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Borehole Instruments for Supercritical Geothermal Reservoirs

Nigel Halladay[1], Jean-Luc Deltombe[2], Jean-Marc Naisse[2], Colin Johnston[3], Francois Lebert[4] and Ragnar Asmundsson[5]

[1]Calidus Engineering Ltd., Unit 7A, Tregoniggie Industrial Estate, Falmouth, Cornwall, TR11 4SN, United Kingdom. [2]Advanced Logic Technology, Batiment A, route de Niederpallen, L-8506 redange sur attert, Luxembourg, [3]Oxford Applied Technology, Oxford University Begbroke Science Park, Sandy Lane, Yarnton, Oxford OX5 1PF, United Kingdom. [4] BRGM - 3, Av. Claude Guillemin - BP6009 - 45060 ORLEANS Cedex 2, France, [5] ISOR - Rangárvöllum - P.O. Box 30, 602 Akureyri, Iceland

[1]nigel@calidusengineering.com, [2]jean-luc.deltombe@alt.lu, [3]colin.johnston@materials.ox.ac.uk, [4]f.lebert@brgm.fr, [5]ragnar.asmundsson@isor.is (corresponding author)

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ABSTRACT

Exploration and exploitation of supercritical geothermal reservoirs requires the use of borehole instruments that can tolerate the reservoir’s high temperature and high pressure environment (above 374 °C and 22 MPa for pure water). In addition, such downhole instruments need to be robust, chemically resistant and present a high level of accuracy. These requirements exceed even that of the aerospace and automotive industries. Mechanical instruments and observation of material processes, such as melting, corrosion and deformation have been used with success in the high temperature geothermal environment, but these methods can only be applied to a limited amount of physical parameters and lack the accuracy needed for proper analysis of the geothermal reservoirs. High temperature tolerant electronic and sensor devices have been developed, along with high temperature batteries, which can be used in the design and assembly of borehole instruments. A description of the requirements and assembly procedures that had to be followed and implemented in new borehole instruments (wireline and slick-line) in the European project HiTI (High Temperature Instruments for supercritical geothermal reservoir characterization and exploitation) is given in this paper and examples of actual measurements using some of these new devices is given. Finally, a description of further implementations, involving both mechanical and electronic aspects, is presented.

1. INTRODUCTION

In high temperature geothermal research and development, out of any research instrumentation, borehole (downhole) instruments need the greatest attention given to robustness and tolerance. Not surprisingly, it has been difficult to manufacture advanced instrumentation functioning at high temperature, in particular at supercritical geothermal conditions, both because of the high cost involved and small market. For this reason simple mechanical tools and materials have been used to record the primary parameters required. Advanced instruments however need to be electronic, for recording physical parameters, communication and on-board processing. Conventional or military grade electronics can be used in heat shielded downhole vessels (dewars) but for longer duration, these electronics need to be of special high temperature design.

When new geothermal wells are drilled, they are researched (logged) using downhole instruments, such as temperature, pressure, fluid flow, resistivity, natural gamma radiation and neutron sensors. The temperature and pressure gauges need to function at the natural temperatures of the wells at any depth, while the other sensor types can often give sufficient information while the well is maintained in a cooled state, as required due to the tolerance limit of much of the downhole drilling equipment. At great well depths and in particular at supercritical geothermal conditions, cooling water pumped down from surface can sometimes fail to maintain fluid temperatures below the tolerance limit of many of the borehole instruments. This is a serious drawback for future geothermal research and development and needs to be addressed. Design solutions are already available but assembly and manufacturing come at a high cost and not manageable by the currently small geothermal energy sector.

2. PROBLEM DEFINITON

In high temperature geothermal areas, well temperature can exceed 300 °C at a well depth below 2000 m and in extreme conditions well temperatures could be close to the crystallization temperature of magma (above 700 °C for basalt at a few km depth). The pressure is normally close to hydrostatic (hot water column with some flow) but is also ruled by reservoir pressure reaching into the well through fractures and finally, in the supercritical zone, pressure is not related to temperature. Chemical corrosion needs to be considered with the geothermal water commonly being mixed with e.g. H_2S, CO_2 and chlorides. Overall, the temperature tolerance of instruments that need to enter the natural *in-situ* state of very high temperature geothermal wells has to be beyond 400 °C, preferably reaching 700 °C for a required duration (normally a few hours) and pressure tolerance above 60 MPa. In cooled wells, instruments need to be able to operate at 300 °C, at the same 60 MPa pressure.

