on hydrogeology and geochemistry of deep fluids.

2004 : Founding of the *Centre for Geothermal Research - CREGE*, an association working as a competence centre. This Swiss network of 60 institutions had a core team of 5 persons based at the CHYN (President: Dr. J. Rognon; Director: Dr. F.-D. Vuataz).

2009 : Establishment of a *Chair in Geothermics* at the CHYN (Prof. Eva Schill). Since then, the CHYN is called *Centre for Hydrogeology and Geothermics*.

2010 : Creation of the *Laboratory for Geothermics – CREGE* (c/o CHYN) by merging the former CREGE team with the Geothermal Laboratory of Prof. E. Schill (10 collaborators).

Geothermal education at the University of Neuchâtel

- *Master of Science in Hydrogeology and Geothermics*
- *Certificate of advanced studies in Deep Geothermal Systems (CAS DEEGEOSYS)*

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GEOTHERMAL ACTIVITIES AT THE UNIVERSITY OF NEUCHÂTEL

UNIVERSITÉ DE NEUCHÂTEL

Scientific research

- Integrated 3D geology models combined with geophysical methods like gravity and cross-validation of the geological interpretation.
- Micro-gravity method to evaluate the porosity of the rocks at depth.
- Electromagnetic methods (Magnetotellurics-MT, Controlled Source Audio-frequency Magnetotellurics-CSAMT, Very Low Frequency-VLF).
- Fluid chemistry and isotopic methods.
- Modelling of coupled processes (thermal - hydraulic - chemical) to understand the resources formation and to help the reservoir management.

Applied studies on deep geothermal resources (cantons, cities, utilities, electric companies, Geo-Energie Suisse, NAGRA)

- Evaluation of regional geothermal potential and resource analysis.
- Optimisation of the resource exploitation.
- Simulation of chemical stimulation for EGS and hydrothermal systems.
- Exploration of Alpine hydrothermal systems.
- Corrosion and scaling in the installations

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GEOTHERMAL CONDITIONS IN SWITZERLAND

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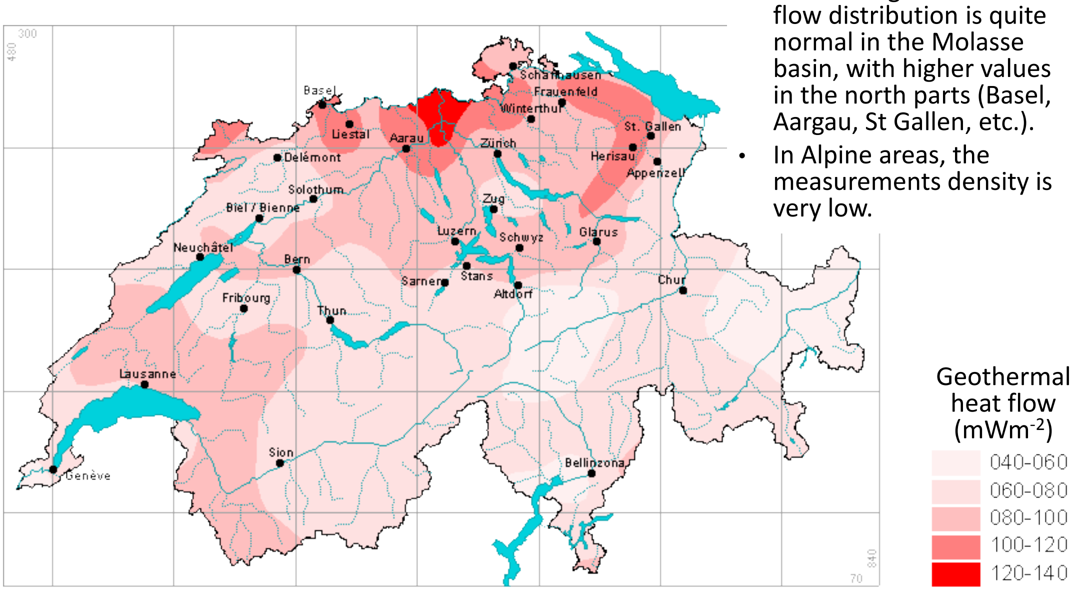
- The Swiss geothermal heat flow distribution is quite normal in the Molasse basin, with higher values in the north parts (Basel, Aargau, St Gallen, etc.).
- In Alpine areas, the measurements density is very low.



Map of the geothermal heat flow in Switzerland (Medici & Rybach, 1995)

GEOTHERMAL CONDITIONS IN SWITZERLAND

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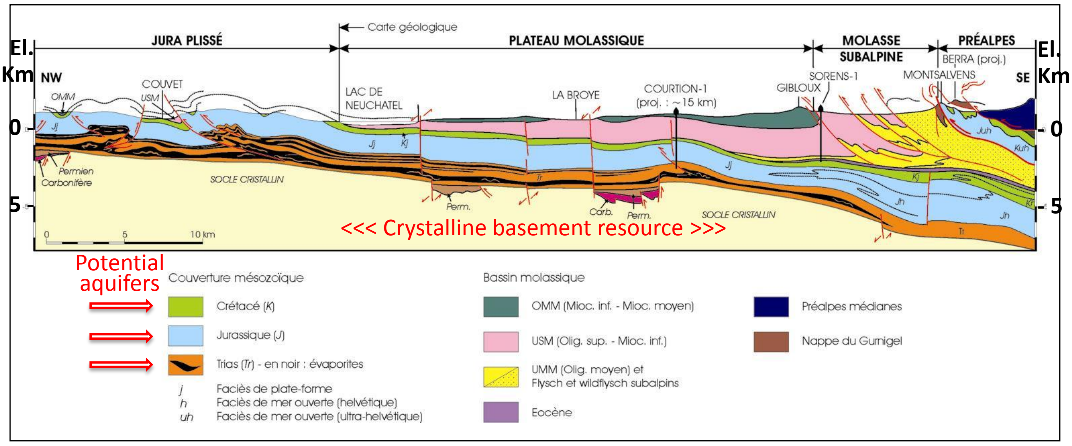
Temperatures and potential resources

- Average geothermal gradient in the Molasse Basin : 30 - 35° C km^{-1}.
- Potential geothermal resources for power production (> 100° C) : below a depth of 3 km.
- Resources: potential aquifers and stimulated geothermal systems.



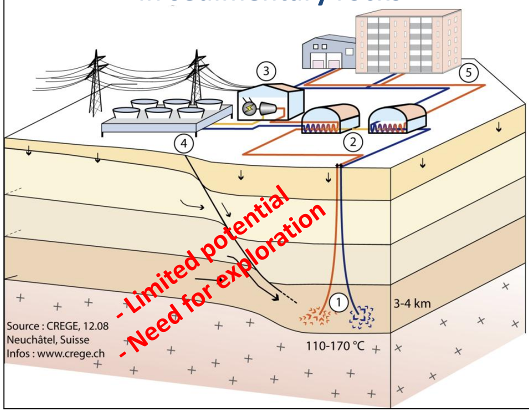
NW-SE geological cross section between Jura and Prealps (PGF, 2005)

OPTIONS FOR SHORT-TERM GEOTHERMAL POWER IN SWITZERLAND

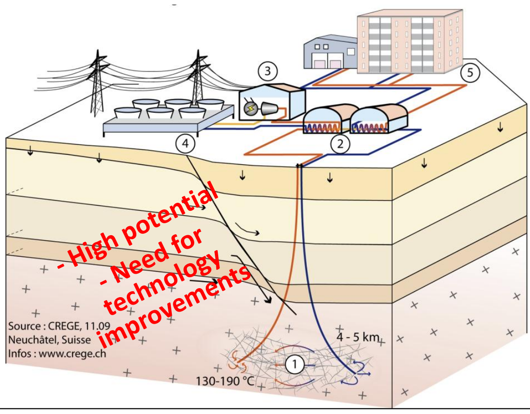
Geothermal installation for power and heat production

1. Production and injection wells.
2. Heat exchangers
3. Binary power plant: turbine and generator
4. Forced convection cooling systems
5. District heating system

Deep aquifer resources in sedimentary rocks



Enhanced Geothermal System in the crystalline basement



WORLDWIDE GEOTHERMAL POWER FROM HYDROTHERMAL SYSTEMS

Installed capacity and produced energy in 2010 for 11 countries with >100 MW el.

Country	MW el.	GWh/y	Nb. power plants
USA	3'093	16'603	209
Philippines	1'904	10'311	56
Indonesia	1'197	9'600	22
Mexico	958	7'047	37
Italy	843	5'520	33
New Zealand	628	4'055	43
Iceland	575	4'597	25
Japan	536	3'064	20
El Salvador	204	1'422	7
Kenya	167	1'430	10
Costa Rica	166	1'131	6

+ 13 other countries

Statistics of the geothermal power plants

- Total capacity: 11'000 MWe in 24 countries
- Total number of units: 526
- Capacity range per unit : 1 to 140 MWe
- Average capacity: 21 MWe
- Number of binary cycle plants: 236 units


Power plant in Tuscany (2x20 MWe)

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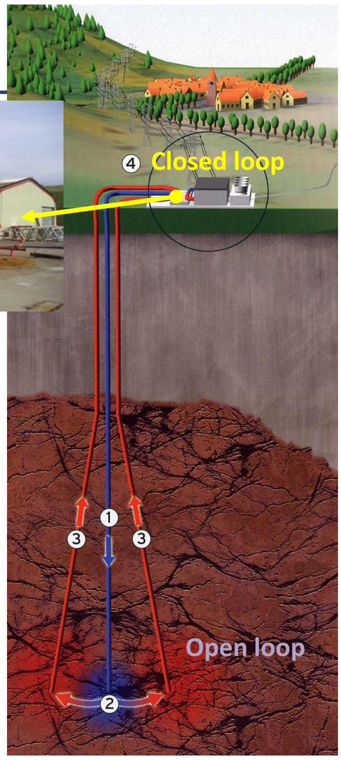
TECHNOLOGY OF ENHANCED GEOTHERMAL SYSTEMS



Principles of EGS

Between 4 to 6 km depth, fractured granites reached 150 to 200° C. They all contain water, but permeability is low and a reservoir has to be created by hydraulic stimulation.

(**1**) High pressure injection of cold water in a deep hot rock enlarges existing fractures and creates a 3D heat exchanger.

(**2**) During exploitation, an open loop circulates fluid from surface to reservoir and back.

→ The surface of heat exchange is THE key parameter for an economic and sustainable energy production.

(**3**) Pumping the fluid heated at depth from production wells.

(**4**) Binary power plant: ORC turbine coupled to a generator.

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TECHNOLOGY OF ENHANCED GEOTHERMAL SYSTEMS

unine UNIVERSITÉ DE NEUCHÂTEL

International situation

Switzerland

- Deep Heat Mining Project in Basel: stopped since December 2006, following several seismic events up to M3.4 triggered by the hydraulic stimulation.
- Since 2011, the company *Geo-Energie Suisse* has started an EGS programme with a selection of best sites in the Molasse Basin.

Rhine Graben

- 1st pilot plant at Soultz-sous-Forêts (Alsace)
- Small industrial plants at Landau & Insheim (D)
- More projects under way in France & Germany.

Australia

- Strong activity on EGS (> 30 companies).
- Very large potential discovered in granitic rocks.
- 1st pilot plant to be commissioned in 2013.

+ projects in Spain, GB, Norway, USA, China, …

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TECHNOLOGY IMPROVEMENTS NEEDED FOR EGS

Operations	Methods, tools & conditions to improve or create
Site characterization	Geophysical methods to detect structures in the basement rocks (MT, Resistiv., Magnetics); Geological models to be adapted to EGS.
Deep drilling	Lowering drilling cost : penetration rate, new drilling methods, horizontal drilling, drilling tools, completion materials.
Well logging	High T-P logging tools; imaging tools (FMI, UBI, etc.), logging while drilling (LWD), fiber optics tools for physical and chemical param.
Reservoir stimulation	Mixed methods of hydraulic + chemical stimulation; proppants in fractures; decrease of induced seismicity; high T-P packers; limitation and control of induced seismicity.
Hydraulic tests	Smart tracers; long-term down-hole monitoring tools.
Well production pumps	Lifetime of ESP and LSP pumps (> 2 yr @> 300 m, > 150°C, > 50 ls^{-1})
Reservoir life-time	Geochemical methods to avoid plugging of the fractures.
Reservoir management	Monitoring, modelling of T-H-M-C processes; soft stimulation.
Commercial scale	Multiple directional drilling from same well pad. Increase reservoir volume and production flow (power plants from < 5 to > 25 MWe).

PHOTONICS AND GEOTHERMAL TECHNOLOGY DEVELOPMENT

Examples of projects in innovative drilling, logging and monitoring

Stimulation with innovative fluid-placement methodology, production logging with fiber optic (FO) with a coiled tubing (Schlumberger)

- A new system enabling real-time and conventional temperature monitoring during acid stimulation of a reservoir using a specific coil tubing in which a FO cable is inserted.

Long-term temperature monitoring by fiber optic at Soultz EGS project (GTC)

- A FO cable was installed in the 2.2 km EPS-1 well at Soultz to measure temperature from 2006 to 2011. Important drift observed, but new solution found to compensate.

Projects of new drilling techniques for geothermal wells

- Since the 1980's, Sandia Laboratories did some research for geothermal drilling with DOE funds, and tried to investigate various technologies: jet-assisted, thermal-assisted, mud hammer, thermal spallation, spark drill, explosive, rock melters, pulsed-laser water-jet.
- Recently, Potter Drilling Co. (USA) manages a 7.5 million US$ project, trying to build and demonstrate a working prototype hydrothermal spallation drilling unit in the lab and on the field.
- Institute of Process Engineering (ETH-Z): on-going research on thermal spallation.
- + new results presented during this workshop.

OUTLOOK

Conditions for significant development of geothermal power in Switzerland

- If geothermal power should be part of the Swiss energy mix in 2050 → **EGS technology** should turn soon from pilot to industrial phases.
- Temperature-depth relation: 150 to 200 ° C at 4.5 to 5.5 km.
- Reservoirs: mostly granitic rocks to be fractured for creation of a heat exchanger.
- Power plants:
  - ✓ 2014-2020: 2-3 pilot plants of 1-3 MWe (1 production well);
  - ✓ 2020-2030: 2-3 industrial plants of 20 MWe (7-8 production wells).
- Swiss EGS potential is high, but development has been slow, due to limited means up to now: **50** MWe for 2030 and **250** MWe until 2050 (OFEN/BFE, 2012).

Main progresses required for the EGS technology

- Drilling: lowering the costs and increasing the availability.
- Stimulation: placed and quantitative reservoir; control of induced seismicity.
- High T-P logging tools; robust production pumps; sustainable reservoir management.

Photonics technology can help the development deep geothermal resources

- Innovative drilling technology.
- Development of logging tools in high T-P environments.
- Equipment for long-term monitoring of reservoir and wells.

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Thank you for your attention !

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5 Potential of Deep Geothermal Energy in the Energy Debate

Hans-Olivier Schiegg, SwissGeoPower (SGP), Uetikon am See ZH, Switzerland

5.1 Abstract, Extended: Short Comment on each Powerpoint Slide

Since deep geothermal energy provides both heat and electricity, in short it is called: geoenergy. In the first section, the physical potential of geoenergy is shown. In the second part, the ”Energy Package 2050” is explained. It represents the base line for the energy debate, finally focussing on the optimal energy mix. In addition, limitations of the energy change are discussed. In section three, the ranking of geoenergy, as a primary energy, is explained, referring to sustainability. Finally, the outstanding assets of geoenergy are listed, from the theoretical, political and technical point of view.

Starting with the physical potential of geoenergy, the temperature depending on depth is shown. The temperature is raising quickly within the earth’s crust, which is 20 to 50 km thick. Below the earth’s crust, the temperature reaches already over 1000°C. In the center of the earth the temperature is nearly 5000°C. Conclusions: I) 99% of the earth’s volume are warmer than 1000°C II) we are sitting on an inexhaustible deposit of heat, due to radioactive decay and condensation heat.

Next point of interest is the distribution of temperature in a plane on a certain depth. Universally valid are the two statements: a) in 10 km depth the temperature is at least 150°C, b) the United States are representative for the entire globe. In 10 km depth, the temperature is over 150°C in the cooler east of the US. In the west, where seismicity is encountered, the temperature is over 300°C.

A map shows the earthquakes all over the world with a magnitude higher than 4. In this concern, Europe is rather similar to California than to the east coast. Thus the question: is in Europe the temperature really around 300°C in 10 km depth? Answer: yes, Europe is comparable to California with about 150°C in 5 km. And Switzerland? According to the extrapolated field data of Basel and Triemli the temperature in 5 km is even 200°C.

Now the decisive question: what energy content corresponds to such temperatures? The heat content of a cube with a) a side length of 10 km and b) a temperature of 240°C equalizes the total yearly energy consumption of the world. Such a cube represents a negligible tiny little bit of the earth’s crust, enveloping the entire globe. Conclusion: the physical potential of geoenergy is unlimited.

Now to section II, to the political energy debate. First: the energy consumption and the ”Energy Change”. The total energy consumption of the world since 1860 until today is shown. Remarkable: a) the explosion of energy consumption after world war II and b) carbon, as oil and gas, increase excessively, without restraint, c) nuclear power is of minor importance, worldwide. And the total energy consumption of Switzerland? The development is more reasonable, compared to the worldwide development. Since the oil crisis in the seventies, there is an obvious flattening of the curve, giving some hope, that an energy change really is feasible.

Blue represents the electric power, produced to over the half by water power, nearly the half by nuclear. The fossil primary energies: coal, oil and gas in brown, red and yellow, constitute the main part. Thus, the political decision for an energy change, intends to replace three quarters of the total energy consumption. To replace these three quarters by renewable energies is a real challenge.

For the implementation of the energy change, the swiss federal council proposes the ”Energy Package 2050”. The following five pilot measures are recommended: 1) energy efficiency, 2) renewable energies, 3) energy tax, 4) fossil power plants, 5) pilot- & demo-plants, as well as lighthouse projects. Due to these measures for the production of electric power, the predicted time curves are shown, representing the development of the energy mix for electric power production until 2050.

Question of interest: what is the optimal mix of the renewable energies? The optimal energy mix needs monetized triple value curves (TWK), one curve for each renewable primary energy. ”Triple value” means considering sustainability, in practice the monetized valuation of each primary energy from point of view of first economy, second ecology and third sociology.

TWK1 represents somehow the prospective stock quotation (Aktienkurs) for a sustainable situation, in contrary to TWK2 for a non-sustainable development, where subsequent to a substantial rise at the beginning a crash follows, which is characteristic for a non-sustainable behavior.

As for any proper scientific statement, both is needed the triple value as the value of expectation and its statistical scattering, as indicated by the Gaussian bell curves. The scattering represents the risk, in finance denominated as volatility. The optimal energy mix is provided by the portfoliotheorie.

The vertical shows the time gradient of the triple value, the ROI, the return on investment. Along the horizontal, the risk is indicated. By mixing the three primary energies PE1, PE2 and PE3 at the partitions 56, 33 and 11, the result is, in respect to 100% of PE3: a) the risk is cut in half, b) the ROI is duplicated. Thus the question, how dominant will geoenergy be in the optimal energy mix?

Yet, first the answer to the question: are there limitations for the energy change? If the energy change is understood as the compensation of both the nuclear and fossil primary energies, in Switzerland 237 TWh per year are to be replaced, which is 370% of the 64 TWh for the yearly electricity consumption as 100%. According to the recent study of the swiss academies of sciences the todays nuclear and fossil 29 TWh can just be equalized by renewable energies and approved technologies.

If more than the 64 TWh/a or 100% shall be compensated, either innovation for new technologies or import are inevitable. Innovation possibilities are shown, as: a) CO2-sequestration for fossil power production and b) 4th-generation nuclear power plants or fusion for nuclear production. However, they are obsolete, since the energy change implies to get rid of them. Energy production by water power is exhausted with the additional 2 TWh/a by proved technologies. Yet, for all new renewable energies theoretically, the full 237 TWh/a or 370% might be imported, due to the listed innovations. Most important: geoenergy differs, compared to the others. Geoenergy is capable to produce the full 370%: a) locally, i.e. without import and b) for less than 10 billions. In addition, also the triple risk is the lowest for geoenergy. As a consequence: geoenergy must have an utterly strong position in the optimal energy mix of the renewable energies.

Is such strong position of geoenergy reflected in the sustainability ranking of geoenergy? The answer is: Yes, according to two earlier studies, a) the ”Energie Trialog Schweiz” of 2008, b) the PSI (Paul Scherrer Institut), dated of 2010. The first study shows geoenergy even at the top. A further remarkable fact is, that the scattering, hence, the risk is the smallest of all the primary energies under consideration. The second study confirms the outstanding position of geoenergy. Conclusion: in both studies geoenergy is ranked very high. Furthermore, the results of a recent inquiry, the so called ”Weissbuch zur Energiewende”, are shown. Each primary energy was qualified by 16 weighted questions, referring to a sustainable power supply.The less malus in grey, the better. Again, geoenergy is top. The result underlines: also post Fukushima, geoenergy is even ranked highest.

As a conclusion: The potential of ”deep geothermal energy” (geoenergy) is extraordinarily high. Theoretically, the potential is unlimited. Politically, the decisive assets of deep geothermal energy are the following facts: a) autonomy, because anywhere existent, thus, b) high supply security of energy (power and heat), c) no cost for resources, hence no export of currencies, d) negligible GAU (maximum credible accident), e) no earthquakes, when closed heat exchanger, f) no dangerous emissions, no waste to be disposed, g) high social acceptance, thus, democratic support. Technically, the potential depends on a) the capability of accessing and exploiting the unlimited occurrence of geothermal energy, b) the economic feasibility of such access and exploitation by new technologies for deep drilling, as by photonics. As a consequence, now various new drilling techniques, based on photonics, will be presented.

SwissLaserNet Workshop / 07.11.2012, Neuchâtel
Photonics for Deep Geothermal Energy Harvesting

POTENTIAL of
Deep Geothermal Energy
in the Energy Debate

Prof. em. Dr. Hans-Olivier Schiegg

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Since **Deep Geothermal Energy** provides both
Heat and **Electricity,** in short it is called : **GEOENERGY**

Table of CONTENT

I PHYSICAL Potential of Geoenergy

II POLITICAL Energy Debate

III QUALIFICATION of Geoenergy

IV ASSETS of Geoenergy

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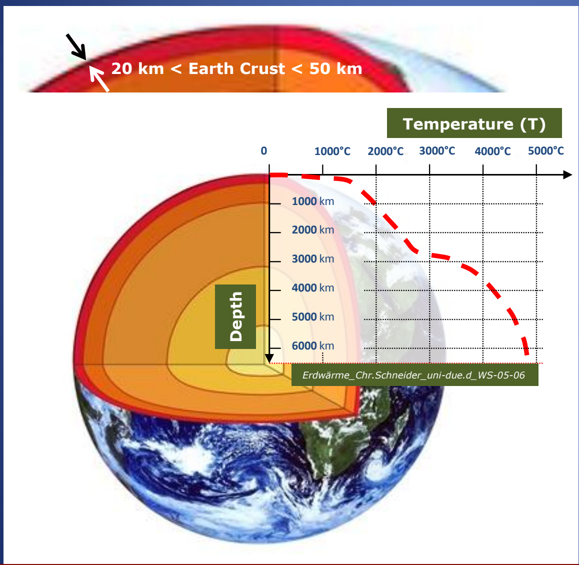
I) PHYSICAL Potential of Geoenergy

a) TEMPERATURE depending on DEPTH



- **Within** the **earth's crust :** the **temperature gradient** is **much higher** than further inside
- At the inner boundary of the earth's **crust :** **T > 1000 °C**
- In the earth's **center :** **T = 5000°C**

➔ **99%** of the earth's **volume : T > 1000°C**

➔ We are sitting on an **inex-haustible occurrence of heat,** due to
  - **radioactive decay**
  - **condensation heat** (the transition of liquid to solid state causes the dint in dotted line)

Next point of interest: **DISTRIBUTION** of **temperature** in a **plane** of a certain **depth**

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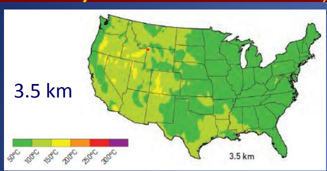
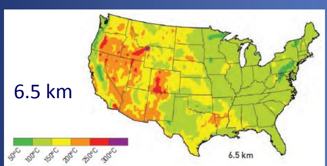
I) PHYSICAL Potential of Geoenergy

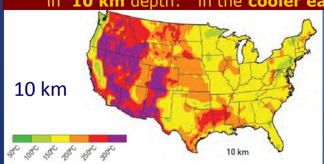
b) DISTRIBUTION of temperature in a plane on a certain depth

Universally valid the two statements: a) in **10 km** depth the temperature is **at least 150°C**, b) **US = representative** for globe

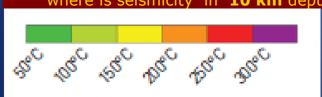




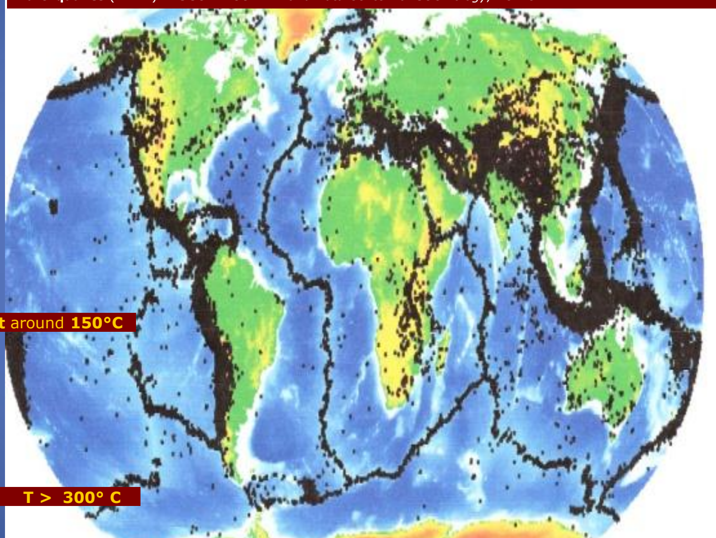
in **10 km** depth: in the **cooler east** around **150°C**



where is seismicity in **10 km** depth: **T > 300° C**



Earthquakes (M > 4) **1980 – 2002** *World Data Center for Seismology, Denver*



EUROPE is rather **comparable** with **West** than East of US
➔ **T** really about **300° C** in **10 km** in **Europe ?**

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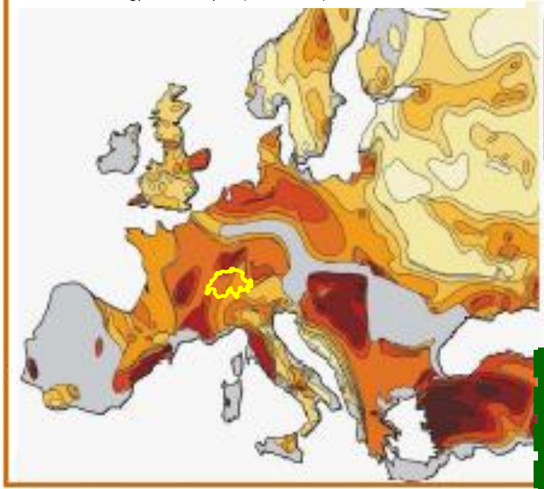
I) PHYSICAL Potential of Geoenergy
c) DISTRIBUTION of temperature in 5000m depth in EUROPE

Yes, Europe is **comparable** to **California** with about **150°C** in **5 km**

p. 97_IEA (International Energy Agency),
Geothermal Energy Annual-Report (06-Jan.2008)



EGS potential in Europe (from Jeroen Schuppers EC report, 17th Executive ... France, 22-23 March 2007)

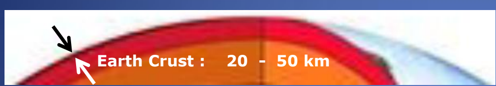
Field experiences:
BASEL: 4'600 m = 175°C
S.19_Geothermie.ch_März 2009
extrapoliert : 5000m = 190°C

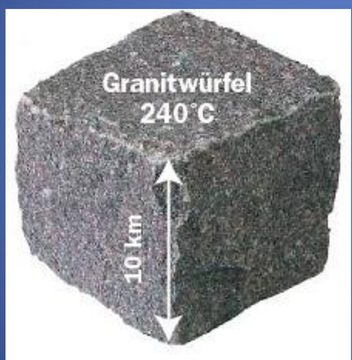
TRIEMLI: 2700 m = 106°C
S.5_Geoth. Newsletter_Febr.2011
extrapoliert : 5000m = 196°C

→ **SWITZERLAND:**
in **5 km** even **200°C**

Decisive question: What **ENERGY CONTENT** corresponds to such temperatures ?

I) PHYSICAL Potential of Geoenergy
d) ENERGY CONTENT at such temperatures





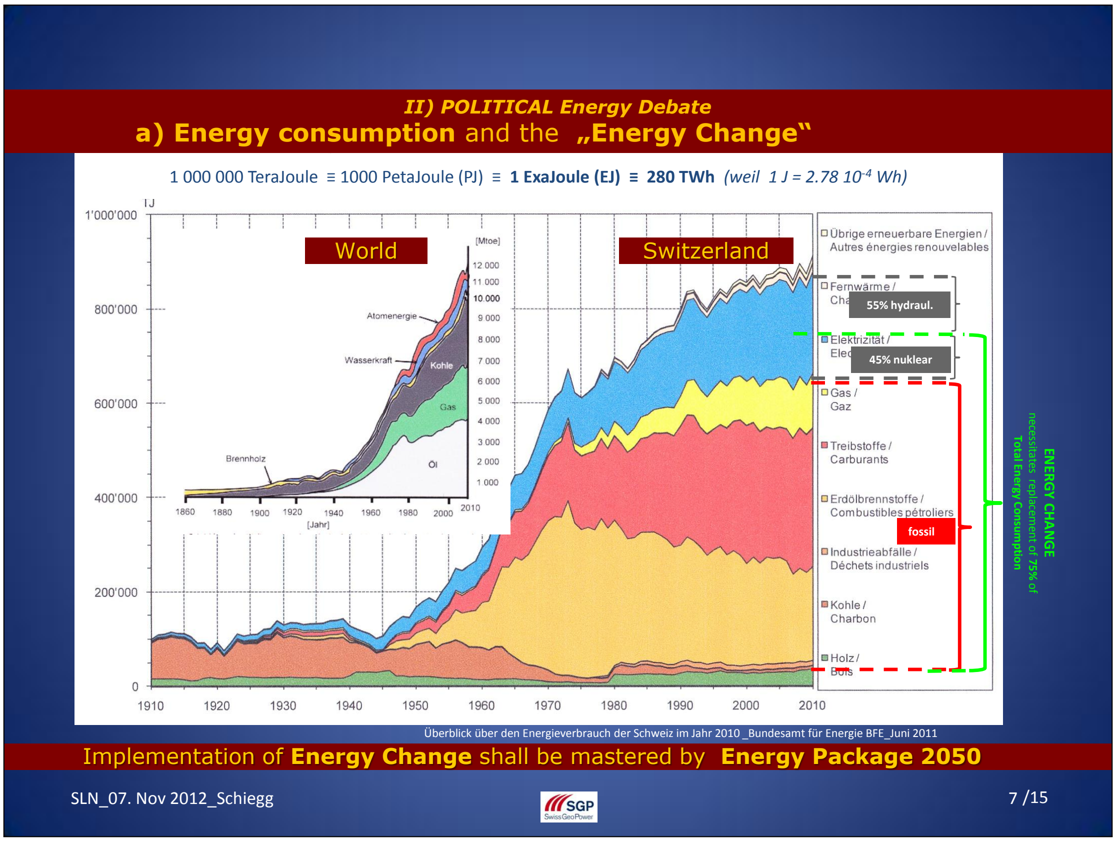
The **heat content** of a **cube** with

- a side length of **10 km,**
- a temperature of **240°C**

equalizes the **total yearly energy consumption** of the **WHOLE world**.

Such a cube represents a **negilgible tiny little bit of the earth's crust,** up to **50** km thick and **enveloping** the **ENTIRE** globe

Conclusion : The **PHYSICAL Potential of Deep Geothermal Energy is UNLIMITED**


II) POLITICAL Energy Debate
a) Energy consumption and the „Energy Change“
1 000 000 TeraJoule ≡ 1000 PetaJoule (PJ) ≡ 1 ExaJoule (EJ) ≡ 280 TWh (weil 1 J = 2.78 10-4 Wh)
TJ
1'000'000
800'000
600'000
400'000
200'000
0
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
World
Switzerland
[Mtoe]
Atomenergie
Wasserkraft
Kohle
Gas
Öl
Brennholz
1860
1880
1900
1920
1940
1960
1980
2000
2010
[Jahr]
Übrige erneuerbare Energien / Autres énergies renouvelables
Fernwärme / Chaleur à distance
55% hydraul.
Elektrizität / Electricité
45% nuklear
Gas / Gaz
Treibstoffe / Carburants
Erdölbrennstoffe / Combustibles pétroliers
fossil
Industrieabfälle / Déchets industriels
Kohle / Charbon
Holz / Bois
ENERGY CHANGE
necessitates replacement of 75% of Total Energy Consumption
Überblick über den Energieverbrauch der Schweiz im Jahr 2010 _Bundesamt für Energie BFE_Juni 2011
Implementation of Energy Change shall be mastered by Energy Package 2050
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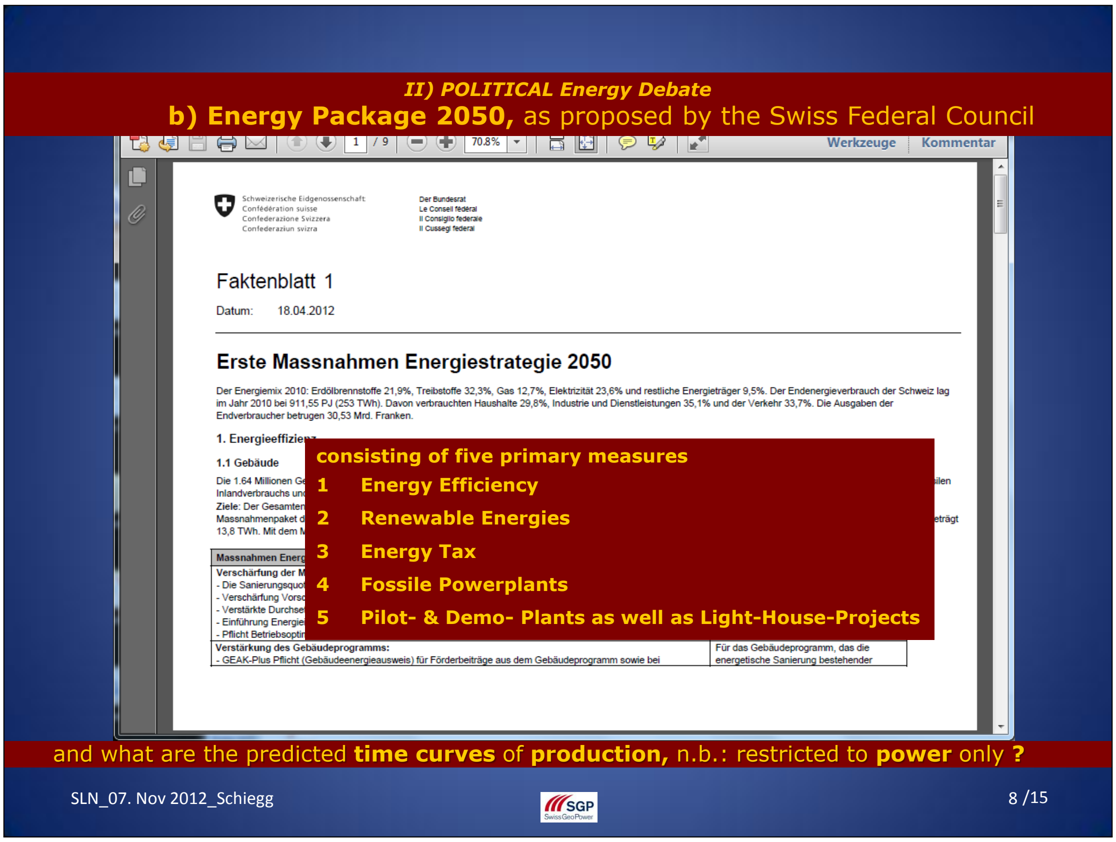
II) POLITICAL Energy Debate
b) Energy Package 2050, as proposed by the Swiss Federal Council
Werkzeuge
Kommentar
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Der Bundesrat
Le Conseil fédéral
Il Consiglio federale
Il Cussegl federal
Faktenblatt 1
Datum: 18.04.2012
Erste Massnahmen Energiestrategie 2050
Der Energiemix 2010: Erdölbrennstoffe 21,9%, Treibstoffe 32,3%, Gas 12,7%, Elektrizität 23,6% und restliche Energieträger 9,5%. Der Endenergieverbrauch der Schweiz lag im Jahr 2010 bei 911,55 PJ (253 TWh). Davon verbrauchten Haushalte 29,8%, Industrie und Dienstleistungen 35,1% und der Verkehr 33,7%. Die Ausgaben der Endverbraucher betrugen 30,53 Mrd. Franken.
consisting of five primary measures
1 Energy Efficiency
2 Renewable Energies
3 Energy Tax
4 Fossile Powerplants
5 Pilot- & Demo- Plants as well as Light-House-Projects
Verstärkung des Gebäudeprogramms:
- GEAK-Plus Pflicht (Gebäudeenergieausweis) für Förderbeiträge aus dem Gebäudeprogramm sowie bei
Für das Gebäudeprogramm, das die energetische Sanierung bestehender
and what are the predicted time curves of production, n.b.: restricted to power only ?
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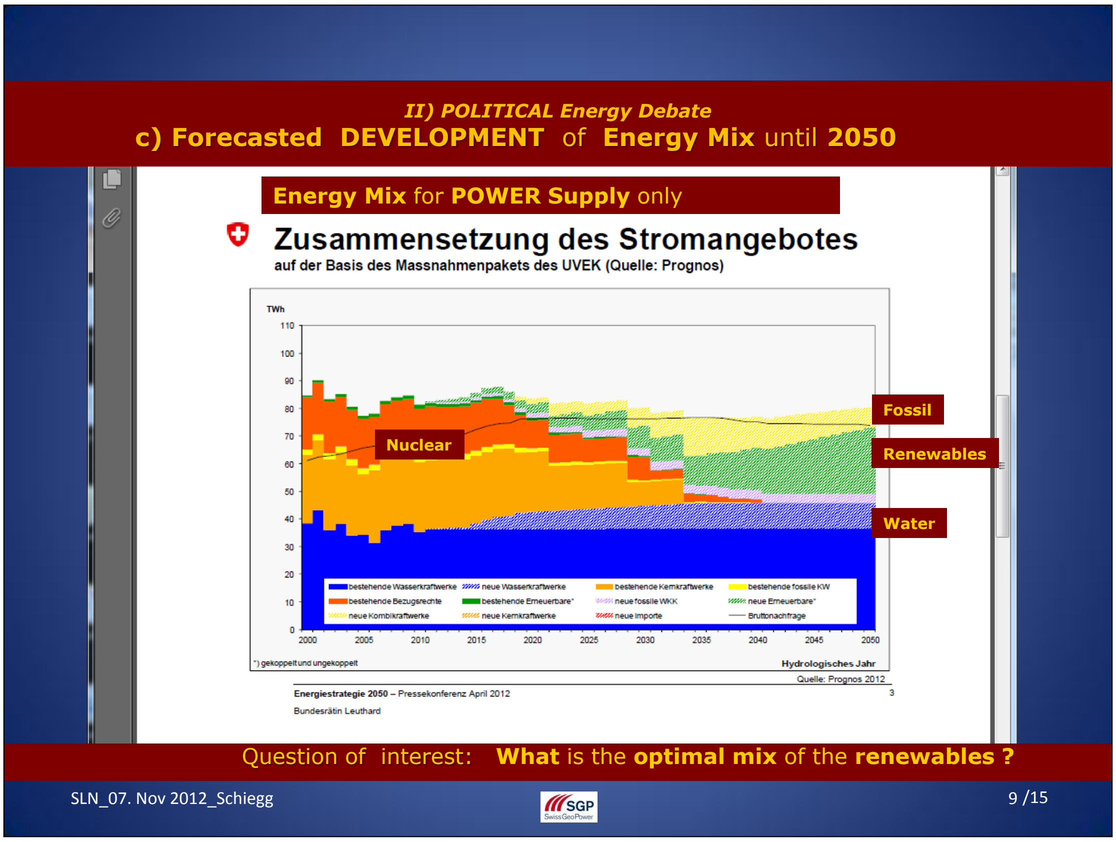
II) POLITICAL Energy Debate
c) Forecasted DEVELOPMENT of Energy Mix until 2050
Energy Mix for POWER Supply only
Zusammensetzung des Stromangebotes
auf der Basis des Massnahmenpakets des UVEK (Quelle: Prognos)
TWh
Nuclear
Fossil
Renewables
Water
bestehende Wasserkraftwerke
neue Wasserkraftwerke
bestehende Kernkraftwerke
bestehende fossile KW
bestehende Bezugsrechte
bestehende Erneuerbare*
neue fossile WKK
neue Erneuerbare*
neue Kombikraftwerke
neue Kernkraftwerke
neue Importe
Bruttonachfrage
*) gekoppelt und ungekoppelt
Hydrologisches Jahr
Quelle: Prognos 2012
Energiestrategie 2050 – Pressekonferenz April 2012
Bundesrätin Leuthard
Question of interest: What is the optimal mix of the renewables ?
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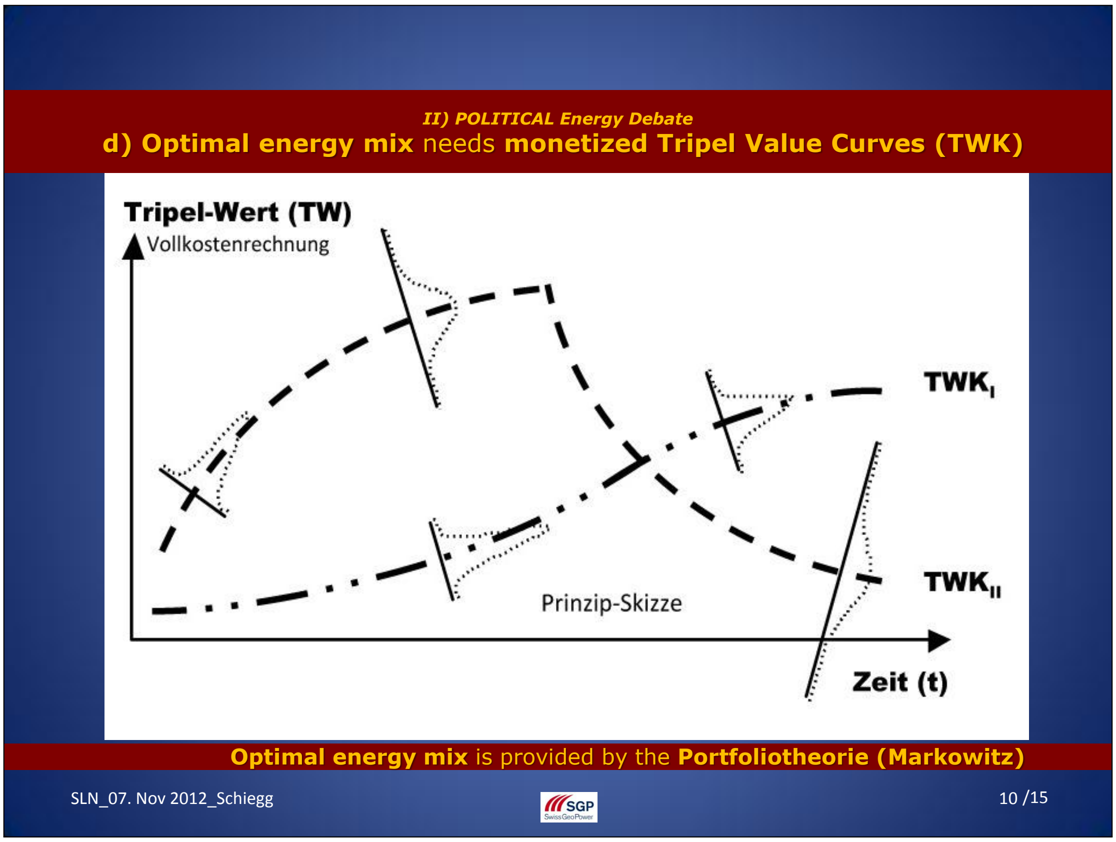
II) POLITICAL Energy Debate
d) Optimal energy mix needs monetized Tripel Value Curves (TWK)
Tripel-Wert (TW)
Vollkostenrechnung
TWK$_I$
TWK$_{II}$
Prinzip-Skizze
Zeit (t)
Optimal energy mix is provided by the Portfoliotheorie (Markowitz)
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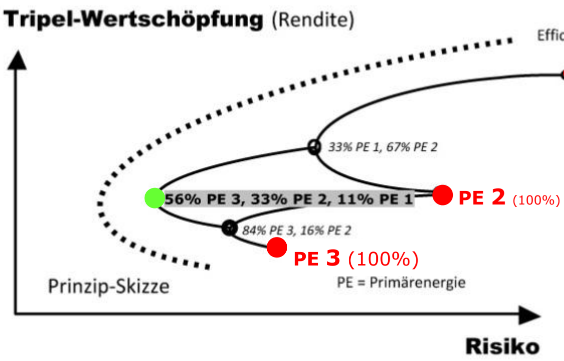
II) POLITICAL Energy Debate
e) Optimal energy mix is provided by Portfoliotheorie (Markowitz)



Gegenüber 100% PE 3, der Primärenergie mit dem geringsten Risiko, hat der

optimale Mix : 56% PE 3, 33% PE 2, 11% PE 1

- ein **halb so grosses Risiko** bei
- einer **doppelt so hohen Wertschöpfung**

Certainly, Geoenergy will be a **dominant player** in the **optimal energy mix**

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II) POLITICAL Energy Debate
f) What IMPORTANCE might have Geoenergy for the Energy Change(*) ?

