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Development of a Novel Logging Tool for 450°C Geothermal Wells

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Abstract

Exploitation of super-critical water from deep geothermal resources can potentially give a 5-10 fold increase in the power output per well. Such an improvement represents a significant reduction in investment costs for deep geothermal energy projects, thus improving their competitiveness. The ongoing European Horizon2020 DESCRAMBLE (Drilling in dEep, Super-CRitical AMBients of continental Europe) project will demonstrate the drilling of a deep geothermal well with super-critical conditions (>374°C, >220 bar) by extending an existing well to a depth of around 3.5km. The drilling operation is depending on verification of the bottom hole pressure and temperature where state-of-the-art electronic logging tools cannot operate reliably. SINTEF has developed a novel pressure and temperature logging tool for this extreme environment. The target specification for the tool is 8 hours logging of temperature and pressure at 450°C and 450 bar.

In this work, we describe the tool requirements and discuss the design choices made with emphasis on the electronics platform and limitations imposed by the available battery technology, as well as the casing and heat shielding. Test results of the tool are presented, including test data from a field-test in a 250°C geothermal well in Larderello, Italy.

Keywords: High Temperature Electronics; High Temperature Batteries; Logging Tool; Geothermal; Supercritical; Harsh Environment Instrumentation.

Introduction

The ongoing project DESCRAMBLE will deepen the existing Venelle 2 well in Larderello, Italy, from its present depth of 2.2 km down to around 3.5 km. The reservoir is expected to contain water at super-critical conditions (>374°C, >220 bar) with a maximum temperature of 450°C. The estimated maximum pressure is more uncertain but a maximum pressure of 450 bar has been specified. Temperature and pressure profiles of the well are important parameters for evaluating the formation properties, inspection of the well completion and for optimizing production. Reliable logging of such extreme temperatures is currently not possible using commercially available P&T logging tools. One example is the electronic K10 tool from Kuster [8] which is rated for a maximum of 350°C for 4 hours of operation. This is basically sufficient for the tripping time only. Estimating the well transient response after drilling fluid cooling requires additional time.

Looking beyond what is commercially available, several research projects have addressed the need for instrumentation for high temperature geothermal wells. In the "High Temperature Instruments for supercritical geothermal reservoir characterisation & exploitation" (HITI) project they developed instruments capable of logging reservoirs up to pure-water super-critical conditions (T<374°C), [3], [1]. The U.S. department of Energy has supported several projects that aim at developing a 300°C capable directional drilling system. [2] describes progress in the development of a 300°C directional drilling system for Enhanced Geothermal Systems (EGS). The system requires a Measurement While Drilling (MWD) tool rated to the same temperature. This tool will require electronics rated to 300°C (i.e. telemetry and power source) possibly in combination with actively cooled electronics rated to 200°C (e.g. inertial sensors). [9] demonstrates the feasibility of manufacturing a 300°C capable directional drilling module based on electronics rated to 300°C. The module uses custom silicon-on-insulator (SOI) integrated circuits, high temperature co-fired ceramic substrate, high temperature die attach and interconnects. The ZWERG project [6], [7] aims to accelerate development of new instruments for geothermal logging and reduce the associated cost. The project is developing an open source platform of modular tool components currently targeted at geothermal wells up to 200°C.

Due to a lack of logging tools that can withstand the extreme temperatures expected, the DESCRAMBLE project is developing a new logging tool that measures P&T with a minimum of 8 hours operation at 450°C. A prototype of the tool has been tested in an offline well at lower temperature (250°C) and further testing is planned in the Venelle 2 well at up to 450°C. In order to accelerate the development, DESCRAMBLE builds on experiences from previous projects by basing the mechanical design on earlier developed high temperature logging tools [3], [1], [5] and [4].

System Overview

As no electrical wireline cables rated to 450°C are available, the tool is based on logging to internal memory, and powered by high temperature batteries.

A pressure housing shields the inner parts from the pressure in the well. Only the nose of the tool is exposed to the well environment. Inside the pressure housing a heat shield (dewar flask) protects the payload (electronics, sensors and batteries) from the extreme outside temperature.

Figure 1. Pressure housing which encapsulates the heat shield. A nose protector protects the temperature sensor and the pressure port.

Figure 2, Pressure port and temperature sensor in the nose of the tool. Pressure and heat shield, and nose protector, are removed.

A pressure port is placed in the nose together with a temperature sensor. The pressure is transferred to the pressure sensor located inside the heat shield via a thin spiraled tube filled with high temperature grease.