Borehole instruments either need to record internally the physical parameters they measure (memory tools) and/or have the ability to transmit the measurement to surface (wireline tools). The memory tools are normally lowered into the borehole on a simple wire, called slick-line, allowing no electric connection to surface and therefore need to operate on their own power and control circuitry. In contrast, wireline tools receive power through a wireline cable that is also used to transmit the measurement to surface readout acquisition systems, managed through computer software. Hybrid tool versions are also possible, allowing a single design to be taken to high temperatures on a slick-line if well temperature exceeds the tolerance limit of the wireline. Also, hybrid tools can be considered to provide backup data storage, if surface communication fails.

Currently, it is considered that the limit of wireline tool operation is around 300 °C; at higher temperatures connectors, sealing, soldering, thermal expansion mismatch, plastic material, circuit boards, batteries and electronics will in combination become ever more problematic. If the internal devices (temperature sensitive components) can be sealed off properly, it is reasonable to build instruments operable to between 500 °C and 600 °C and lasting at those temperatures for a short time.

Heat shielding is most commonly achieved using dewars, which are housings built over the heat sensitive tool sections. No active cooling devices are normally used. The heat isolation volume can be evacuated, but non-convective air is a good thermal insulator. Figure 1 shows a theoretical curve of the temperature evaluation of an internal section, protected with a heat shield, assuming that the environment is the only source of heat. An advanced heat shield, possibly in more than one layer, can protect the internal sections from external temperature for a number of days and in those cases, the greater concern is the heat produced internally, since the internal heat cannot escape to the outside. The internal heat is produced by active components, including mechanical and electronic devices (circuitry). This heat can be considered to increase in a linear fashion, while the instrument is operating. This latter time limit can be increased by using low-power components and select only the required integrated circuitry for each application so as not to waste energy on unused functions.

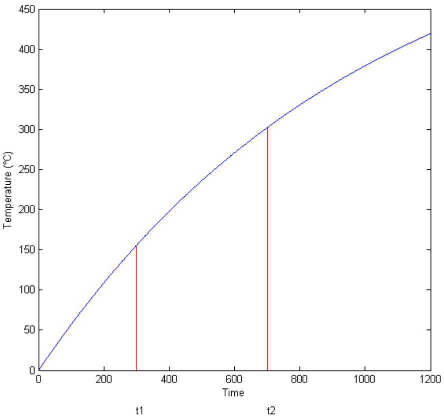

Figure 1: A heat shielded instrument is placed in a 600°C environment. Over time, the internal section heats up from 0 degrees to the environment temperature. If the internals survive at 300 °C, the operational time is longer (t2>t1). Double temperature tolerance more than doubles the time duration.

2. HiTI INSTRUMENTS

In the HiTI project, a number of downhole instruments have been built, and new experience has been gained in many of the areas mentioned above. An overview of HiTI activities is presented by Massiot et al. (2010). One of the project's goals is to provide the required downhole instruments that can tolerate the high temperature environment expected to be encountered in a geothermal research project called Iceland Deep Drilling Project (IDDP), where exploitation of supercritical geothermal fluid is being attempted for the first time (Fridleifsson, G.O., (2003) and Friðleifsson, G.Ó. et al. (2010)).

A summary of the downhole instruments that have been built in the project follows:

2.1 Wireline temperature sensor to 300 °C

Commercial wireline cables are rated to 300 °C but not many instruments survive at that temperature, with standard oil & gas industry temperature gauges not lasting beyond 200 °C. In previous work, current HiTI partner BRGM met some success with a wireline logging tool which was designed for a temperature range of 0 to about 200 °C (Gable et al. (1989) and Guerin, G. et al. (1995)). The sensor was a stable thermistor quadripole: two wires for current feeding and two wires for voltage measurement. In the HiTI project, BRGM is designing a tool based on the same concept: No electronics are located inside, since no current electronic assembly can survive for an extended period (undefined) in these severe conditions.

The tool has a simple design (current design is shown in Figure 2). The sensor element consists of three platinum masses electrically connected in parallel (not a non-metallic thermistor as in the early design) situated at the bottom of the tool, which consists of a corrosive-resistant steel alloy tube (Inconel 625) containing four wires that connect to a high temperature cablehead made by Calidus Engineering and used together with other HiTI instruments.

