# High Temperature Instruments for Supercritical Geothermal Reservoir Characterisation & Exploitation

## Publishable summary report

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A publishable summary report of the European STREP Project HITI, carried out in 2007-2010, contract no.: 019913.

*The* ***HiTI*** *project is a 6th Framework European funded project in 2007-2010 that has provided new geophysical and geochemical sensors and methods that can be used to evaluate deep geothermal wells up to supercritical conditions (temperature above 374°C for pure water and pressure beyond 220 bar). Supercritical geothermal wells are presently non-conventional but may provide a very efficient way to produce electricity from a clean, renewable source. The first in a series of research wells aimed at reaching supercritical conditions has been drilled for this purpose into a Icelandic volcanic zone at Krafla, as part of the IDDP ("Iceland Deep Drilling Project") and with joint funding from Icelandic industry and science.*

*Aimed to explore supercritical wells and to enhance production from them, HiTI has developed, built and tested in the field new downhole tools and developed chemical approaches for deep high temperature boreholes. The new set of tools and methods have been chosen to provide a basic set of data needed to describe the supercritical reservoir structure and dynamics including the evolution of the borehole condition during production. The set of new instruments can tolerate high temperature & pressure in a highly corrosive environment. Slick-line memory tools up to 400°C and wireline tools up to 300°C have been developed – the latter temperature constraint is due to the present limitation in wireline cables (320°C).*

*The work was divided into the following work packages:*

***WP#1*** *– Project management.*

***WP#2*** *- Well fluid properties are the key parameters that need to be obtained to evaluate the energy potential of a supercritical geothermal reservoir. This work package addressed the instrumental development needed to acquire temperature, pressure, fluid flow and fluid conductivity, using wireline and slick-line instruments.*

***WP#3*** *– Structure and dynamics of the geothermal reservoir was needed to assess the sustainability of hot to supercritical fluid production from thermodynamic, petrophysical, thermomechanical and economical points of view.*

***WP#4*** *- Higher temperatures and corrosiveness in geothermal wells may lead to production difficulties. Monitoring of all relevant parameters in an operating geothermal system allows actions to preserve production integrity. This work package addressed well casing and cement integrity using acoustic techniques and continuous temperature monitoring on a fibre optic cable (distributed temperature sensing).*

***WP#5*** *- Once instruments had been assembled and research methods developed, they were demonstrated in-situ at the IDDP-1 well site and in other parts of the "Iceland geothermal laboratory". Successful interpretation of data extracted with the new instruments and methods marked the final milestone and landmark of the overall project. ISOR managed the data sampling, using e.g. both available logging trucks with slick lines to operate memory tools and a high-temperature wireline cable to operate surface communicated instruments.*

***WP#6*** *- Most of the technologies used for geophysical and geochemical measurements and fluid sampling into deep wells are available up to 200°C. Some of them can be adapted to temperatures up to 350-400°C, but very few technologies are available at 500°C. The objectives of this work package were 1) to establish a state of art of the accessible and existing technologies at temperatures as large as possible and 2) prospective strategies and new concepts to develop new reliable tools and to perform geophysical and geochemical measurements up to 500°C where no appropriate tools exists. Investigations were focused on electronics, ultra-high temperature resistant materials, use of cooling processes (chemical solids or gases) or new chemical sensors and use of optical fibres.*

***WP#7*** *- Project dissemination activities.*

# 1. MultiSensor, PLT400, 400°C

A memory based production-logging tool (Multi-sensor) (Figures 1 and 2) was designed and built by Calidus Engineering and demonstrated in hot wells in Iceland. The tool is capable of measuring pressure, temperature, flow rate and casing collar location at borehole temperatures up to 400°C.

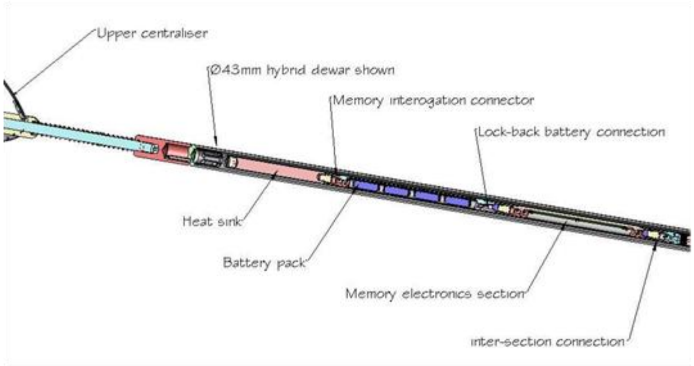


Figure 1: Drawing of a MultiSensor tool section

Figure 2: The HiTI MultiSensor demonstrated in IDDP-1 at Krafla in July 2010.