ENERGIEWENDE = Ablösung nuklearer und **fossiler** durch **erneuerbare** Primärenergien

Realisierbarkeit der Optionen (grün)

Primär-Energie	STROM-Produktion Schweiz, realisiert 2011 BFE, Tab.24 (1)		Ablösung durch Zusatz-Potentiale realisierbar: technisch maximal mit erprobter Technik, Prognosen ATWS (2)	theoretisch (wenn Vorkommen existent, doch mit erprobter Technik nicht nutzbar, dazu also Innovation notwendig): Innovation	Schweiz	Import	Kosten und Risiken: Kosten, Innovation	Kosten, HV-Netz & Speicherung	Tripel-Risiko	Break even	Pay-Back
	%	TWh	TWh		%	%	CHF				
fossil	4	3	Energie-wende: Ersatz	CO2-Sequestrierung	Energie-wende: 0	Energie-wende: 0	> 10 Mia.(3)	Devisenexport			
nuklear	41	26		- 4. Generat. - Fusion			> 100 Mia.	> 10 Mia.			
total		29									
Wasser	54	34	2	erschöpft	0	0		> 10 Mia.			
Sonne	0.2	0.15	15	à la Desertec	0	> 370	> 10 Mia.	> 10 Mia.			
Wind	0.1	0.07	4	Swimming Mega-Parks	0	> 370	> 10 Mia.	> 10 Mia.			
Boden	0	0	3	Non-abrasive Drilling	> 370	0	< 10 Mia.	0			
Bio	0.7	0.42	4	Förderinitiative BioProFi (4)	0	< 370	< 10 Mia.	> 10 Mia.			
total	100%	64 TWh	29	(*) 370% = 237 TWh = Gesamt-Energieverbrauch (=Strom, Wärme, Mobilität) Schweiz/2011 Tab.1(1)							

(1) Bundesamt für Energie Schweizerische Gesamtenergiestatistik 2011,
(2) www.akademien-schweiz.ch/.../Zukunft_Stromversorgung_Kurzfassung
(3) [PDF] 000000290408 - Bundesamt für Energie BFE, S.9
(4) http://www.bmbf.de/foerderungen/16947.php

Geoenergy must have an **utterly strong position** in the **optimal energy-mix**

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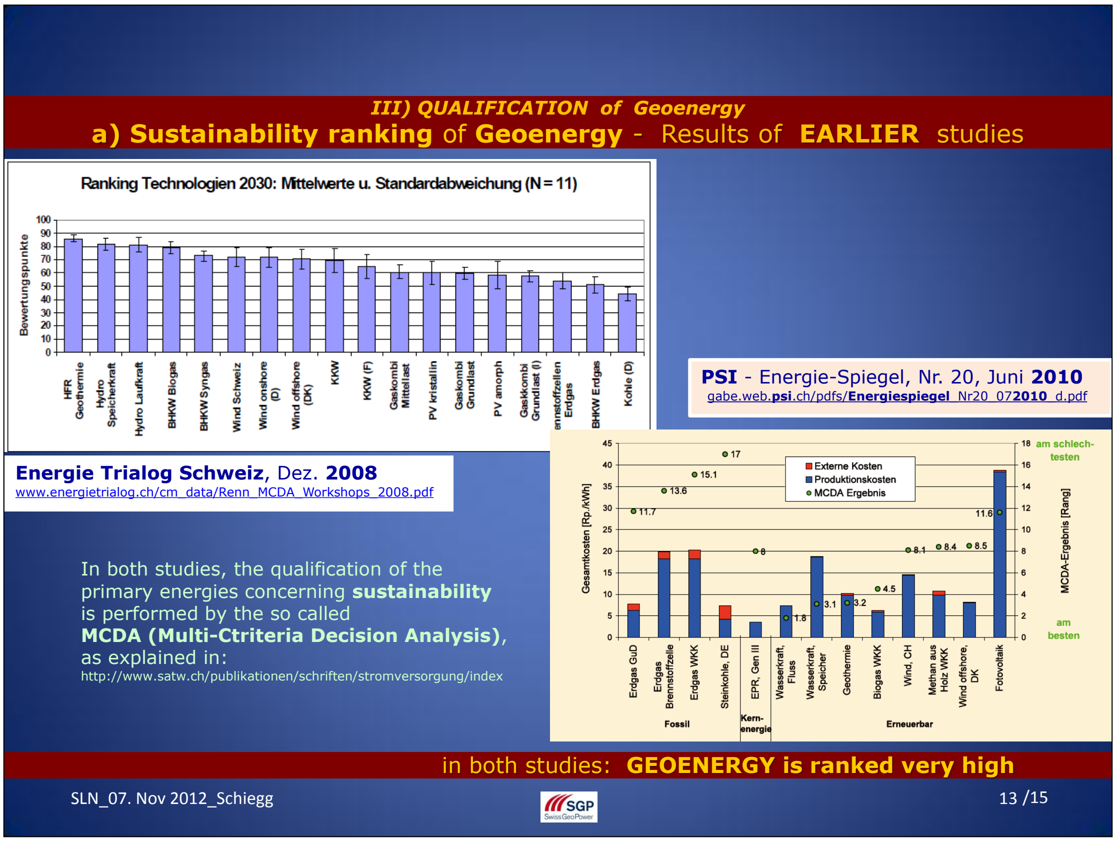

III) QUALIFICATION of Geoenergy
a) Sustainability ranking of Geoenergy - Results of EARLIER studies
Ranking Technologien 2030: Mittelwerte u. Standardabweichung (N = 11)
Bewertungspunkte
HFR Geothermie
Hydro Speicherkraft
Hydro Laufkraft
BHKW Biogas
BHKW Syngas
Wind Schweiz
Wind onshore (D)
Wind offshore (DK)
KKW
KKW (F)
Gaskombi Mittellast
PV kristallin
Gaskombi Grundlast
PV amorph
Gaskombi Grundlast (I)
Brennstoffzellen Erdgas
BHKW Erdgas
Kohle (D)
Energie Trialog Schweiz, Dez. 2008
www.energietrialog.ch/cm_data/Renn_MCDA_Workshops_2008.pdf
PSI - Energie-Spiegel, Nr. 20, Juni 2010
gabe.web.psi.ch/pdfs/Energiespiegel_Nr20_072010_d.pdf
Externe Kosten
Produktionskosten
MCDA Ergebnis
Gesamtkosten [Rp./kWh]
MCDA-Ergebnis [Rang]
am schlech-testen
am besten
Erdgas GuD
Erdgas Brennstoffzelle
Erdgas WKK
Steinkohle, DE
EPR, Gen III
Wasserkraft, Fluss
Wasserkraft, Speicher
Geothermie
Biogas WKK
Wind, CH
Methan aus Holz WKK
Wind offshore, DK
Fotovoltaik
Fossil
Kern-energie
Erneuerbar
In both studies, the qualification of the primary energies concerning sustainability is performed by the so called MCDA (Multi-Ctriteria Decision Analysis), as explained in:
http://www.satw.ch/publikationen/schriften/stromversorgung/index
in both studies: GEOENERGY is ranked very high
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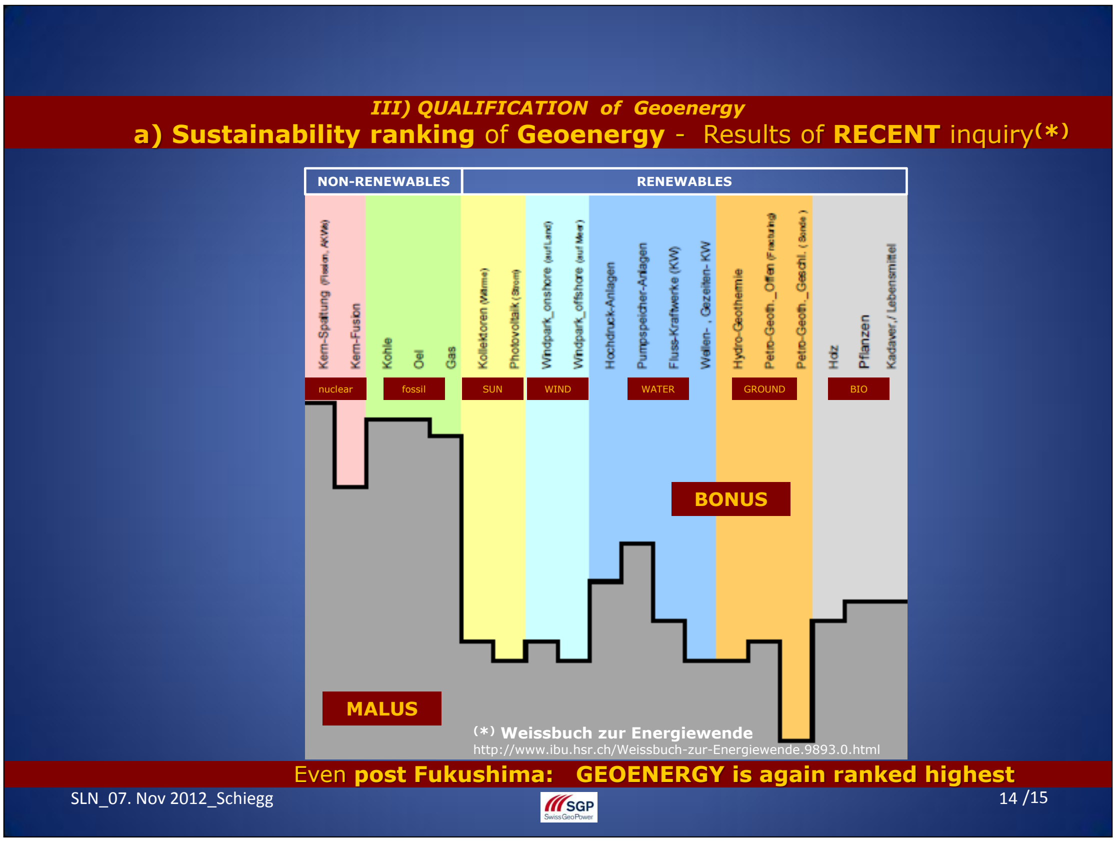

III) QUALIFICATION of Geoenergy
a) Sustainability ranking of Geoenergy - Results of RECENT inquiry(*)
NON-RENEWABLES
RENEWABLES
Kern-Spaltung (Fission, AKWs)
Kern-Fusion
Kohle
Oel
Gas
Kollektoren (Wärme)
Photovoltaik (Strom)
Windpark_onshore (auf Land)
Windpark_offshore (auf Meer)
Hochdruck-Anlagen
Pumpspeicher-Anlagen
Fluss-Kraftwerke (KW)
Wellen-, Gezeiten- KW
Hydro-Geothermie
Petro-Geoth._Offen (Fracturing)
Petro-Geoth._Geschl. (Sonde)
Holz
Pflanzen
Kadaver,/ Lebensmittel
nuclear
fossil
SUN
WIND
WATER
GROUND
BIO
BONUS
MALUS
(*) Weissbuch zur Energiewende
http://www.ibu.hsr.ch/Weissbuch-zur-Energiewende.9893.0.html
Even post Fukushima: GEOENERGY is again ranked highest
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IV) ASSETS of Geoenergy

"The Potential of *Deep Geothermal Energy* in the Energy Debate"

The **potential** of "Deep Geothermal Energy" (Geoenergy) is **extraordinarily high :**

- **Theoretically**, the potential is unlimited

- **Politically**, the decisive assets of deep geothermal energy are the following **facts:**
  - **autonomy**, because anywhere existent
  - thus, **high supply security** of energy (power and heat)
  - **no cost** for ressources, hence no export of currencies
  - **negligible GAU** (maximum credible accident)
  - **no earthquakes**, when CLOSED heat exchanger,
  - **no dangerous emissions**, no waste to be disposed
  - high **social acceptance**, thus, democratic support

- **Technically**, the potential

  - **depends on** the **CAPABILITY of accessing and exploiting** the so most interesting **unlimited occurrenc**e of geothermal energy

  - is limited to the **economic feasibility of such access and exploitation** by **necessarily new technologies** for deep drilling, as by **photonics**

Therefore, **new drilling techniques,** based on **Photonics**, will be presented as next

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6 Physical Rock Properties Relevant for Deep Drilling

Hansruedi Schneider, HSR University of Applied Sciences Rapperswil, IBU Institute for Civil Engineering and Environment, Rapperswil SG, Switzerland

6.1 Abstract

The effectiveness of any method for drilling deep wells is determined to a great extent by the physical-mechanical properties of the rock and primarily by the strength, elastic and viscoelastic properties. In addition to the absolute values of the rock properties, their dependency on temperature, pore pressures, in situ stresses as well as unloading-reloading cycles play an important role.

When a well is drilled, the rock surrounding the hole must take the load that was previously taken by the removed rock. As a result, the in situ stresses are significantly modified near the bore hole wall. A significant increase in stress results around the wall of the hole, that is, a stress concentration. The basic problem is to know, and to be able to predict, the reaction of the rock to the altered mechanical loading. This is a classical, though not very easy, rock mechanics problem.

Well bore stability, a great concern for drilling deep wells down to 10 km depth, is largely dominated by the in situ stress system in comparison with the strength properties of the rock at the depth considered as well as the corresponding temperature. The local stress distribution around a well bore is controlled by mechanical (in-situ stresses), chemical, thermal, and hydraulic effects.

If the redistributed stresses around the bore hole exceed the rock strength, either in tension or compression, then bore hole instability may result.

Stress-induced bore hole failures can be grouped into the following classes:

- **Hole collapse** or enlargement due to brittle rock failure of the wall
- **Hole size reduction** due to ductile rock failure presented by time-dependent plastic flow of rock into the bore hole
- **Tensile splitting** of the rock from excessive well bore pressures

A wide variety of analytical and numerical models exist for predicting well bore stresses and modes of instability for nearly all possible loading conditions, well geometries, rock properties and wellbore fluids.

In order to evaluate the potential for well bore stability a realistic constitutive model must be used to compute the stresses and/or strains around the well bore. The computed stresses and strains must then be compared against a given failure criterion. Numerous shear failure criteria such as Mohr-Coulomb, Drucker-Prager, von Mises, modified Lade criteria and others are proposed in the literature. The Mohr-Coulomb shear-failure model is one of the most widely used models for evaluating bore hole collapse.

At higher temperatures and in situ pressures the efficiency of many drilling methods are not known. Most probably they will become less efficient due to more ductile rock behavior at elevated temperatures in greater depths.

For this reason study of the elastic properties of rocks at high temperatures is of great practical and theoretical importance. Dedicated laboratory tests and in-situ stress measurements are desir-

able to have more confidence in predictions achieved with analytical or numerical modeling tools.

6.1.1 Sources

[1] ARGE Geothermie Espace Bern, *Grundlagenstudie Tiefengeothermie Espace Bern*, 45 p; Juni 2010

[2] Fuchs F., *Conceptual Model for a geothermal enhanced district heating grid in Thun*, CAS DEE-GEOSYS University of Neuchâtel, 18 p; 2011 - 2012

[3] Fjaer, E., Holt R.M., Horsrud P., Raaen A.M. and Risnes R. *Petroleum related Rock Mechanics*, Developments in Petroleum Science 53, Elsevier, 2008

[4] Labhart, T., *Geologie der Schweiz*, 1992

[5] Jaeger, J.C. and Cook, N.G.W., *Fundamentals of Rock Mechanics*, Methuen, 1969

WORKSHOP

PHOTONICS FOR DEEP GEOTHERMAL ENERGY HARVESTING

Physical rock properties relevant for deep drilling

Hans R. Schneider, PhD

Prof. of Geotechnical Engineering

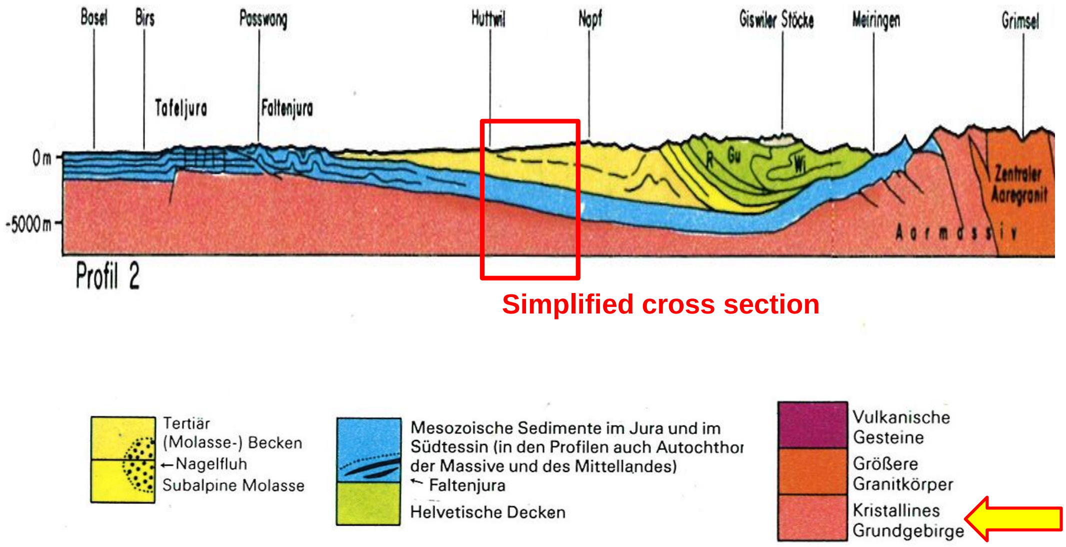
Neuchatel, November 7, 2012

HSR HOCHSCHULE FÜR TECHNIK RAPPERSWIL

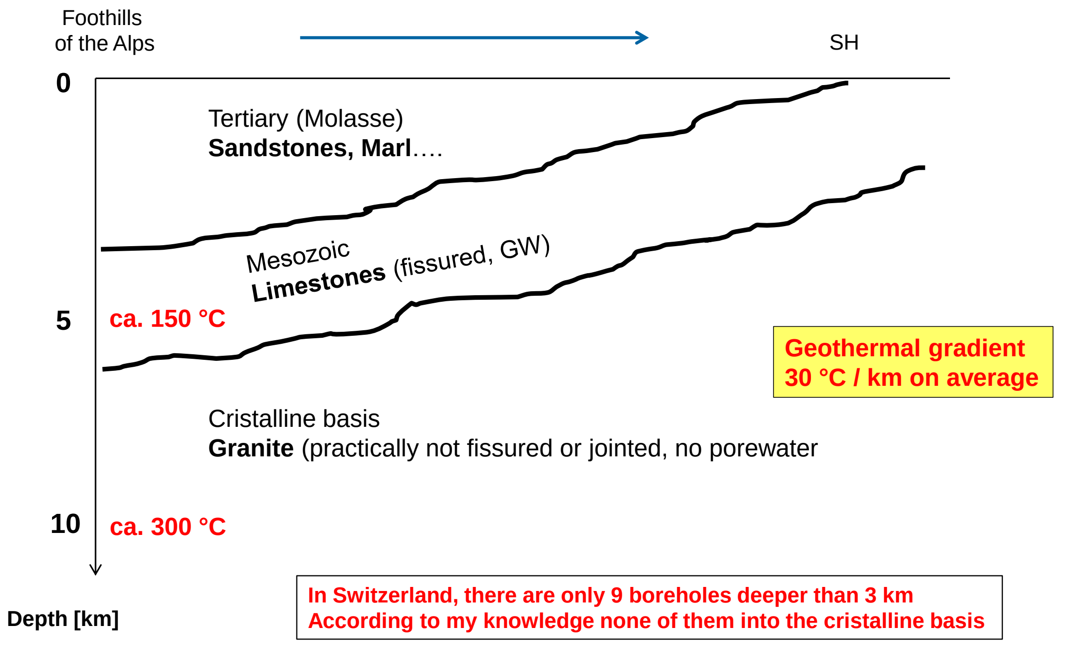
FHO Fachhochschule Ostschweiz

Geological-tectonic cross section for Switzerland

(from Labhart T. P.: Geologie der Schweiz, 1992)



Simplified cross section for conceptual considerations



What do we need to know to estimate the borehole stability

- **Rock stresses *in situ***
  - vertical overburden stresses σ_V
  - horizontal (tectonic) stresses σ_{Hmax} and σ_{hmin}
  - Pore pressures p_0
- **Rock failure strength**
  - Shear strength parameters such as
    - angle of internal friction and
    - cohesion

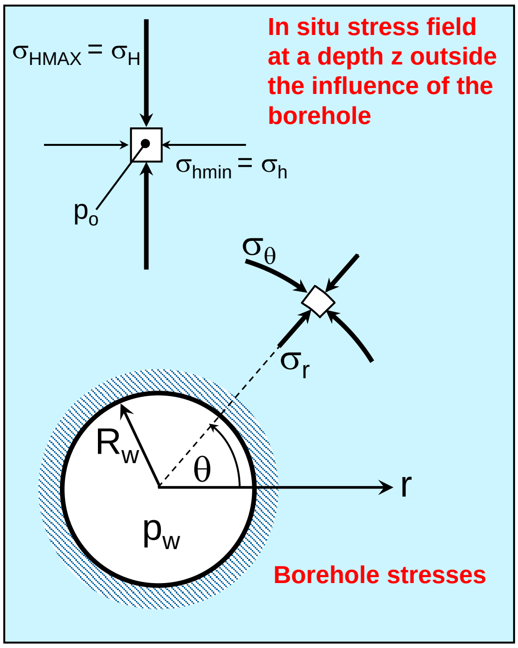
As a function of rock temperature and the existing In situ stresses

- **Pressure p_w inside the borehole**
  - from some kind of casing
  - mud pressure

Insitu stresses in the rock and borehole stresses

- The in situ stress field consists of natural earth stresses and pressures, generated by gravity, tectonics…
- A reason for different horizontal stresses at a certain depth z (= anisotropic stress state) is tectonic stresses.
- Borehole stresses are generated by creation of an opening in a natural stress field

As a result, a stress concentration is produced around the borehole, and so the *in situ* stresses are modified. This could lead to rock failure



In situ stresses in the rock

- The vertical principal in situ stress σ_v is usually assumed to be equivalent to the weight of the overburden, i.e.

$$\sigma_v = z \cdot \gamma$$

- Generally the ratio of the minimum horizontal stress $\sigma_{h\,min}$ to the vertical stress σ_v is within the limits of:

$$\frac{\sigma_{h\,min}}{\sigma_v} = 0.3 \text{ to } 1.5$$

- and the ratio of the maximum horizontal stress $\sigma_{H\,max}$ to the minimum horizontal $\sigma_{h\,min}$ stress ranges from:

$$\frac{\sigma_{H\,max}}{\sigma_{h\,min}} = 1 \text{ to } 2$$

1 = isotropic stress field

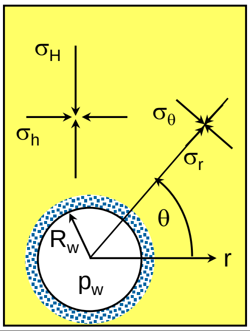
Stresses around vertical boreholes in anisotropic stress field

Stress calculation approach for Linear Elastic rock behavior based on the “Kirsch” Equations

$$\sigma_r = \frac{\sigma_H + \sigma_h}{2}\left(1 - \frac{R_w^2}{r^2}\right) + \frac{\sigma_H - \sigma_h}{2}\left(1 + 3\frac{R_w^4}{r^4} - 4\frac{R_w^2}{r^2}\right)\cos 2\theta + p_w\frac{R_w^2}{r^2}$$

$$\sigma_\theta = \frac{\sigma_H + \sigma_h}{2}\left(1 + \frac{R_w^2}{r^2}\right) - \frac{\sigma_H - \sigma_h}{2}\left(1 + 3\frac{R_w^4}{r^4}\right)\cos 2\theta - p_w\frac{R_w^2}{r^2}$$

$$\sigma_z = \sigma_v - 2\nu_{fr}(\sigma_H - \sigma_h)\frac{R_w^2}{r^2}\cos 2\theta$$

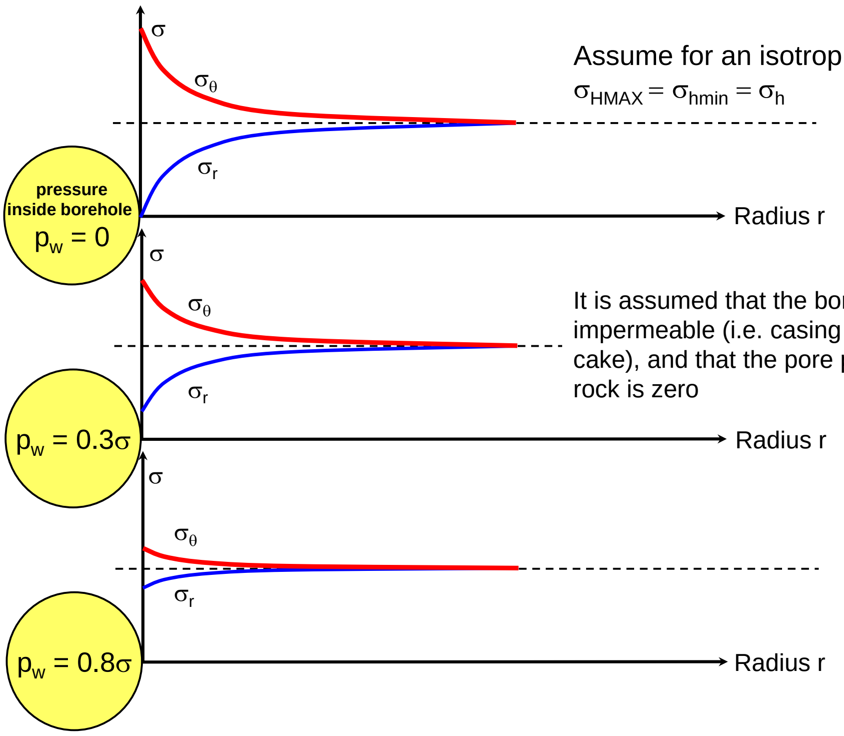


At the wall of the borehole ($r = R_w$) the equations simplify to:

$$\boxed{\begin{aligned} \sigma_r &= p_w \\ \sigma_\theta &= \sigma_H + \sigma_h - 2(\sigma_H - \sigma_h)\cos 2\theta - p_w \\ \sigma_z &= \sigma_v - 2\nu_{fr}(\sigma_H - \sigma_h)\cos 2\theta \end{aligned}}$$

θ is measured relative to the direction of the major horizontal stress σ_H

Stresses around vertical boreholes

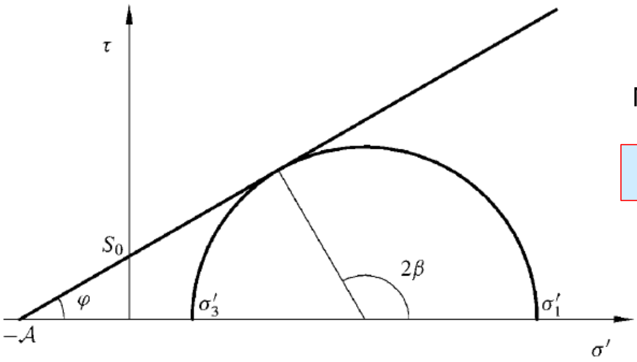


Assume for an isotropic stress field

$\sigma_{HMAX} = \sigma_{hmin} = \sigma_h$

It is assumed that the borehole wall is impermeable (i.e. casing or perfect mud cake), and that the pore pressure in the rock is zero

Borehole failure criteria based on Mohr-Coulomb



Mohr-Coulomb failure criterion

$$\boxed{\tau = S_0 + \sigma \cdot \tan\varphi}$$

S_0 = cohesion [kPa]

φ = angle of internal friction [°]

redefining $\beta = \frac{\pi}{4} + \frac{\varphi}{2}$

$C_0 = 2 \cdot S_0 \cdot \tan\beta$

$$\boxed{\boldsymbol{\sigma_1 = C_0 + \sigma_3 \cdot \tan^2\beta}}$$

reformulated
Mohr-Coulomb failure criterion

Conditions for shear failure in vertical borehole for isotropic stress field and impermeable borehole wall

$\sigma_1 \geqslant \sigma_2 \geqslant \sigma_3$	Borehole failure occurs if
$\sigma_\theta \geqslant \sigma_z \geqslant \sigma_r$	$p_w \leqslant p_f + \frac{2(\sigma_h - p_f) - C_0}{1 + \tan^2\beta}$
$\sigma_z \geqslant \sigma_\theta \geqslant \sigma_r$	$p_w \leqslant p_f + \frac{\sigma_v - p_f - C_0}{\tan^2\beta}$
$\sigma_z \geqslant \sigma_r \geqslant \sigma_\theta$	$p_w \geqslant p_f + 2(\sigma_h - p_f) - \frac{\sigma_v - p_f - C_0}{\tan^2\beta}$

and hydraulic fracturing occurs at $p_{w,max} = 2 \cdot \sigma_h - p_f + T_O$

where T_O = tensile strength of the rock

The principal stresses at the borehole wall are

$$\sigma_r = p_w$$

$$\sigma_\theta = 2\sigma_h - p_w$$

$$\sigma_z = \sigma_v$$

Source: Fjaer, E., Holt R.M., Horsrud P., Raaen A.M. and Risnes R., 2008,

In summary we can state

- σ_θ is the tangential stress, also called the hoop stress
- σ_θ lies parallel (tangential) to the borehole wall
- **The magnitude of σ_θ is affected by:**
  - In situ stresses
  - Stabilizing pressure inside the borehole
  - Temperature and rock behavior
- **The most critical stress conditions are around a borehole**
  - High σ_θ values can lead to rock failure or yield
  - Lower σ_θ values usually imply stability

What information do we need to successfully lower a deep borehole and keep it open

- **First, we need stresses around the borehole**
  - In **situ stresses** are vital
  - Temperature profile; thermally induced changes in stress affect both the tangential and the axial stress.
  - In some cases, rock properties are also needed
- **Then, we must compare the maximum shear stress with the rock strength**
  - We need to know the **rock strength for the in situ temperature, creep behavior for long term stability and deformation properties**

- **If stress exceeds strength, the rock will yield or "fail"**

What information do we need to successfully lower a deep borehole and keep it open

- **The only possibility to stabilize a borehole from failing or yielding is by providing some kind of lateral support p_w from within the borehole. This could be:**
  - some casing
  - fluid pressure
- **It is of greatest importance to estimate/calculate/control this stabilizing support during all phases of drilling. If a fluid pressure is used, care has to be exercised to be within the pressure band of possible minimum and maximum values**

References

- ARGE Geothermie Espace Bern, «Grundlagenstudie Tiefengeothermie Espace Bern», 45 p; Juni 2010
- Fuchs F., «Conceptual Model for a geothermal enhanced district heating grid in Thun, CAS DEEGEOSYS University of Neuchâtel, 18 p; 2011 - 2012,
- Fjaer, E., Holt R.M., Horsrud P., Raaen A.M. and Risnes R. «Petroleum related Rock Mechanics», Developments in Petroleum Science 53, Elsevier**,** 2008,
- Labhart, T., «Geologie der Schweiz», 1992
- Jaeger, J.C. and Cook, N.G.W., «Fundamentals of Rock Mechanics», Methuen, 1969

HSR
HOCHSCHULE FÜR TECHNIK
RAPPERSWIL
FHO Fachhochschule Ostschweiz

7 High Power Laser for Rock Drilling

Mark S. Zediker, Foro Energy Inc., Littleton, Colorado, USA

7.1 Abstract

Foro Energy has developed a unique hardware platform to transmit up to 20 kW of fiber laser power through a multi-km optical fiber opening up new applications in oil, gas, geothermal and mining industries. These energy industries spend in excess of $100 billion per year to extract the natural resources that power the economy, employing a conventional technology toolkit of mechanical cutters, explosives, chemicals, and high pressures. Foro Energy's mission is to drill and perform a variety of other operations faster, safer, cheaper, and more effectively than today's tools. One of the major applications for this technology is a laser based drilling system for drilling ultra-hard crystalline rock formations in the down-hole environments found in each of these industries.

Foro Energy's laser drilling system drilled through ultra-hard crystalline rock with a higher rate of penetration and a lower weight on bit than can be achieved with a conventional tri-cone drilling bit. The rate of penetration is important in drilling applications because the faster the bore hole can be drilled, the less it will cost. The lower weight on bit also translates to a reduction in drilling costs because of the less power required to operate the drilling equipment as well as the reduced mechanical stress on the rotating components. The reduced mechanical stress on the rotating components means that the rotating equipment and the bit are going to have better reliability and the drilling crew will spend less time tripping the bit into and out of the bore hole.

The Foro Energy laser drilling system is a highly customized coil tube drilling rig that has been outfitted with a laser power transmission system and a laser drilling assembly. The laser power transmission system consists of a 20 kW laser, an industrial grade optical fiber to connect the laser to an optical slip ring, a high power optical slip ring, a fiber optic packaged for deployment down-hole, a custom down-hole fiber optic connector to terminate the fiber, and a high power optic system for shaping and synchronizing the beam with the rotation of the bit.

The core of the Foro Energy laser drilling system is its laser power transmission system which can deliver >10 kW of laser power at the distal end of a multi-km long optical fiber. The power transmission system is designed to minimize the Rayleigh scattering while suppressing the non-linear phenomenon such as Stimulated Brillouin Scattering and Stimulated Raman Scattering. Stimulated Brillouin Scattering is the major concern in a power transmission system because once it reaches threshold it begins to reflect power backwards in the fiber. Not only does this reduce the efficiency of the power transmission but it also poses a serious threat to the reliability of the launch optics and the laser system. Foro Energy has successfully engineered a power transmission cable, launching 20 kW into the fiber and measuring 18 kW exiting a 1.5 km long optical fiber. The power output showed no measurable non-linear effects and the attenuation of the optical fiber is attributed entirely to the Rayleigh scattering losses in the fiber.

The Foro Energy down-hole laser drilling assembly successfully drilled through the 35 ksi ultra-hard crystalline rock using the power delivered by the optical fiber to the down-hole laser beam formation

system. The rate of penetration was 4x the rate of a conventional tri-cone bit.

The laser beam sweeps over the surface of the rock, creating temperatures in excess of 600°C causing macro and micro fractures of the rock surface. These fractures result in a substantial weakening of the rock and with the aid of mechanical cutters the weakened rock can easily be scraped off of the surface. The degree of weakening of the rock can be determined by the weight on bit required by the drill bit as it advances into the bore hole. When the laser system is operating, it typically requires less than 1’000 lbs weight on bit to advance the drill bit, however, when the laser is turned off, the weight required increases by 10x and the rate of penetration drops significantly. A conventional tri-cone bit was unable to advance through the rock at 1/4x the rate of the Foro Energy bit with 20’000 lbs weight on bit.

Summary: ForoEnergy has developed a platform technology capable of delivering high optical power to remote locations. We have successfully developed each of the components of the power transmission system that enables many new applications in the oil, gas, geothermal and mining industries.

This success was only possible with the dedication of a unique team of people made up of engineers from the laser and drilling industries. Also special thanks to Colorado School of Mines for their assistance analyzing the rock samples during the process development.

Acknowledgment - This material is based upon work supported by the Department of Energy, ARPA-E, under Award Number AR0000044.

7.2 Questions

Max. bore hole depth (m)

The laser-mechanical drilling process has been tested extensively over significant distances in a laboratory test rig environment and, through integration of laser hardware to a coiled tubing drilling rig, under the ground for extended periods of time in a proof-of-concept operation. Foro Energy is working with a set of industry partners to mature the technology beyond this current pre-commercial stage.

Max. respectively min. or optimal bore hole diameter (cm)

Foro Energy designs to standard industry bore hole diameters as specified by industry partners. Fundamentally, there is not a hard upper bound but technical requirements of course increase at large bore hole sizes.

Volume capacity of rock excavation at the bore hole bottom (cm^3/s)

The laser-mechanical drilling process enables a step changes in drilling rate (2-4x) relative to a conventional mechanical-only drilling at the same bit size through ultra hard rock.

Mode of operation of rock excavation at the bore hole bottom

The laser-mechanical drilling process uses the high power laser to first destroy the rock's strength, allowing a conventional mechanical bit to then remove the softened rock at extremely low WOB (weight on bit, <1000 lbs) and extremely low torque (<300 ft-lbs).

Transport/disposal of cuttings to the surface

Drilling debris was cleared with conventional oilfield packages. Please see the answer to question 1 above.

Environmental conditions during drilling (air, water, mud...) at the bore hole bottom

Foro Energy integrates its laser hardware platform with conventional oilfield equipment. In one of the initial proof of concepts for the drilling application, this conventional oilfield equipment included conventional oilfield packages to clear debris from bore hole bottom. In each application, the product road map framework emphasizes maximizing the probability of technical success in each successive step.

Main risks of the drilling method

Foro Energy views potential risks as in line or lower relative to conventional oilfield technology.

Drilling cost at depth of 100 m, of 1'000 m, and of 5'000 m

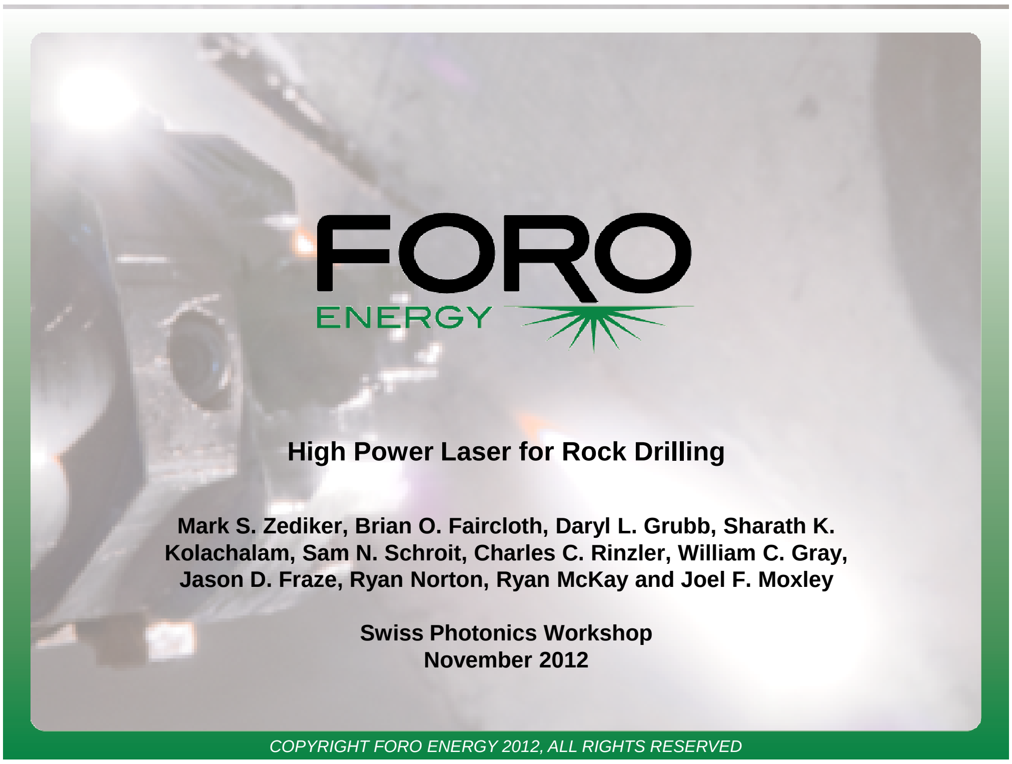
The laser-mechanical drilling process enables: i) step changes in drilling rate (2-4x); ii) extremely low WOB (<1000 lbs); iii) extremely low torque (<300 ft-lbs); iv) longer bit life; and thus, v) lower drilling cost per foot.

Status of development, publication of the previous R&D results

Foro Energy is working with a set of industry partners to mature the technology beyond the current pre-commercial stage. There is no publication of previous R&D results.

Main advantage/disadvantage of the drilling method

The laser-mechanical drilling process enables: i) step changes in drilling rate (2-4x); ii) extremely low WOB (<1000 lbs); iii) extremely low torque (<300 ft-lbs); iv) longer bit life; and thus, v) lower drilling cost per foot.