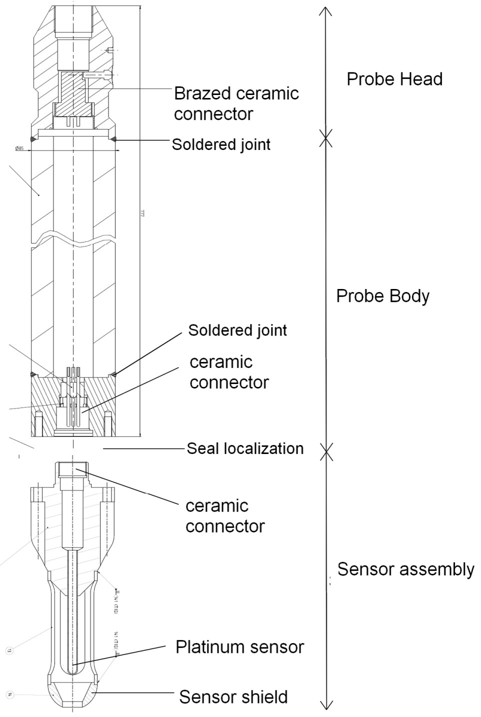

Figure 2: Design of the BRGM wireline temperature sensor.

Temperature measurements are performed at surface with signal passing through a Rochester high temperature wireline cable (4-conductor) purchased in the HiTI project.

Measurement method

The platinum sensor links temperature changes to electric resistivity changes. The resistance of the sensor is measured using four wires. Two wires are used for current feeding and measurement, while the other two wires are used for voltage measurement (see Figure 3). Voltage and current measurements are obtained using an automated multimeter, deriving the platinum resistance that are linked with temperature using known calibration data.

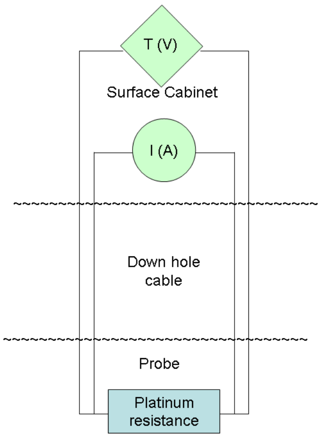

Figure 3: Schematics of the measurement method

Expected performance

By using the expected wireline cable transmission characteristics, the temperature precision has been simulated over the functional temperature range, giving a temperature reading accuracy within 0.11 °C.

2.2 Multisensor to 400 °C

The Multisensor is a production logging tool in the traditional sense in that it measures flow rate, temperature, pressure and casing collar location (CCL). In addition it will measure fluid conductivity. Those versed in the technology will recognise these measurements and perhaps see little innovation, however once the operational temperature is considered then the challenges arise. The standard technique is to package the electronics into a heat shield and otherwise produce a conventional tool assembly but the 400 ˚C temperature eliminates standard sealing methods (O-rings), wire and connectors. The architecture of the tool has to be such that essential features and components are thermally protected or otherwise fully rated for the temperature. A very high performance heat shield assembly capable of delivering an operational life of some 4 hours at 400 ˚C requires sufficient heat sinks, effective end stop assemblies and thermal insulation. Metal seals are used in a modified form to overcome their unreliability and the general sealing arrangement designed such that the environmental cleanliness required is more easily met in field conditions.

The Multisensor uses a standard quartz gauge pressure sensor that is located deep within the tool structure, the pressure being fed to the sensor by a small capillary tube that prevents both thermal transfer to the gauge and enables a buffer solution to be used protecting the gauge from corrosion. The temperature sensor has to work at full environmental temperature and pressure with fully welded connections. The most challenging sensor has been the fluid conductivity which with its insulated electrodes has required a very careful choice of materials and construction including pressure balancing to minimise the stress on the seals. The flowmeter (spinner) is a titanium impeller with magnet and reed switch sensing giving speed and direction. Exposed wiring has to be of a glass or ceramic insulated form and connections achieved by micro-welding using ceramic based epoxy materials to insulate joints.

In order to promote safe operation the use of standard lithium batteries is avoided as these can explode when overheated. Custom developed, very low power electronics enable the tool system to be operated from batteries that have reduced chemical energy and less risk of explosion. The multi sensor is designed to operate in memory mode for very high temperature operation and where available, in surface read out mode on a wireline at lower temperatures. The Multisensor is 57 mm (2.25") in diameter and approximately 6 m in length.

2.3 Dual laterolog resistivity to 300 °C

The Dual laterolog is of a conventional geometry but fully re-engineered to work at 300 ˚C. This has, through experimentation been determined to require a pressure balanced electrode array assembly with welded wiring. As with many logging tools the laterolog design is a proprietary matter and little real design data published. Therefore, much of the tool system has been a reinvention of the wheel. The electronics are packaged into a heat shield that in turn forms one of the electrodes to keep excess length to a minimum. The tool is 73 mm (2.875") in diameter and approximately 10 m in length.