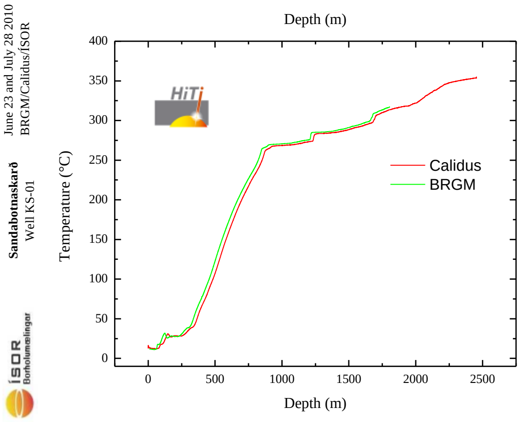


Figure 3: Temperature readings from both high temperature borehole instruments developed in HiTI.

## 2. High temperature wireline T sensor

A wireline sensor (Figure 4) measuring temperatures up to 320°C was developed by Bureau de Recherche Géologiques et Minières (BRGM).

The electrical resistance changes of platinum with temperature are used for recording, using four wireline conductors, two for current feeding and two for voltage readout over the platinum sensor. This analogue tool was designed at BRGM, based on an earlier conception of R. Gable, for operation beyond 300°C and pressures up to 1000 bar. Its Inconel 625 body is highly resistant to corrosion.

Temperature response times were evaluated at different logging speeds. Calibration was performed at Calidus Engineering facilities up to 300°C.

The new temperature sensor was demonstrated by Francois Lebert from BRGM together with ISOR in a high temperature well at Krafla (Iceland).

Figure 4: BRGM temperature tool before going into a high temperature well at Krafla.

## 3. Dual Laterlog (DLL), 300°C

A surface read-out (SRO) resistivity tool based on the Dual Laterolog (DLL) principle for use at temperatures up to 300°C to permit open hole formation evaluation and characterization was developed by Calidus Engineering.

## 4. Televiewer with casing thickness and cement evaluation to 300°C and Gamma ray (GR) detector, 300°C

A high temperature televiewer (Figure 5) with casing inspection analysis and a gamma ray detector was shown to perform at temperatures of 300°C. The tools were developed by Advanced Logic Technology (ALT).

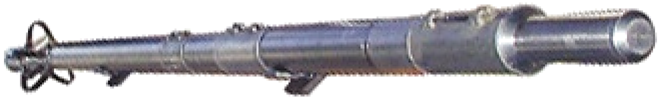


Figure 5: Acoustic televiewer to 300°C

The purpose of the acoustic borehole imaging tool is to provide detailed, oriented caliper and structural information on the basis of high resolution, ultrasonic travel time and amplitude images. The travel time is used to determine exceptionally accurate borehole diameter data, which makes the tool ideal for borehole deformation description (stress field analysis) and casing inspection. The amplitude of the reflection from the borehole wall represents the acoustic (elastic) properties of the surrounding rock therefore, the tool is ideal for fracture detection and geotechnical rock classification.

The high temperature televiewer with casing inspection analysis and a gamma ray detector was demonstrated in three wells in the high temperature areas of Krafla and Bjarnarflag, NE-Iceland. The combined 6.26 m long tool is called ABI85-92, but it has a modular design and the televiewer and gamma units can be operated separately. The three wells were chosen for demonstration were 1) open hole well (K-18) near a known supercritical geothermal area in Krafla, 2) a deviated well (KS-01) reaching beyond 300°C in the bottom liner and 3) a well in Bjarnarflag (B-14) with temperature approaching 300°C in the cased section.

In well KS-01, the gamma instrument, GR85, was able to operate to 300°C with no loss in data quality (Figure 6). Gamma spectrum recorded in the open hole section was positively compared with ISOR’s previous natural gamma radiation measurements. Temperature and pressure was measured independently using a calibrated Kuster K10 high temperature tolerant tool, owned by ISOR.

On December 15th 2009, the high temperature televiewer was successfully demonstrated at 300°C in the Bjarnarflag well completing one of the project’s deliverables (Figure 7).

Both televiewer and gamma tool tests lasted for several hours in the hot environment and only heat generated internally was seen to affect the electronic temperature. The internal temperature rise was approximately 5.5°C per hour at 270°C borehole temperature, meaning that the tool could last around 18 hours in that environment.