FORO
ENERGY
High Power Laser for Rock Drilling
Mark S. Zediker, Brian O. Faircloth, Daryl L. Grubb, Sharath K. Kolachalam, Sam N. Schroit, Charles C. Rinzler, William C. Gray, Jason D. Fraze, Ryan Norton, Ryan McKay and Joel F. Moxley
Swiss Photonics Workshop
November 2012
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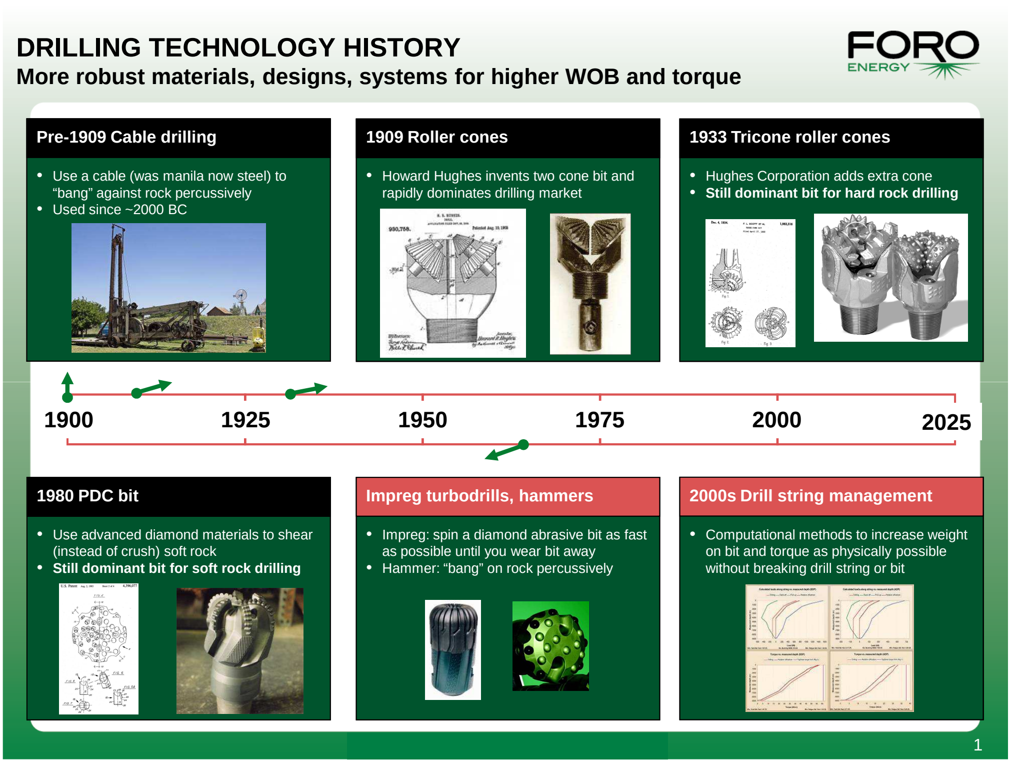

DRILLING TECHNOLOGY HISTORY
More robust materials, designs, systems for higher WOB and torque
FORO
ENERGY
Pre-1909 Cable drilling
Use a cable (was manila now steel) to "bang" against rock percussively
Used since ~2000 BC
1909 Roller cones
Howard Hughes invents two cone bit and rapidly dominates drilling market
1933 Tricone roller cones
Hughes Corporation adds extra cone
Still dominant bit for hard rock drilling
1900
1925
1950
1975
2000
2025
1980 PDC bit
Use advanced diamond materials to shear (instead of crush) soft rock
Still dominant bit for soft rock drilling
Impreg turbodrills, hammers
Impreg: spin a diamond abrasive bit as fast as possible until you wear bit away
Hammer: "bang" on rock percussively
2000s Drill string management
Computational methods to increase weight on bit and torque as physically possible without breaking drill string or bit
1

Laser Drilling for Oil, Gas and Geothermal Wells

FORO ENERGY

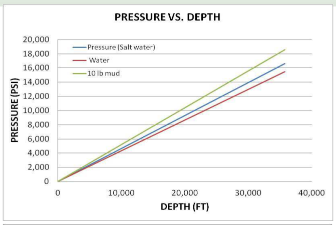
- A major portion of the world's energy is trapped beneath and in very hard rocks
- Foro Energy is developing a revolutionary drilling process which combines high power laser energy with oil field "dumb" iron to enable drilling of ultra hard crystalline rocks
- System tests at up to 20 kW successful in initial trials
- Foro Energy has demonstrated the optical and mechanical components for the successful deployment of laser energy in remote locations under high g loads, high temperatures and high pressures

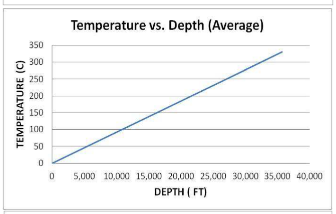
2

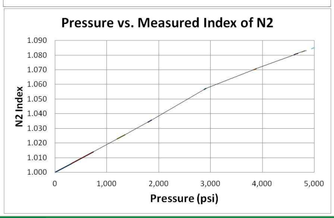
The Challenges of Laser Drilling

FORO ENERGY

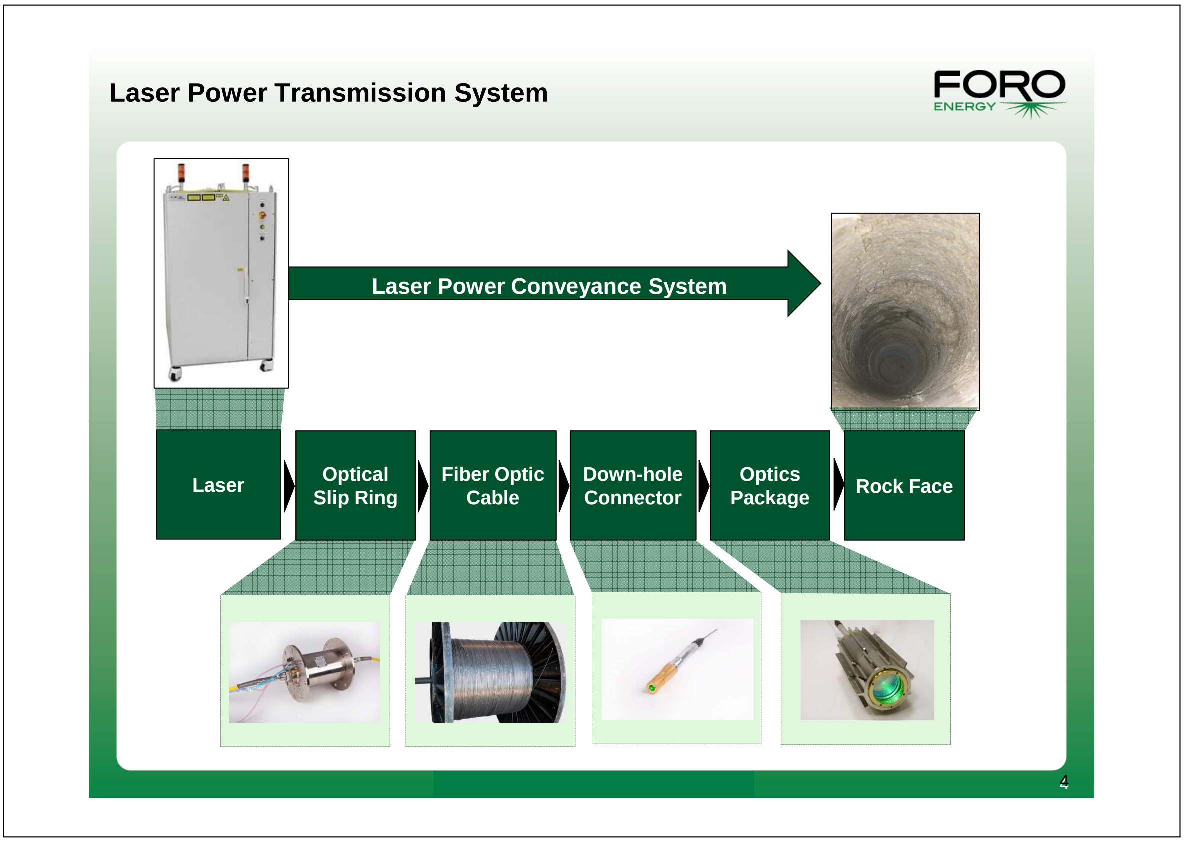
- The pressure can exceed 10,000 psi for the optical system at depths up to 20,000 feet
- The temperature can exceed 150 C for the optical system at depths up to 20,000 feet
- The laser must be transmitted through a transparent "fluid" or gas
- Liquid nitrogen is readily available and can be delivered at pressures up to 10,000 psi on site
- Gas becomes supercritical at these pressures and begins to behave like a liquid
  - Optical systems no longer perform as designed due to refractive index variations with pressure
  - Not feasible to have adjustable optical systems due to the high g environment which can exceed 250 g rms and 500 g shock

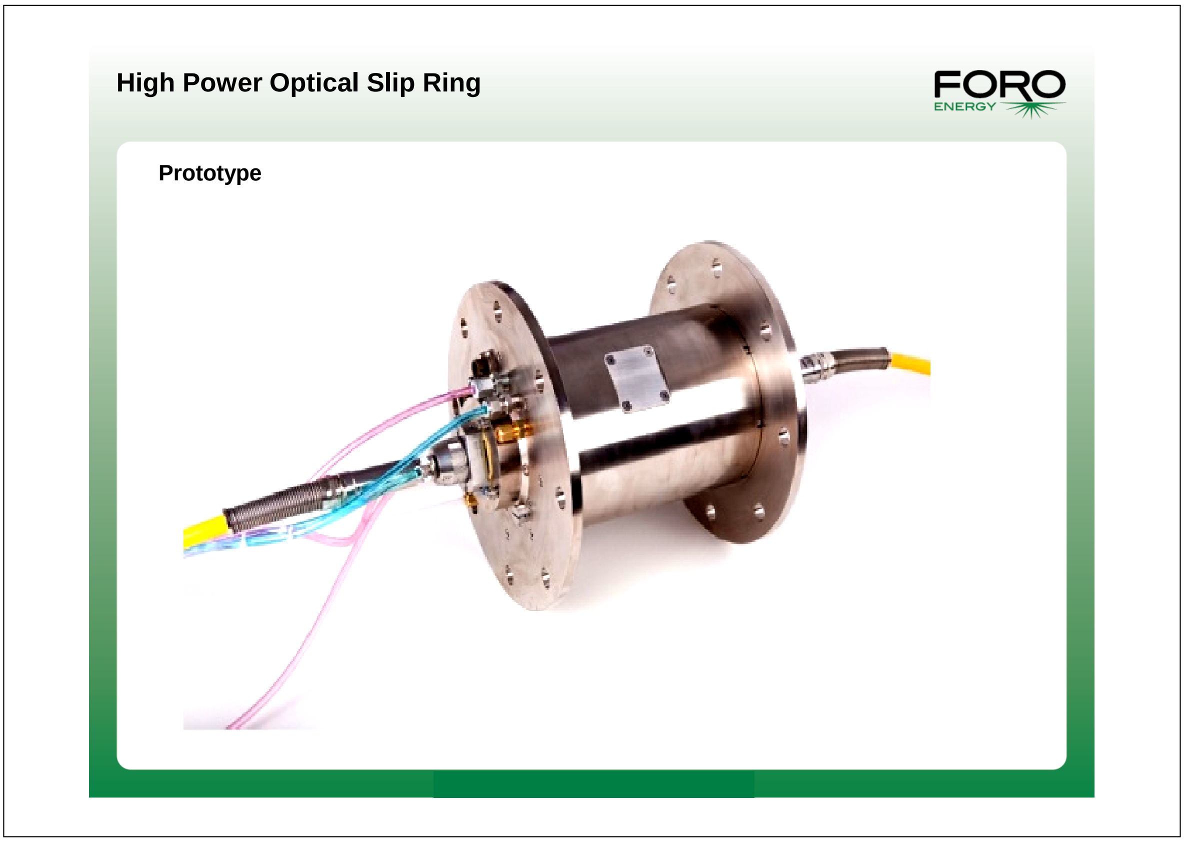






3


Laser Power Transmission System
FORO ENERGY
Laser Power Conveyance System
Laser
Optical Slip Ring
Fiber Optic Cable
Down-hole Connector
Optics Package
Rock Face
4

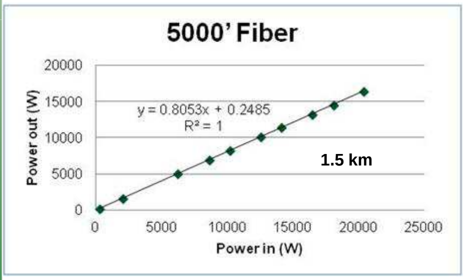

High Power Optical Slip Ring
FORO ENERGY
Prototype

High Power Fiber Optic Power Transmission

FORO ENERGY

20 kW 1.5 km Transmission Test

Fiber Packaged in SS tubing designed to minimize fiber strain



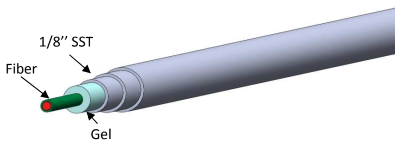
• >20 kW launched into 1.5 km long optical fiber with minimal non-linear effects

- *•Highly Linear Power in /Power out curve*
- *•No significant SRS spectral signature*

6

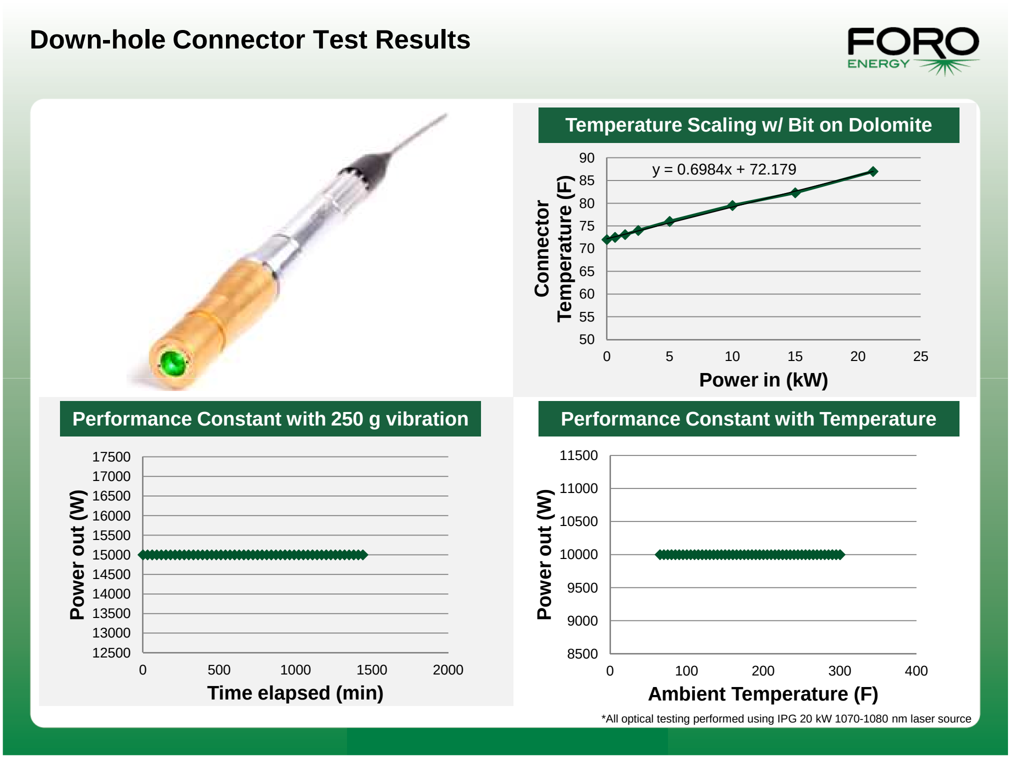
Fiber Optic Cable Performance Data

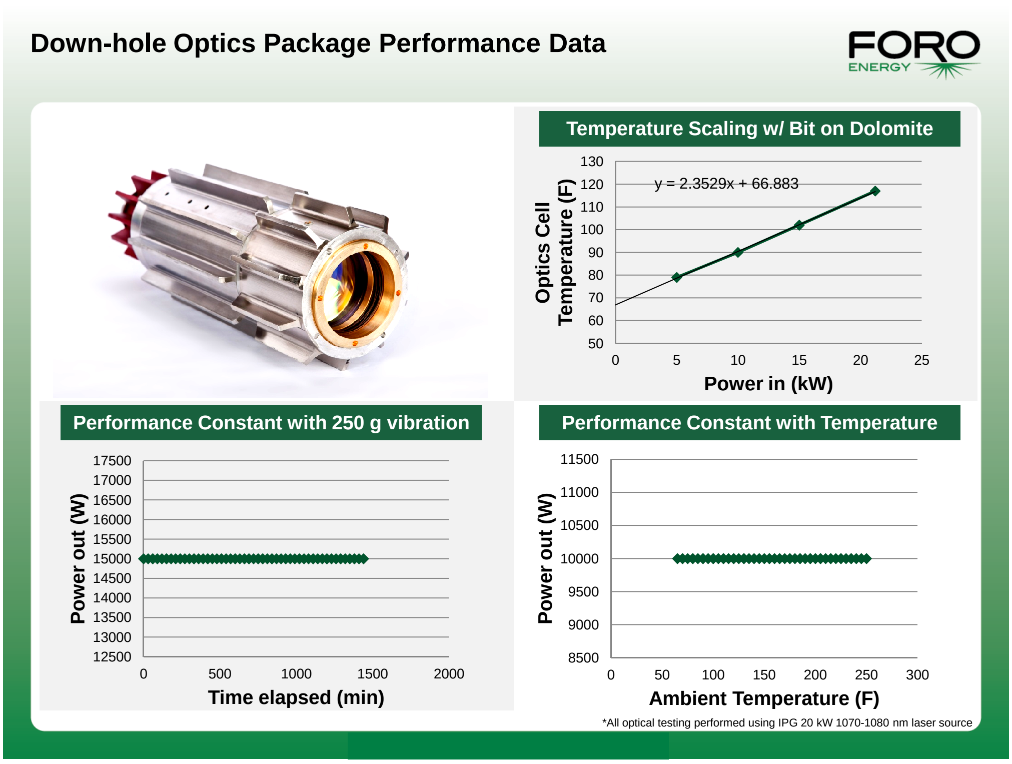
FORO ENERGY



• Fiber optic packaging tested to 250 g and 200 C (400 F)

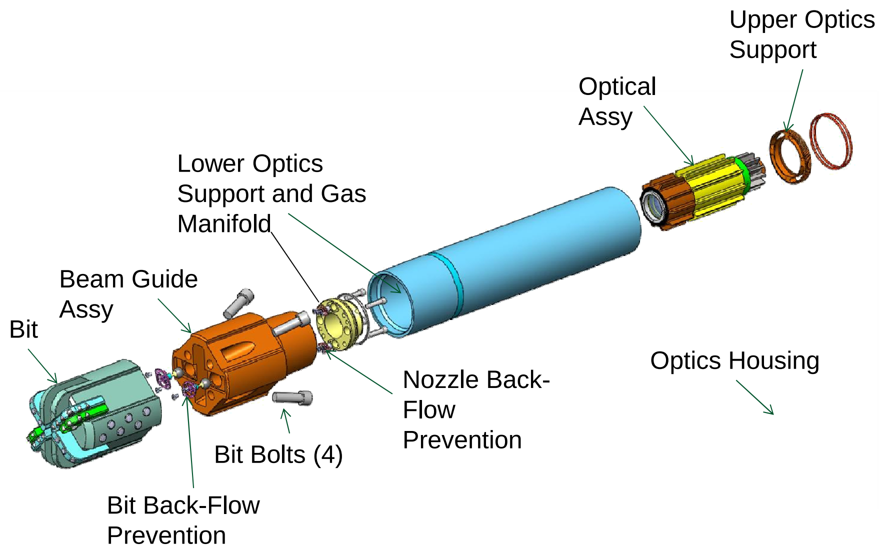
- **•Output power and mode quality monitored during testing**


Down-hole Connector Test Results
FORO
ENERGY
Temperature Scaling w/ Bit on Dolomite
y = 0.6984x + 72.179
Connector Temperature (F)
Power in (kW)
Performance Constant with 250 g vibration
Power out (W)
Time elapsed (min)
Performance Constant with Temperature
Power out (W)
Ambient Temperature (F)
*All optical testing performed using IPG 20 kW 1070-1080 nm laser source


Down-hole Optics Package Performance Data
FORO
ENERGY
Temperature Scaling w/ Bit on Dolomite
y = 2.3529x + 66.883
Optics Cell Temperature (F)
Power in (kW)
Performance Constant with 250 g vibration
Power out (W)
Time elapsed (min)
Performance Constant with Temperature
Power out (W)
Ambient Temperature (F)
*All optical testing performed using IPG 20 kW 1070-1080 nm laser source

HIGH POWER LASER DRILLHEAD, BIT ASSEMBLY

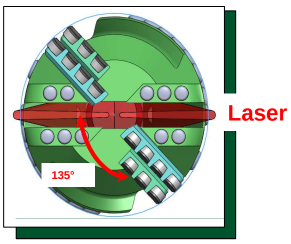
Simultaneously satisfies mechanical and laser specifications

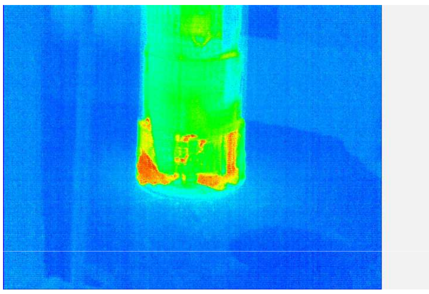


10

Laser Mechanical Rock Drilling Process

Laser-Mechanical Drill Bit



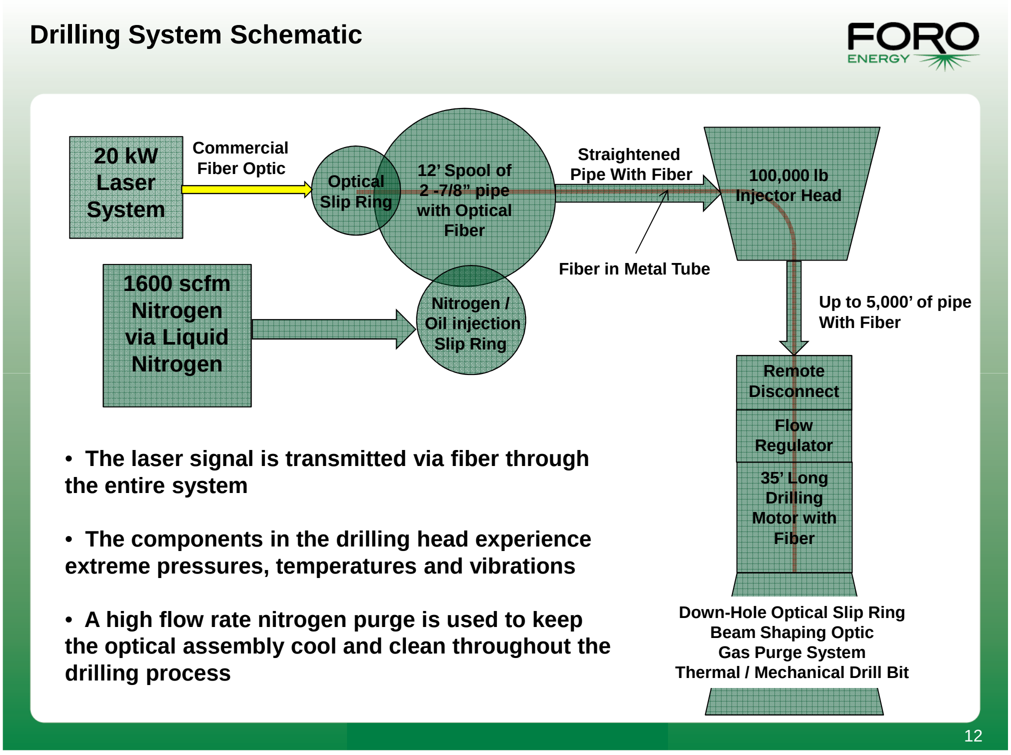


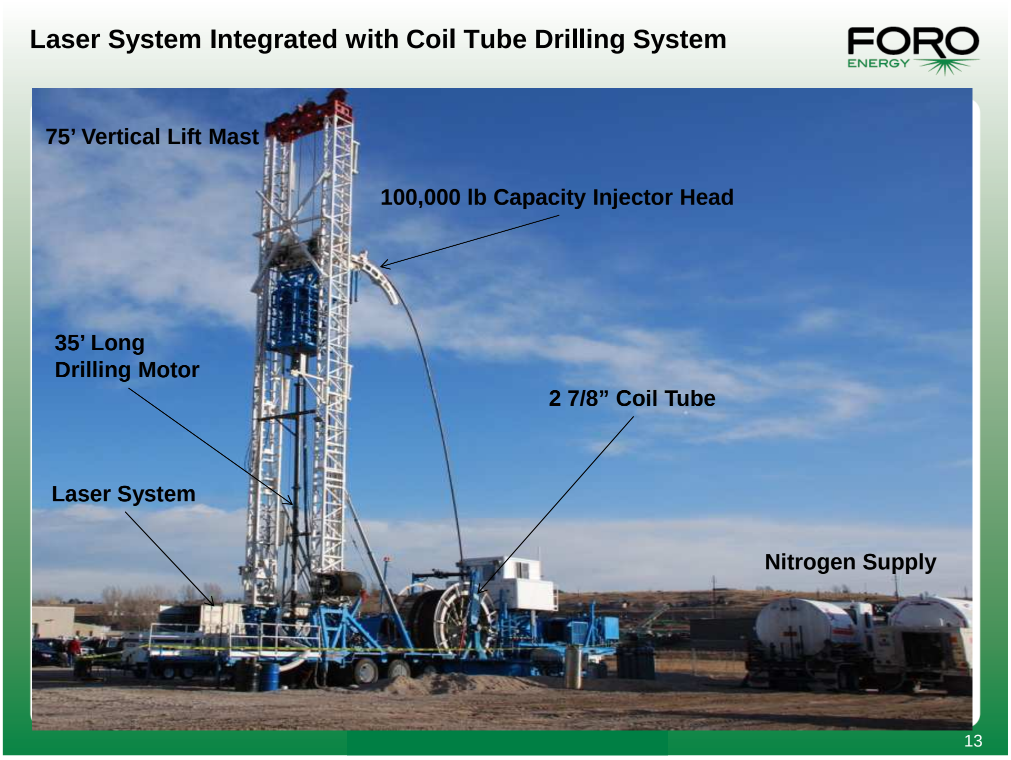
- Laser based drilling process developed for most ultra-hard crystalline rock:

• Granite:	>25 ksi
• Basalt:	45 ksi- 60 ksi
• Travis Peak Sandstone:	35 ksi
• Dolomite:	35 ksi
• Limestone:	35 ksi
• Quartzite:	40 ksi

- Mechanical cutters scrape away the “soften” layer
- Conventional drill bit: 20,000 lbs weight on bit, 1,000 ft. lbs torque
- Laser drill bit: <1,000 lbs weight on bit, <100 ft. lbs torque

11


Drilling System Schematic
FORO ENERGY
20 kW Laser System
Commercial Fiber Optic
Optical Slip Ring
12' Spool of 2 -7/8" pipe with Optical Fiber
Straightened Pipe With Fiber
100,000 lb Injector Head
Fiber in Metal Tube
1600 scfm Nitrogen via Liquid Nitrogen
Nitrogen / Oil injection Slip Ring
Up to 5,000' of pipe With Fiber
Remote Disconnect
Flow Regulator
35' Long Drilling Motor with Fiber
• The laser signal is transmitted via fiber through the entire system
• The components in the drilling head experience extreme pressures, temperatures and vibrations
• A high flow rate nitrogen purge is used to keep the optical assembly cool and clean throughout the drilling process
Down-Hole Optical Slip Ring
Beam Shaping Optic
Gas Purge System
Thermal / Mechanical Drill Bit
12


Laser System Integrated with Coil Tube Drilling System
FORO ENERGY
75' Vertical Lift Mast
100,000 lb Capacity Injector Head
35' Long Drilling Motor
2 7/8" Coil Tube
Laser System
Nitrogen Supply
13

Laser Drilling for Oil, Gas and Geothermal Wells

- Foro Energy is developing a revolutionary drilling process which combines high power laser energy with oil field “dumb” iron to enable drilling of ultra hard crystalline rocks
- System tests at up to 20 kW successful in initial trials
- Foro Energy has demonstrated the optical and mechanical components for the successful deployment of laser energy in remote locations under high g loads, high temperatures and high pressures

14

8 Challenges in Hydrothermal Spallation Drilling for Deep Heat Mining Projects

Martin Jörg Schuler, ETH Transport Processes and Reactions, Zurich, Switzerland

8.1 Abstract

Hydrothermal spallation drilling (HSD) is a promising alternative drilling technology that could prove to be economically advantageous over rotary techniques for drilling deep wells in hard rock formations needed e.g. for geothermal energy production [1-3]. This drilling technique uses the properties of certain rock types to disintegrate into small disk-like fragments when heated up rapidly by a highly energetic jet. In spallation drilling a hot fluid jet impinges on the rock surface. High heat fluxes are transferred from the hot jet to the solid rock. Due to the low thermal conductivity of rock, only a thin upper layer is heated up rapidly to high surface temperatures and thus steep temperature gradients are induced. This hot upper layer thermally expands confined by the cold surrounding rock and therefore high stresses appear. The surface temperature must be clearly below the rock fusion temperature, because the rock should react with fracturing and not with deformation to the induced stresses. At naturally present flaws in the rock near the surface, the fracturing process begins. These fractures propagate in stress direction parallel to the surface and combine with other fractures. Buckling and arching occurs when the upper rock layer loses more and more its mechanical contact to the rock underneath. Finally rock particles are ejected from the surface. The momentum flux of the hot fluid jet flushes away the formed rock cuttings and therefore the newly exposed still cold rock surface is as well impinged by the hot jet. Hence the process continuous and finally results in the drilling progress e.g. [4-10].

In water (resp. water-based drilling fluid) filled bore holes below 2 kilometers depth, water exceeds its critical pressure (221 bar) and hence hydrothermal flames can be applied to provide the required heat to spall the rock. One such potential spallation drilling head consists of a combustion chamber fed by water, fuel and an oxidant. Fuel and oxidant are preheated and afterwards ignited to form a hydrothermal flame in the aqueous environment of the burning chamber. The water present in the combustion chamber is heated up to high, supercritical temperatures (374°C) and ejected through a nozzle together with the combustion products. This highly energetic jet is finally directed towards the rock surface to induce thermal fragmentation [11-13].

Basic phenomena of such hot mostly supercritical water jets are investigated to further develop HSD under realistic temperature and pressure conditions found down hole. High heat transfer rates from the hot jet towards the cold and dense environment (drilling fluid) are detected as drawback. Because of these significant radial heat losses, a certain amount of valuable energy in transferred to the environment instead to the rock surface. These entrainment effects lower the overall efficiency of the HSD process. The heat transfer of the impinging jet towards the rock surface can be seen as crucial parameter in the process. Therefore also the heat transfer mechanisms of impinging supercritical water jets and hydrothermal flames are characterized and optimized over a wider

range of conditions. Additionally an ignition system able to ignite hydrothermal flames under the challenging conditions found at the bottom of the bore hole is shortly introduced and explained.

Experiments are conducted in two high pressure setups (up to 500 bar and 600°C) able to simulate the temperature and pressure conditions found in great depth. Both high pressure vessels have limited optical access and are equipped with a preheating and injection system providing hot jets over a wide range of operating conditions. Linear displacement units are mounted on top and at the bottom of the vessel to move measurement devices.

Additionally a numerical model based on a commercial CFD tool was developed to gain deeper inside into the system that could not be realized by means of measurements. Conservation of momentum, mass and energy including the thermophysical properties of the different components are the basis of the model. In case of a round jets at high Reynolds numbers, the realizable k-ε turbulence model is suggested [14, 15]. Finally all numerical results are validated with the experimental measurements and show an acceptable agreement.

8.1.1 Sources

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8.2 Questions

Max. bore hole depth (m)

Unknown for hydrothermal spallation drilling. In field tests of spallation drilling at ambient conditions in air, Browning et al. reached a maximal depth of 335 m.

Max. respectively min. or optimal bore hole diameter (cm)

Unknown for hydrothermal spallation drilling. For spallation drilling at ambient conditions, a huge diameter range is reported in literature up to 45 cm (Los Alamos Laboratory, USA, 1985).

Volume capacity of rock excavation at the bore hole bottom (cm^3/s)

For hydrothermal spallation drilling (HSD), penetration rates have never been determined in experimental studies or field tests. For shallow applications of spallation drilling at ambient conditions in air, a huge variety of penetration rates is published in literature. These variations appear due to the different applied burner configurations and operating conditions. The drilling performance of course also depends on the treated rock type itself. In field tests of Browning et al., a maximal drilling velocity of 15.8 m/hr in granite is reported for a hole diameter between 0.2 m to 0.25 m and a drilling depth of 335 m ($\sim$ 175 cm^3/s).

Mode of operation of rock excavation at the bore hole bottom

In spallation drilling a hot fluid jet impinges on the rock surface. High heat fluxes are transferred from the hot jet to the solid rock. Due to the low thermal conductivity of rock, only a thin upper layer is heated up rapidly to high surface temperatures and thus steep temperature gradients are induced. This hot upper layer thermally expands confined by the cold surrounding rock and therefore high compressive stresses appear. The surface temperature must be clearly below the rock fusion temperature, because the rock should react with fracturing and not with deformation to the induced stresses. Fracturing at naturally present flaws in the rock near the surface occurs. These fractures propagate in stress direction parallel to the surface and combine with other fractures. Buckling and arching occurs when the upper rock layer loses more and more its mechanical contact to the rock underneath. Finally rock particles are ejected from the surface. The momentum flux of the hot impinging fluid jet flushes away the formed rock cuttings and therefore the newly exposed still cold rock surface is as well impinged by the hot jet. Hence the process continuous and finally results in the drilling progress.

Transport/disposal of cuttings to the surface

The rock cuttings are transported in an upward stream of drilling fluid in the annulus between drill string and bore hole wall.

Environmental conditions during drilling (air, water, mud...) at the bore hole bottom

The hot impinging jet down hole is operated in an aqueous and dense environment of water and/or water-based drilling fluid.

Main risks of the drilling method

Entrainment of cold surrounding drilling fluid into the hot jet results in a fast cool down of the jet before impinging on the rock surface. Because of these significant radial heat losses, a certain amount of valuable energy in transferred to the environment instead to the rock surface. These entrainment effects lower the overall efficiency of the HSD process. The rock behavior in the field when mas-

sive stresses in the rock formation act on the rock to be thermally fragmented is still unknown. The possibility is given that rock under field conditions reacts different to the applied thermal stresses compared to the used rock samples in laboratory experiments. For the spallation process, it is essential that the treated rock reacts brittle and not ductile to the induced heat shocks.
Significantly lowered drilling performance of HSD in sedimentary rock formations (Limestone, Sandstone, ...)
The development of a sensor system applicable at the harsh conditions found down hole to record drilling performance, hole diameter, drilling direction and distance between nozzle and rock surface is not yet realized.

Drilling cost at depth of 100 m, of 1’000 m, and of 5’000 m

The drilling costs for hydrothermal spallation drilling are still unknown. But it is expected that HSD performs well in hard rock formations (e.g. granite). In sedimentary formations, conventional rotary drilling methods outperform the spallation technology. Hence HSD is especially suitable for hard rock formations met in great depth. There, it is expected that the drilling costs rise linearly with depth, contrary to conventional drilling methods, where the costs rise exponentially with depth. A final cost estimation for the HSD technology has not been done yet.

Status of development, publication of the previous R&D results

Basic investigations of important phenomena linked to hydrothermal spallation drilling are already published or in the preparation. For example entrainment effects of supercritical water (>374°C and >221 bar) jets are characterized for a wide range of conditions experimentally and theoretically by means of modeling. Different heat flux sensors are developed and applied under the harsh conditions of supercritical water to detect the crucial parameters (heat flux and surface temperature) in HSD under realistic temperature and pressure conditions. Additionally an ignition system was developed to ignite hydrothermal flames in an aqueous environment. A patent on hydrothermal spallation drilling is also handed in.

Main advantage/disadvantage of the drilling method

The big difference between the presented technology and conventional mechanical drilling methods is that HSD uses heat shocks instead of mechanical forces to break the rock. Thus HSD can be seen as a nearly ”contact-free” drilling approach. One of the major advantage is that wear and tear of the drilling head in operation is minimized and thus significantly less frequent replacement of worn-out drilling heads is expected contrary to state of the art drilling approaches. Especially the absence of expensive trip time for replacement of drilling bits will reduce drilling costs. Also enhanced drilling velocities in hard rock formations are expected as additional advantage.

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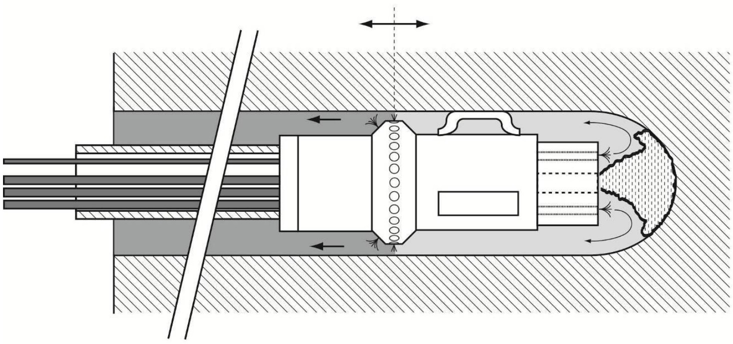
Department of Mechanical and Process Engineering

"Challenges in Hydrothermal Spallation Drilling for Deep Heat Mining Projects"

SLN-workshop "Photonics for Deep Geothermal Energy Harvesting" Neuchâtel, Switzerland, 07.11.2012

M. Schuler, T. Rothenfluh, P. Stathopoulos, D. Brkic, T. Meier, Ph. Rudolf von Rohr

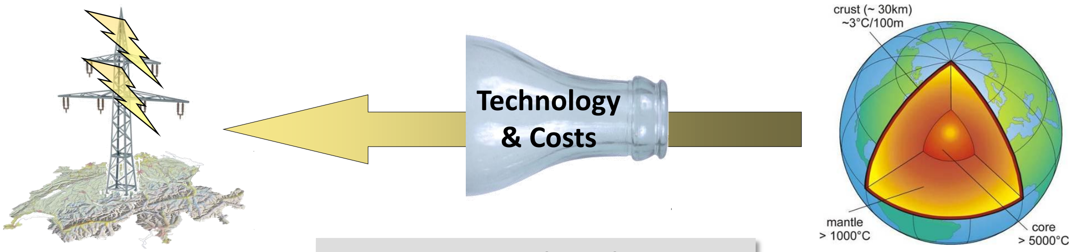


Overview

- Introduction
- Spallation Rock Drilling
- Background and Motivation
- Challenges in Hydrothermal Spallation Drilling (HSD)
  - Entrainment and turbulent mixing
  - Heat transfer of impinging hot jets
  - Ignition of hydrothermal flames
- Main Risks for Hydrothermal Spallation Drilling
- Conclusions
- Outlook

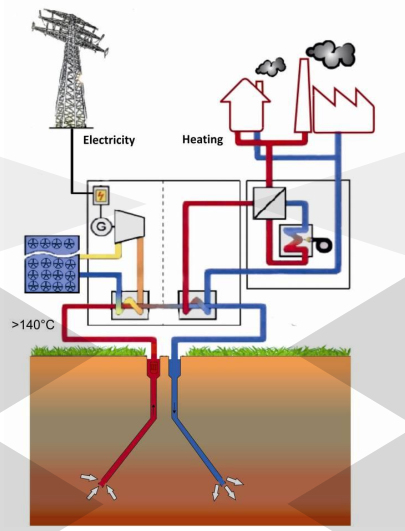
Geothermal Energy - Technology as Bottleneck

Energy Demand **Geothermal Potential**



Overcoming Bottleneck
Developing necessary technologies and reducing costs

Geothermal Power Plant – Technical Challenges



Electricity
Rankine and Kalina cycle

Drilling
- decreasing costs
- improve convential concepts
- alternative drilling concepts

Accessing reservoir
- hydro-fracturing
- induced seismicity
- characterization

Heating
improved use of waste heat

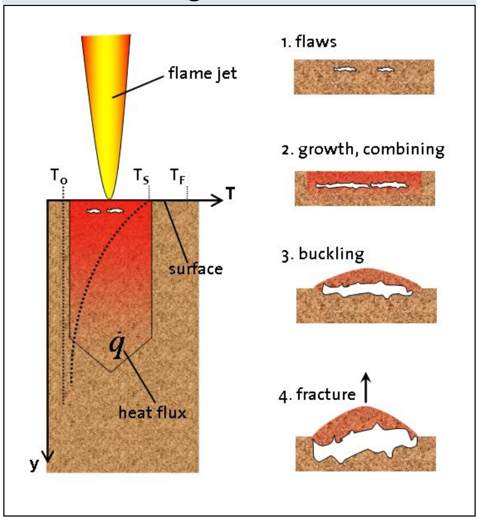
Surface prediction tools
- estimation of reservoir potential
- decreasing costs

Operation
- corrosion problems
- mineral deposits

Sources: Heuze et al. (2003)

Spallation Rock Drilling

Rock fracturing mechanism



(Preston et al. 1934, Rauenzahn et al. 1986)

Crucial parameters

Granite (Barre, USA)

Heat flux: $\dot{q}$ ***> 1.0 MW/m²***

Surface temperature: $T_s - T_o = \Delta T_s \sim 500°\ C$

R. M. Rauenzahn et al. 1989 and J. W. Tester et al. 1990

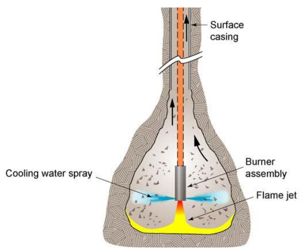
Main advantages

- ***Heat shocks instead of mechanical forces to break the rock***
- ***"Contact-free" drilling approach***
  - ***Less frequent replacement of drilling heads***
  - ***Less trip time in the drilling process***
  - ***Reduced drilling costs***

WO Patent, J. North, 1996
US Patent, Potter et al., 1998

Spallation Rock Drilling

Field test of spallation drilling at ambient conditions



Rock	Hole dimensions	Drilling rate
Limestone	15 cm x 15 cm	0.6 m/hr
Quartzite	13 cm x 30 cm	3.6 m/hr
Rhyolite	20 cm x 60 cm	2.5 m/hr

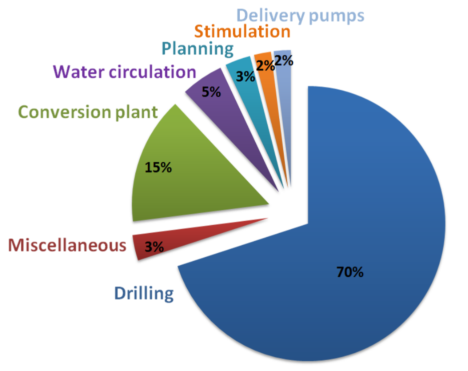
R. E. Williams, R. M. Potter and S. Miska, 1996

Researcher	Year	Rock	Depth	Diameter	Drilling rate	Fuel - oxidizer	Chamber pressure	Air flow
Browning et al.	1981	Granite, Conway, USA	335 m	0.2 - 0.25 m	15.8 m/hr	Fuel oil & air	34 bars	34.4 m³/min
Browning et al.	1981	Granite, Barre, USA	130 m	0.35 - 0.4 m	7.6 m/hr	Fuel oil & air	8.6 bars	34.4 m³/min
Los Alamos Laboratory	1985	Granite, Pedernal, USA	30 m	0.35 - 0.45 m	6–7 m/hr	Fuel oil & air	7.6 bars	31.5 m³/min

Sorce figure: Donald Dreesen, Los Alamos National Laboratory, Robert Bretz, New Mexico Institute of Mining and Technology, 2004