The laterolog will have fluid temperature and conductivity sensors included in the measurements.

2.4 Televiewer to 300 °C, ABI92

The ABI92 (Acoustic Borehole Imager) is an acoustical scanner rated to 300°C and 140 MPa based on the technology of the slim hole televiewer ABI40. These tools generate an image of the borehole wall by transmitting rotating ultrasound pulses and recording the amplitude and travel time of the signal reflected at the interface between the fluid and formation (borehole wall). The purpose of the tools is to provide detailed, oriented caliper and structural information, complemented by the borehole fluid temperature. The travel time is used to determine borehole diameter data, which makes the tool tailored for borehole deformation description (stress field analysis) and also casing inspection. The amplitude of the reflection from the borehole wall is representative of the acoustic (elastic) properties of the surrounding material.

The different segments of the ABI92 are connected with joints allowing field assembly. This architecture also permits the swapping of the sensor segment or to connect other modules: natural gamma spectrometer for instance, in-line centralizers or even future modules. In-line centralizers can be inserted in the string of the module or segment. Nevertheless, slip-over centralizers are also usable to shorten the tool if necessary. Good centralization is an important aspect to acquire good data.

The cartridge segment includes the electronics, which have been heat shielded in a dewar. Inside, a heat sink stores the heat coming from the environment and from the enclosed electronic components. This system allows more than 15h of operation at 275 °C and survival to 300 °C. The electronic architecture uses a 14 Bit A/D converter directly coupled to a FAST 75 Mops digital signal processor (DSP). The DSP is performing data processing operations in real time on each individual ultrasonic wave train enabling high dynamic range of signal detection and easy field operation in a wide variety of logging situations. Magnetometers and accelerometers provide the information necessary for the orientation of the images. The internal temperature is monitored with two temperature sensors.

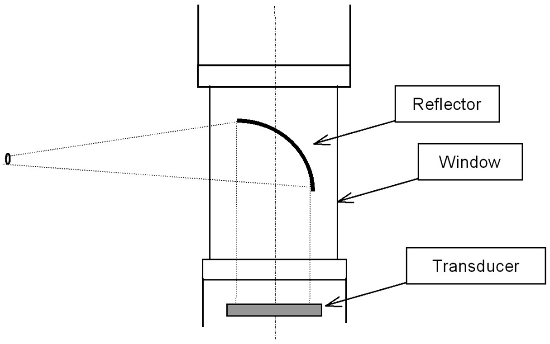

Figure 4: Principle of the acoustic sensor.

Due to its function, the sensor segment cannot be heat shielded. It has been adapted to withstand the harsh environmental conditions. The acoustic wave, generated by the fixed transducer, propagates along the axis of the tool body and then reflected perpendicular to this axis by a special reflector that focuses the beam to a high energy point (see Figure 4). The radial distance of the focal point from the axis of the tool is given by the shape of the reflector. The frequency of the transmitted wave is determined by diverse factors such as ceramic composition, the diameter and the thickness of the piezo transducer. This televiewer operates around 1.2 MHz. The reflector is mounted on a rotating support, which enables the firing of ultrasonic waves around 360°. Sampling rates of 72, 144 and 288 measured points per revolution are available, thus at maximum resolution a near continuous image of the borehole wall is made. The higher sampling rate can be used for a better resolution in larger diameter boreholes but is less useful in small diameters due to the overlap of the sampling points. Moreover, this segment is equipped with two temperature sensors, which record the sensor's internal temperature and the environmental fluid temperature.

The acoustical system is protected from the borehole fluid in an oil filled envelope with an acoustical window made of plastic compound. The envelope is pressure balanced by the help of a piston. This prevents the window from being crushed at high pressure.

The external diameter of the cartridge is 92 mm. The tool with the cartridge and sensor segments weighs 115 kg and is 3.8 m long. With two in-line centralizers, it weighs 163 kg and is 5.5 m long (see drawing on Figure 5).

An extensive testing of the sensor segment in an autoclave has permitted the verification of the performance up to the full range of temperature and pressure. These autoclave tests showed good results up to 300 °C. As part of the HiTI project, the tool was field tested successfully at the beginning of 2009 in Krafla, Iceland, up to 285 °C.