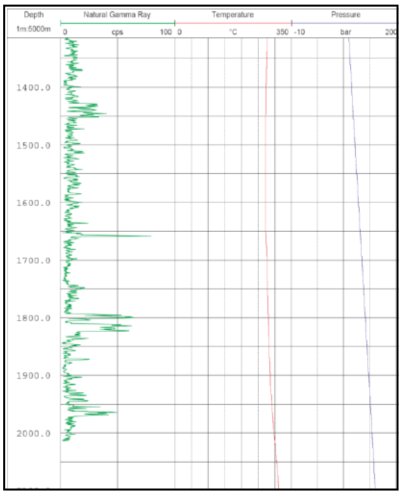


Figure 6: Natural gamma ray measurement performed up to 300°C at 146 bar (deviated well, KS-01 at the Krafla geothermal field)

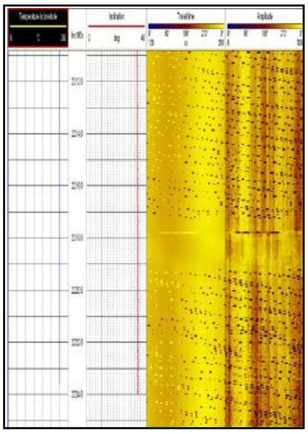


Figure 7: Temperature in the far left column is recording 300°C over the measured section (2211-2224 m). Both travel time and amplitude show 7” liner perforation (casing holes) and a liner joint. Note the near-perfect centralization at tool inclination 34° from vertical, achieved using stiff in-line centralizers.

## 5. Distributed temperature sensing, 300 °C

A novel high temperature fibre optic cable (Figure 8) was developed by GeoForschungs-Zentrum Potsdam (GFZ-Potsdam) and nkt cables GmbH, with the goal of providing accurate temperature profiles with a high temporal and spatial resolution at temperatures approaching 300°C. The cable has successfully been tested up to 280° C under laboratory conditions prior to installation in Iceland.

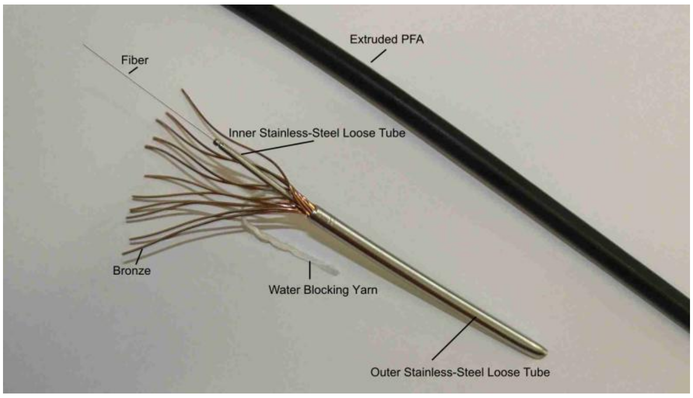


Figure 8: Fibre optic temperature sensor cable developed by GFZ-Potsdam and nkt cables GmbH

For fibre optic distributed temperature sensing (DTS), an optical fibre is used as sensing element. Based on Raman backscattering along the fibre, temperature profiles can be acquired. Since no electronics have to be lowered down-hole, DTS is especially suited for high temperature applications. Developed for monitoring temperatures in hazardous environments, DTS based systems have been increasingly used for wellbore applications in the past two decades.

On May 3rd 2009, the new DTS sensor cable was permanently installed together with a 300 m casing section in well HE-53 in the Hellisheidi geothermal field, southwest Iceland. Measurements were performed during cementing of the casing and during the cement hardening process in order to evaluate different steps of the cementation process.

After the cementation, drilling proceeded and the well was completed to a depth of 2407 m. During the onset of a flow test in July/August 2009 (Figure 9), continuous temperature measurements were performed for two weeks. In the course of this field campaign, temperatures were successfully measured up to 230°C.