Background and Motivation

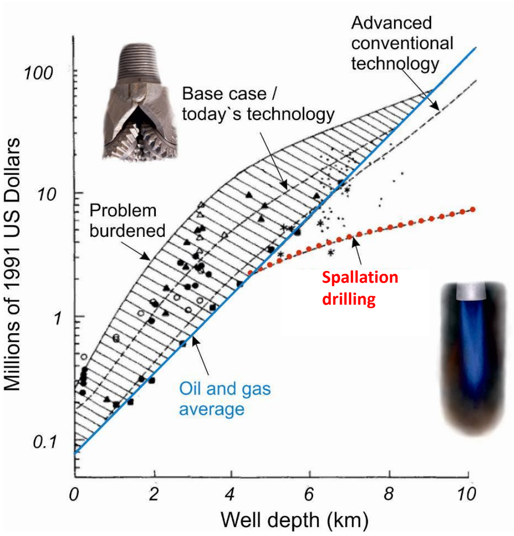
Costs for a geothermal power plant (Germany)



(Tiefe Geothermie in Deutschland, BMU, 09/2007)

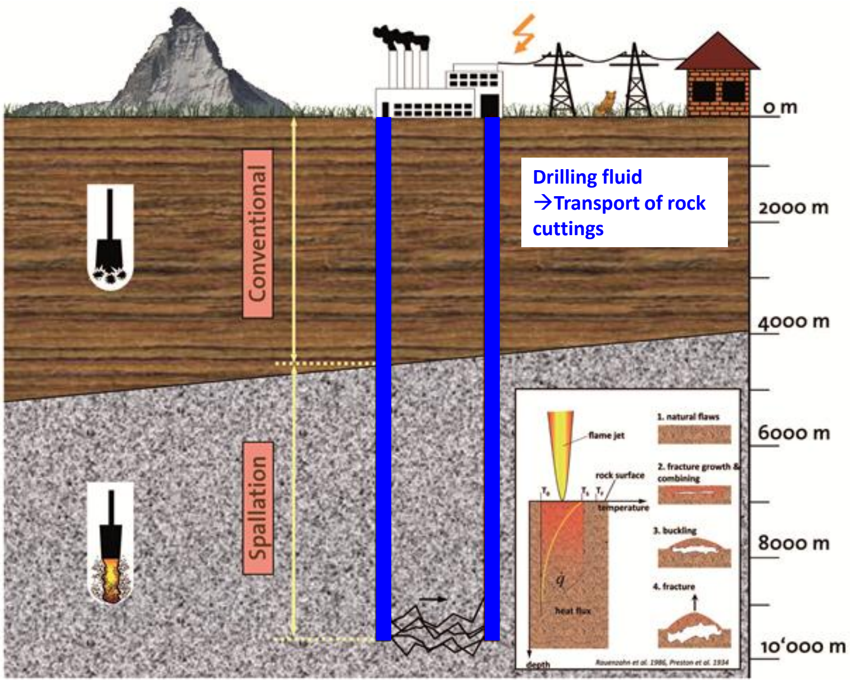
➯ **The drilling costs account for about 70% of the total costs**

Drilling cost development with depth



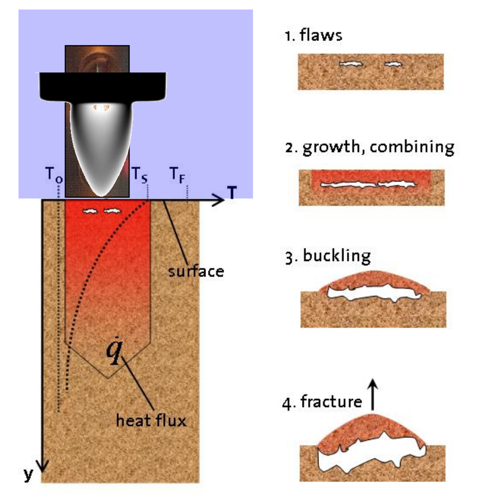
WO Patent, J. North, 1996
US Patent, Potter et al., 1998

Background and Motivation



Background and Motivation

Spallation drilling in great depth → Hydrothermal spallation drilling (HSD)

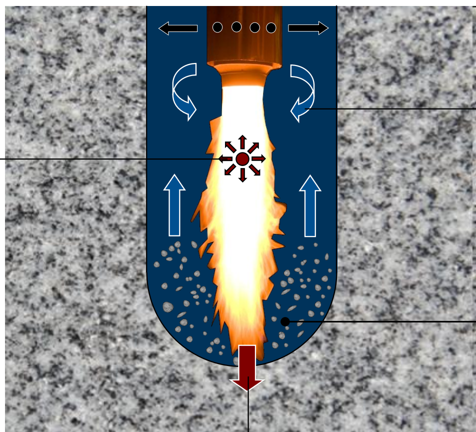


(Preston et al. 1934, Rauenzahn et al. 1986)

- Drilling fluid required for deep wells
- Spallation drilling in a e.g. water-based drilling fluid
  → ***"Hydrothermal Spallation Drilling" (HSD)***
  C. R. Augustine, PhD Thesis, MIT, 2009

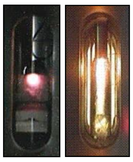
- **Possible heat sources for HSD**
  - Hot supercritical water (SCW) jets

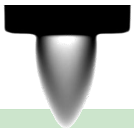
Challenges in Hydrothermal Spallation Drilling (HSD)



Combustion in aqueous environment

- Hydrothermal flame
- Ignition
- Location of reaction
- Decay of additives





Entrainment

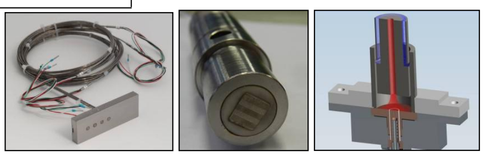
- High velocity differences
- High ρ and h differences
- Strong change in properties

Particle transport

- In treatment zone
- In annular zone
- Different injection systems

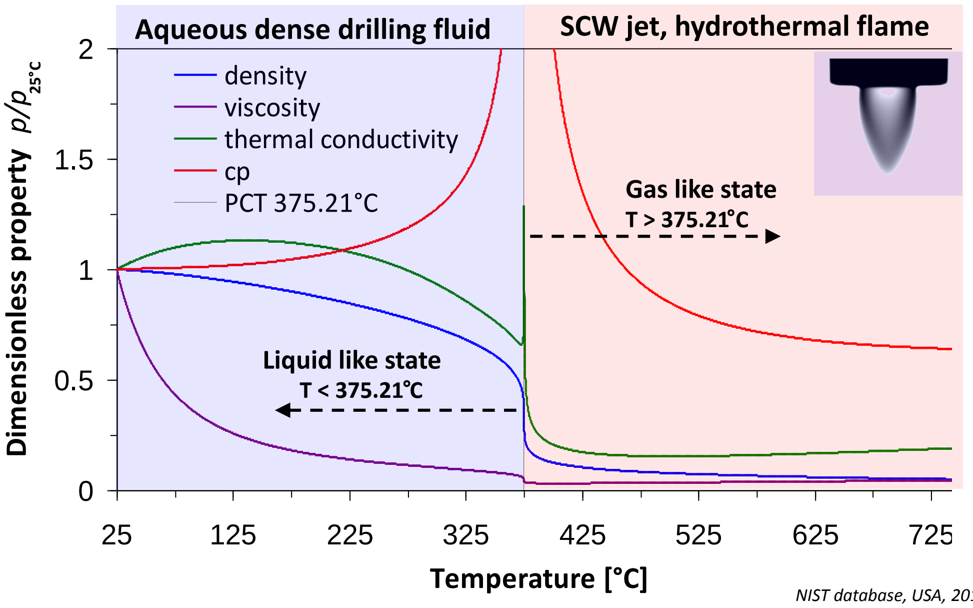
Heat transfer

- Crucial for spallation performance
- Dependency on operating conditions
- Different nozzle and burner systems
- Different sensor types



Entrainment

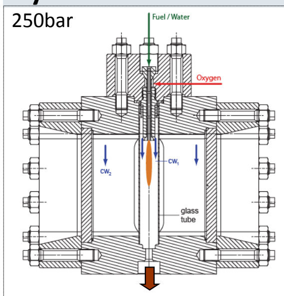
Thermo-physical properties of water at 224bar (below 2km depth)

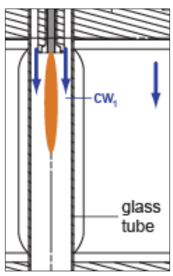


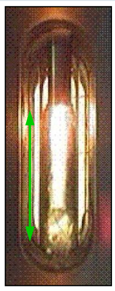
NIST database, USA, 2011

Entrainment - Hydrothermal Flame

Hydrothermal flame in a confined setup



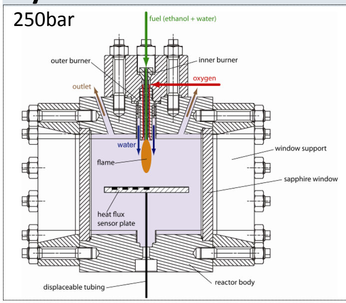


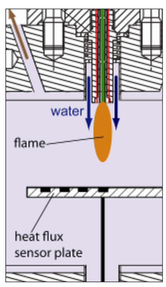


Hydrothermal flame

- 1.9 g/s fuel
- 1.5 g/s oxygen
- 15 g/s inner cooling water (CW_1)
- Nozzle diamter 6 mm
- **Long reaction zone (10 cm)**
- **Intensive combustion process**

Hydrothermal flame as a free jet





Hydrothermal flame

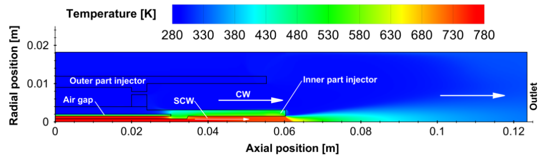
- Ball-shaped flame jet (1 cm)
- Massive entrainment rates
- Fast quenching of reaction

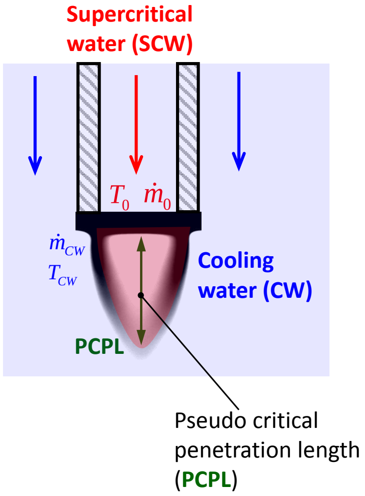
→ ***Significant heat losses***
→ ***Fast cool down***
→ ***Less efficient combustion***

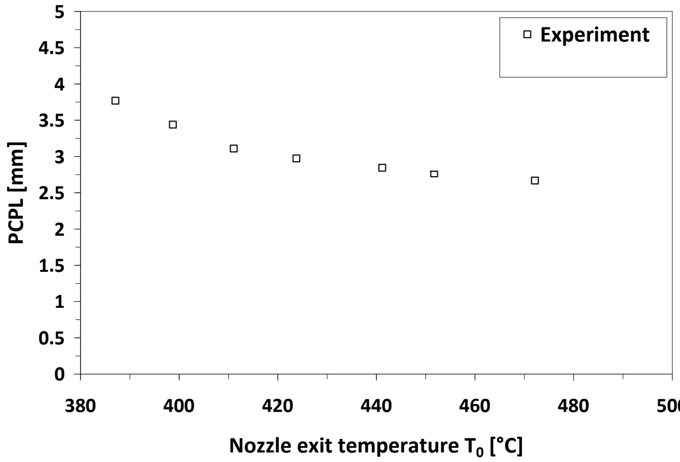
Entrainment Supercritical Water Jet

Comparison Experiment - Simulation

- T_0 varying, $\dot{m}_0$ = 4 g/s
- T_{CW} = 20 ° C, $\dot{m}_{CW}$ = 65 g/s





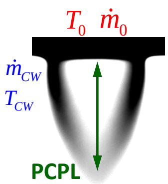


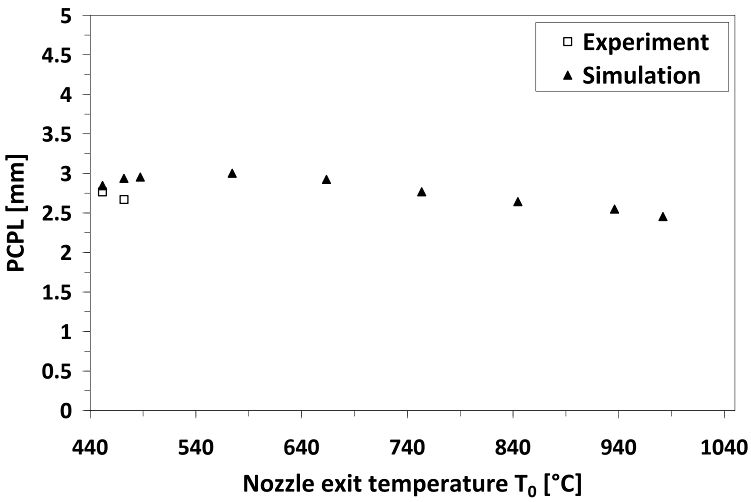
Rothenfluh et al. 2011

Entrainment Supercritical Water Jet

Comparison Experiment - Simulation

- T_0 varying, $\dot{m}_0$ = 4 g/s
- T_{CW} = 20 ° C, $\dot{m}_{CW}$ = 65 g/s
- Pressure: 224 bar
- Exit nozzle diameter d_0 = 3 mm

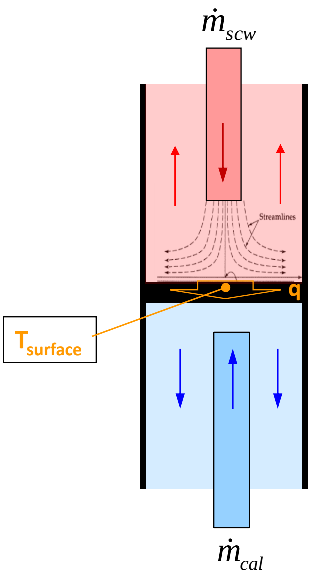


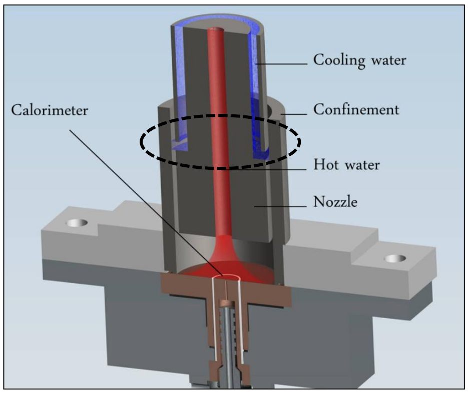


Rothenfluh et al. 2011

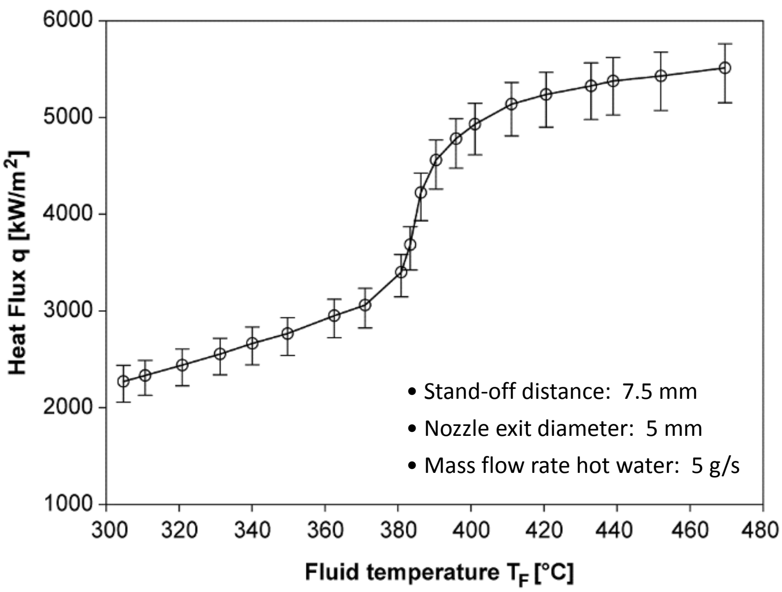
Heat Transfer Supercritical Water Jet

Heat transfer of confined impinging supercritical water jets



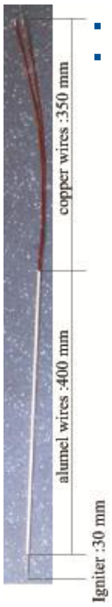


Heat Transfer Supercritical Water Jet



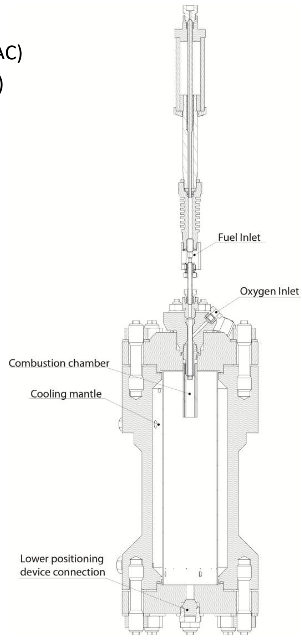
Ignition of Hydrothermal Flames

Igniter

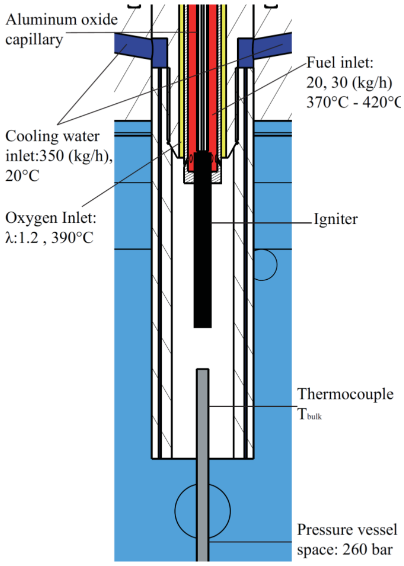


- V_{max}:230V (AC)
- I_{max}: 9 A (AC)

Experimental Setup



Flame Ignition



Main Risks for Hydrothermal Spallation Drilling

- **Entrainment and turbulent mixing**
  - Fast cool down of the jet before impingement
  - Lower the overall efficiency of hydrothermal spallation drilling
- **Rock behavior in the field under stress conditions**
  - Rock under stress conditions behaves different compared to laboratory experiments during hydrothermal spallation drilling
- **Significantly lowered drilling performance in sedimentary rock formations** (Limestone, Sandstone, …)
- **Development of a sensor system applicable at the harsh conditions found down hole**
  - Record drilling performance, hole diameter, drilling direction
  - Distance between nozzle exit and rock surface (SOD)

Conclusions for Hydrothermal Spallation Drilling

→ *A long way to go for developing hydrothermal spallation drilling*

Entrainment and turbulent mixing

- ***Entrainment effects have to be considered in hydrothermal spallation drilling***
- ***High heat transfer to drilling fluid reduces heat transfer to rock surface***
- ***Efficiency of hydrothermal spallation drilling reduced by entrainment***

Ignition of hydrothermal flames

- ***Electrical ignition of hydrothermal flames under the harsh conditions found downhole possible***

Heat transfer of impinging jets to the rock surface

- ***High heat transfer rates under supercritical aqueous conditions***
- ***Quite promising for hydrothermal spallation drilling***

Engineering tool

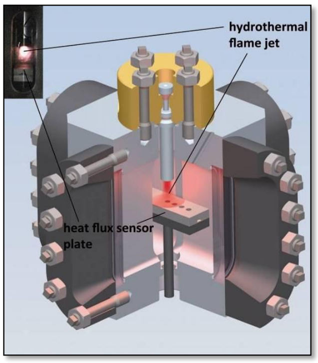
- ***CFD model able to predict entrainment and heat transfer reasonable well***
- ***Tool for the design of a possible "HSD spallation drilling head"***

11/9/2012 | ETH Zurich, schuler@ipe.mavt.ethz.ch | 19

Outlook: Spallation @ ETH Zurich

Former SCWO Plant

up to 300bar and 300° C



- Basic investigations of SCW-jets
  - Entrainment effects
  - Heat transfer
- Heat flux sensor development
- Development of a engineering tool
- HSD experiments with SCW-jets
  - Squared rock samples (5cm x 4cm x 1.5cm)

HSD Pilot Plant

up to 500bar and 600 ° C

- Heat flux sensor development
- Burner developments
- Hydrothermal flames
  - Ignition, Characterization
  - Heat transfer, Optimization towards HSD
- HSD experiments
  - Rock samples (10cm x 20cm)

Ambient Spallation Plant

melting)

- Parametric studies for optimization
- Alternating heating and cooling
- Penetration rates

11/9/2012 | ETH Zurich, schuler@ipe.mavt.ethz.ch | 20

Financial Support

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Swiss Federal Office of Energy SFOE

FNSNF
SCHWEIZERISCHER NATIONALFONDS
ZUR FÖRDERUNG DER WISSENSCHAFTLICHEN FORSCHUNG

swisselectric research

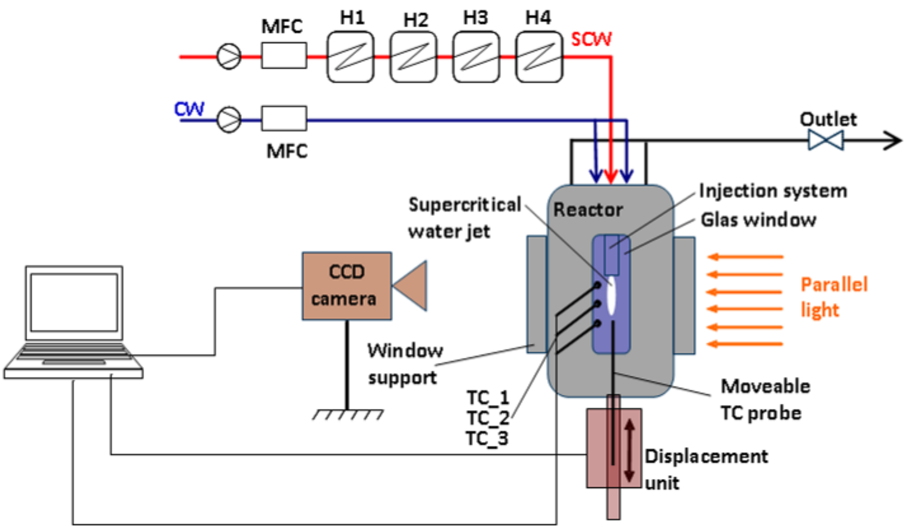
Collaborations

International Partnership for Geothermal Technology

EERA
European Energy Research Alliance
JointProgrammeGeothermalEnergy

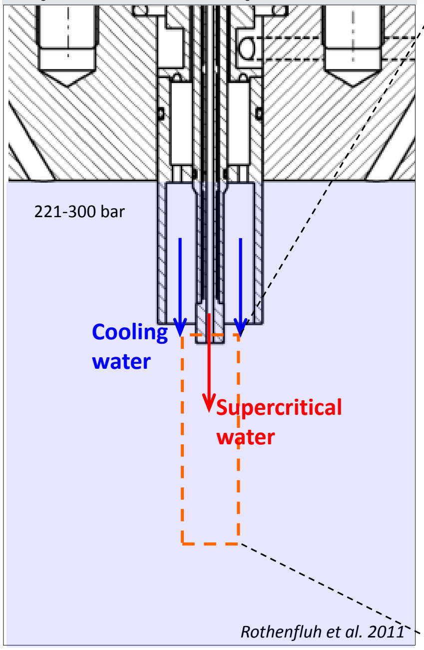
HSD: Entrainment

Experimental Setup

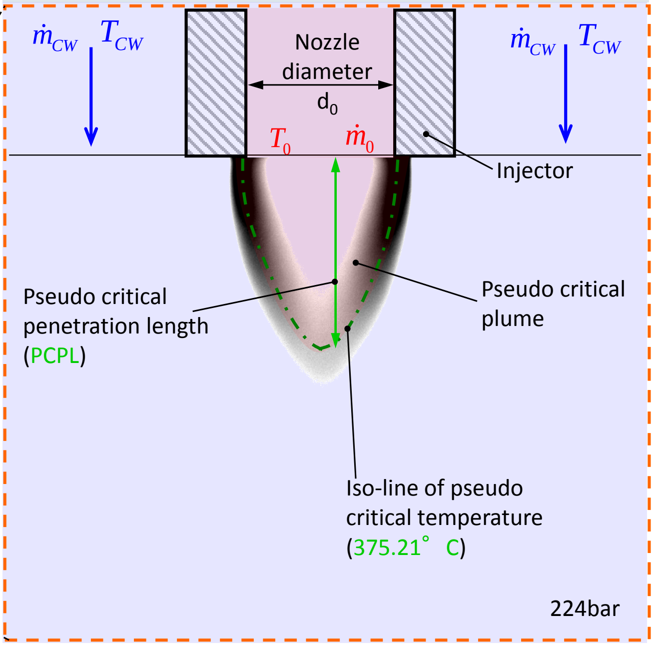


Entrainment Supercritical Water jet

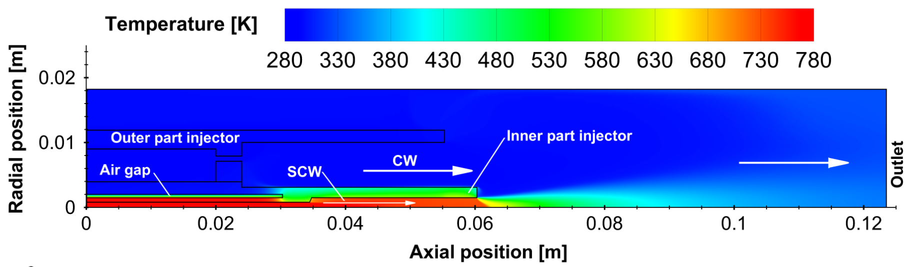
Experimental Setup

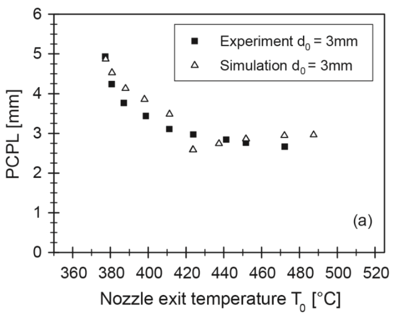


Experimental Methods



Simulations of SCW-jets



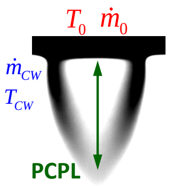


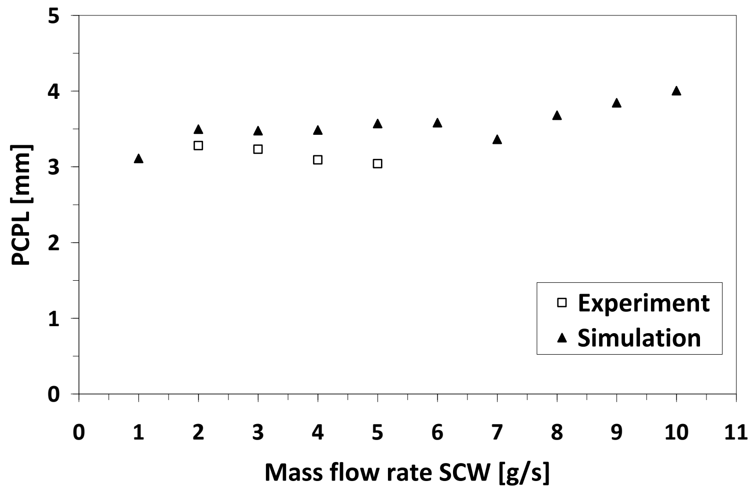
- **Thermo physical properties of water via UDFs (NIST)**
- **Structured grid (800`000 - 2‘000‘000 cells)**
- Realizable k-epsilon turbulence model (rke)
- 2D and 3D domain
- …

HSD: Entrainment

Comparison Experiment - Simulation

- T_0 = 410° C, $\dot{m}_0$ varying
- T_{CW} = 20 ° C, $\dot{m}_{CW}$ = 65 g/s
- Pressure: 224 bar
- Exit nozzle diameter d_0 = 3 mm

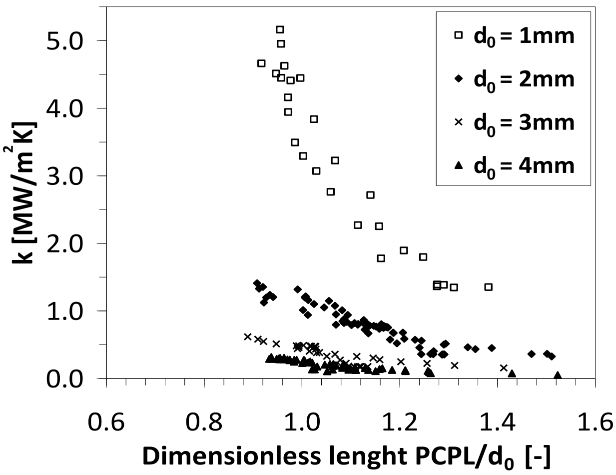


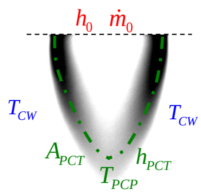


Entrainment SCW Jets – Overall Heat Transfer Coefficient

Overall heat transfer coefficient

$$k = \frac{\dot{m}_0 \cdot (h_0 - h_{PCT})}{A_{PCT} \cdot (T_{PCP} - T_{CW})}$$





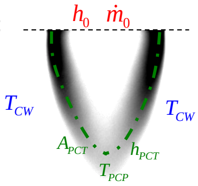
- Increasing overall heat transfer coefficient k with
  - increasing T_0
  - increasing SCW mass flow rate
  - decreasing nozzle diameter d_0
- **For the highest energy inputs**
  → Highest values for the heat transfer coefficient
  → Shortest PCPL

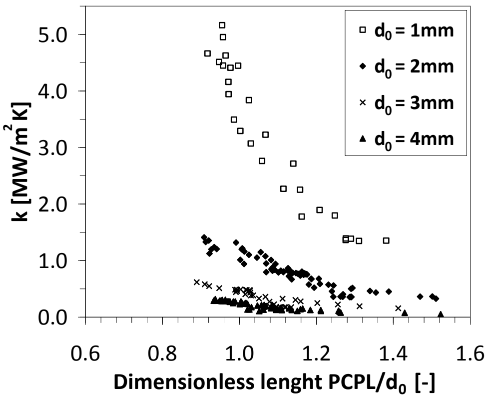
Entrainment – Overall Heat Transfer Coefficient

Supercritical water jet

Overall heat transfer coefficient

$$k = \frac{\dot{m}_0 \cdot (h_0 - h_{PCT})}{A_{PCT} \cdot (T_{PCP} - T_{CW})}$$





Direct contact steam condensation

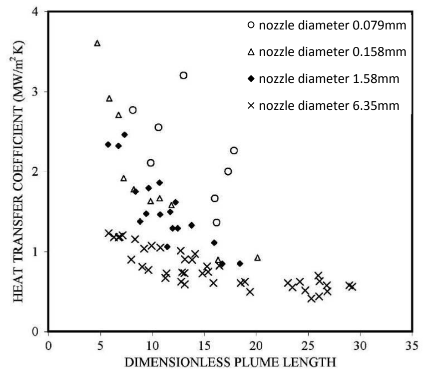


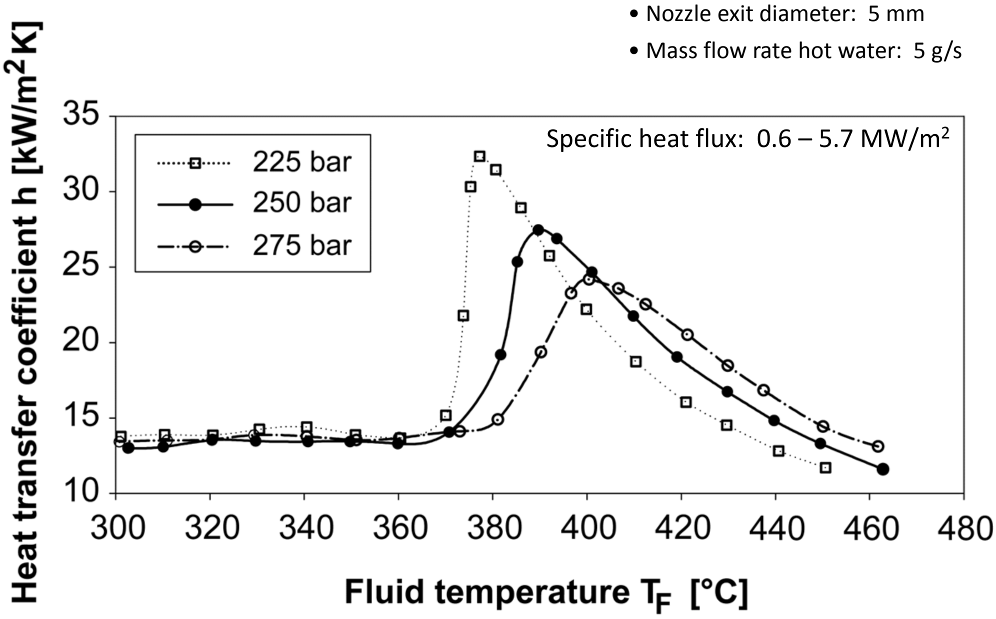
Fig. 13. Heat transfer coefficient variations with nozzle diameter (Kerney et al., 1972). Flat, $d = 0.000079$ m ●; flat, $d = 0.00158$ m ♦; flat, $d = 0.00635$ m ×; conical, $d = 0.000158$ m ▲.

- Latent heat release during condensation
- Removal of this energy is limiting step
- Elevated plume length in two phase region of water

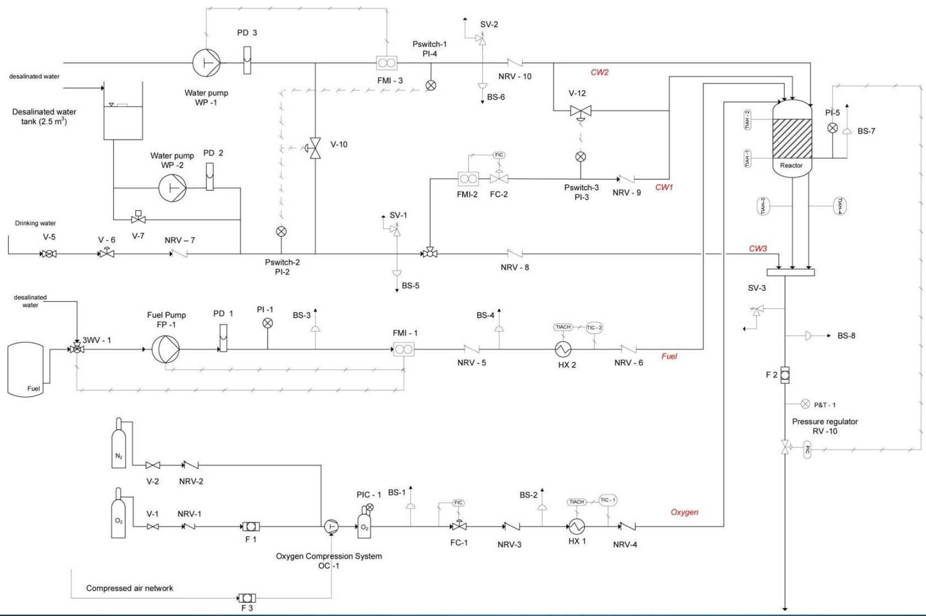
P. J. Kerney et al. 1972, S. S. Gulawani et al. 2006

Heat Transfer Supercritical Water Jet

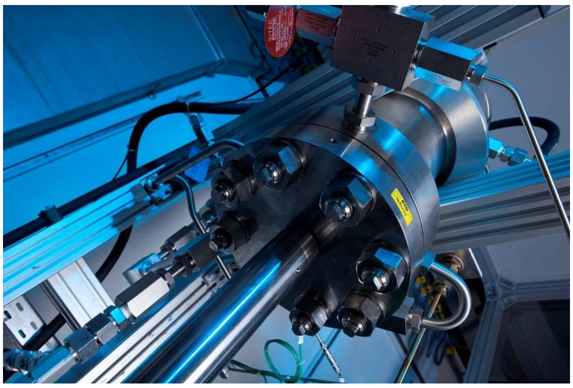
- Stand-off distance: 7.5 mm
- Nozzle exit diameter: 5 mm
- Mass flow rate hot water: 5 g/s



Hydrothermal Spallation Drilling Pilot Plant

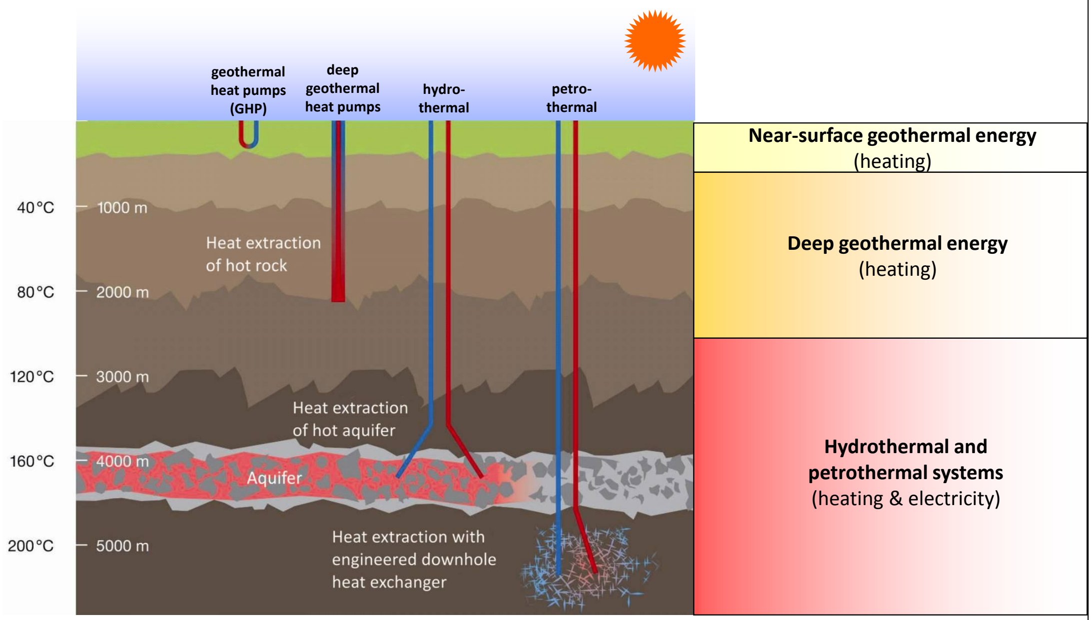


Hydrothermal Spallation Drilling Pilot Plant



Hydrothermal Spallation Drilling Pilot Plant

Geothermal Systems

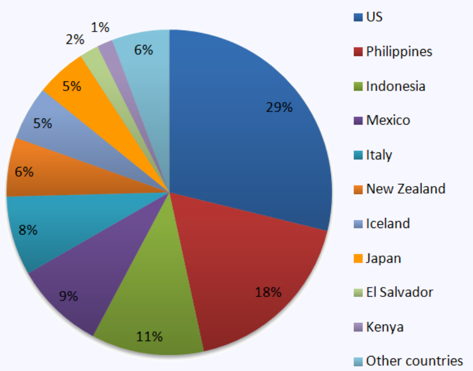


Sources: Lund, Freeston, Boyd (2010), www.geothermie.stadt.sg.ch

Geothermal Energy Production Worldwide

Electricity generation

10.7 GW$_{el}$ (2009)

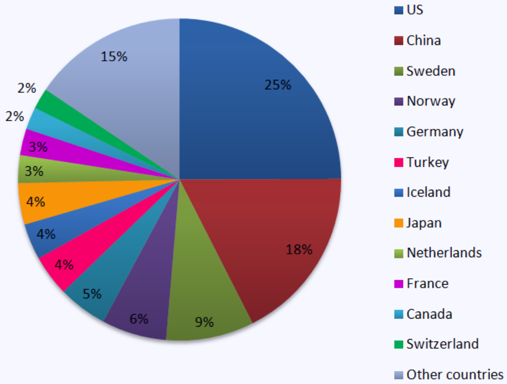


Additional facts

- 10.7 GW corresponds to 0,7% of world capacity
- Installed capacity in CH (2009): **6.56 GW$_{el}$**

Heat generation

50.6 GW$_{th}$ (2010)



Addtional facts

The "top five" for installed capacity (W/population): Iceland, Sweden, Norway, New Zealand and Switzerland

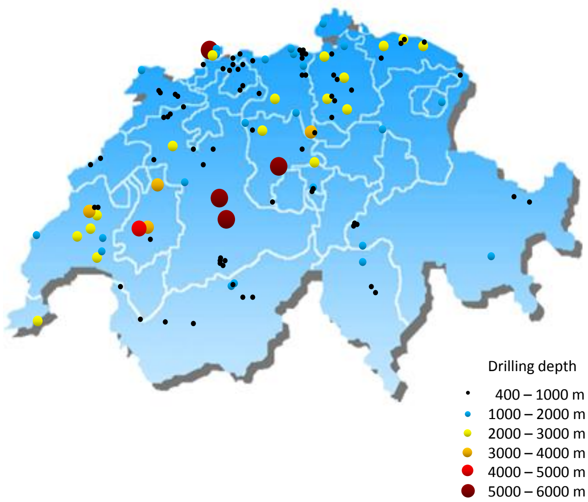
Sources: Lund, Freeston, Boyd (2010), Bundesamt für Energie

Geothermal Energy Production in Switzerland

- **Over 40** geothermal drilling companies in Switzerland (2009)
- **Installed Power**

Electricity	0.0 W$_{el}$
Heat	1.06 GW$_{th}$

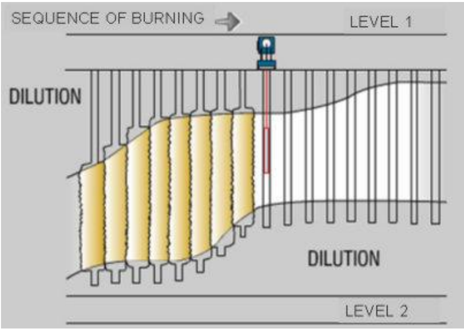
Geothermal heat pumps	1.02 GW$_{th}$
Bathing and swimming	34.9 MW$_{th}$
Tunnel water	2.4 MW$_{th}$
District heating	3 MW$_{th}$
Individual space heating	2 MW$_{th}$
Air conditioning	1.4 MW$_{th}$



Sources: Rybach, Signorelli (2010), geothermie.ch

Spallation Drilling in Application

Spallation drilling in Canada, Russia and Ukraine

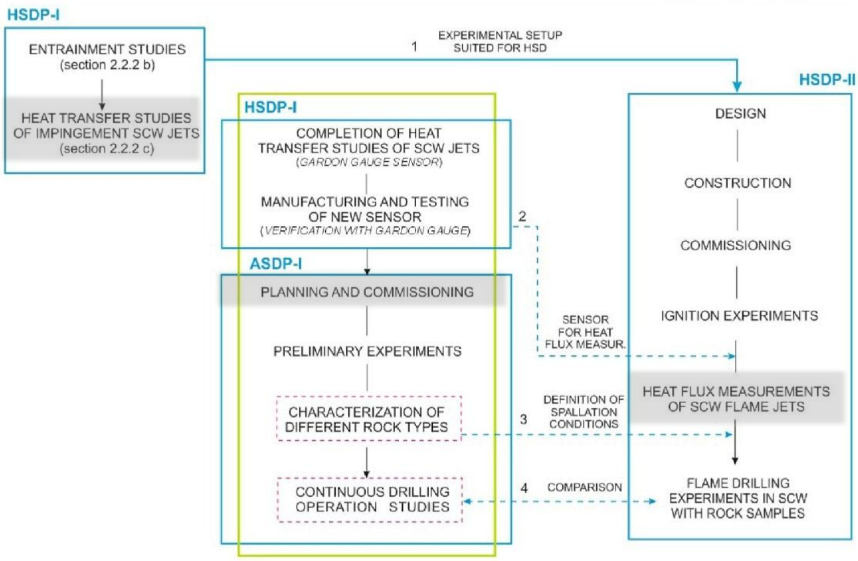


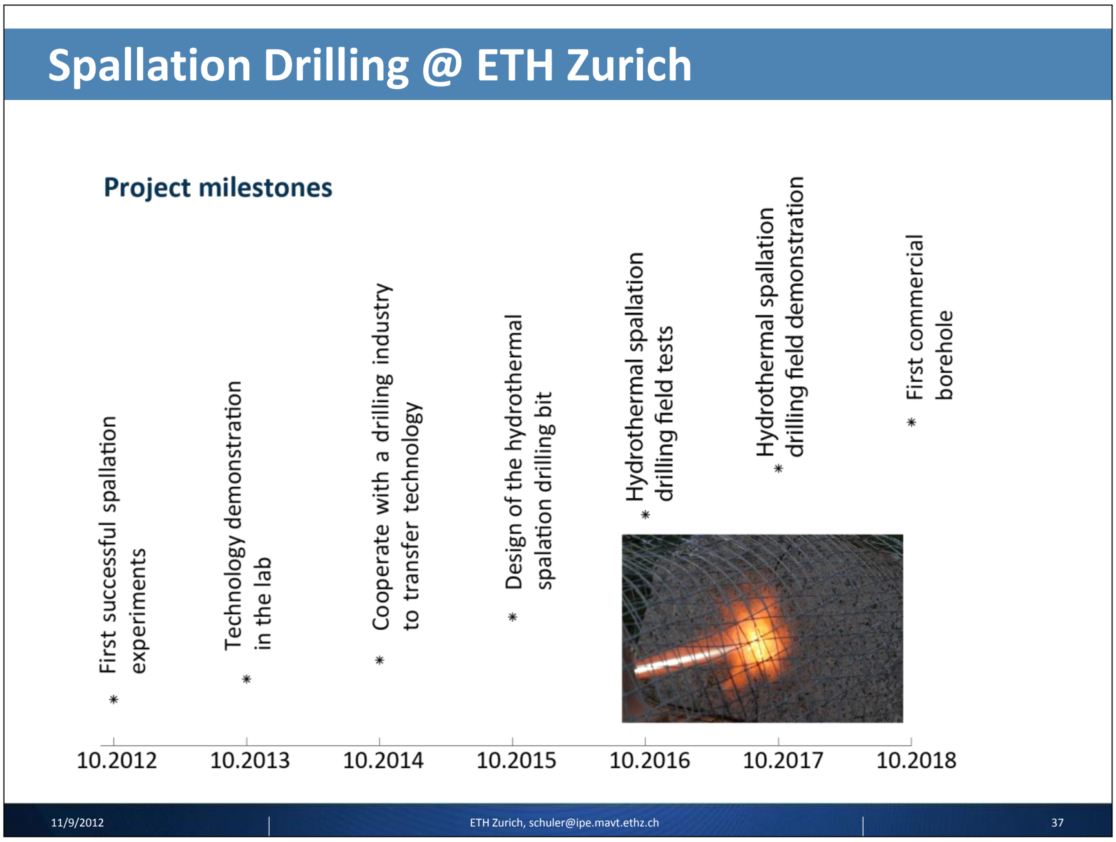
Selective ore extraction by means of spallation drilling

spallation drilling plant in the field

(CIM Bulletin, Poirier et al. 2003)

Spallation Drilling @ ETH Zurich




Spallation Drilling @ ETH Zurich
Project milestones
First successful spallation experiments
Technology demonstration in the lab
Cooperate with a drilling industry to transfer technology
Design of the hydrothermal spalation drilling bit
Hydrothermal spallation drilling field tests
Hydrothermal spallation drilling field demonstration
First commercial borehole
10.2012
10.2013
10.2014
10.2015
10.2016
10.2017
10.2018
11/9/2012
ETH Zurich, schuler@ipe.mavt.ethz.ch
37

9 Laser Machining of High Strength Materials

Jochen Deile, Trumpf Inc., Farmington, USA

9.1 Abstract

Presented is, in part one, a brief comparison of the main laser platforms that are commercially available today with regard to their output power level, beam quality, wavelength and other beam characteristics. Even though laser power levels that are relevant for laser drilling of rocks have been demonstrated with several laser types only the thin disk and fiber laser platforms meet the requirements for the other characteristics at this point. While CO2 lasers can produce hundreds of kilowatts of output power their wavelength of about 10 µm makes it impossible to transport the laser beam through optical fibers. Diode lasers can be scaled to relevant power levels at wavelengths that can be transmitted through a fiber beam delivery system, but currently this would be cost prohibitive.