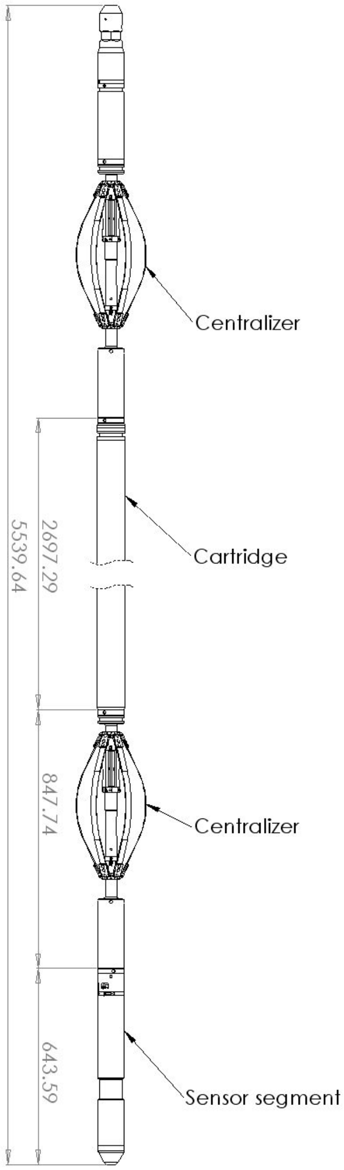

Figure 5: Televiewer ABI92 with in-line centralizer

2.5 Natural gamma spectrometer to 300 °C, GR85

Unlike the televiewer (ABI92), the sensor of the natural gamma spectrometer doesn't have to be directly exposed to the environment. Therefore, the architecture is simpler. Everything is contained in the cartridge, which used the same dewar and heat sink system as the televiewer cartridge. This module can be used alone or stacked on the ABI92. Its survival time at high temp is same as the televiewer.

The gamma detector is a NaI (Tl) scintillation crystal with a ruggedized photomultiplier tube (PMT). The internal temperature is monitored with one temperature sensor.

The diameter of the GR85 module is 85 mm. It weighs 80 kg and is 2.4 m long.

This module was successfully field tested up to 300 °C in the beginning of 2009 in Krafla, Iceland. It has also been field tested stacked on the televiewer ABI92 up to 285 °C.

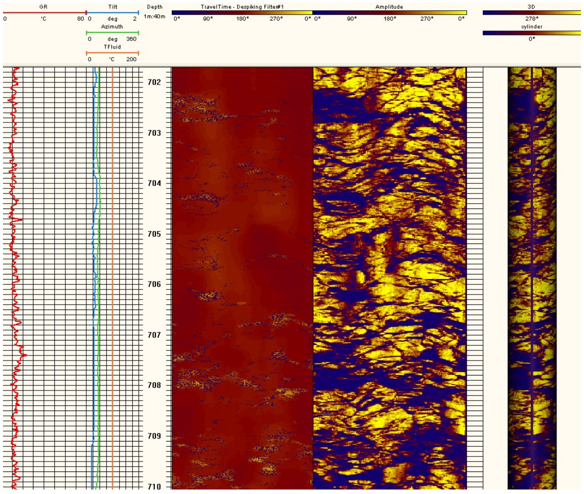

Figure 6: Example of gamma total count and acoustic scanning acquired with the GR85 and the ABI92 in Krafla, Iceland.

FUTURE ELECTRONIC DESIGN CONCEPTS

Most commercial work in high temperature electronics relevant to well logging applications has concentrated on the oil & gas sector. However, with most downhole tools currently rated to only 175 °C there is a gap in capability for logging applications in deeper and hotter environments including geothermal wells. Most current developments are limiting their upper operating temperature to 225 to 250 °C as typified by Honeywell's DeepTrek programme or Cissoid's collaboration with the Universite catholique Louvain where active device fabrication is based on Silicon-On-Insulator (SOI) technology. It is also difficult to see how SOI can be stretched to operate at temperatures much above 300 °C. A few organisations, including NASA and Cree, amongst other European organisations are working with wide band gap semiconductors such as SiC, GaN and diamond with potential operating temperatures in excess of 500 °C. These technologies are less well developed than SOI and will undoubtedly serve only limited markets. However, developments in other application areas has accelerated their potential availability for use in conventional electronics at these high temperatures, e.g. SiC technology has been accelerated due to its use as a substrate for light emitting diode manufacture. Current programmes are underway to develop a full SiC device capability in a number of commercial organisations. It is expected that SiC device technology for 500 °C operation will be at Technology Readiness Level of 5-6 by 2012 which could see its deployment in supercritical geothermal wells.

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