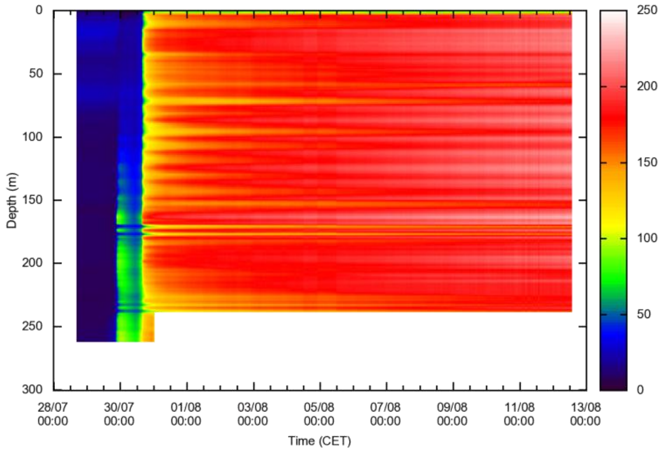
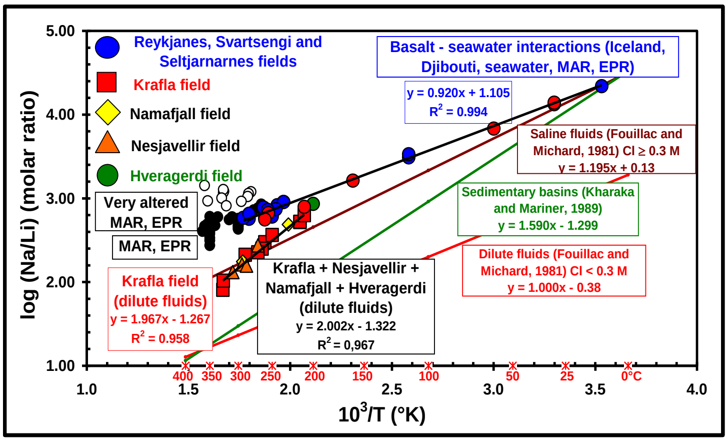


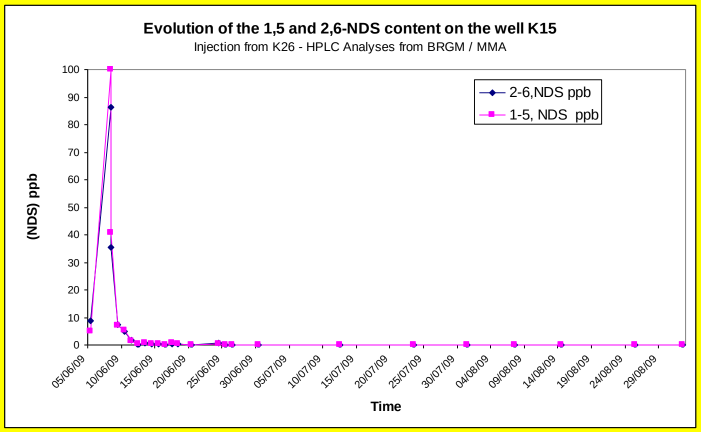
Figure 9: Temperature profiles recorded with depth at different times using the distributed temperature sensing (DTS) technique within the annulus of well HE-53 in Hellisheidi, SW-Iceland. Different colours correspond to different temperatures.

## 6. Li thermometry and organic tracers to 350°C

To estimate the reservoir temperature using the chemical Na/Li geothermometer, fluid samples were collected by BRGM (in collaboration with ISOR) at high-temperature (HT) wellheads in different geothermal fields (Krafla, Namafjall, Nesjavellir, Hveragerdi, Reykjanes and Svartsengi). A new thermometric relationship (up to 325°C) was obtained for the HT dilute geothermal waters. The saline geothermal waters from Reykjanes and Svartsengi follow the Na/Li relationship characteristic of the seawater derived fluids interacting with basalts up to 365°C as in the emerged Asal rift (Djibouti) or in the oceanic ridges and rises. Uncertainty in the temperature estimations is ±25°C.



The existence of several Na/Li thermometric relationships, thermodynamic considerations and the isotopic Li analyses, performed by ICP-MS/MC seem to show that the Na/Li ratios not only depend on the temperature but also on other parameters such as the fluid salinity and origin, the nature of the reservoir rocks in contact with the geothermal fluids, or the control by clay secondary minerals such as illite or Na-, Li- micas.



Organic compounds such as 1,5-, 1-6 and 2,6-nds (naphthalene disulfonate family) were used by BRGM in the Krafla geothermal field to carry out tracer tests (in collaboration with ISOR and Landsvirkjun) in high temperature geothermal wells including the IDDP-1 well (i.e. up to 350°C). The tracing tests displayed exceptionally high apparent linear velocities for the tracers, low recovery rates, major groundwater flow directions and a few likely modifications of the tracer molecules due to the high temperatures of the geothermal fluid. Those results are consistent with the very high temperature of some parts of the Krafla field, the high reservoir capacity (storativity) and the intensely fractured Krafla geothermal area.

# 7. High pressure, high temperature cell

Géosciences Montpellier (GM/CNRS) has developed a cell to measure the electric conductivity of basalts under supercritical conditions.