The most widely used type of beam delivery fiber is made of fused silica. The losses in this material reach a theoretical minimum of about 0.2 dB/km for a wavelength of 1.55 µm. At a wavelength of about 1 µm, where high power thin disk and fiber lasers are available, the losses are just below 1 dB/km which results in very high losses for fibers that are several kilometers in length. The high losses in the beam delivery system and the resulting difficulties in transporting tens of kilowatt of laser power over long distances can be addressed by either improving the delivery fibers in regard of losses and power handling capabilities or by developing high power laser sources at 1.55 µm wavelength.

In part two the processes used in typical industrial laser applications are shown and compared to laser drilling applications in rocks. The two dominating processes in industrial applications are melting and evaporation of the material. Both of these processes are undesired when drilling of rocks since they reduce the efficiency of the spalling process. Spalling is a process that causes the rock to fail due to thermal stresses induced by the laser radiation. Finally, some drilling results in Sandstone and Limestone with a 5 kW solid state laser are presented.

9.2 Questions

Max. bore hole depth (m)

Determined by drilling concept.

Max. respectively min. or optimal bore hole diameter (cm)

Determined by drilling concept.

Volume capacity of rock excavation at the bore hole bottom (cm^3/s)

Determined by drilling concept and available laser power.

Mode of operation of rock excavation at the bore hole bottom

Spalling/Laser drilling.

Transport/disposal of cuttings to the surface

Determined by drilling concept.

Environmental conditions during drilling (air, water, mud...) at the bore hole bottom

The environmental conditions are determined by the drilling concept, the laser provides only the process energy. The published results for laser drilling of rocks were typically generated by using an assist gas such as nitrogen, compressed air, helium or argon.

Main risks of the drilling method

Reliable beam delivery systems have to be developed. They have to be able to transport many tens of kilo-watt of laser power over long distances (km) in a harsh environment.

Drilling cost at depth of 100 m, of 1’000 m, and of 5’000 m

Not available.

Status of development, publication of the previous R&D results

Not available.

Main advantage/disadvantage of the drilling method

Not available.

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Laser Machining of High Strength Materials

Jochen Deile
Manager Laser Development
TRUMPF Inc.
Farmington, CT
USA

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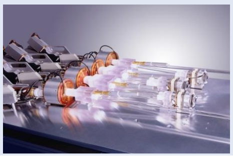
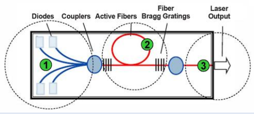
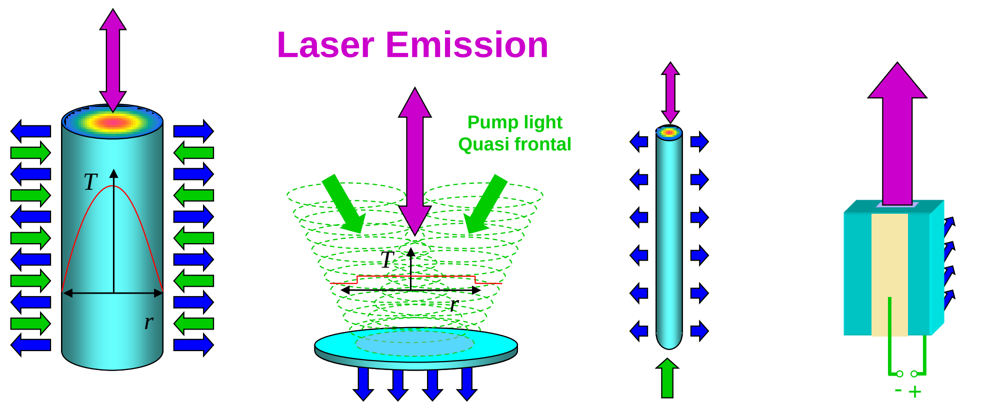
Outline

- Available industrial laser technologies
- Industrial beam delivery systems
- Applications

Laser type		Available power	Delivery fibers
CO_2		1,000..20,000 W	No fiber beam delivery available
Thin disk		1,000..20,000 W	50-1,000 µm
Fiber		1,000..20,000 W	50 – 300 µm
Diode		1,000..15,000 W	400-1,000 µm

Current Solid State Laser Concepts

Rod Laser **Thin Disk Laser** **Fiber Laser** **Diode Laser**



- Parabolic temperature profile
- Cooling and Pumping
- lamp- and diode pumped

- Flat temperature profile
- Back-side Cooling
- Diode pumped

- Cooling via lateral area
- Side or endpumped
- Diode pumped

Direct conversion of current to light

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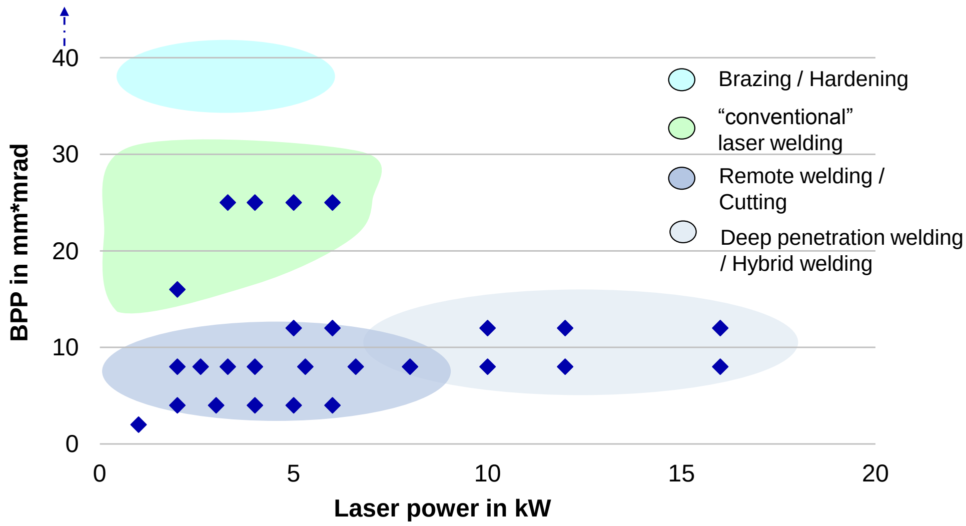
Product Portfolio TruDisk Lasers



Deep Geothermal Energy Harvesting 7 Nov. 2012 5

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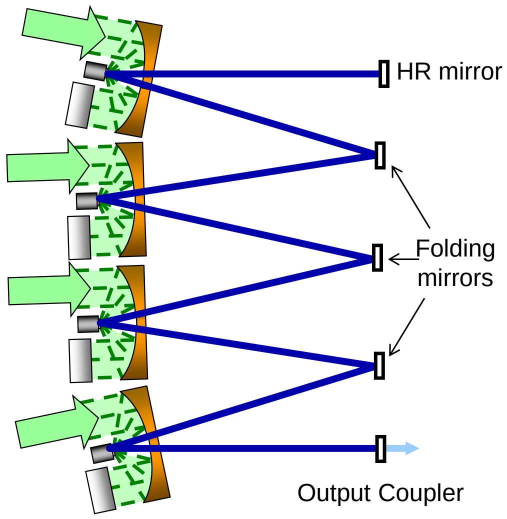
Power Scaling: Serial Coupling



⇒ ***Intensitites are constant***

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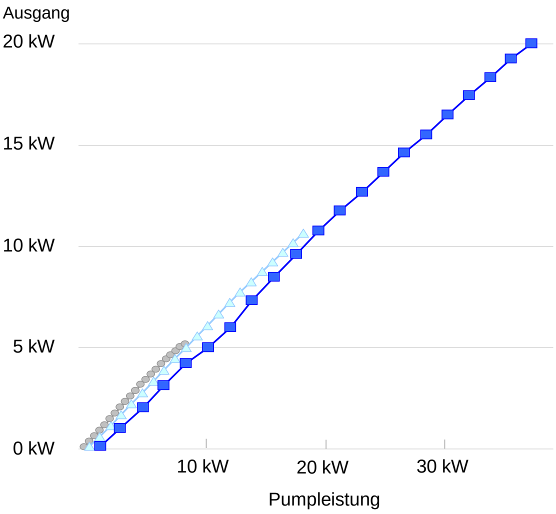
Power Scaling: Serial Coupling



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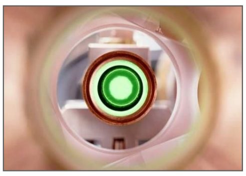
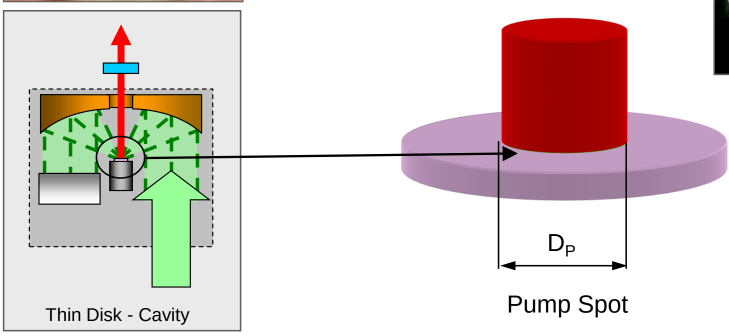
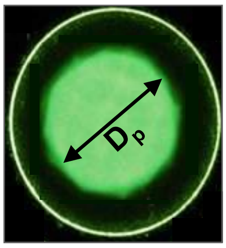
Power Scaling: Pump Spot Size



a specific laser power can be extracted per unit of area $\Rightarrow P_L \sim D_p^2$





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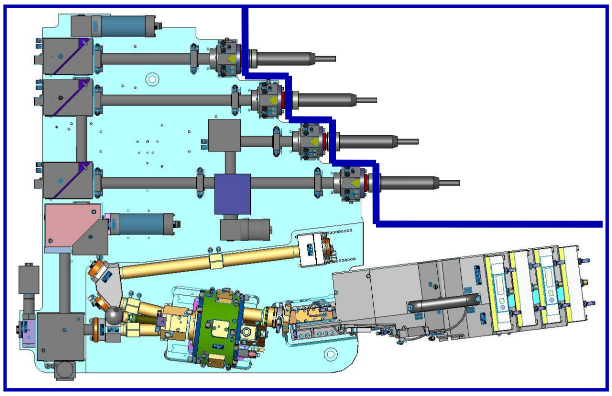
TruDisk System Design and Advantages



1. Modular configuration
2. Highest diode lifetime
3. Optimized/ Efficient resonator design
4. Insensitive to back reflections
5. Power feedback control
6. Industrial proven beam management

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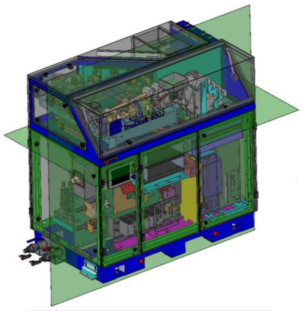
Advantages of a Modular Equipment Configuration



- Modular concept throughout the entire laser system (Beam generation, beam management, Control, chiller)
- Fast exchange of all components on site
- Monitoring of all components possible

=> Minimizing downtime in case of failures

- Upgradeability e.g. of beam management possible on site
- No splicing needed

High reliability, minimized downtime and flexibility!

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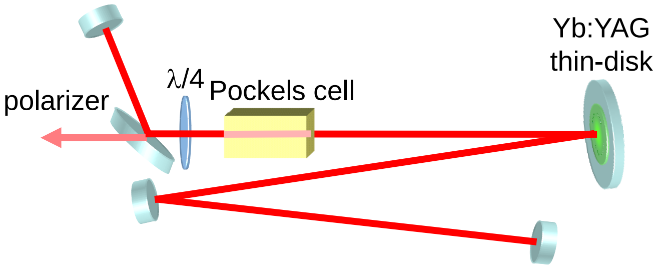
Excursion: Thin Disk based ns Laser



Laser Setup based on TruDisk platform

Pulse generation by Cavity dumping

⇒ Stable operation also at high repetition rate
⇒ Flexibility to realize various pulse durations
⇒ Pulse duration independent of operation condition

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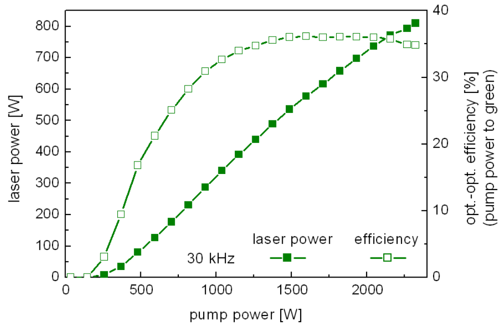
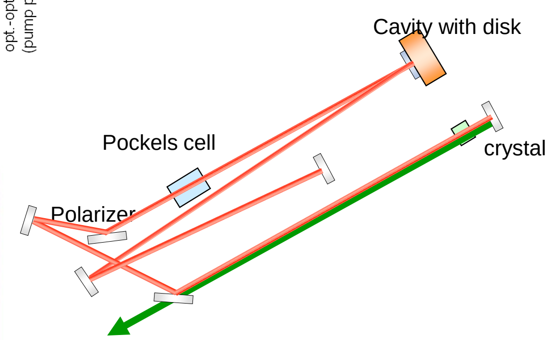
Thin Disk based ns Laser with cavity internal SHG



Specifications	TruMicro 7050	TruMicro 7250
Power / W	750	400
Wavelength / nm	1030	515
Pulse duration / ns	30	300
max. Pulse energy / mJ	80	10
Repetition rate / kHz	5 - 100	20 - 100
Fiber delivered	≥ LLK04	≥ LLK01
Fiber exits	up to 4	up to 4
Applications	Edge Deletion (PV), Cleaning, Drilling, Cutting	Cutting, Annealing, Drilling



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Outline

- Available industrial laser technologies
- Industrial beam delivery systems
- Applications

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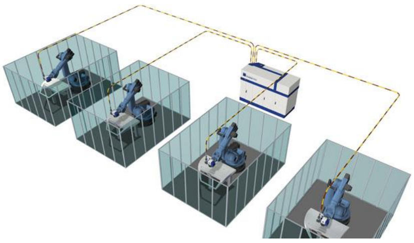
Beam Delivery Systems for Industrial Applications

Laser Light Cable (LLK): Delivery fiber with different core geometry
Fiber shape: Round or square



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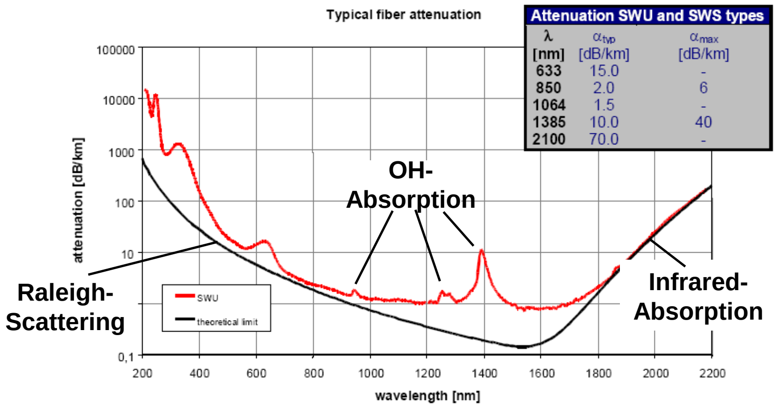
Absorption in Silica Fibers



Attenuation in optical fiber is caused primarily by both scattering and absorption, and for longer wavelengths IR absorption.

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Beam delivery systems - losses

Fiber length [km]	0.1	1	3
Attenuation per length [per km]	1	1	1
Total attenuation [dB]	0.1	1	3
Input power [W]	20,000	20,000	20,000
Output power [W]	19,545	15,887	10,024
Power delivered	98%	79%	50%

Additional losses post fiber – Halocarbon fluids

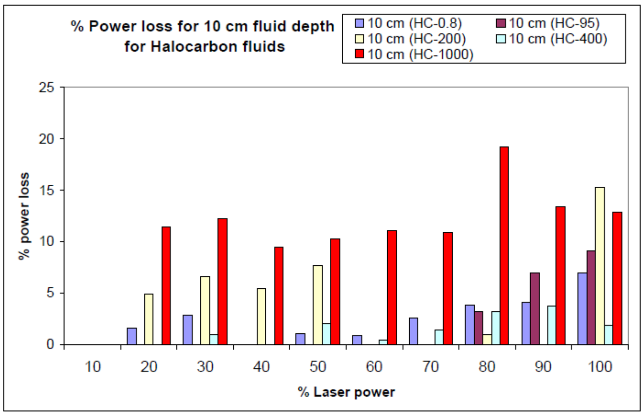
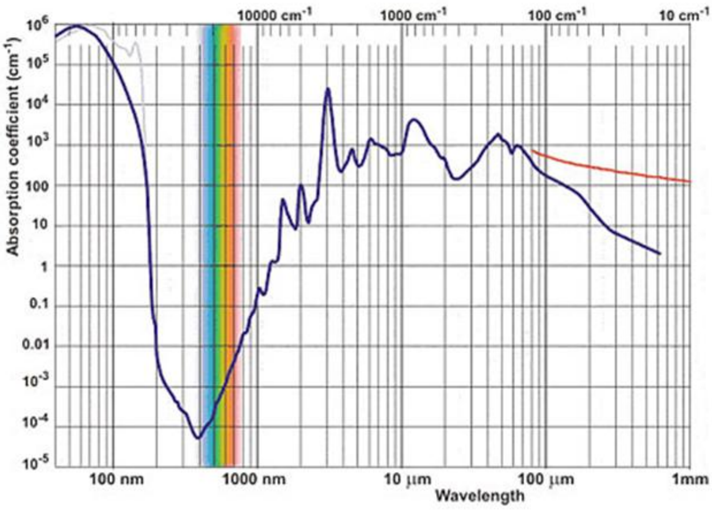


Figure 66. Percentage Loss in laser power for 10 cm fluid depth for various halocarbon fluids

Source: Laser Drilling – Drilling with the Power of Light - Gas Technology Institute, 2007

Additional losses post fiber – H_2O



Lambert law:

$$I = I_0 e^{-\alpha x}$$

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Outline

- Available industrial laser technologies
- Industrial beam delivery systems
- Applications
  - Ultra short pulse applications
  - Sheet metal processing
  - Rocks

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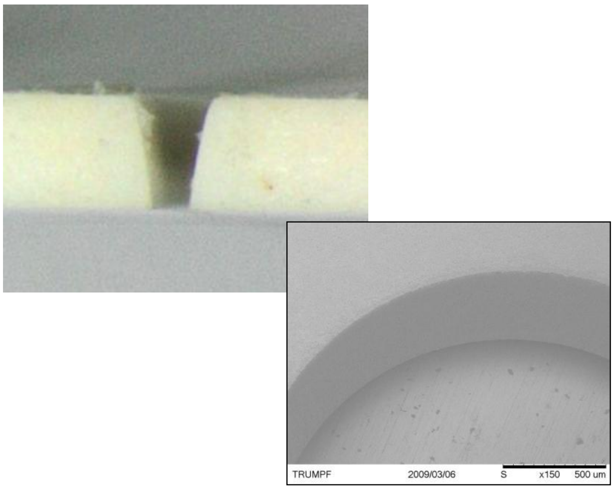
Cutting of Ceramics (Al_2O_3, ZrO_2)

Request:
- Cutting of ZrO_2 ceramic
- Thickness: 0.3 mm
- No recast layer
- No micro cracking

Solution:
- TruMicro 5050
- 10 mm/s effective speed
- No recast
- No micro cracking
- 10° Taper



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Drilling of Ceramics

Request:

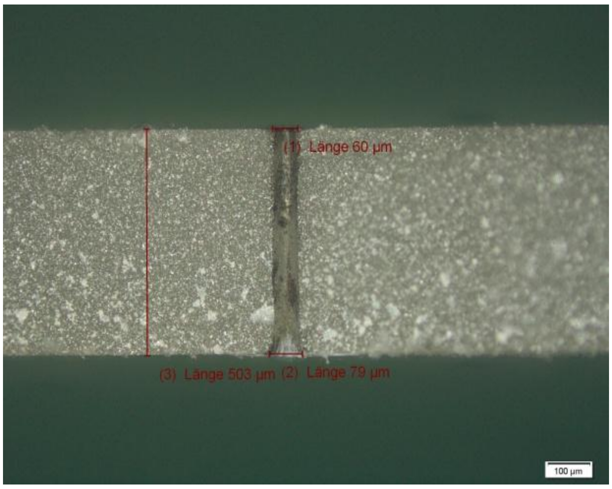
- Straight holes in AlN and Al_2O_3 ceramics
- Thickness 0.5 mm
- 60 µm diameter

Solution:

- TruMicro 5050 / 5070

Result:

- Almost straight hole
- > 20 holes / s
- No burr



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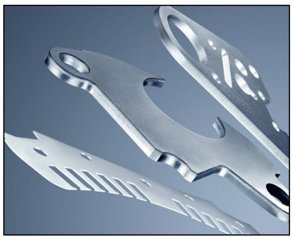
Laser Cutting Processes

- Laser fusion cutting with Nitrogen: Mild steel, Stainless Steel, Aluminum
- Oxidation cutting with Oxygen: Mild steel; up to 50 mm thickness
- High speed cutting with Nitrogen / air: Mild steel, Stainless Steel, Aluminum
- Sublimation (vaporization) cutting: Non metals

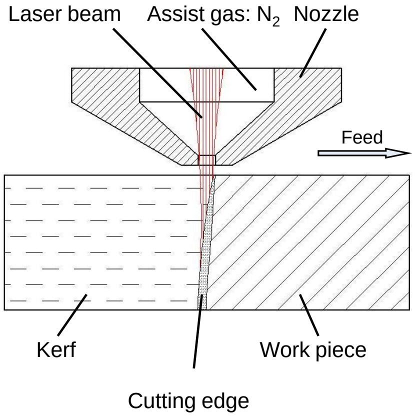


TRUMPF

Fusion Cutting with Inert Assist Gas

Process characteristics:

- No reaction between assist gas and melt pool
- Only laser supplies process energy
- High assist gas pressures required
- Mild steel can be cut w/o oxidation
- Work piece can be painted or welded w/o additional pretreatment



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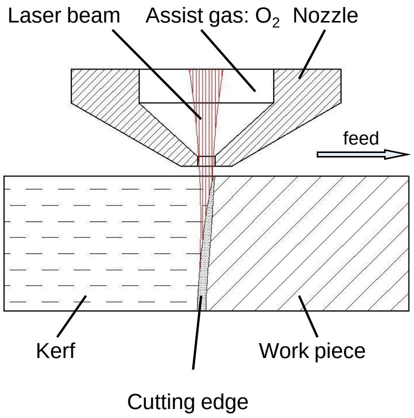
TRUMPF

Oxidation cutting

Process characteristics:

- Oxidation process between meld pool and assist gas
- Available process energy equals sum of laser power plus reaction energy
- Laser heats up work piece to ignition temperature of Oxygen
- Process is sensible to surface conditions in thick material
- Absolute temperature of work piece needs to be minimized



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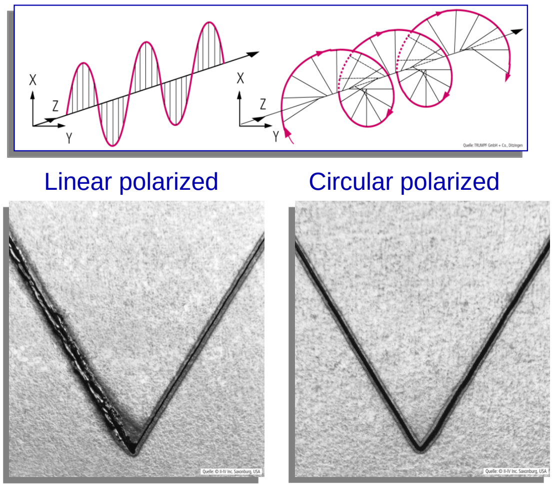
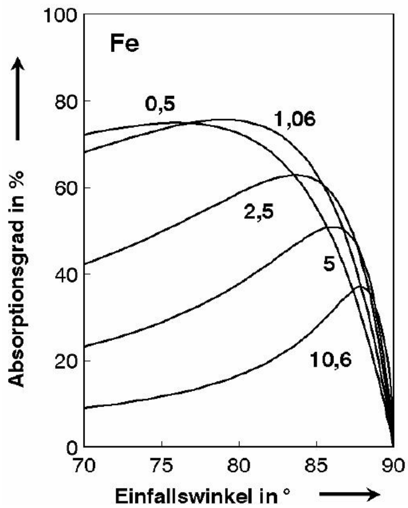
TRUMPF

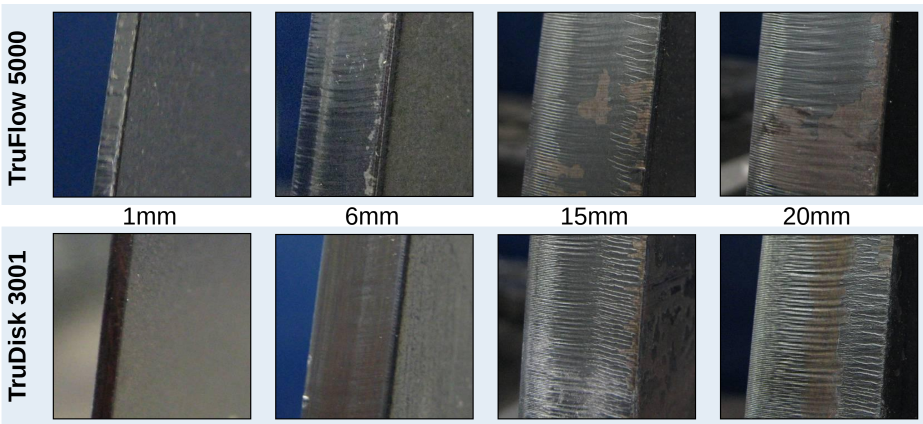
Other important characteristics





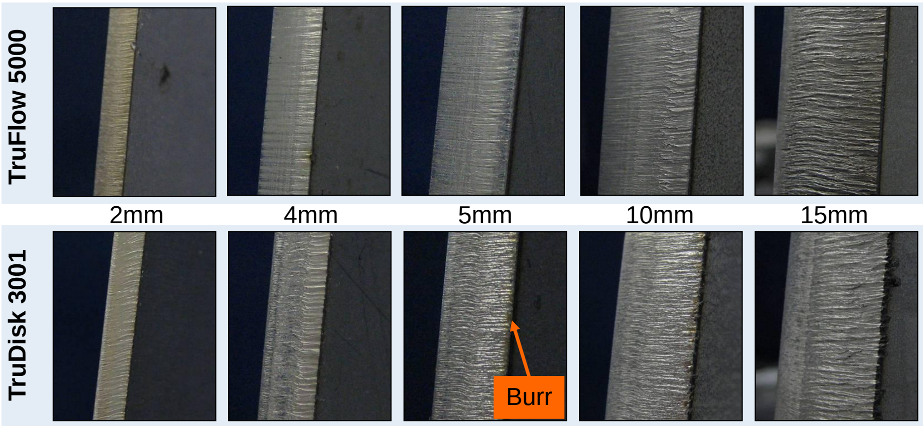
TRUMPF

Cutting Mild Steel with Oxygen as Assist Gas



TRUMPF

Cutting SS with Nitrogen as Assist Gas



TRUMPF

Cutting Thick Stainless Steel with 1 µm Wavelength

Material: Stainless steel L316, Thickness : 30 mm

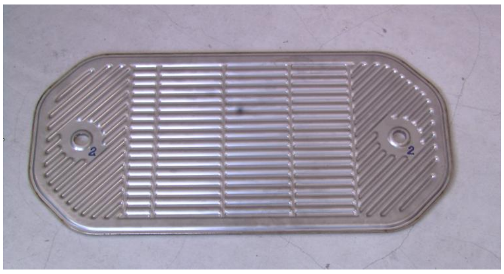
Power: 16kW
LLK Ø: 200µm
Speed: 300 mm / min
Spot diameter: 560µm
Gas Pressure: N_2 / 7 bar

Power: 16kW
LLK Ø: 200µm
Speed: 150 mm / min
Spot diameter: 200µm
Assist gas: None

TRUMPF

Cutting and welding of Titanium

- Liquid and hot Titanium is highly reactive
- Hardness increases and ductility decreases
- Use of Argon as process gas

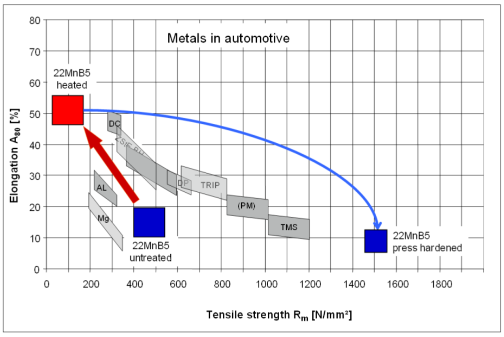


TRUMPF

Laser Cutting of Hot Formed Material

The tensile strength of 22MnB5 before processing is comparable to mild steel. When the material is heated it is very ductile, which allows great formability.

After quenching the steel it changes to be very hard and with a high tensile strength.

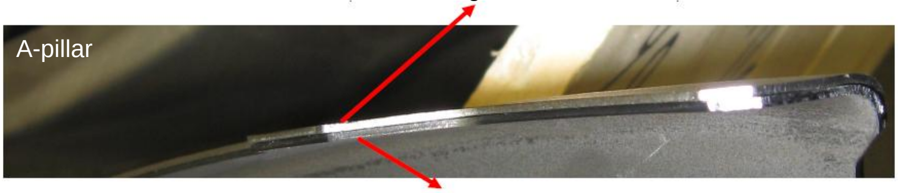


TRUMPF

Laser Cutting of Hot Formed Material

1. High pressure Nitrogen cutting
2. Air cutting with Industrial compressed air
   → reduced gas consumption (example A-pillar: 100 l/part air vs. 177 l/part N2)
   → reduces gas cost

N2, clean edge



Compressed air cut, slightly darker colored edge but no loose particles or scale

TRUMPF

Reservoir Type Rock Processing

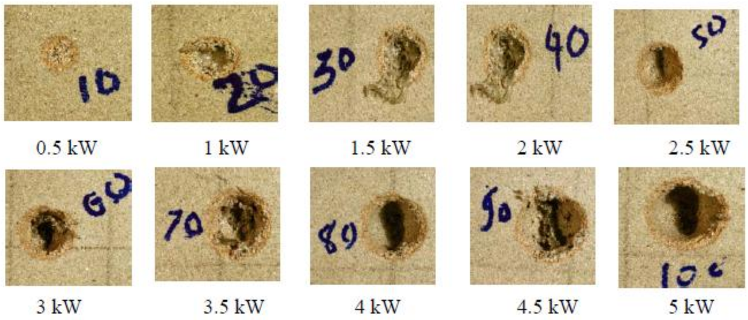
- **Goal**: Increase drilling speeds, reduce drill bit replacements, enable penetration of granite (same penetration rate of laser beam for soft and hard rocks)
- **Material**: Rocks penetrated for natural gas extraction are shale sandstone, limestone, granite
- **Processes**: Spalling, melting, vaporizing
- **Key aspects**:
  - Specific energy (kJ/cc) required to remove rock (energy input/volume removed)
  - Spalling is most efficient for drilling
  - Minimize reflection and scattering of beam to maximize absorption in rocks
- **Secondary effects**:
  - Melting of rock
  - Beam absorbing exsolved gases
  - Induced fractures in surrounding rock

TRUMPF

Sandstone

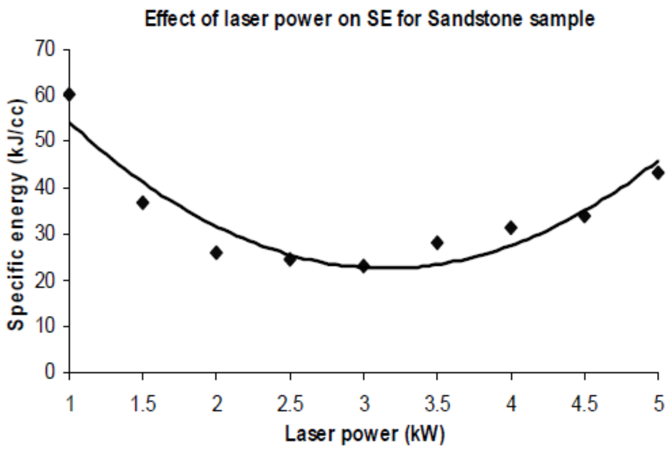
Source: Laser Drilling – Drilling with the Power of Light - Gas Technology Institute, 2007

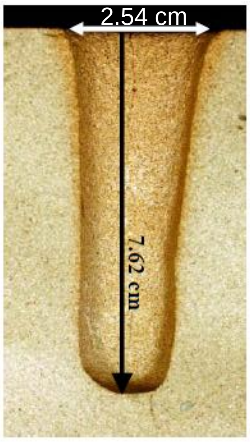
- Process: Spallation
- Laser power: 0.5 .. 5.0 kW cw
- Spot size 8.9 mm
- Purge: Air 75 to 100PSi
- Exposure time: **8s**



TRUMPF

- Material: Berea sandstone
- Same expose time and spot size
- Melting at 3 kW and above
- Below 3kW no melting but less spallation





Cross-section of a hole in Sandstone by spallation (3 kW, 62s)

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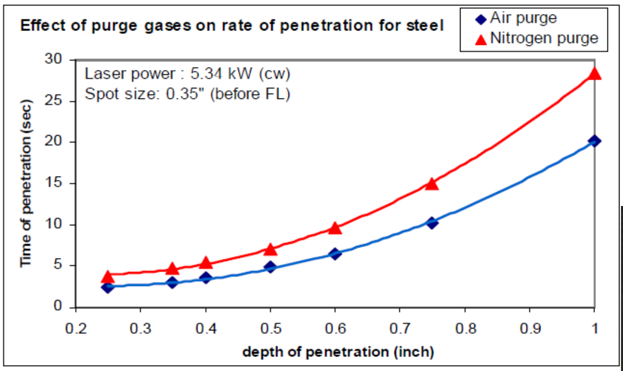
Limestone

- Limestone has a different chemical composition as sandstone
  ➔ different interaction with laser beam
- Thermal dissociation produces CO_2
- No melting observed up to 5 kW

Source: Laser Drilling – Drilling with the Power of Light - Gas Technology Institute, 2007

TRUMPF

Steel



Source: Laser Drilling – Drilling with the Power of Light - Gas Technology Institute, 2007

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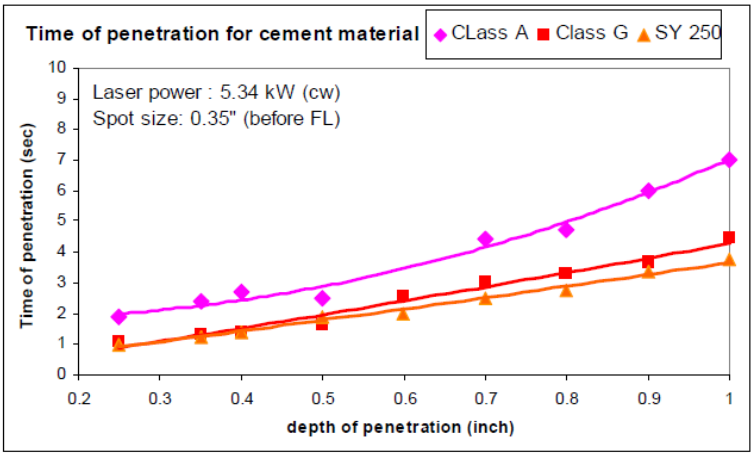
Cement



Source: Laser Drilling – Drilling with the Power of Light - Gas Technology Institute, 2007

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And now I look forward to your questions!

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10 SuperDeep-FusionDrilling

Werner Foppe, Foppe Technologien, Cologne, Germany

10.1 Abstract

SuperDeep-FusionDrilling is a game-changer technology, melting down a 10’000-20’000 meter super deep well in a year in continuous manner at constant diameter in a range of 500-1000 mm and more, simultaneous cased by a strong, seamless steal-casing and without rock-melt-lifting, because overburden-rock-melt is forced into the surrounding of the melting-zone under the dead load of the drilling-machine and the heavy-liquid flooded the wells.

To mine SC(supercritical) GeoSteam on GW-scale the steal-cased last few kilometer - of two or three super deep wells in distance of some kilometer from each other - are perforated and the super deep wells are flooded with water. Under the water-dead-load (1000-2000 bar) and in surrounding of hot-rock (400-500°C) water gets supercritical (374°C/221 bar). The viscosity of supercritical water (SCW) drops to zero, therefore SCW is able to invade the crystal-spaces of rock without resistance. On this way the pressurized water in the super deep wells creates in some month a gigantic Supercritical-Subsurface-Boiler (SSB) with dozens of km^3 without high-power pressure-pumps, hydro-frac and earthquake-risk. Last but not least the enthalpy of SCW is 10 times of 300°C/30 bar conventional geothermal steam on Island.

10.2 Questions

Max. bore hole depth (m)

10’000-20’000 m

Max. respectively min. or optimal bore hole diameter (cm)

50-200 cm diameter for SuperDeep-GeoPower site of 80-120 cm

Volume capacity of rock excavation at the bore hole bottom (cm^3/s)

The capacity of rock excavation at a speed of 5 mm/s and a bore hole-diameter of 1000 mm is close to 4000 cm^2/s.

Mode of operation of rock excavation at the bore hole bottom

Electrical melting energy.

Transport/disposal of cuttings to the surface

Displacement of the liquid fused rock into the surrounding solid by litho-frac under the weight of the drilling construction and heavy liquid.

Environmental conditions during drilling (air, water, mud...) at the bore hole bottom

Liquid fused rock.

Main risks of the drilling method

Big, fluid-free cracks. In karst regions a conventional exploration well is required.

Drilling cost at depth of 100 m, of 1’000 m, and of 5’000 m

€3300/m for a 20 km pit with a inner diameter of 1000 mm at an outer diameter of 1200 mm and a steel casing of 100 mm (cost fraction for steel: €1700).

Status of development, publication of the previous R&D results

Technologies and materials for the execution of the SuperDeep-FusionDrilling are available in the market. Patents are partially disclosed at the WIPO.

Main advantage/disadvantage of the drilling method

Advantages: Continuous fusion-drilling technique with simultaneous buildup of strong steel casing, up to 500 m per day. Closed pit environment prevents oil- or gas-fields from blowing out, when they are passed during the drilling, as well as it prevents the pit from breaking under capacity overload. No need to transport cuttings to the surface, since they are pressed into the surrounding formations. No abrasion of the drilling head. Highly efficient inductive use of melting energy via coils inside of the carbon head. High re-usability of most parts of the drilling head.