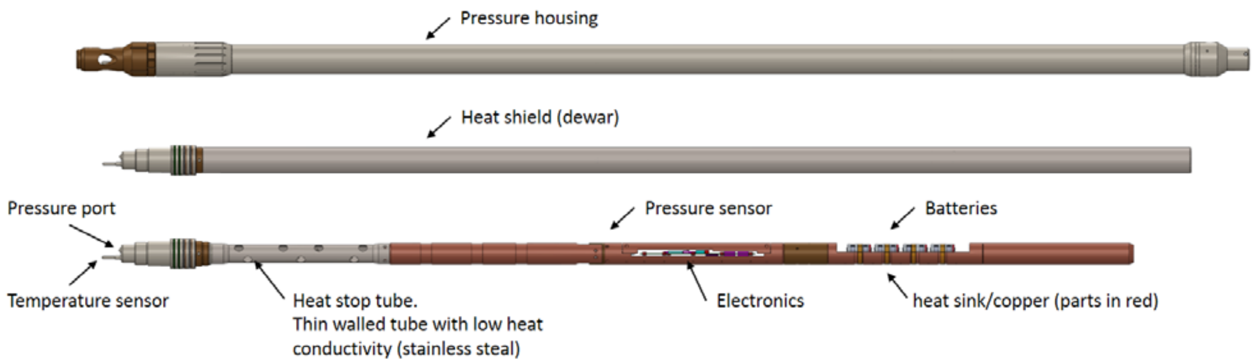

Figure 3. Top: The complete tool with pressure housing. Temperature sensor and pressure port is to the left (nose) and connection for the slickline wire is to the right in picture. Center: Pressure shield and nose protector removed. Picture show the nose of the tool and heat shield. Bottom: Heat shield removed. Picture show the inner parts of the tool. Electronics located in the middle of the tool.

A metal seal rated to above 450°C is used to seal the tool. Optionally, a high temperature O-ring can be used in logging operations below 300°C (short operation up to 325°C possible).

The heat shield is produced by National K Works and is rated to 450°C.

Operational and measurement specifications of the tool are listed in Table 1 and Table 2.

Table 1: Operational specifications

Max External Temperature	450 °C
Max External Pressure	450 bar
Outer Diameter	76.2 mm (3")
Tool length (without centralizers)	260 cm
Tool Weight (without centralizers)	50 kg
Max Tool Running Time @450°C	6 hours

Table 2: Measurement specifications

Pressure accuracy	0.5 bar
Pressure resolution	0.125 bar
Temp. accuracy	Better than 5°C
Temp. resolution	0.125 °C
Sampling rate	0.1-10 Hz
Storage	36000 datapoints x 3 (P,T,t)

High Temperature Electronics Platform

All the electronics are assembled on a single 6-layer, dual-sided polyimide PCB, measuring 44 x 260 mm.

Except for a few passive components, rated for +200ºC, all components are rated for at least +225ºC.

Figure 4. Picture shows assembled PCB mounted in the electronic slot of the heat sink.

A simplified block diagram is shown below:

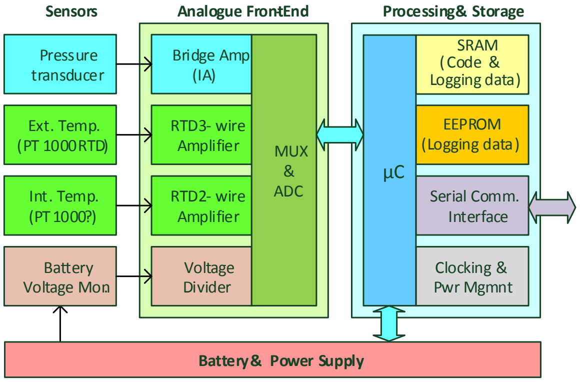

Figure 5. Simplified block diagram.

Microcontroller and memory

The core of the system is an ARM Cortex-M0 microcontroller from RelChip, RC10001. This includes 4 kB of SRAM and a reasonable selection of digital peripherals, but unfortunately no flash or other non-volatile memory. Since the few currently available high temperature, high-capacity non-volatile memory devices are expensive and physically large, static SRAM (RelChip RC2110836) is used both for code, program data, and acquired logging data. A subset of logging data is also backed up to serial EEPROM (Honeywell HTEE25608) to ensure that some data can be retrieved even in case of power failure.

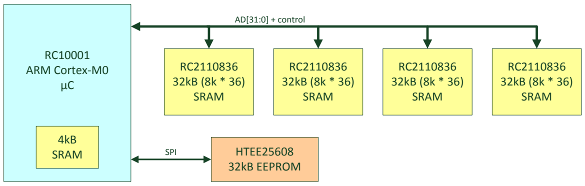

Figure 6. µC memory system.

One obvious disadvantage with this scheme is that the program must be loaded into memory each time the tool is powered up. This is handled by a hard-coded bootloader in the µC which receives application code over a serial port from an external PC.

The RelChip SOI components are quite remarkable, combining +300ºC rating with higher performance than most alternatives. Unfortunately, in the Early Adopters Program the microcontroller samples had faults and oddities causing some headache. For instance, the four memory chips could not be combined into a contiguous memory area, but RelChip was very responsive and assisted us in finding work-arounds.