In order to evaluate the reservoir properties, the physical properties of basaltic rocks have to be studied under geothermal conditions, i.e, high temperature (200-600°C), high confining pressure (50-200 MPa), pore pressure (0-100 MPa), and more specifically under supercritical conditions. In particular, laboratory measurements of electrical conductivity or resistivity of basaltic rocks as a function of temperature, pressure, fluid nature (phase, chemistry) are essential to interpret the downhole electrical resistivity measurements and large scale magnetotelluric data. These measurements can give important informations regarding reservoir properties, such as porosity, pore space geometry topology, rock mass alteration, fracturation as a function of pressure and temperature.

A measurement cell was designed so that electrical conductivity could be measured in the case where the sample is surrounded by a metallic jacket, as required by the expected temperatures, higher than 200°C (Violay et al, 2009). A 4-electrodes method was developed for this purpose (Figure 10), based on the guard ring electrode method. The measurement cell has been inserted in a commercial gas pressure vessel (Paterson press-Géosciences Montpellier) that routinely generates high temperatures (>600°C) and high pressure (>200 MPa) conditions (Figure 11).

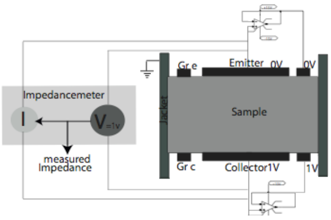


Figure 10: Experimental cell designed to measure the electrical conductivity at high pressure, high temperature and pore fluid pressure.

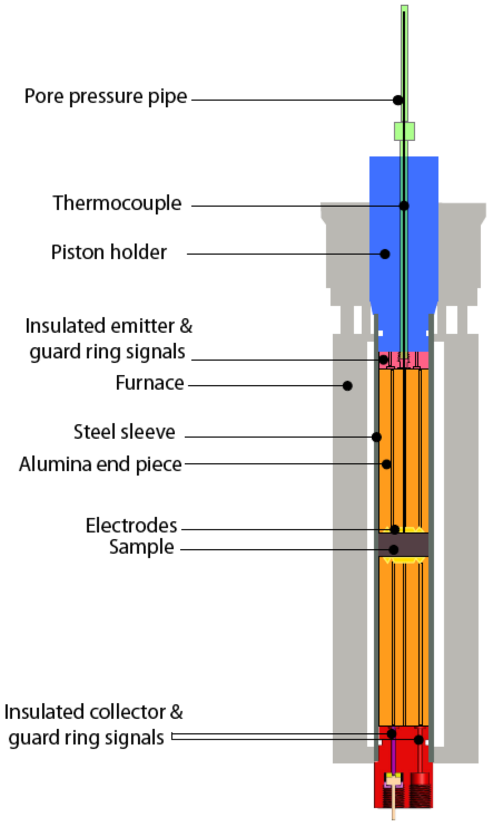


Figure 11: The experimental set-up adapted in the Paterson gas pressure vessel.

The method was tested on porous and highly permeable sandstones, under saturated conditions (Figure 12) and at a pore pressure of 220 bar. The first measurements on basalts up to 350°C have also been performed (Figure 12). They show an increase of electrical conductivity temperature up to about 300°C and then a stabilization of electrical conductivity. To better understand geophysical data, additional measurements are required to characterize the conductivity of different types of basalts. The effect of temperature, pressure, salinity, alteration degree can be now tested in this new cell.

Figure 12: Electrical conductivity of three sandstones of different lengths and two different basalts up to 350 °C. The pore pressure is 220 bar and the water conductivity was 1.5 mS/cm and 0.59 mS/cm for basalts and sandstones, respectively.

## 8. Prospective strategies

The review of existing sensors and instruments (e.g. temperature, electrical conductivity, pH sensing and downhole fluid sampling), rated to perform borehole measurements under high temperature - high pressure conditions, frequently highlights a limitation near 250°C / 250 bar with survival possible up to 400°C. One of the major concerns comes from the electronics that frequently needs to be associated with the sensors, but Silica-On-Insulator or Silicon Carbide printed circuits appears to be promising to withstand harsh conditions. By coupling the most promising technologies, such as fibre optic sensing, HT rated electronics, with passive and active thermal shielding (i.e. coupling the capacitive properties of insulators with Stirling and/or Peltier energy dissipaters), in-situ real time monitoring of water physico-chemical parameters under HT/HP conditions should be realistic within some years, thanks to research efforts that are currently underway or that will be done in forthcoming years.

Oxford Applied Technology Ltd (Oxatec) participated in the HiTI project prospective strategies with specialisation on managing innovation and exploitation of advanced materials and microsystems for harsh environments, in particular high temperatures. Oxatec are involved in several European and UK programmes which focus on increased reliability of materials at higher temperatures, including electronic packaging and interconnects and lead-free solders for aerospace applications. These projects focus on developing microstructural evolution and physics of failure models to allow improved reliability to be designed into high temperature electronic systems.

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