Photonics
for
Deep Geothermal Energy Harvesting

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SuperDeep - Drilling - Technology
for
Deep Geothermal Energy, Oil & Mineral Harvesting by SC-(supercritical) Water & Self-burial of radioactive waste

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Energy resource
SuperDeep-HotRock

- SuperDeep-Hot Rock (400°C – 600°C) is the only available cost-effective and clean <u>energy source</u> for all countries

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Energy resource
SCW(super-critical-water) inHotRock

- SCW(super-critical-water) is the ideal transport- and storage-medium for energy-mining out of SuperDeep-Hot Rock to transform the stored heat to high-pressure process-steam, electricity or to make use of dissolver for crude oil

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Energy resource
SuperDeep-GeoPower

- SC(supercritical) – GeoPower out of SuperDeep-Hot Rock is potentially available on Earth at GW-scale, every-where round a clock without competition

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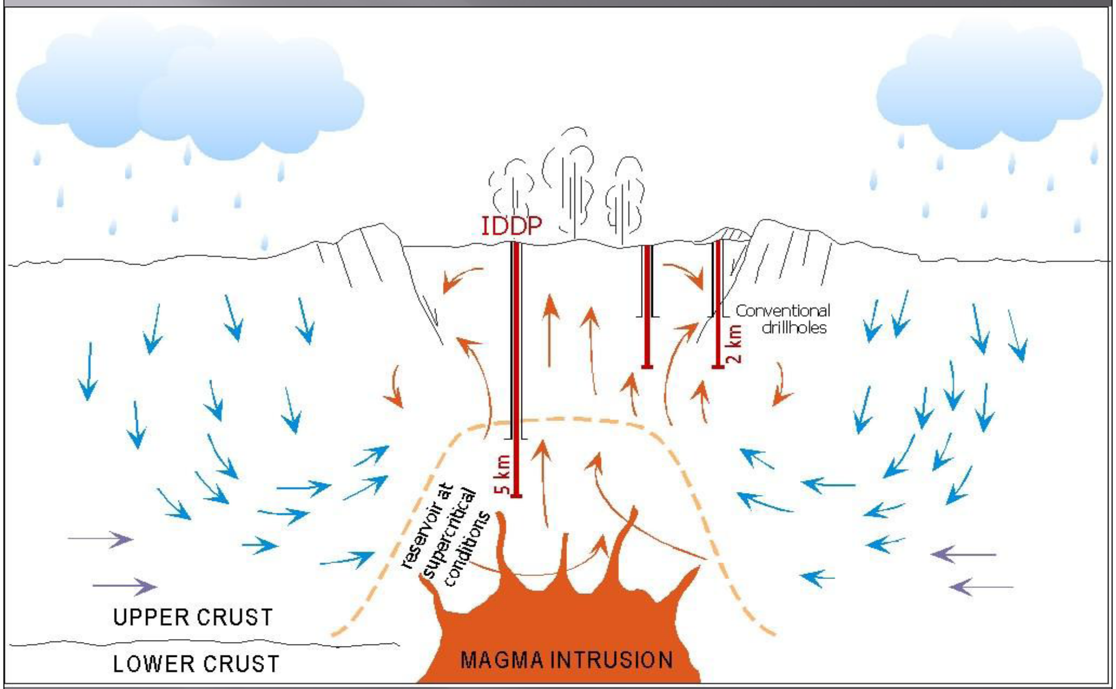
By drilling deeper we should reach supercritical conditions (IDDP –Island Deep Drilling Project)



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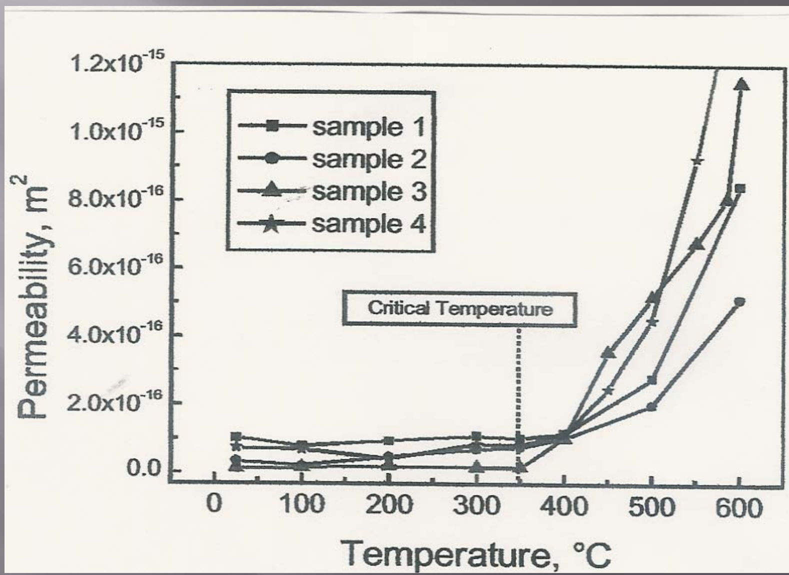
Permeability of water escalates at critical-point(374°C/220 bar)



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Viscosity of SCW(super-critical-water) at critical point is going to zero

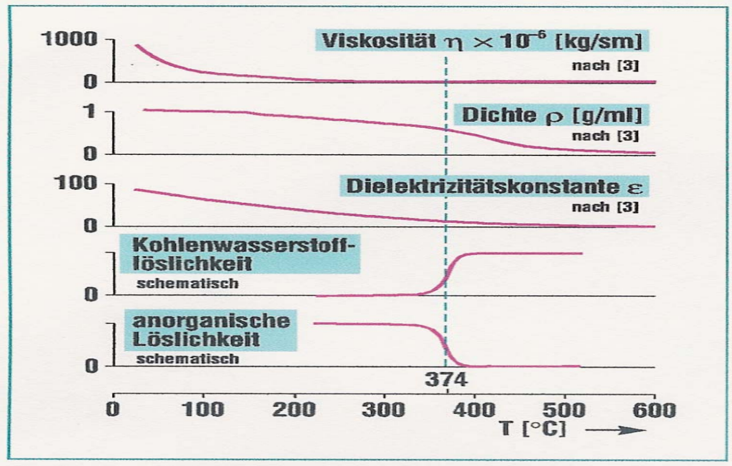

Abb. 2: Die Änderung wichtiger Eigenschaften von Wasser beim Übergang in das überkritische Gebiet bei einem konstanten Druck von 400 bar.

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Why conventional drilling ist unable to mine SCW in SuperDeep Hot Rock ?

KTB – Resumee und Ausblick

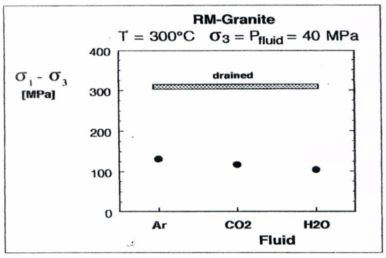

Abb. 8. Bruchfestigkeit eines Granits im Triaxial-Experiment mit und ohne Einwirkung von Fluiden.

- The compressive and shear-forces of hot rock drops dramatically in vicinity of water
- Conventional drilling works open-hole(with-out casing by drilling)
- Under SuperDeep condition the rock change from brittle to ductile
- The unsealed well collaps under the overburden rock in vicinity of water at high temperature (300°C) excessive easier as with-out water. (s. picture left)

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I.

SUPER-DEEP

FUSION DRILLING

‚GAMECHANGER‘ in SuperDeep-Drilling-Technology

Unique selling points SUPER-DEEP FUSION-DRILLING

Continuous Fusion-Drilling with large, constant diameter

- 20 km SuperDeep Wells by constant diameter in meter range
- Continuous Fusion Drilling without round-trips
- Continuous steel-casing by steel-bar fusion at drilling
- Overburden-rockmelt displacement in rock surroundings
- Pressure-burden of the rock in the well-surrounding
- None overburden-rockmelt hoisting
- None drill-bid changing and round-trips
- None openhole-drilling(casing by drilling)
- None colappsing of uncased well by drilling
- None fluide-, gas- or steam-flash

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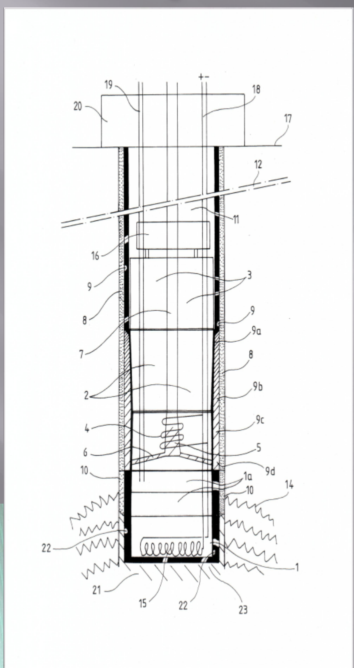
SuperDeep-FusionDrilling-Robot



1. Carbon Fusion-Drilling-head, 1a Cooling parts
2. Conical Compactor
3. Cooling element
4. Induction coil
5. Steel-melt
6. Steel feed-pipe
7. Continuous steel-bar
8. Rock-melt casing
9. Cast -steel casing, 9a – 9b solidified steelmelt, 9c – 9d steel-melt casing
10. Solidified rock-melt barrier between rock-melt and steel-melt casing
11. Shaft flooded with heavy liquid
12. SuperDeep-Well in progress
14. Created cracks back-filled with rock-melt
15. Tube-coil for electromagnetic power-supply in melt direct at rock-face
16. Hydraulic-Molch with integrated high-pressure pump
17. Surface
18. Self-supported power- supply-line
19. Cooling-water supply-line
20. Installation- and Deinstallation-Automat
21. Pressurised rock-melt cracks are runnig ahead of the rock-melting zone
22. Fusion-Drill-head enlarged by diameter of the cast-steel casing
23. Rock-melt pressure-pillow

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SUPERDEEP-FUSION-DRILLING

PRINCIPLE OF FUNCTION:

20 kilometer SuperDeepWell with constant diameter in meter range and seamless steel-casing at construction-time of only few months are no illusions but a technical consequence of Fusion Drilling.

The Fusion-Drilling-Robot starts in a conventional drilled steel-cased start-shaft of 100 meter or so, creating a steel-bath around the fusion-drilling-head (1) by melting down the steel-bar (7). Function of the steel-bath is it to initiate rock-melt, so alternative magnetic fields of the coils in the fusion-drilling-head are able to heat up the rock-melt by eddy current just at the rock-front in the fusion-area. On this way energy-efficiency is optimized and cooling-energy minimized.

In the course of FusionDrilling the rock-melt at the cooling-part (1a) of the fusion-drilling-head (1) becomes viscous and solidified to a burning hot rock-casing. At the same time viscous steel-melt from the steel-bar (7) over the steel feed-pipes (6) is pressed in the space between the fresh created rock-casing around the upper part (1a) of the fusion-drilling-head and the conical compactor (2) building up a strong, seamless steel casing.

During the further course of FusionDrilling the viscous steel-melt (9d – 9b) is cooling down, solidified to a burning hot steel-casing and compressed and tempered by the conical compactor (2) to a strong steel-casing (9). To accelerate the fusion-drilling process the stable but hot steel-casing is after-cooled by the heavy-fluid (11) in the gap between the steel-casing and the cooling element (3).

Main-function of the heavy-fluid – the SuperDeep-Well or Shaft is flooded:

1. a steady increase of compression force on the Fusion-Drilling-Robot correcting the increasing pressure for rock-melt displacement with increasing dept
2. act with buoyant force stabilizing on the self-supporting strength of the different supply lines (7), (18), (19)
3. act as lubricant during recovery of the Fusion-Drilling-Robot at lifting by Hydraulic-Molch (16) and High-pressure Water-pump in connection with Installation- & Deinstallation-Robot(20)

Exception of CARBON-Fusion-Drilling-head (1) and Conical-compactor (2) all parts of the Fusion-Drilling-Robot are recycled by dismounting for construction of the next 30 – 40 SuperDeep-Wells. After recovery of the Fusion-Drilling-Robot a super-deep shaft with constant, big diameter and a strong steel-casing is production-ready, able to withstand the high shear-forces in the depth for a century production-time in a GW SC(supercritical)-GeoPower-station.

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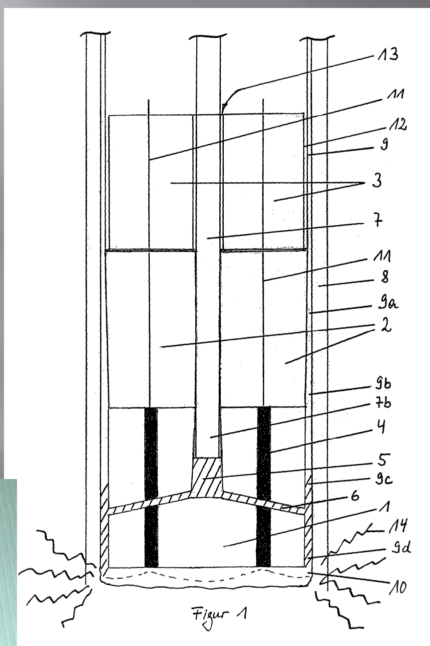
Laser- & Electrode Fusion-Drilling



Altenative to the presented SuperDeep-FusionDrilling-Process & Device I´m holding International Patens of other FusionDrilling-Processes & Devices like Electrodes or Laser as installed in position (4) The Laser-Patent is not disclosed, therefore I cannot give detailed information

At installation of Electrodes a continuous power-line is needed (position 11)

At installation of Laser a continuous fiber-glas power-line is needed (position 11) both are at the market

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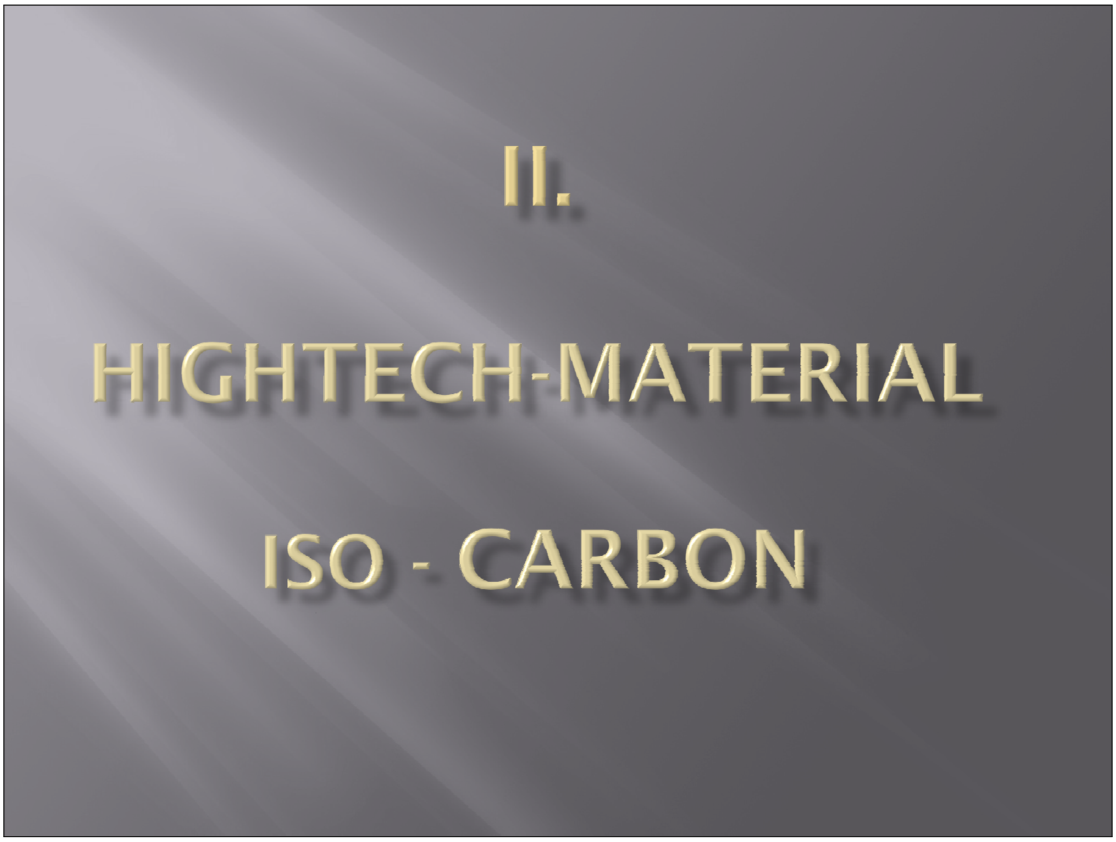
II.
HIGHTECH-MATERIAL
ISO - CARBON


Carbon/Steel-melt Materialtest
2000°C & 2000bar
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Elektron-microscopic cut across Steel-annulus & Carbon-cylinder

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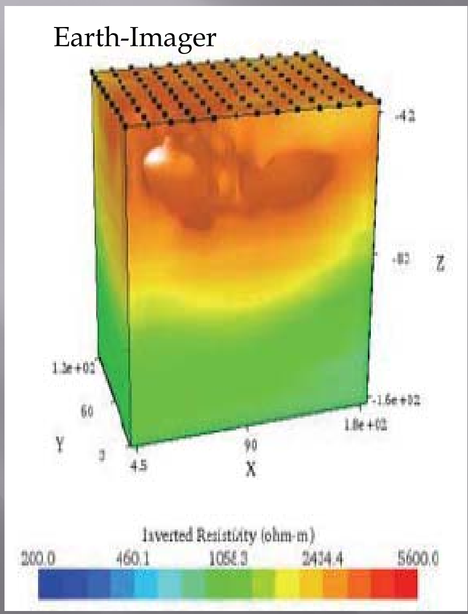
III.

ELECTRICAL RESISTANCE TOMOGRAPHY

Subsurface Imaging



Elelectrical Resistance Tomography is an ideal tool of subsurface imaging

The electric-current run through the created rockmelt in front of the Carbon Pressure-Bit of the SuperDeep-FusionDrilling-Robot

The different resistivity of rock and rockmelt gives an exact position of the rock-melt layer and enables the FusionDrilling-Robot by a special computer-program to stear the fusion-drilling-process (s. picture left gives an imagination)

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IV.

ROCK-MELT DISPLACEMENT

IN

COMPACT ROCKFORMATION IN NATURE & TECHNIQUE


Volcano-Crack-Formation
La Palma
1
2
3
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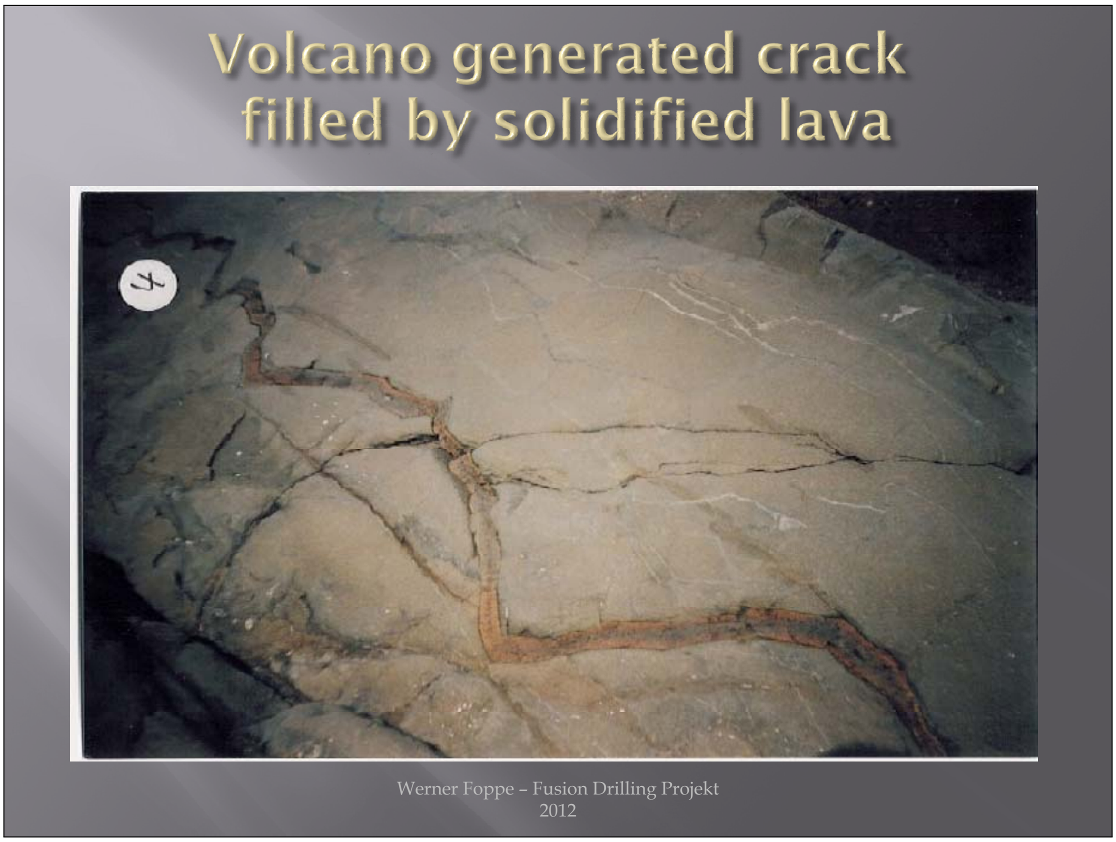
Volcano generated crack
filled by solidified lava
4
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2012

Displament of Rock-melt in a Basaltbloc by ‚Litho-Jet' Fusion-Drilling

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Demonstration of Thermit-melt Displacement in dolomite & chalk stone quarry

- **Thermit-reaction is a cost-effective demonstration-tool to simulate rock- & iron-melt displacment at high-pressure by generation of 3000°C reaction-heat.**
- **Conventional drilled wells are filled up with Thermit-powder, blocked with packer and blow-up by electric ignition**

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Steam blow off after Thermit-Reaction in the steep face of Dolomit-Quarry

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Dolomit- Quarry with a big excavator to exposure the injected Thermit-melt

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Conglomerated gravel-packer by heat-release of Thermitreaction

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Horizontal heat-reaction(white-coloured) in fraced Dolomite and melt-casing

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Well-casing by Thermit-melt (black) and solidified Dolomite-melt (white)

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Excavation of Test-well in Chalk-Quarry after Thermit-Reaction

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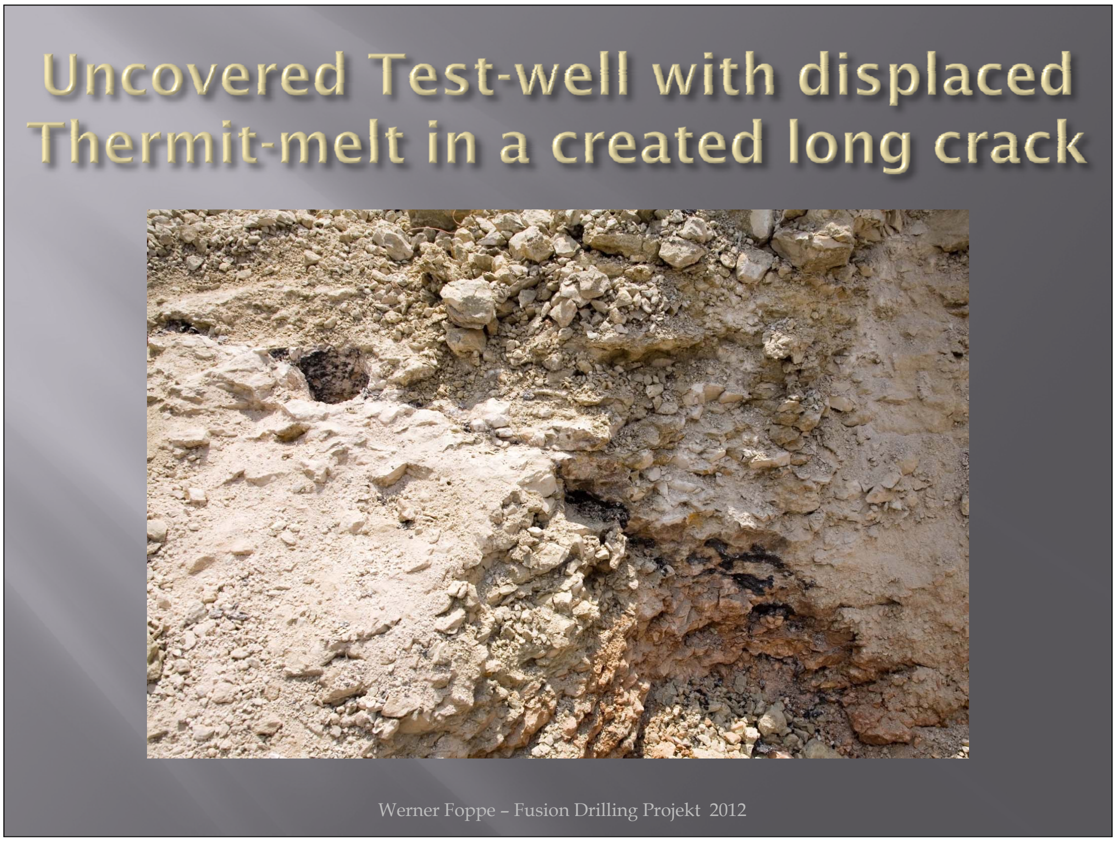
Uncovered Test-well with displaced Thermit-melt in a created long crack
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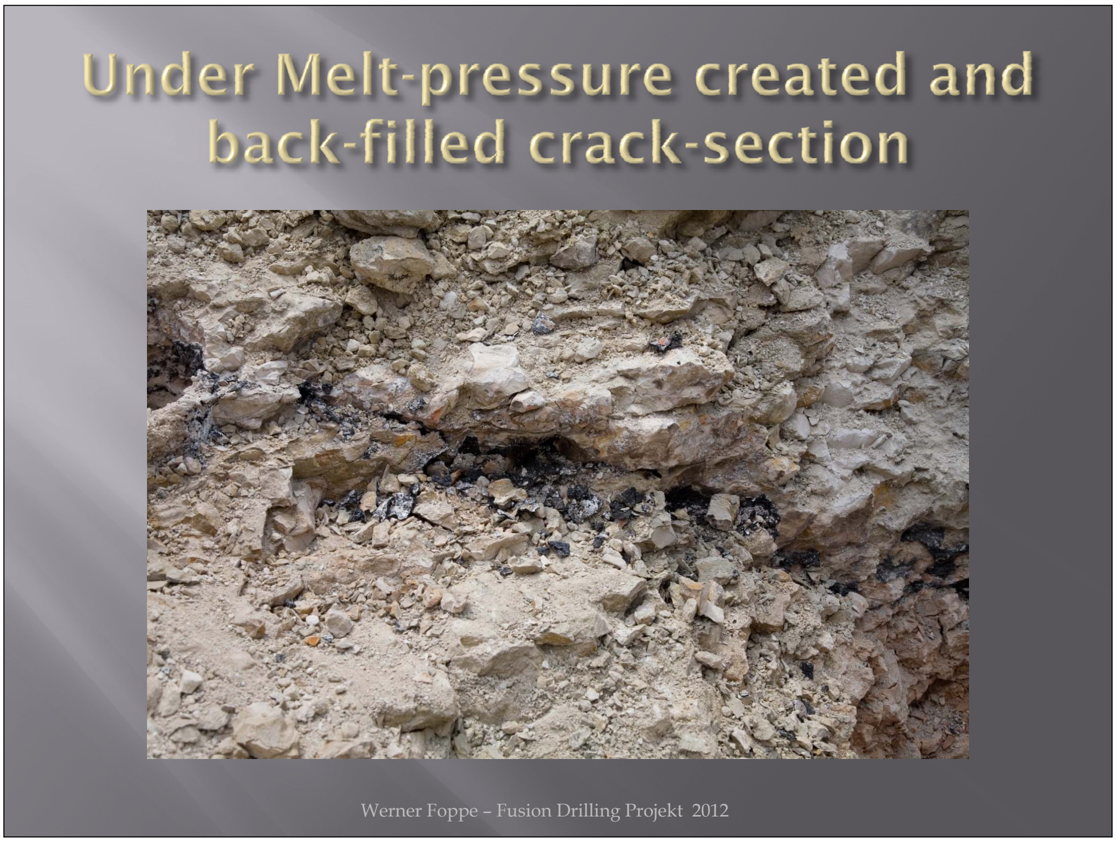
Under Melt-pressure created and back-filled crack-section
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Crack to both side of the Test-well by Thermit-reaction back-filled Thermit-melt
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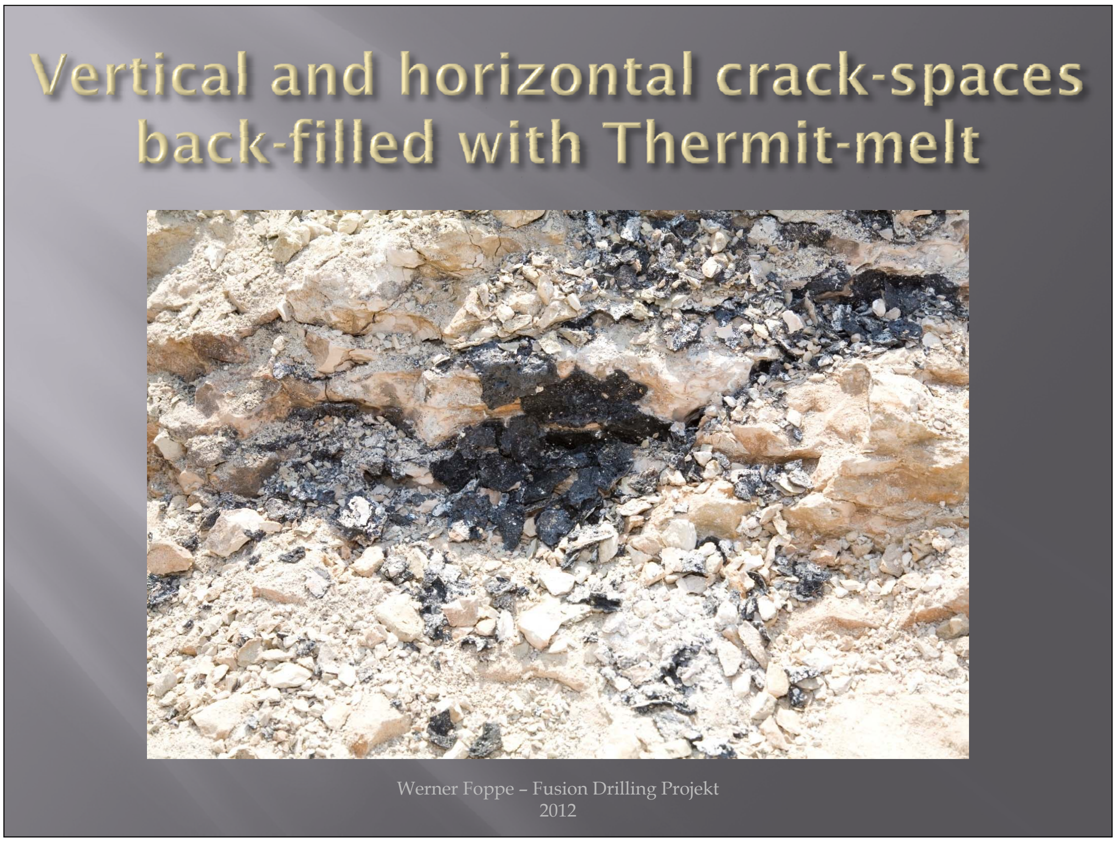
Vertical and horizontal crack-spaces back-filled with Thermit-melt
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2012

Displaced Thermit-melt in Chalck-quarry exposed by hand and excavator

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2012

SC(SUPERCRITICAL) - GEOPOWER

SOLUTION of Global Energy & Climate Problem

SC(supercritical)-GeoPower

- SC(supercritical)Water(SCW) is the medium to mine the stored energy in hot-rock with high efficiency and without fracing-problems
- SCW is able to create large SSB(Supercritical-Subsurface-Boiler) in ductile hot-rock too, where fracing does not work

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SuperDeep-Fusion-Drilling
Application-Technologies

- **SC-GeoSteam at GW-Scale everywhere on Earth**
- **Globale cost-effective Processteam- & Powerproduction by SC-GeoSteam**
- **SC-GeoSteam Injection in oilfields (90% recovery of original Oil in place(OOIP)**
- **SC-Geosteam Oil-refining (simple pressure-reduction of SC-Oil-fluide)**
- **SC-GeoSteam Fluide-minin g(ore-minerals dissolve at high pressure 1500bar)**
- **Self-burial of spend-fuel - Absolut save disposal-solution**
- **Recycling of CO2 to CH4 in SSB by 15-20 km SuperDeep-Wells**
- (CCS = Carbon Capture & Storage, SSB = Supercritical-Subsurface-Boiler)

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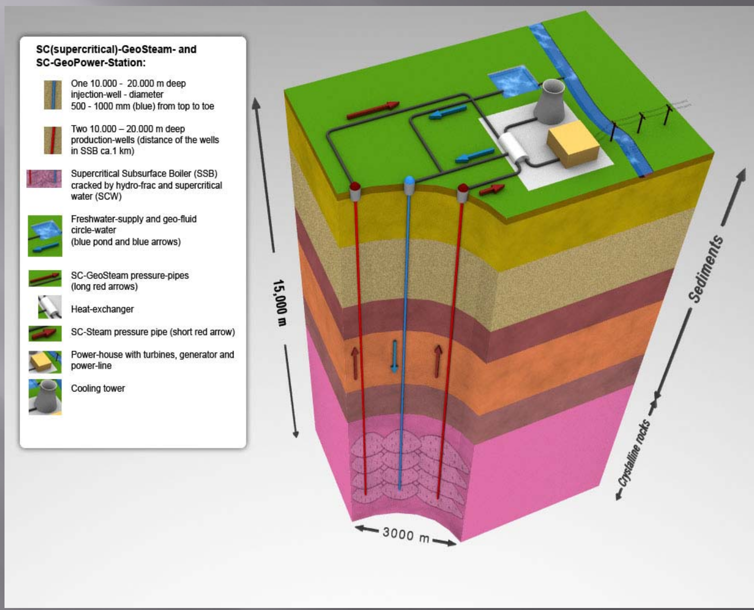
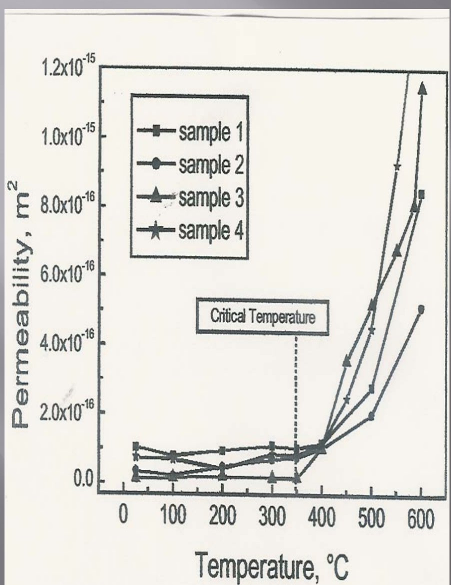
SC-GeoSteam & SC-GeoPower Plant



Special Properties of SCW in Rocks



The Viscosity of Super-Critical Water(SCW) behind the critical point is going to zero. The permeability of the rocks escalates by rising temperature and pressure behind the critical point

SCW invaded all cracks and fissures and makes HydroFrac dispensable and deminish the impedance of the (SupercriticalSubsurfaceBoiler)

The solubility of minerals in the rock is rising steep behind the pressure range of 1500 bar and makes Fluide-Mining economic in combination with Energy-Mining

The solubility of SCW makes it an ideal agens to Oil-Mining in all Oilfields by SC-GeoSteam-Injection and makes the 2/3 of OOIP available, remaining in ‚exausted Oil-fields

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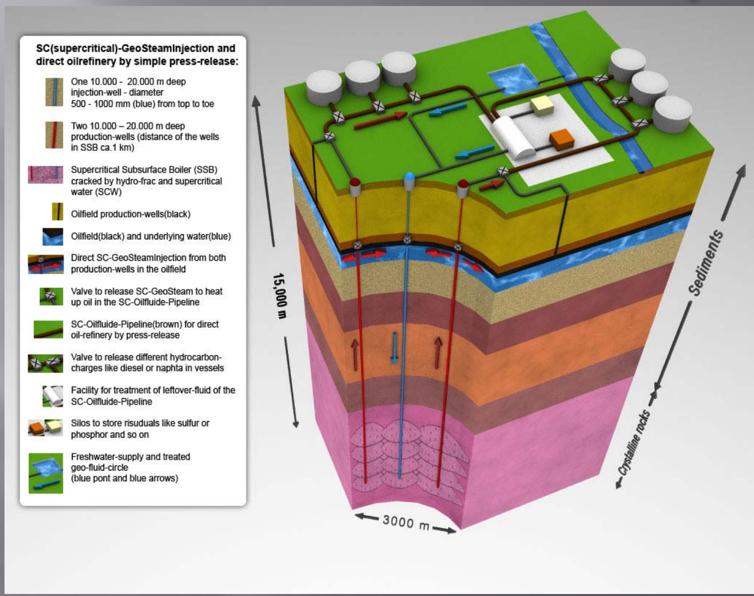
SC-GeoSteam-Injektion & Oil-extraction & refinery

kneier consult



Special Properties of SCW in Rock and Oil

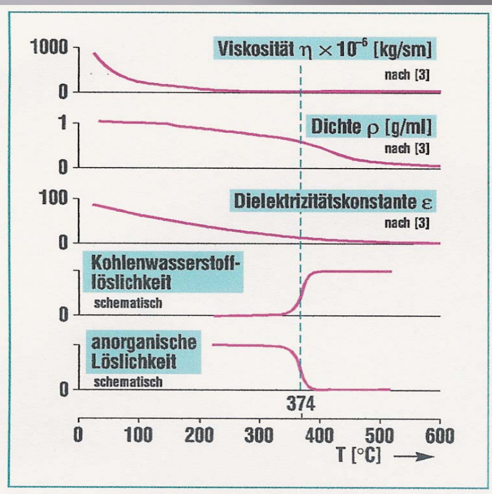


Abb. 2: Die Änderung wichtiger Eigenschaften von Wasser beim Übergang in das überkritische Gebiet bei einem konstanten Druck von 400 bar.

- The Viscosity of Super-Critical Water(SCW) behind the critical point is going to zero. The permeability of the rocks escalates by rising temperature and pressure behind the critical point
- SCW invaded all cracks and fissures and makes HydroFrac dispensable and deminish the impedance of the SSB (SupercriticalSubsurfaceBoiler)
- The solubility of minerals in the rock is rising steep behind the pressure range of 1500 bar and makes Fluide-Mining economic in combination with Energy-Mining
- The solubility of SCW makes it an ideal agens to Oil-Mining in all Oilfields by SC-GeoSteam-Injection and makes the 2/3 of OOIP available, remaining in ‚exausted Oil-fields

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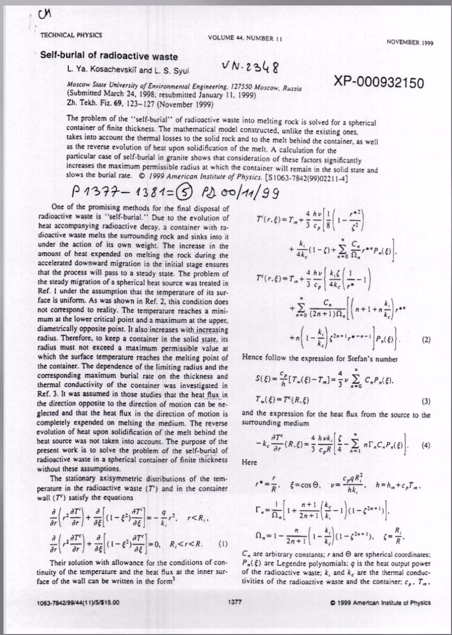
Self-burial of radioactive waste (1)



TECHNICAL PHYSICS — VOLUME 44, NUMBER 11 — NOVEMBER 1999

Self-burial of radioactive waste

L. Ya. Kosachevskiĭ and L. S. Syui

VN-2348 XP-000932150

Moscow State University of Environmental Engineering, 127550 Moscow, Russia
(Submitted March 24, 1998; resubmitted January 11, 1999)
Zh. Tekh. Fiz. 69, 123–127 (November 1999)

The problem of the "self-burial" of radioactive waste into melting rock is solved for a spherical container of finite thickness. The mathematical model constructed, unlike the existing ones, takes into account the thermal losses to the solid rock and to the melt behind the container, as well as the reverse evolution of heat upon solidification of the melt. A calculation for the particular case of self-burial in granite shows that consideration of these factors significantly increases the maximum permissible radius at which the container will remain in the solid state and slows the burial rate. © 1999 American Institute of Physics. [S1063-7842(99)02211-4]

P 1377 – 1381 = 5 PD 00/11/99

The radioactive, heat-releasing spent-fuel normally is sealing in glass-melt casket

The spent-fuel caskets are deposited in the lower half of a 20 km SuperDeep-Shaft with 200 cm in diameter and a strong casing out of high-temperature metal . The upper part of the well is steel-cased.

After filling-up the lower 10 km of theSuperDeep-Shaft with heat-releasing spent-fuel the shaft is squished off and shut down by an explosion

Under its own weight, heat-release and surrounding-heat of rock the havy-metal filled up shaft is under the drag of force of gravity on a long steady 6000 km trip to the center of the Earth with 300 m per year of never see again

It's the safest way to get rid off the dangerous mess

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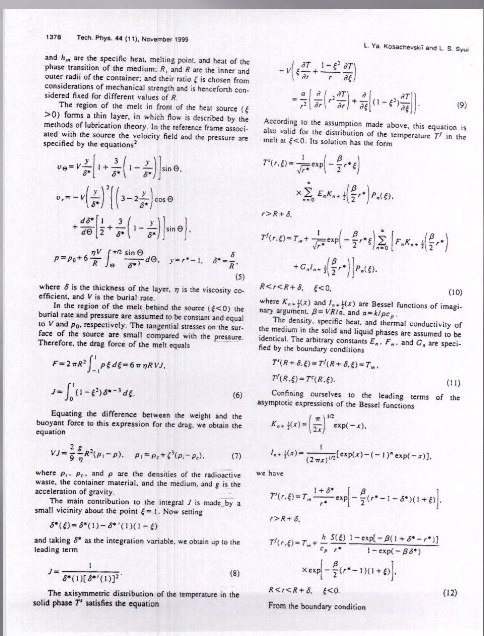
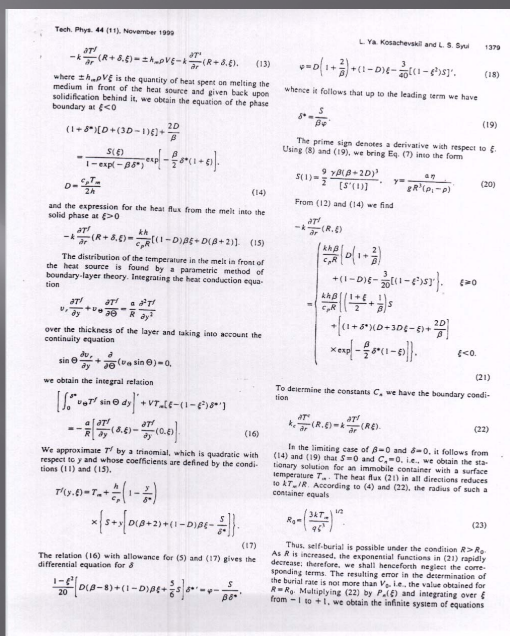
Self-burial of radioactive waste (2)





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Self-burial of radioactive waste (3)

1380 Tech. Phys. 44 (11), November 1999

L. Ya. Kosachevskiĭ and L. S. Syui

$$\frac{4n\chi}{(2n+1)\beta}C_n+\sum_{k=0}^{\infty}C_k\left\{\frac{3}{10}P_k(0)P_n(0)+\frac{n}{2n+1}\left[\frac{3}{10}(n+1)-(-1)^{k+n}\right]\Psi_{k,n-1}-\frac{n+1}{2n+1}\left[\frac{3}{10}n+(-1)^{k+n}\right]\Psi_{k,n+1}+(-1)^{k+n}\left(1+\frac{2}{\beta}\right)\Psi_{k,n}\right\}=\frac{\chi}{2}\frac{\zeta}{\beta}\int_{-1}^{1}P_n(\xi)\,d\xi-\frac{3}{2\nu}Q_n,$$

$$Q_n=D\left(1+\frac{2}{\beta}\right)\Psi_{0,n}+(1-D)\Psi_{1,n},$$

$$\Psi_{k,n}=\int_0^1 P_k(\xi)P_n(\xi)\,d\xi,\quad \chi=\frac{k_i}{k},\quad n=0,1,\dots. \tag{24}$$

We confine ourselves to a finite number N of the constants C_n and the first N equations. For $N=2$ we have

$$C_0=\frac{3}{\nu}\frac{\Delta_0}{\Delta},\quad C_1=-\frac{3}{\nu}\frac{\Delta_1}{\Delta};$$

$$S(1)=\frac{4}{3}\nu(C_0+C_1),\quad S'(1)=\frac{4}{3}\nu C_1;$$

$$\Delta_0=\frac{2}{3}\chi\zeta\nu\left(1+2\chi\Gamma_1+\frac{19}{80}\beta\right)-\frac{1}{2}(7+8\chi\Gamma_1)D-\left[1+\frac{59}{40}D+\chi\Gamma_1(1+D)\right]\beta-\frac{1}{480}(97+77D)\beta^2,$$

$$\Delta_1=\chi\zeta\nu\left(-1+\frac{1}{30}\beta\right)+6D+\frac{1}{20}(35+47D)\beta+\frac{1}{40}(15+7D)\beta^2,$$

$$\Delta=1+8\chi\Gamma_1+\frac{1}{20}(43+64\chi\Gamma_1)\beta+\frac{119}{300}\beta^2. \tag{25}$$

The parameter β is found from the equation

$$\Delta_0-\Delta_1=\frac{\Delta}{4}S(1), \tag{26}$$

where, according to (20),

$$S(1)=\frac{9\chi}{32}\left(\frac{\Delta}{\Delta_1}\right)^2\beta(\beta+2D)^3. \tag{27}$$

Since $S(1)\ll 1$, Eq. (26) reduces to a quadratic equation. When $R>R_0$, it has one positive root

$$\beta(\nu)=\frac{1}{277+161D}\{[36L^2+(277+161D)M]^{1/2}-6L\},$$

$$L=110+153D+40\chi\Gamma_1(1+D)-5\chi\zeta\nu,$$

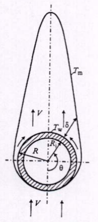

FIG. 1. Physical model of the geometry of the problem.

$$M=\frac{1}{3}\chi\zeta\nu(5+4\chi\Gamma_1)-\frac{1}{2}(19+8\chi\Gamma_1)D, \tag{28}$$

which specifies the dependence of the burial rate on the radius and heat output power of the heat source, as well as the physical characteristics of the medium. According to (2), the maximum temperature is achieved on the line $\xi=-1$ at the point

$$r_m^*=-4\frac{\zeta^2}{\Omega_1}C_1; \tag{29}$$

and equals

$$T^i(r_m^*,-1)=T_m+\frac{h\nu}{6c_p}\left[1+2\frac{k_i}{k_c}(1-\zeta)+\frac{r_m^*}{\zeta}(r_m^*+2\Omega_1)\right]. \tag{30}$$

The container has its highest temperature at the upper critical point on the inner surface of the wall:

$$T^c(R_i,-1)=T_m+\frac{4}{3}\frac{h\nu}{c_p}\left[\frac{k_i}{4k_c}(1-\zeta)+\left(1+\frac{\zeta}{\Omega_1}\right)C_0\right]. \tag{31}$$

Equating it to the melting point of the container T_*, we find the maximum permissible value of ν:

$$\nu_*=\frac{3}{G}\left\{\left(1+\frac{\zeta}{\Omega_1}\right)[876D+(277+161D)\beta_*]-S_*(445+464\chi\Gamma_1)\right\},$$

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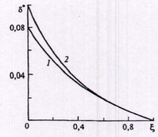

FIG. 2. Thickness of the melt zone at $\xi>0$.

$$G=180\chi\zeta\left(1+\frac{\zeta}{\Omega_1}\right)-\frac{k_i}{k_c}(445+464\chi\Gamma_1)(1-\zeta),$$

$$S_*=\frac{c_p}{h}(T_*-T_m). \tag{32}$$

Substituting it into (26), we obtain a quadratic equation for the corresponding value $\beta=\beta_*$. According to the definitions of these parameters, the maximum radius and burial rate are found using the formulas

$$R_*=\frac{1}{\zeta}\left(\frac{hk_i}{c_p q}\nu_*\right)^{1/2},\quad V_*=\frac{a}{R_*}\beta_*. \tag{33}$$

When $N>2$, the problem requires a numerical solution.

Let us consider the case of the self-burial of radioactive waste housed in a container composed of the high-temperature ceramic NbC in granite when $q=130\,000$ W/m^3. We take the following values for the physical constants (in SI units):[4] $\rho=2700$, $c_p=1301$, $k=3.013$, $h_m=585\,800$, $T_m=1200\,°C$, $\eta=10$; $\rho_c=7820$, $k_c=44$, $T_*=3480\,°C$; $\rho_i=7800$, $k_i=36$.

For $\zeta=0.9$ we obtain $R_*=1.221$ m, $V_*=376.28$ m/year, $S(1)=0.855\times10^{-4}$, $S'(1)=-0.684$, $\delta^*(1)=0.359\times10^{-5}$, and $\delta^*(-1)=4.012$.

At the point $\xi=0$ the expressions (14) and (19) give fairly close values: $\delta^*(-0)=0.092$ and $\delta^*(+0)=0.099$. At

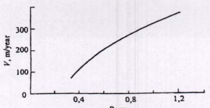

FIG. 3. Plot of the dependence of the burial rate on the container radius for $\zeta=0.9$.

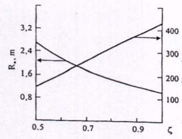

FIG. 4. Plots of the dependence of the maximum radius and burial rate on ζ.

$\xi=1$ the container is in direct contact with the solid medium and has a temperature exceeding its melting point by 0.14 °C. The maximum temperature within the container at the point $r_m^*=0.639$, $\xi=-1$ equals 3540.96 °C. The melt zone and the computational model of flow are shown in Fig. 1. In Fig. 2 curve 1 corresponds to the boundary of the melt zone in the region $\xi>0$ defined by Eq. (18), and curve 2 corresponds to the approximate formula (19). In the range $0.5<\xi\leq1$ they essentially coincide. The maximum difference between them at $\xi=0$ amounts to 0.019. Since the motion of the container depends mainly on the conditions in the vicinity of $\xi=1$, the accuracy of formula (19) is fully satisfactory. Formula (6) with allowance for (19) gives $J=139.04\times10^6$, and the value obtained from the approximate formula (8) is 0.05% higher. According to (23), $R_0=0.338$ m corresponds to a zero burial rate. Figure 3 shows a plot of $V(R)$ specified by formula (28). For the radius R_0 it gives $V_0=68.39$ m/year, which represents the maximum error caused by neglect of the exponential term in (21). As ζ is increased from 0.5 to 1, the radius R_* decreases from 2.683 to 1.025 m, and V_* increases roughly according to a linear law from 150.08 to 429.94 m/year (Fig. 4). A comparison with the results in Ref. 2 for $\zeta=1$ shows that consideration of the heat flux and the reverse evolution of heat upon solidification of the melt at $\xi<0$ increases R_* by 0.298 m and diminishes V_* by 44 m/year. The melt zone behind the container becomes 1.5 times longer.

The results obtained depend weakly on the choice of the value of N. For example, for $N=10$ the values of R_* and V_* increase by 1.53% and 0.51%, respectively, and for $N=100$ they increase by 1.62% and 0.56%.

[1] S. H. Emerman and D. L. Turcotte, Int. J. Heat Mass Transf. 26, 1625 (1983).
[2] L. Ya. Kosachevskiĭ and L. S. Syui, Zh. Tekh. Fiz. 64(6), 7 (1994) [Tech. Phys. 39, 524 (1994)].
[3] L. Ya. Kosachevskiĭ and L. S. Syui, Geoékologiya, No. 1, pp. 96–102 (1995).
[4] I. K. Kikoin (ed.), *Tables of Physical Constants. A Handbook* [in Russian], Atomizdat, Moscow (1976), 1008 pp.

Translated by P. Shelnitz

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Cost-Estimation of SuperDeep-FusionDrilling-Technology

Imput variables

Dollar/Euro		1,47	
Full-load hours	Bh/a	7500,00	
Grid-losts inland	%	0,00	
Specific weight - steel	Mg/m^3	7,85	
Enthalpie to melt steel	MWh/Mg	0,45	
Price of Steel	US$/Mg	600,00	
Price of Steel	€/Mg	408,72	
Melting-energy requirements of MSD-project	kJ/cm^3	2,4 - 4,2	
Melting-energy requirements of MSD-project	MWh/m^3	0,92	
Buying price - Ground	€/m^2	4,00	
Purchaseprice - Heat	€/MWh	2,00	
Purchaseprice - Power	€/MWh	130,00	
Price of Water	€/m^3	3,00	
Price of Additives	€/Mg	100,00	
Maintenance of MSD-Drilling-Machines	% der Invest/a	0,12	
Operation-costs	% der Invest/a	0,03	
Operating time - MSD-Drilling-Machine	a	20,00	
Operating time - SC-GeoPower Station	a	60,00	
Interestrate	%	0,12	
Manpower - MSD-Drilling	Number of pers.	12,00	
Costs of Manpower	T€/a	100,00	
Protective wall against tube- or well-disruption	T€/km	300,00	nach 2, S. 230

SC-GeoPower-Station - Technical/physical characteristics

Production-well	2	2,00
Total SC-Steam-production / 2 wells	MWth	4000,00
Electric power-Production well	MWel	1000,00
Total Electric-power / 2 wells	MWel	2000,00
Full-load hours: Electric-power	Bh/a	7500,00
On-site power	%	0,05
Gross Power-production/a	MWhel/a	15000000,00
Net Power-production/a	MWhel/a	14250000,00
28 MW-HydroPower	MWhel/a	210.000.00

Technical-physical characteristics of Supercritical Subsurface Boiler(SSB)

Enthalpy / Total Well-Produktion	MWth	4000,00	40fold enthalpy as in conventional supercritical geothermal wells on Island
Volume-flow / Production-well	m³/s	12,40	
Mass-flow / Production-well	kg/s	4040,00	
Drillrisk / Well-failure	m	0,00	SCW invades all kind of rocks
Production-well / SC-GeoPower-Plant	m	2,00	
Total wells / SC-GeoSteam-Plant	m	3,00	
Number of superdeep wells / in lifetime of the drilling-machine	3/a	60,00	Minimum live-time of Maglev-SuperDeep-Drilling Machine 10 years

Cost-Estimation of SuperDeep-FusionDrilling-Technology (Page I)

Comment: These 3 Page cost-estimation I worked out on a workshop together with engineers of one of the bigges power-producer in Germany 4years ago. At that time I favored a Maglev-SuperDeep-FusionDrilling-Robot (MSD-Project), a much more expensive design as the favored SuperDeep-FusionDrilling-Robot in this presentation. The imput variables are unchanged. Well-diameter 0,60/1 m are changed, so steelcasing-wall 0,05/0,10 m but overall comparable. The mass-flow of one meter diameter superdeep-production-wells is three-times higher as in production-well of 0,6 m diameter and at the same rate of flow the Power-Inital-Cost is **under 3€/MWh**.

The cost-estimation of 3 superdeep-fusion-drilled wells to run a SC(supercritical) – GeoPower-Station on GigaWatt-Scale presens:

Imput -variables, Technical/physical characteristics of a SC-GeoPower-Station, Technical-physical characteristics of Supercritical Subsurface Boiler, Fusion-Drill-Cost, Material-Cost, Cost of overground building calculation, Calculation of specific-cost of SC-GeoSteam- & SC-GeoPower-Station, Power Initial-Cost gives everyone the posibility to verify the Cost-Estimation and to vary Imput–Variables.

Construction-Phase for a SuperDeep-FusionDrilling-Robot (4 - 5 years)

Construction-Phase for 3 x 20.000 m SuperDeep-Wells (12 month)

Construction-Phase for a 3000MW SC-GeoPower-Station (4 years)

The Initial-Cost of SC-GeoPower = €3,69/MWh or **0,37 Cent/kWh**

10times more cost-effective as Brown-coal Power in Germany

100times more cost-effective as SolarDerivates(wind-/solar-power)

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Cost-Estimation of SuperDeep-FusionDrilling-Technology (Page 2 & 3)

19.11.2012

Combined SC-Geo Steam- / SC-GePower-Plant short steamline back and forth	m	100,00	nach 3, Folie 21 - Kompakte SC-GeoSteam Anlage in Kombination mit dem
Long cost-intensive steam-lines not nessesary	m	100,00	
Avarage well-depth	m	15000,00	
Outer diameter of well	m	0,70	Innendurchmesser + Wand
Circular well cross-section	m²	0,38	
Well-volume	m³	5772,68	
Thickness of Cast-metal casing	m	0,05	
Surface of metal casing	m²	0,10	
Weight of metal-casing/m	MG/m	0,70	
Steel-consumption + losses	Mg/ well	15000,00	
Energy consumption of steel-melting	MWh/ well	6750,00	
spezific energy consumption of rock- melting	kJ/cm³	2,5-4,2	
spezific energy consumption of rock- melting	MWh/m³	0,92	Mittlerer Wert für Gesteinaufschmelzung
spezific energy consumption of rock-melting/well	MWh/well	5291,62	
energy consumption of steel- and rock-melting	MWh/well	12041,62	
Energy consumption of 3 production-ready wells	MWh	36124,86	
Drilling speed	mm/s	6,00	
Drilling speed	m/d	518,40	
Drilling speed (rounded off)	m/d	500,00	
Drilling-time of three wells	d	90,00	
Drill-time (rounded off)	a	0,30	
stuff requirement	p	12,00	
Surface consumption	km²	1,00	Compact-Power-Station
Realty-price	€/m²	4,00	
Drilling costs			
Planing, Technical Sekurity Tests, State Amission	T€	300,00	
MSD-Fitting-Automat	T€	10000,00	
Maglev-Tubetrain, 15000 m, 3000 Modules	T€	96000,00	dito
Carbon-Modules	T€	6000,00	dito
(ERT) Electrical Resistance Tomography Automativ assistence steer- & control-system	T€	25000,00	dito
Power-Generator	T€	0,00	Net-power
Transport-equippment(train / truck	T€	10000,00	
The unexpected	T€	26000,00	dito
Unexpected surcharge after Foppe	T€	200000,00	
Sum MSD-Drilling-Machine	T€	373300,00	dito
Share in MSD-Drilling-Machine at SC-GeoSteam-Project over a live-time of 20 years	T€	18665,00	
Service and maintenance at drill-periode	T€	671,94	
Material-cost / steel			
Electric power / drilling	T€	18392,37	
Electric power / Maglev Elevator/MaglevTubeTrain	T€	4696,23	
Manpower-costs / drilling	T€	3120,00	
Concession, advisory assessment	T€	360,00	
Well-side exploration / 3D-Seismologie	T€	50,00	
Site-evaluation	T€	800,00	
Permissions, etc.	T€	200,00	

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2

19.11.2012

Drill-site arrangement	T€	100,00	
Recultivation of the workside	T€	500,00	
Transport, Logistik	T€	300,00	
Prebore / Start-Tube, 100 m	T€	3500,00	
Perforation der Gusseisenverschalung im Bereich des späteren Wärmetauschers	T€	3600,00	
Initiation of SSB(Supercritical Subsurface Boiler)	T€	300,00	
Buildings	T€	3000,00	2 installed 30MW high-pressure water-turbine are converted to pumps flooding all 3 superdeep wells together
Sum of Drilling-costs		2000,00	Anmerkung: kein weiterer Zuschlage für Unvorhergesehenes, da bereits Zuschlag von 200 Mio. € von Hr. Foppe eingerechnet.
	T€	60255,54	
Specific drilling-costs of the SC-GeoSteam-Station of 4000 MWth			
Specific drilling-cost conventional drilling Island / Landsvirkjun 2007	T€	1,34	
Cost-ratio of MSD-drilling / conventional drilling	T€	1,40	
	T€	0,96	
Cost of overground buildings/ Calculation of single positions			
Consession			
SC-GeoFluide(Gravity forced Natural Circle) Injection-well=1500bar/Production-well=500-1000bar	T€	2000,00	
Geothermal Fluide-circle	T€	0,00	No pump-work requires, in contrary 50 MW High-pressure waterpower available by 2 installed 30 MW high-pressure water-pumps respectively water-turbine.
Fluide-clean up and Mineral-separation-system	T€	0,00	
2000 MW SC-GeoPoweranlage / 300€/kW	T€	4400,00	
Industrial Buildings	T€	600000,00	SC-Power-Technology with highes stand of art with ca. 50% efficiency. The cost-intensive fuel-part is eliminated. Investment-reduction at 300T€/MW.
Planing & Consessions (10% of SC-GeoSteam & SC-GeoPower Plant Invest)	T€	750,00	
Sum of single positions + SC Geopower Station	T€	61040,00	
Specific initial cost	T€	668190,00	
	T€/MW	168,00	
Calculation of all specific-cost of SC-GeoSteam and SC-GeoPower Station / Construction phase 4 years			
Capital equipment overground			
Investment Drilling-equipment	T€	668190,00	
Total Investment 4000MWth SC-GeoPower-Station	T€	60255,50	
Capital-costs	T€	728445,50	
Operating-costs KW (2,5 % of Investment)	T€/a	87510,95	
Overall-costs	T€/a	18211,14	
Power initial-cost	T€/a	105722,09	
Power initial-cost	€/MWh$_{el}$	3,69	
	€cent/kWh$_{el}$	0,37	

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3

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Investment: 3000MWel SC-GeoPower-Station

3x20 km Steal-cased SuperDeep-Wells with inner-Diameter of 1m, outer-Diameter of 1,20 m

- Cost of 6000MW SC-GeoSteam- & 3000MW SC-Geopower- Station
  - **Power-costs:** (€50/MW/h) rock-melt & steel-melt= €7,5Mio. + other €2,5 Mio. **= €10 Mio.**
  - **Steel-costs:** (€600/to), (2,84 to/m x 60.000 m) €600 x 2,84 x 60.000=€102 Mio. ca. **= €100 Mio.**
  - **Drilling-costs:** €1500 m (inclusive investmencost of drilling-equipment) **= €90 Mio.**
  - SC-GeoSteam-station with secondary-heatexchanger in the production-well **= €50 Mio.**
  - 3000MW SC-GeoPower-station (turbines, generator, transformer) **= €450 Mio.**
  - Industrial-park-area, buildings, water-supply, **=€200 Mio.**
  - Others: **=€100 Mio.**
  - **Gesamtkosten: =€ 1 Mrd. =€1000 Mio.**
  - **Investment-cost SC-GeoPower = (300 €/KW)** / Solar-Derivates = (3000 €/KW) **= 10fold**
  - **Life-time 3000MW SC-GeoPower = 80 Years** / Solar-Derivates = 20 Jahre = 4 x 3000MW = **12000 MW**
  - **Availability SC-GeoPower/8000h**, SolarDerivate / 2000h = 4fold = 4 x 3000MW **= 12000 MW**
  - **Efficiency SC-GeoPower 60%** / SolarDerivate / 20% = 3fold = 3 x 3000MW **= 9000 MW**
  - 2 x 3000MW Gase-Power-stations as substitute-capacity (lifecycle 40 years) **= 6000MW**
  - 3000MW SC-GeoPower / 39.000MW Solar-Derivates = 13fold power-capacity & 117fold costs **= €117 Mrd**
  - **Findings: 3000MW SC-GeoPower-Station** requires at benchmarking- & cost-comparison to Solar-Derivates at least: **10 times SolarDerivate-Capacity & 100 times SolarDerivate-Investment**
  - The Initial-Cost of SC-GeoPower under €3/MWh or **0,3 Cent/kWh**

Werner Foppe – Fusion Drilling Projekt 2012

Literature:

- Literature:
- LA-4547 'A Prilimary Study of Nuclear Subterrene'
- LA-5422 A Versatile Rock-Melting System & LA-5979 PDF 1973 - 76
- IDDP (Island Deep Drilling Project), IDDP_DEEP_VISION
- Self-burial of radioactive waste (Technical Physics, Vol. 44 Nr.11 – 1999)
- Wenlu Zhu, Glenn A. Gaetani, Florian Fusseis, Laurent G. J. Montési and Francesco De Carlo:
- Microtomography of Partially Molten Rocks: Three-Dimensional Melt Distribution in Mantle Peridotite,
- Report, *Science* 1 April 2011: Vol. 332 no. 6025 pp. 88-91, *DOI:* 10.*1126*/science.1202221
- http://www.wvcoal.com/201010282335/Research-Development/united-technologies-converts-co2-to-formic-acid.html
- **Extraction of Taiheiyo coal with supercritical water–HCOOH mixture**
  Department of Chemical Engineering, Tohoku University, Aoba 07, Aramaki, Aoba-ku, Sendai 980-8579, Japan
- www.wvcoal.com/.../princeton-**recycles-co2**-with-us-government-support.html
- **LABORATORY SIMULATION OF GRANITE-FLUID INTERACTIONS UP TO**
- **SUPERCRITICAL CONDITIONS**
- Greg Bignall1*, Nakamichi Yamasaki2 and Toshiyuki Hashida3
- 1Research Laboratory of Hydrothermal Chemistry, Kochi University, 2-5-1 Akebono-cho, Kochi shi, Kochi-ken, 780-8520, Japan
- 3Research Institute for Fracture Technology, Tohoku University, Aoba-ku, Sendai-shi, 980-8579, Japan
-
- **INVESTIGATION OF HEAT EXTRACTION**
- **FROM SUPERCRITICAL GEOTHERMAL RESERVOIRS**
- Toshiyuki Hashida1, Kazuo Hayashi2, Hiroaki Niitsuma3, Koji Matsuki3,
- Noriyoshi Tsuchiya3 and Katsuto Nakatsuka3
- 1 Fracture Research Institute, Tohoku University, 01 Aza-Aoba, Aramaki, Aoba-ku, Sendai, 980-8579 Japan
- 2 Institute for Fluid Science, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, 980-8577 Japan
- 3 Department of Geoscience and Technology, Tohoku University, 01 Aza-Aoba, Aramaki, Aoba-ku, Sendai, 980-8579 Japan
- **Improving Gas Well Drilling and Completion with High Energy Lasers – Brain C. Gahan Gas Technology Institute United States.**

Werner Foppe – Fusion Drilling Projekt 2012

11 Deep Geothermal Energy; Photonics for Harvesting

Arlid Rødland, Norwegian University of Science and Technology, Trondheim, Norway

11.1 Abstract

THE EPB STORY: The cost of drilling the bore hole is generally acknowledged to constitute 70-90% of the geothermal energy development cost (CAPEX), highest for geothermal HDR projects and therefore viewed as critical. Holder of the state of the art drilling technology is the petroleum industry, not a cheap technology because of the petroleum industry's high paying power and therefore no direct answer to geothermal need. The paper discusses availability of geothermal energy based on existing drilling technology and concludes that because of its high cost level such energy is economically available only in regions with abnormally high geothermal temperature gradients which leads to government subsidies in all other regions which in turn may be a hindrance for new technology to develop. Furthermore, the paper focuses on the quality of the desired geothermal energy and points out that there is too much priority on electricity. This leads to sky-high demands on the access (=drilling) technology since geothermal wells must then penetrate to higher temperature strata, more challenging also because they are deeper situated, as opposed to hot water energy which might be had at less depth. The prevailing global energy demand is on heating and cooling, consequently geothermal hot water energy would by substitution avail large quantities of electricity for other and higher applications.

The presentation proceeds to present the good news by introducing adapted conventional technology (ACT) and delivers examples what ACT can do. One such example is on the hydraulic energy spent in the hole-making, a major cost item in the state of the art. One example shows that the hydraulic energy consumption may be reduced by 70% by hose return circulation which have already been tested and tried. When this and other modifications are entered into the borehole cost equation the \$/m - number falls from the internationally agreed conventional technology US \$ 2000-3000/m to about half, which in turn could bring hot water geothermal energy to the wellhead for less than 10 euro cents per kilowatthour; probably a market acceptable price in our times. Of importance in the perception of this analysis are the wide differences between regions in the cost of drilling; the given number most relevant for amiably pressurized sedimentary drilling and a conventional final diameter; nevertheless a much improved image of geothermal energy availability. The implication however is that ACT is something the geothermal energy community themselves will have to achieve, since no one else have the motivation.

The paper then stops briefly at a listing of novel drilling technologies as they have emerged during the first decade of the 21st century by proponents of different origins. Common for them all is that they have roots going up to fifty years back into earlier times. The paper picks out one of them, the so-called electro pulse boring method (EPB) for deeper presentation and analysis, also called electro discharge drilling or plasma drilling.

It originated in the Soviet Union during the 1950s within the military complex. First awareness in the West was in

1984 by a defector during debriefings in London. He spoke about it as an earth drilling method but his tales did not stand to belief and it went unattended. After that there was nothing until a Russian émigré in 1995 brought it onto a Western researcher's desk. The documentation was scanty but indicated successful makings both of slim bore holes and large vertical shafts down to some hundred meters, in a variety of rocks including sedimentary permafrost. Of the competence centers one in Siberia seemed the more solid and several expeditions subsequently went there to investigate. The ensuing Norwegian-Russian EPB development project rested on the Russian for all the electrics and physics of the development and on the Norwegian for its drilling application. November 2003 saw a turning point in the form of a patent application which defined EPB in a new format aimed to enhance the pulse energy application, notably details like the down-hole pulse generator (DHPG), active electrode gap management, manipulated electrode bottom contact and bore hole bottom coverage by sweep which would allow for fewer and larger electrode gaps and ultimately larger excavated volumes per pulse of the rock matrix. The first patent materialized 2004 and in the following years was expanded into all relevant countries, the last of them pending until this day.

The paper proceeds directly to the bottom line in the form of kWh wellhead price for geothermal hot water energy as it may appear when extracted by EPB according to its parameters as they now are and with EPB applied on a perceived heat-exchanger-in-one-hole concept; one large diameter 4-branch HDR well to 6000 m TD. The resulting wellhead price is 1 Eurocent per kWh. The energy part of the presented case is represented as a free consultant's work based on the global average temperature gradient, thus aiming to qualify availability everywhere, while the bore hole part rests on the technology platform of the EPB development project and the productivity parameters it as concluded.

The project relevant EPB version employs a pair of electrodes submerged in a high-resistivity fluid, one high voltage and one grounded situated at a distance S from each other and only touching the rock, no WOB (weight on bit). An electric pulse is applied between the electrodes. Given correct pulse characteristics it will discharge along a curved surface inside the rock matrix body, the volume of rock above that surface coming loose in an instant. This is the commonly known electro discharge excavation format. Less known is the significance of the crack structure which the pulse creates around. By repeated pulses it will in time cause much larger rock volumes to come loose, how much larger and when depending on pulse characteristics and ambient conditions. To understand and be able to manipulate these functions is mandatory in order to obtain acceptable EPB productivity. Added hydraulic or mechanical (or other) interaction increases productivity, i.e. a given (cracked) volume comes loose sooner. bore hole pressure causes the well-known hold-down and must (as in other drilling) be countered by increased breakage energy; in sedimentary wet formations the bore hole pressure differential (over the formation pore pressure), in HDR the full bore hole pressure. Experiments with marginal EPB energy application will show the hold down effect as a marked reaction to increased pressure. EPB holes in HDR should preferably be made dry except around the bottom hole assembly (BHA).

Industrially relevant EPB technology platform parameters are pulse energies 2-5 kJ and pulse repetition frequencies up to 20 Hz applied on electrode gaps S = 12-15 cm for deep HDR bore holes of diameter 15-20" (inches), drilled by rotating bits (bottom coverage by sweep) and auxiliary energies applied (hydraulic and mechanical). This requires a DHPG capable of sustained 500 kV pulse voltage which should constitute no more than 70% of its design capacity; a tribute to a target minimum of 107 load cycles between equipment (= capacitor; according to current technology) failures. The DHPG will be integrated into the BHA, be situated near the bit and have outside diameter so as to leave a minimum of 30 mm annular space open in the bore hole for cuttings to pass; finally have input power 80-200 kVA by an industrial 220/380 V AC generator situated at the surface.

Optimized for minimum breakage energy early (pre-project) data shows 80-45 J/cm^3 for S=10-20 cm corresponding to 20-10 kWh/m^3, smallest energy value for the largest gap (S). A 6000 m HDR bore hole of 20″ diameter has 1215,5 m^3 of volume, accordingly consumes breaking energy total 24.300 kWh in (20 kWh/m^3). Optimization aside for the benefit of increased volume productivity has increased energy application by a factor of 2-2.5, thus 60.000 kWh for the subject bore hole. EPB technology platform data indicates specific breakage volumes 19-125 cm^3 per pulse for S= 12 cm, actual value depending primarily on degree of perfection of electrode management (= positioning & singularity). This indicates 36 days net drilling time to TD 6000 m (Total Depth; 19 cm^3/pulse, 20 Hz). Calculated generator power supply indicates 71,5 kVA. Cost of breakage is thus €2.50 per meter provided that the kilowatt-hours may be had for €0.25 apiece.

EPB alone is a breakage issue, no drilling. In order to drill it needs the context of a drilling rig. The nearest alternative is that of conventional drilling. EPB could be incorporated to replace the bit in a conventional rotary drilling process and might even function well. However, its unequaled low energy consumption would drown completely in the overall rig cost and even the excavating efficiency might be offset by the lost time caused by switching from rotary to EPB and back as the situation might require.

Three issues stand out in the making of an EPB drill rig. The foremost issue concerns the cuttings' transport from the bore hole. Annular flow return in a 20″ hole requires conditioned mud and 5000-6000 kW pumping power and is a major cost item. Hose return may reduce it by 70% as mentioned above and conditioned mud will not be needed. Novel developments exist in the form of wire line drilling concepts which may reduce it even further. The second issue concerns tonnage. Since EPB needs no WOB there is no need for heavy pipe (= drill collars), and since hoses may be made buoyant there is no drill string tonnage at all. Issue #3 concerns casing. EPB inherently makes bore hole bigger than the bit that made it. Casing may therefore be installed immediately behind the BHA and progress with the bit as hole is being made. In HDR the casing could be intermittent and made of expanded aluminum.

The EPB rig may thus be a very light rig. Examples indicate numbers like 100 tons lift capacity; 200 kW pumping and 1000 kW hoist to be adequate for the 6000 m job. This revised rig concept implies a very significant cost reduction; capex and opex. This is EPB in the practical context, a breakage method set in an adapted rig framework, given by its own premises. With everything counted the order of magnitude could come to €100(2010) per meter for 6000 m HDR 20″ bore hole. This is the explanation for the one cent wellhead price per kilowatt-hour hot water energy. EPB, in summary: An emerging technology with an established fact base indicating a 20″ HDR geothermal well @ €100/m producing geothermal energy anywhere in the world at €1 per 100 kWh.

11.2 Questions

Max. bore hole depth (m)

Limitations as for other drilling methods (temperature, pressure, bore hole stability). Various means exist for abating limitations. Ex: By availability at the hole bottom of means like fluid circulation and electric power EPB shows reduced vulnerability to high temperatures.

Max. respectively min. or optimal bore hole diameter (cm)

Current minimum diameter $\approx$ 200 mm (by miniaturization of pulse generator); no maximum. EPB excavates more and more efficient as diameter increases since electrode inter-distance may be increased and more energy deployed; tested and tried up to tunnel-relevant parameters. For deep bore holes cuttings removal is assumed to become the limiting factor, currently diameters are at 0,5-1,0 m; for lesser depths concepts exist for diameters of 1,8 m and bigger.

Volume capacity of rock excavation at the bore hole bottom (cm^3/s)

Current (documented) performance while drilling (granite) 380 cm^3/s; in laboratory (ideal electrode positioning vs matrix) 125 cm^3/pulse (x20 = 2506 cm^3/s granite). These values are relevant for bore hole diameters 300-600 mm; larger values for larger diameters.

Mode of operation of rock excavation at the bore hole bottom

Excavation by high voltage/high energy electric pulses between electrodes positioned adjacent to the rock surface (=bore hole bottom); includes auxiliary means for immediate removal of broken or cracked matrix (hydraulically, mechanically or other). Example values: 500 kV, 5000 J, 20 Hz.

Transport/disposal of cuttings to the surface

By conventional means (annular fluid circulation) or proprietary innovative methods (ex: Fluid circulation/hose return (cfr presentation); also other non-disclosed methods).

Environmental conditions during drilling (air, water, mud...) at the bore hole bottom

A high resistivity fluid layer to surround the electrodes; fluid contamination acceptable up to a case specific maximum (typically 20%). Fluid examples: Water, synthetic oils, mineral oils.

Main risks of the drilling method

High electric voltage handling at the drilling rig, 1 kV (regular industrial operations) or 40 kV (current), and assumed to be most pronounced during hydrocarbon (gas) drilling. Procedures exist and must be thoroughly observed. Other than that the normal drilling risks exist and must be handled properly (typically bore hole pressure), to some extent by novel procedures because of the different characteristics of EPB.

Drilling cost at depth of 100 m, of 1'000 m, and of 5'000 m

Studies show that bore hole cost of €100/m is the relevant target value given EPB routine performance (incl. novel auxiliary systems) according to its currently documented excavation capacity; the number typically valid for ⌀15-20″ HDR D6000 m bore holes. It should be understood that this is not an immediate target parameter and that it may only be reached over time by persistent and qualified development in a relevant format.

Status of development, publication of the previous R&D results

Technology platform established, ready for application's development; 1-2 applications finished 1st Stage of engineering. Time needed for applications development assumed at 36 months (= commencement of prototype/industrial operations). The technology platform was developed 1996-2011 in a closed project with minimal publication.

Main advantage/disadvantage of the drilling method

Advantages: Unsurpassed volume excavation capacity and unsurpassed excavation energy efficiency; example values 9 m^3 per hour (= above #4) at an energy consumption of $\approx$ 20 kWh per excavated cubic meter for a 20″ bore hole in granite, adequately powered by a 100 kW electric generator; more cubic meters and less specific energy for larger diameters.

Disadvantages: Fundamentally different from current drilling technology; all systems must be renewed, therefore high threshold entry into the industries.

Final words (personal): Multiple hole-making technologies did I examine, novel and not novel, during my 35 year guardianship of the principal Norwegian academic chair on the subject of drilling: Never did I see anything even remotely near what EPB will do on hard rock and diameters.

Deep Geothermal Energy

Photonics for Harvesting

by Prof Arild Rødland NTNU* November 7th 2012 Neuchatel Switzerland

ABOUT

Drilling for Geothermal Energy

"...where we are and where we go..."

THE EPB STORY

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THE SITUATION 2012

▼

GEOTHERMAL ENERGY

ONLY WHERE ELEVATED TEMP GRADIENTS ARE PRESENT

REASON?
ACCESS (= drilling) COST TOO MUCH.
= 60-80% OF GEOTHERMAL DEVELOPMENT COST
acc to independant accessment

SOLUTION?

- ***Government SUBSIDIES***
  GOVERNMENTS GUARANTEE 18-28 EU CENTS PER KILOWATTHOUR FOR NEW ENERGY
  - which stalls development of new technology
- ***New, cheap drilling methods***
  WHAT THIS PRESENTATION IS ABOUT

THE SITUATION 2012 II

▼

GEOTHERMAL ENERGY

OVER-FOCUS ON ELECTRICITY

WHICH ELEVATES SKY-HIGH THE DEMANDS ON TECHNOLOGY

DEEPER WELLS, HIGHER TEMPERATURES*

*Strenthens image of geothermal energy only for the geologically privileged

While the fact is that

the biggest energy demand is on heating and cooling; perfectly served

by

hot water energy*

*which will in turn relieve demand on other electricity for it to serve higher purposes

Now, then

▼

WHAT DRILLING TECHNOLOGY CAN DO

STATE OF THE ART

Well cost US$ 1500-3000 /m

6000m DEPTH RANGE; sedimentary lowest, HDR highest;, STANDARD FINAL DIAMETER*

*Oilfield Standard = 8½" open - 7" cased borehole; 4 CASINGS**

**LARGER COST MUCH MORE

▼

ENERGY PRICE* ?

10 - 20 EU¢ / kWh

*Model calculation for a specific well configuration;
hot water energy at wellhead at average HDR geological conditions

THE GOOD NEWS:

▼

There is

IMPROVEMENT POTENTIAL

LOOK TO THE CONCEPT OF

ADAPTED CONVENTIONAL TECHNOLOGY

*ACT

ACT ? WHERE DO WE LOOK ?

▼

Not the oil industry*

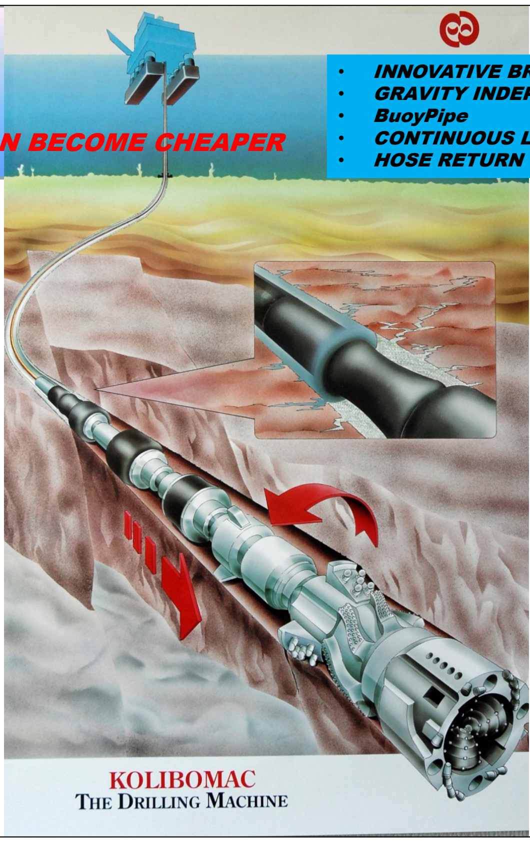
*Neither motif nor need.

ACT

EXAMPLES

HOW WELLS CAN BECOME CHEAPER

- INNOVATIVE BREAKAGE
- GRAVITY INDEPENDANCE BY WELL TRACTOR
- BuoyPipe
- CONTINUOUS LINER
- HOSE RETURN

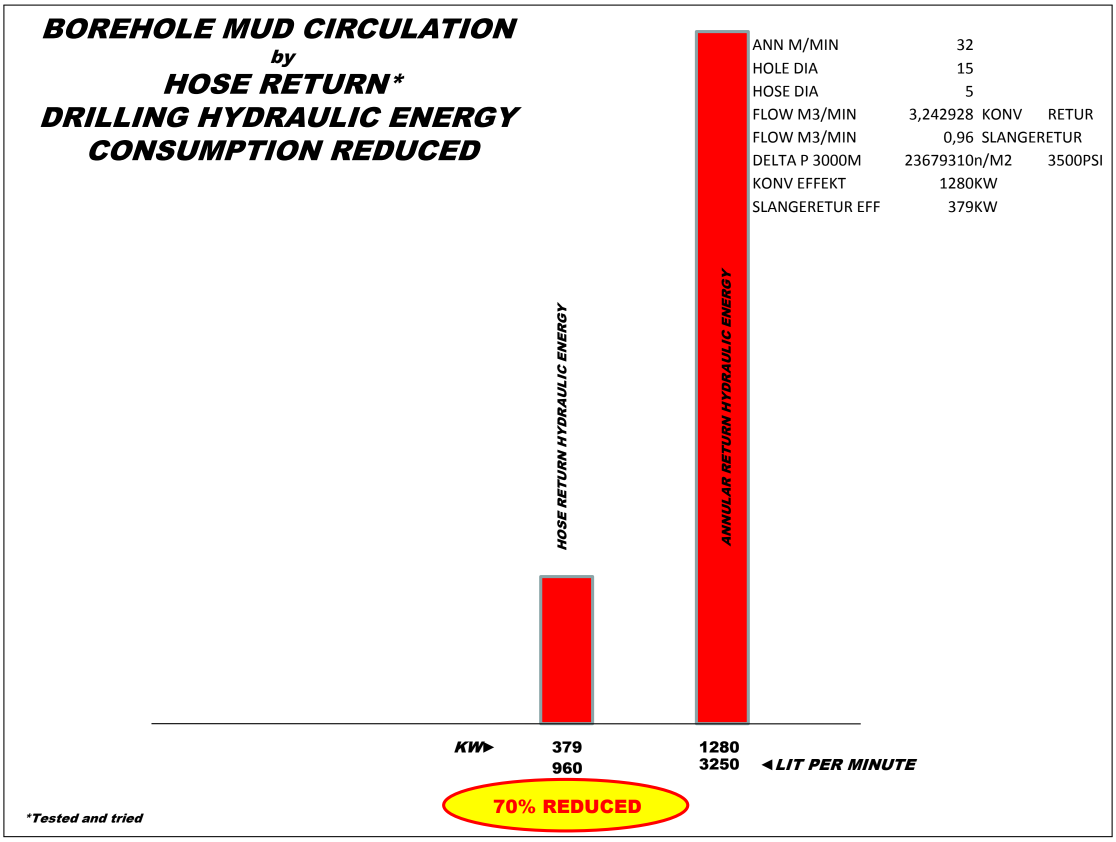


LET'S TAKE A LOOK

WHAT ONLY

HOSE RETURN

MAY ACHIEVE



In Summary

WHAT ACT CAN DO

Adapted Conventional Technology

▼

1000-1500 US$ / m

=

< 10 EU¢ / KWh*

i.e. not an unacceptable energy price in our times

**Model calculation for a specific well configuration;*
hot water energy at wellhead at average HDR geological conditions

DRILLING TECHNOLOGY
Novel Methods 2012

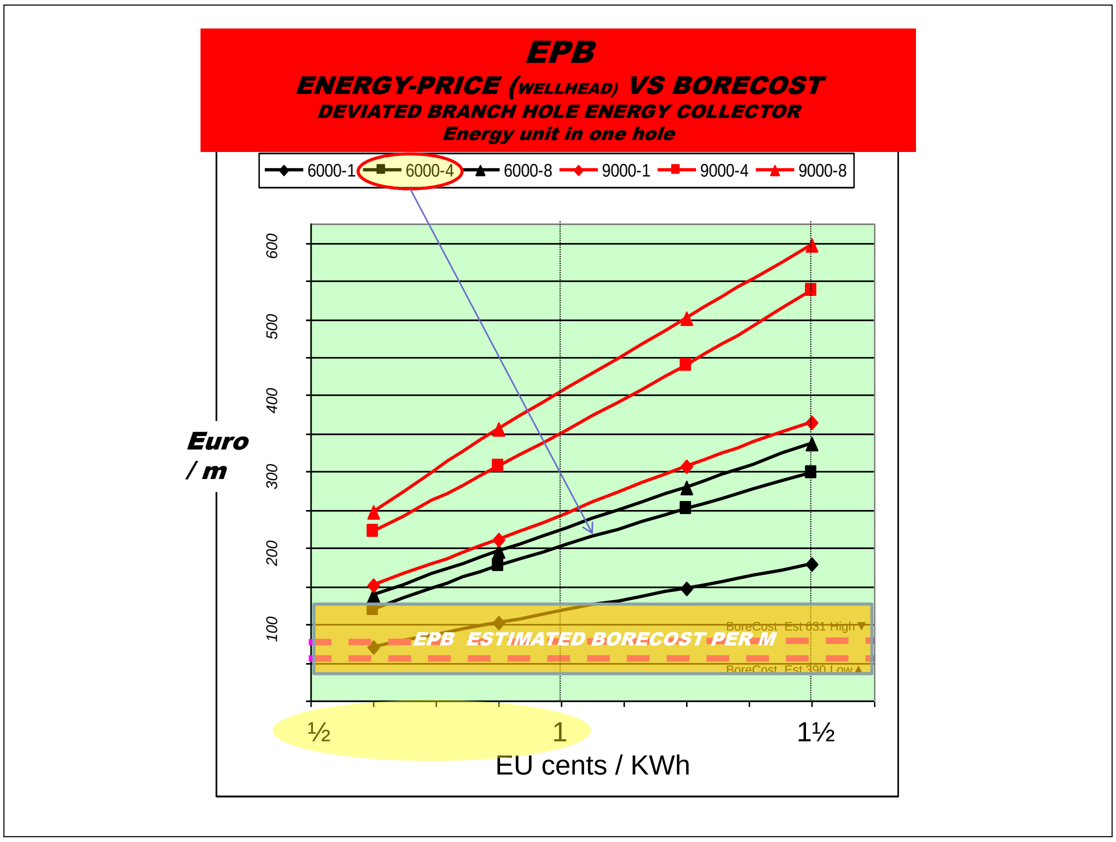
- ❖*Flame Spallation and Fusion Drilling (1998)**
- ❖*Chemically Enhanced Drilling (2000) **
- ❖*Electro Pulse Drilling (EPB) (2005) **
- ❖*Metal Shot Abrasive-Assisted Drilling (2006) **

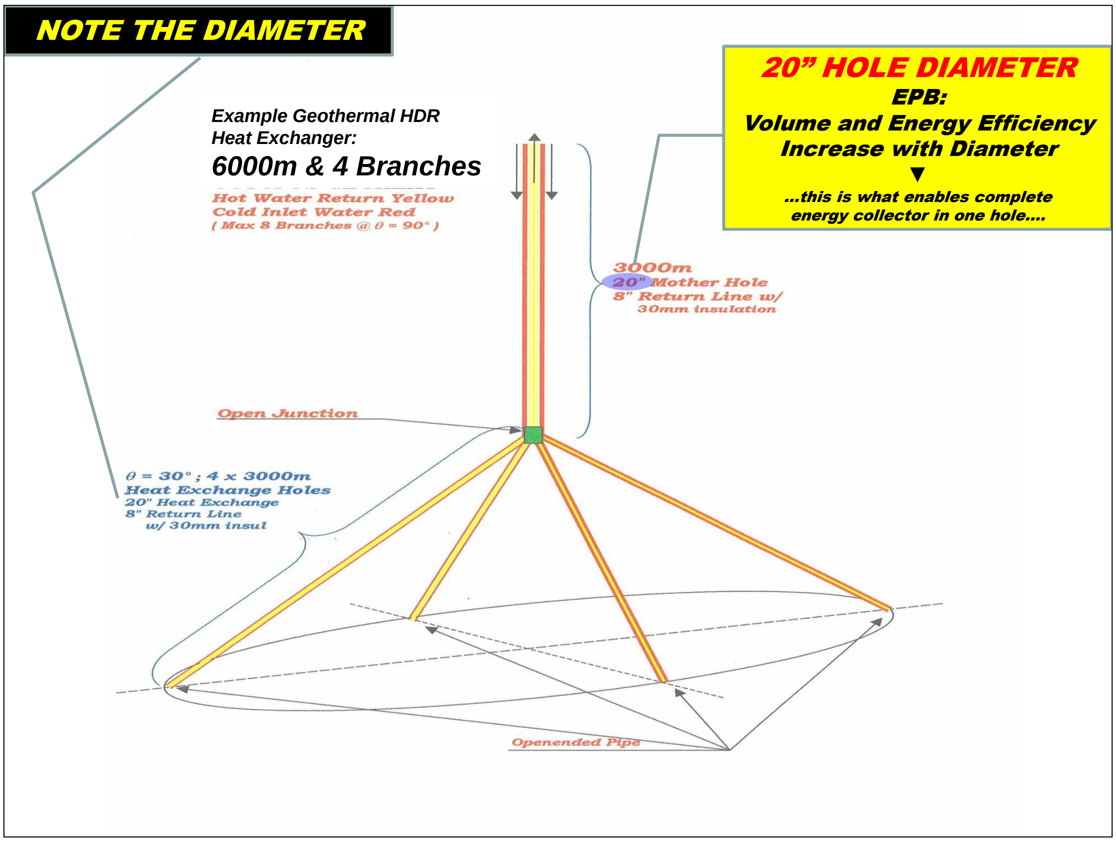
THIS PRESENTATION CONCERNS EPB

****CFR GOOGLE FOR DETAIL***

EPB
Electro Pulse Boring

What can it do?


EPB
ENERGY-PRICE (WELLHEAD) VS BORECOST
DEVIATED BRANCH HOLE ENERGY COLLECTOR
Energy unit in one hole
6000-1
6000-4
6000-8
9000-1
9000-4
9000-8
Euro / m
600
500
400
300
200
100
EPB ESTIMATED BORECOST PER M
½
1
1½
EU cents / KWh


NOTE THE DIAMETER
20" HOLE DIAMETER
EPB:
Volume and Energy Efficiency Increase with Diameter
...this is what enables complete energy collector in one hole....
Example Geothermal HDR Heat Exchanger:
6000m & 4 Branches
Hot Water Return Yellow
Cold Inlet Water Red
(Max 8 Branches @ θ = 90°)
3000m
20" Mother Hole
8" Return Line w/ 30mm insulation
Open Junction
θ = 30° ; 4 x 3000m
Heat Exchange Holes
20" Heat Exchange
8" Return Line
w/ 30mm insul
Openended Pipe

CLOSED LOOP
HEAT EXCHANGER
IN ONE HDR **HOLE**

-a concept for guaranteed
GEOTHERMAL ENERGY

availability
EVERYWHERE

-no groundshaking
(guaranteed)

EPB
Electro Pulse Boring

How can that be?

EPB

It is
HARD ROCK EXCAVATION TECHNOLOGY
by

Electric Pulses

discharged between

fluid submerged electrodes

in contact with

the Rock Matrix

▼

IT EXCAVATES ROCK
IN AMAZING VOLUMES
AT A MINIMUM OF APPLIED ENERGY
WHEN PROPERLY FORMATTED AND APPLIED

EPB
Pulse Characteristics

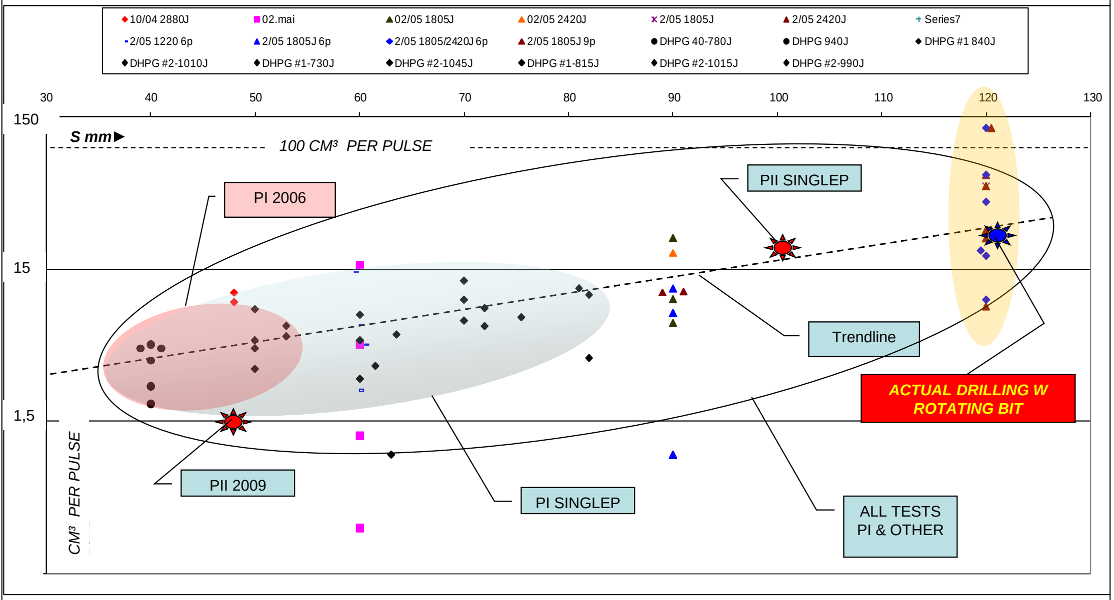
EXAMPLE *(magnitudes)*

PULSE:	Value	Unit
VOLTAGE	500	KV
AMPS	10	KA
PEAK POWER	5	GW
AVG POWER CONSUMPTION	25	KW
DURATION	300	nSec
REPETITION FREQUENCY	10	Hz
DURATION; of TOT TIME	0,001	‰

EPB FACT BASE

S30-S120 SUMMERIZED SEPT 2011

VOLUME PER PULSE; **FUNCTION OF ELECTRODE GAPS (all singlepuls exp, varierende ladN, virg & non-virg locations)**



VOLUME EXCAVATOR

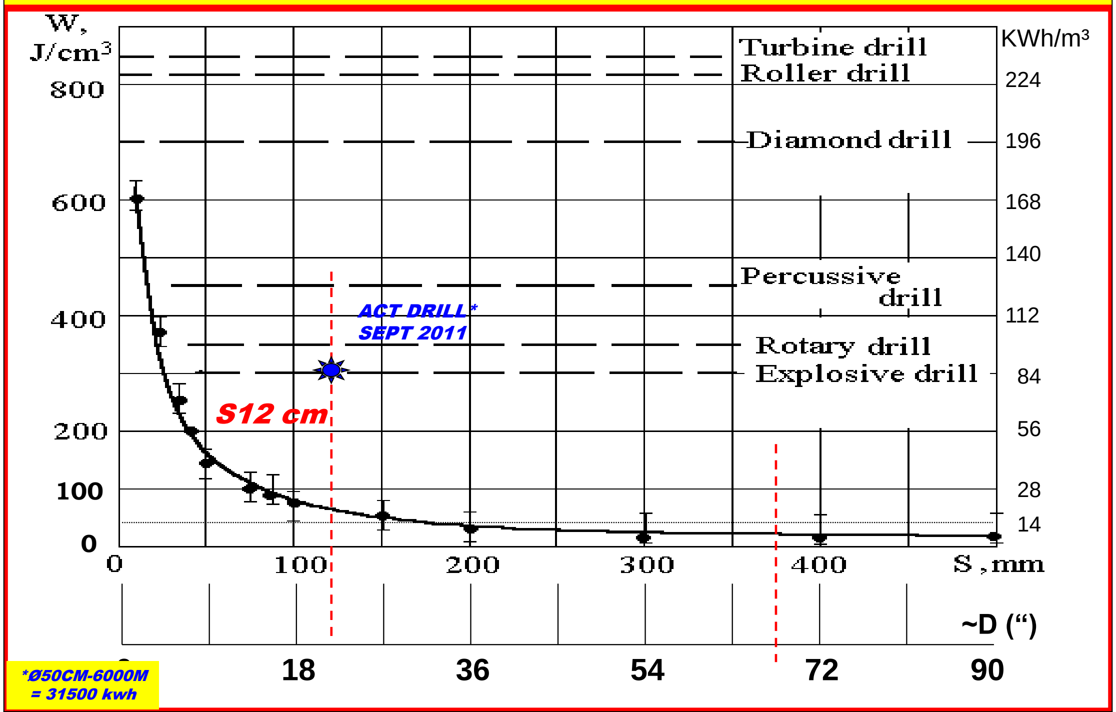
Example relevant for Granite

- ***EXAMPLES***

Distance S ***Electrode Gap cm***	***Excavated*** ***Per Pulse***	***Excavated*** ***Per Hour***	***= Drill Speed*** ***Mtr Per Hour Ø20" Borehole***
➢ ***S = 10***	***20 cm³***	***1,4 m³***	***7***
➢ ***S = 15***	***100 cm³***	***7 m³***	***35***
➢ ***S = 50***	***1000 cm³***	***70 m³***	***na***

State of the Art 20Hz Pulse Repetition Frequency. Distance between electrodes: S. Pulse Energy according to S

EPB Breaking Energy



ENERGY EFFICIENT EXCAVATOR

Examples

➢ EXAMPLES Granite	Excavated Per Pulse	Energy per m³
➢ S = 12 cm:	100 cm³	20 KWH
➢ S = 50 cm:	1000 cm³	5 KWH

Distance between electrodes: S. Pulse Energy according to S

Epb is:
VOLUME EXCAVATOR + ENERGY EFFICIENT
& COST EFFECTIVE

SOME OTHER FAVOURABLE CHARACTERISTICS

Details yes, but important ones

- ***EPB favours LARGE DIAMETER BOREHOLES; faster, more energy efficient and cheaper;***

  more and more so as the diameter increases

- ***An EPB borehole diameter is bigger than the bit which made it;***

  it allows the option open
  to protect the hole as it is being drilled

in Summary:

EPB : An Emerging Technology

and
The Established Fact Base
indicates

*20" HDR GEOTHERMAL WELL**

@ €100 /m *(or less)*

i.e.

geothermal energy

at

€1 per 100 KWh *(or less)*

…general availability…

*Example values; real values may differ.

REALLY; NOT EPB ALONE, BUT

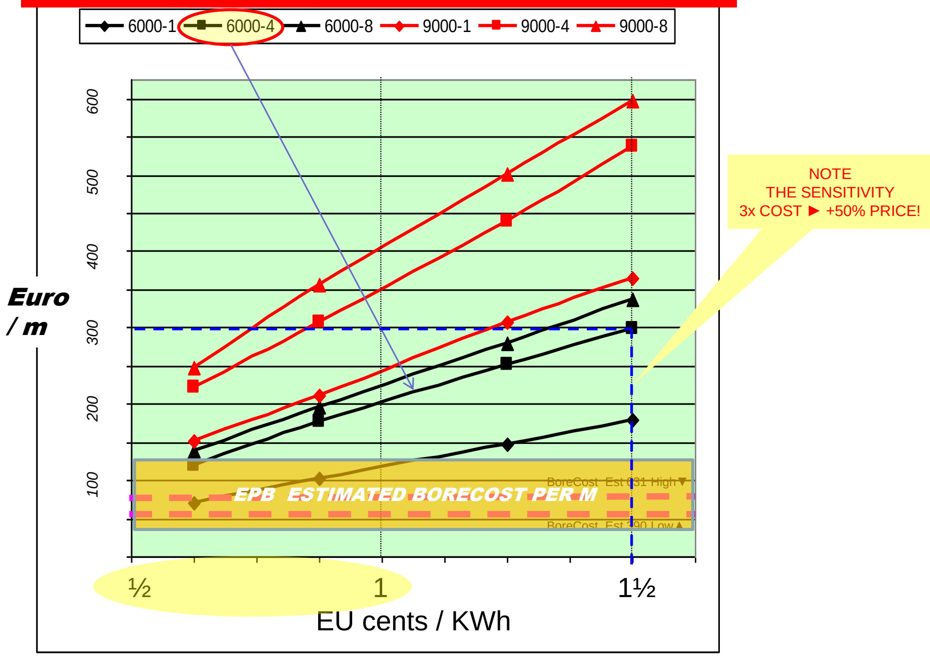
+ EPB

= 20 KWH / m³ BREAKAGE*
= 70% REDUCED HYDRAULIC ENERGY*
= ONE DIAMETER CASING TOP TO BOTTOM *

≈ 100 € / m
20" HDR D6000m

**Example values*

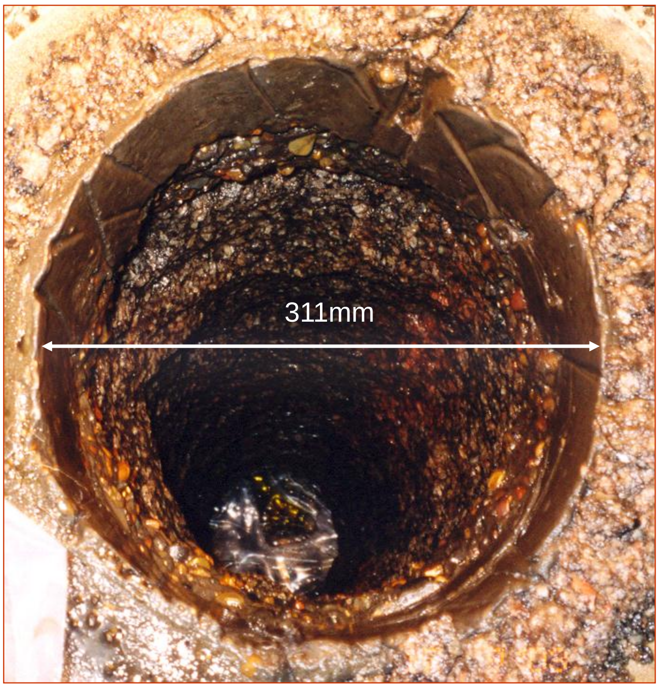
EPB
ENERGY-PRICE (WELLHEAD) VS BORECOST
DEVIATED BRANCH HOLE ENERGY COLLECTOR
Energy unit in one hole



EPB

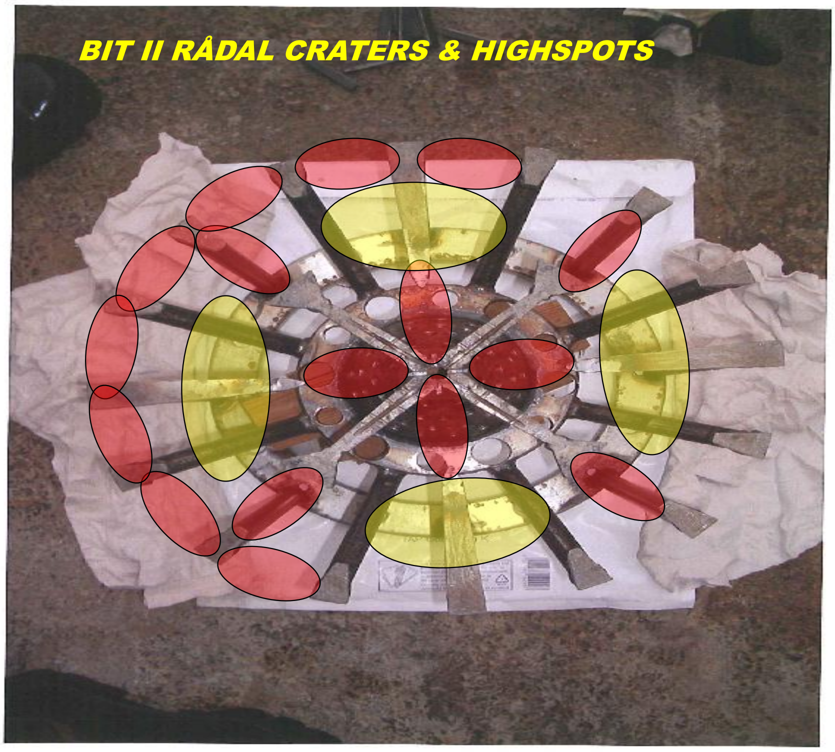
Pictures from 15 years of R&D

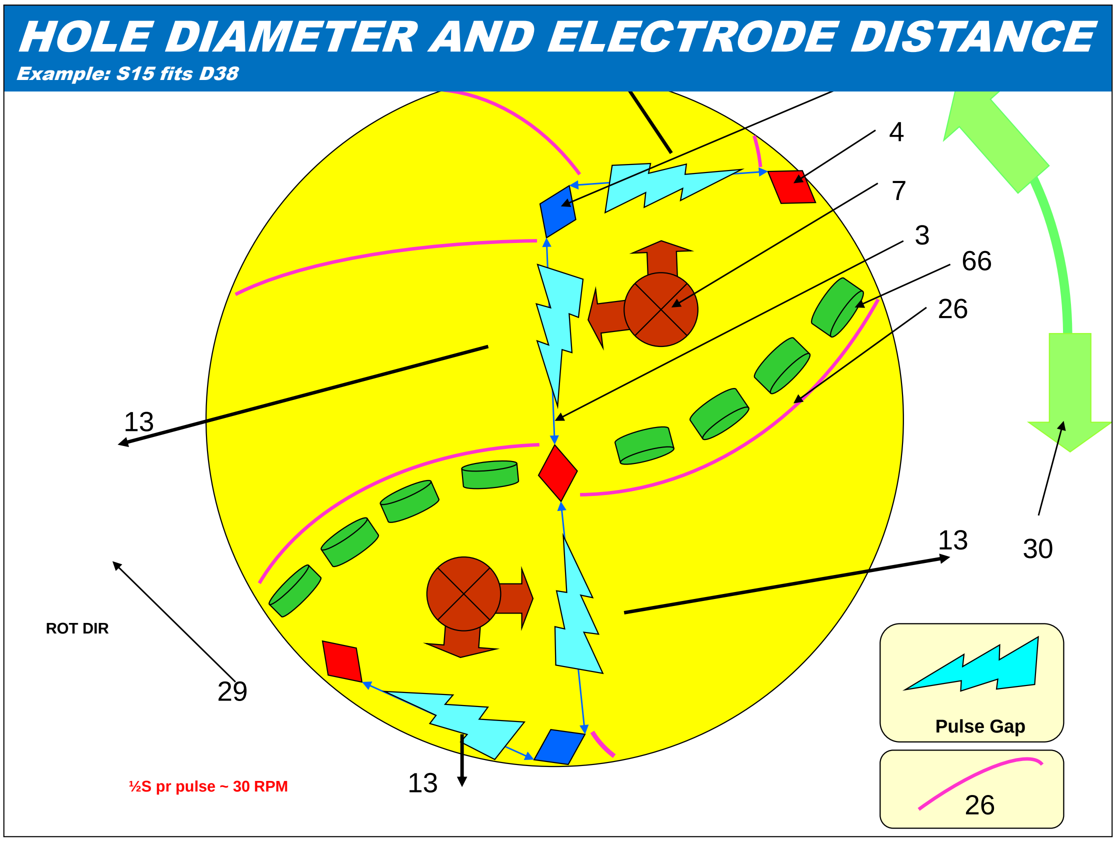
EPB 2003: Drilling Full Scale in Granite



A LATER BIT DESIGN

LATER DESIGN YET INDICATING CRATERS & HIGHSPOTS




HOLE DIAMETER AND ELECTRODE DISTANCE
Example: S15 fits D38
4
7
3
66
26
13
13
30
ROT DIR
29
Pulse Gap
26
½S pr pulse ~ 30 RPM
13

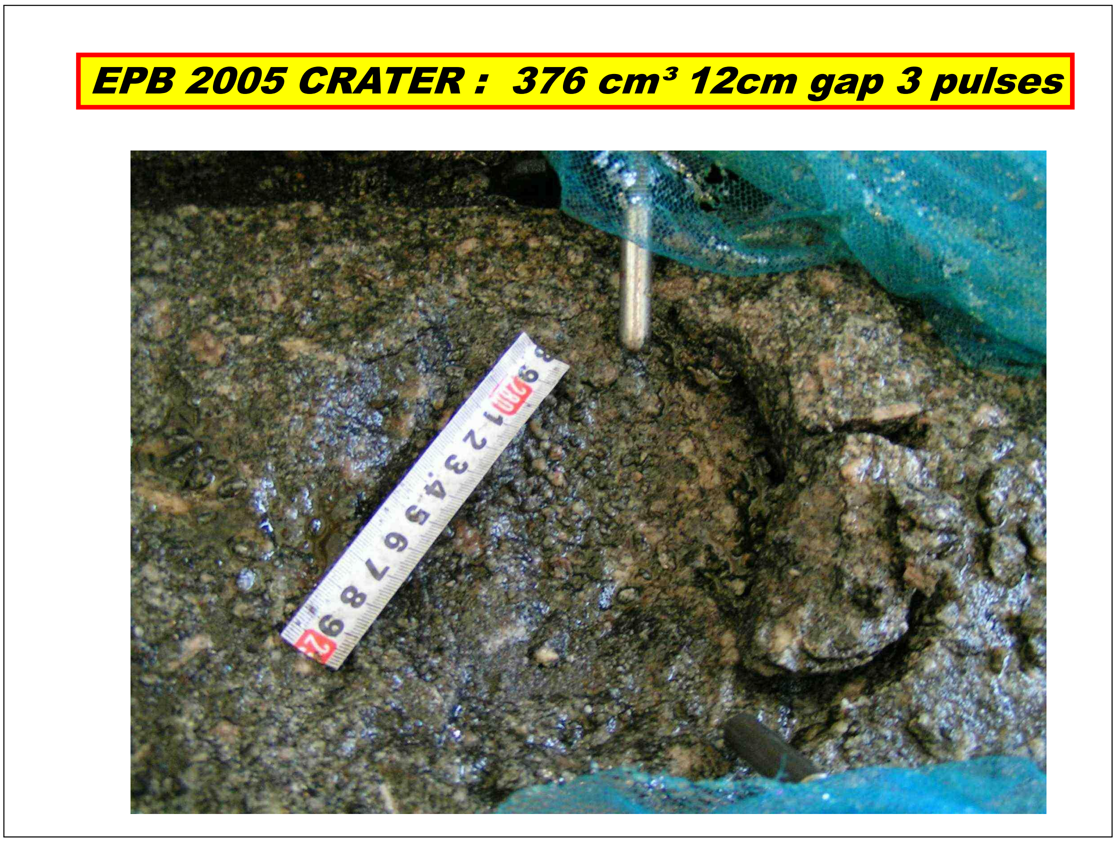
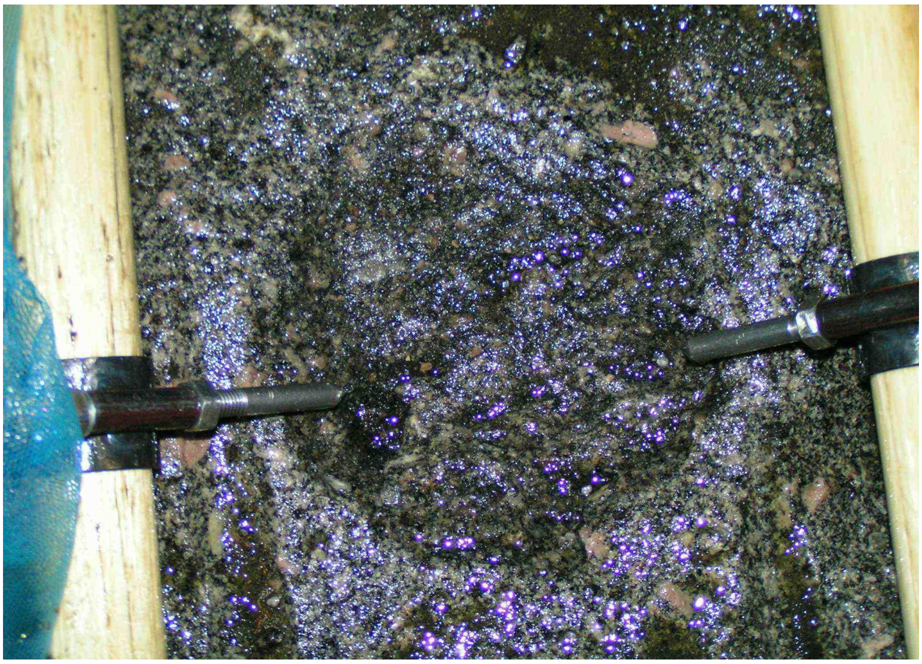
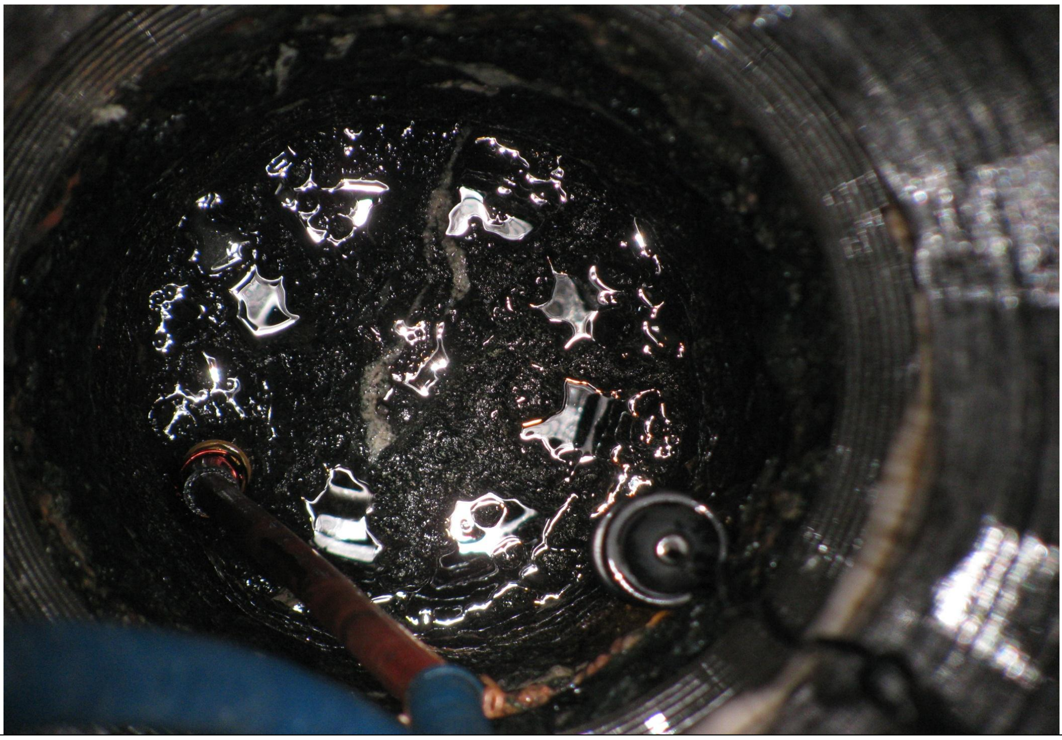

EPB 2005 CRATER : 376 cm³ 12cm gap 3 pulses

Fig Exp feb 2005: Crater at 12cm gap-3 pulses



2009 BOREHOLE FOOTPRINT



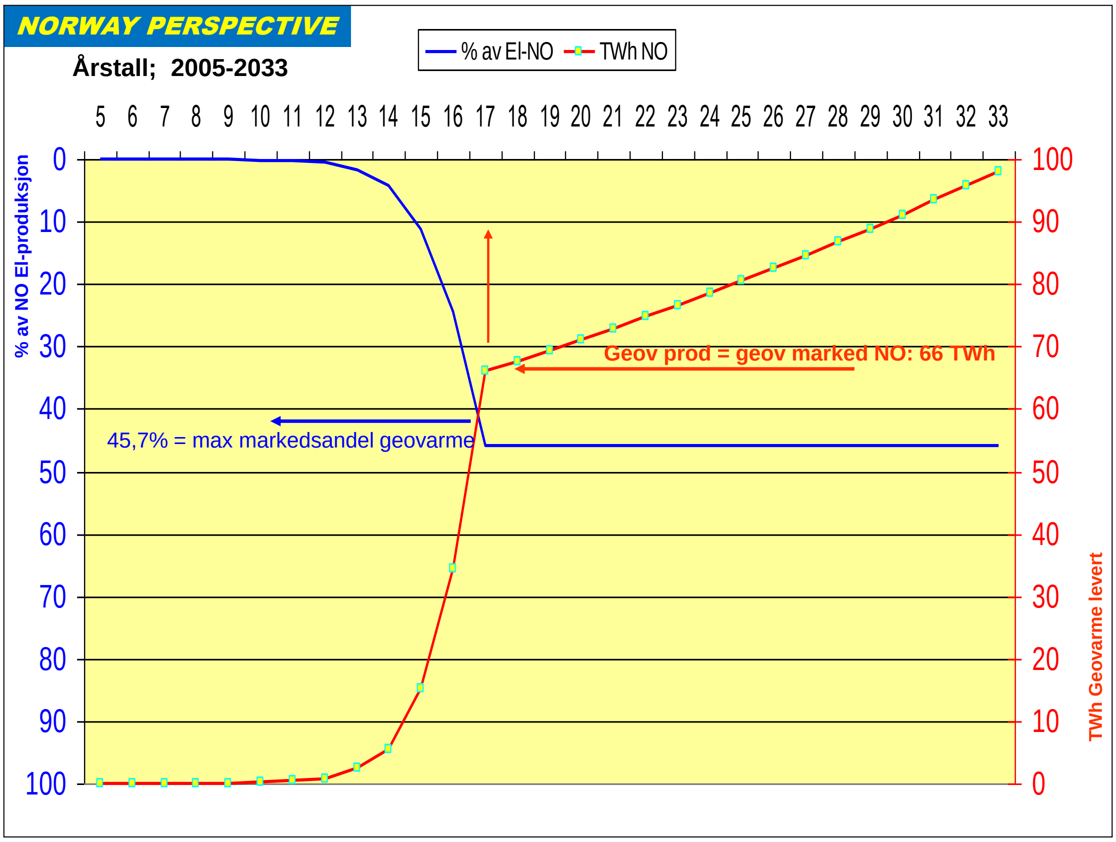
2009 CUTTINGS SELECTION

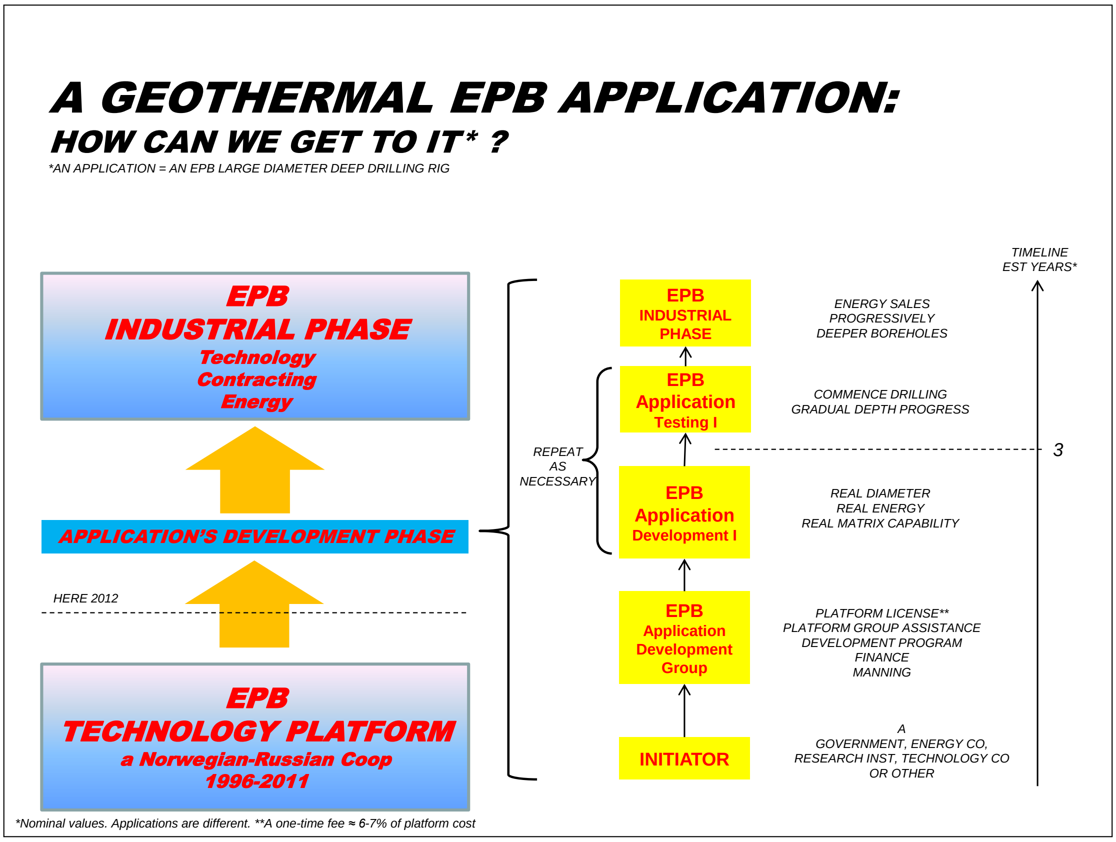
2009 EPB TESTRIGG BERGEN-NORWAY

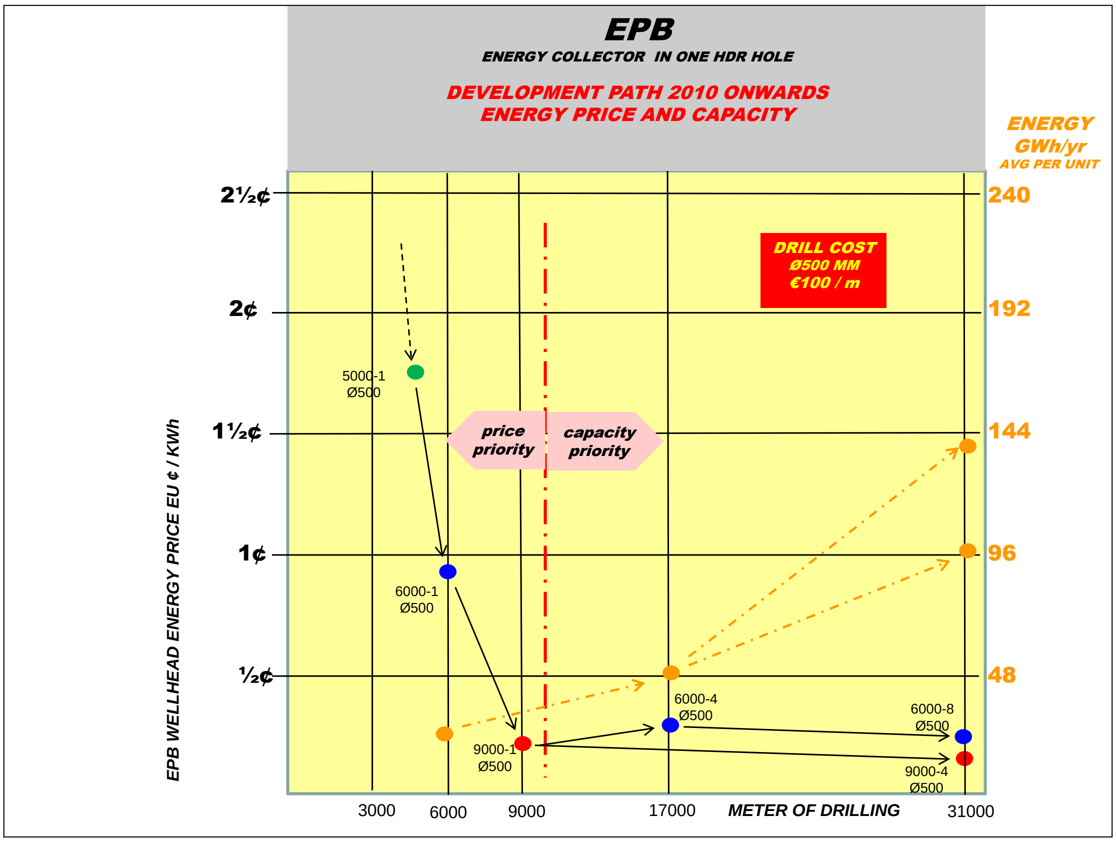
EPB

Electro Pulse Boring

Where do we go from here?




A GEOTHERMAL EPB APPLICATION:
HOW CAN WE GET TO IT* ?
*AN APPLICATION = AN EPB LARGE DIAMETER DEEP DRILLING RIG
TIMELINE
EST YEARS*
EPB
INDUSTRIAL PHASE
Technology
Contracting
Energy
APPLICATION'S DEVELOPMENT PHASE
HERE 2012
EPB
TECHNOLOGY PLATFORM
a Norwegian-Russian Coop
1996-2011
REPEAT
AS
NECESSARY
EPB
INDUSTRIAL
PHASE
ENERGY SALES
PROGRESSIVELY
DEEPER BOREHOLES
EPB
Application
Testing I
COMMENCE DRILLING
GRADUAL DEPTH PROGRESS
3
EPB
Application
Development I
REAL DIAMETER
REAL ENERGY
REAL MATRIX CAPABILITY
EPB
Application
Development
Group
PLATFORM LICENSE**
PLATFORM GROUP ASSISTANCE
DEVELOPMENT PROGRAM
FINANCE
MANNING
INITIATOR
A
GOVERNMENT, ENERGY CO,
RESEARCH INST, TECHNOLOGY CO
OR OTHER
*Nominal values. Applications are different. **A one-time fee ≈ 6-7% of platform cost


EPB
ENERGY COLLECTOR IN ONE HDR HOLE
DEVELOPMENT PATH 2010 ONWARDS
ENERGY PRICE AND CAPACITY
ENERGY
GWh/yr
AVG PER UNIT
DRILL COST
Ø500 MM
€100 / m
EPB WELLHEAD ENERGY PRICE EU ¢ / KWh
2½¢
2¢
1½¢
1¢
½¢
240
192
144
96
48
5000-1
Ø500
6000-1
Ø500
9000-1
Ø500
6000-4
Ø500
6000-8
Ø500
9000-4
Ø500
price
priority
capacity
priority
3000
6000
9000
17000
METER OF DRILLING
31000

Where do we go from here, cont'd:

OR

FULL STOP

THE SITUATION 2012 III

▼

EPB

COUNTER-FORCES HAVE MOBILIZED

1 **OIL COMPANIES PROTECT GAS:** THE SHALE GAS INITIATED PRICE COLLAPS:
They need no cheap geothermal competitor

2 **UTILITY COMPANIES PROTECT ELECTRICITY:** MARKET WORRIES:
They need no 1¢ /Kilowatthour geothermal energy competition

3 **SUBSIDY TAKERS PROTECT SUBSIDIES:** POLITICAL WORRIES:
The politicians must not learn about 1¢ /Kilowatthour drilling technology

4 **TECHNOLOGY COMPANIES PROTECT MARKET POSITIONS:**
PROGRESS GOOD ONLY WHEN INVENTED HERE

THE OLD LESSON IS HERE AGAIN:
PROGRESS DON'T COME EASY

PERSONAL AT THE END:

VOUCH

from a drilling professor

who

guarded his chair with diligence for 35 years:

Inventions in multitude came past my desk.
Never I saw an as promising one as EPB.
True, many a bridge shall have to be crossed
before fly like a 747 it does
but fly it will, it already does
Wilbur & Orville
are thoroughly past

THIS ENDS

the

PRESENTATION

Thank You for the Attention