Sensors and analog front-end.

Pressure is sensed by a bridge-type transducer from Kulite, connected to a programmable instrumentation amplifier from SGA. Since the transducer cannot withstand the external temperature, it is mounted close to the PCB inside the heat shield. Pressure is transferred from outside by a thin, coiled tube filled with high temperature grease.

External temperature is sensed by a PT1000-element mounted at the nose of the tool. Because of relatively long cabling, wiring resistance is partly compensated by a simple three-wire amplifier. A PT1000 element with a similar amplifier is also used for measuring the internal temperature at the PCB.

The ADC system consists of a quad analog switch (Honeywell HT1204) used as four-input multiplexer, followed by a 12-bit A/D converter (Honeywell HTADC12). The fourth input on the mux is used for monitoring the battery voltage.

Power Supply

Designing the power supply and power management system was, in many ways, the most challenging task. The main constraint is the high internal resistance in, and corresponding low current available from, the batteries (Electrochem VHT200) at low temperature; only a few mA. The most suitable low-dropout regulator we came across, X-Rel XTR70025, may draw close to 3mA in idle, which is too much. A low-power LDO, X-Rel XTR75015, is therefore connected in parallel, and the high-power regulator switched in as needed only.

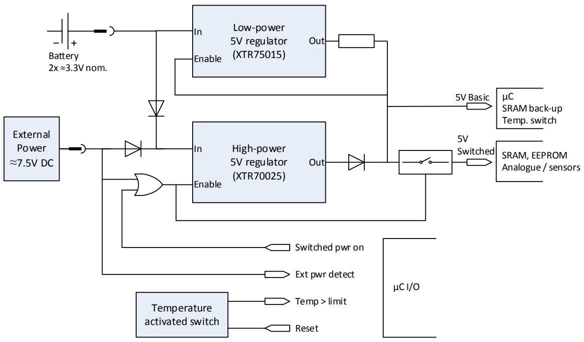

Figure 7. Principle of dual-regulator power supply.

The block diagram shows the principle only; the actual implementation is somewhat different. The input diodes are replaced by a MOSFET transistor to reduce voltage loss, and the output diode on the high-power regulator is replaced by a switch on the regulator ground pin.

Note the feedback from the regulator output to the enable input on the XTR75015. This inhibits start-up of the power supply when battery is fitted, until external power is connected. Mounting and sealing the tool takes time, and it is important to avoid draining the battery during this operation. When ready for deployment, external power is applied and the high-power regulator starts. This also enables the low-power regulator. Now code can be loaded into SRAM, and the tool tested. When everything is ready, external power is removed, the high-power regulator is disabled, and most peripherals are powered down. This includes external SRAM, but the memory content is preserved by maintaining voltage from the low-power regulator to a dedicated pin. In low-power mode, the µC therefore can execute code from internal memory only.

A thermistor is connected to a comparator, switching a microcontroller pin when internal temperature rises above a preset level where the battery can deliver sufficient power for normal operation. Then the microcontroller enables the high-power regulator and rest of the electronics as required.

Software challenges

The embedded software design for the tool is basic. Temperature and pressure as well as battery voltage are measured and stored at regular intervals, the intervals are configurable. When the tool is connected, data is transferred serially to a program where it is converted, visualized and stored.

However, the high temperature hardware design puts constraints on the firmware. The power usage needs to be minimized, particularly when operating at low temperatures due to the battery design. Operation is divided into three modes; low temperature, high temperature and connected. The most demanding mode is low temperature. In this mode, the power usage should be minimized, hence the microcontroller is running code from internal RAM at low frequency and all external components including SRAM are in low power mode. For every measurement, the microcontroller is switched to high frequency operation, peripherals are powered and code from external SRAM is executed. Measured data is stored in the external SRAM. The operation is similar in high temperature mode, however every fourth sample from the external SRAM is copied to the external EEPROM as more power is available. In high temperature mode, the sampling frequency is typically much higher than for low temperature mode as this is typically the area of interest.

Switching between different microcontroller frequencies makes exact timestamping of measurement data inaccurate as the switching time is unsymmetrical. This is handled by introducing a timing correction factor as well as calibration with the external slickline depth logger.

Power and batteries

Being a slickline tool the electronics need to be powered by on-board batteries. The tool needs to be operational both topside at ambient temperature as well as downhole with elevated temperatures up to 450°C. Even though the batteries do not see the full outside temperature of 450°C, it still represents a large and challenging temperature range of around 200°C. Since no commercially available cell can operate at the full temperature range, the operation domain can be split into three categories:

Low temperature applications, maximum internal temperature of 165°C. Electrochem PMX165C can be used with operating temperature range of -20°C to 165°C. Critical temperature of these cells, meaning operating temperature (measured on the cell case) where the cells become unstable and over time can vent or explode, is 165-180°C.

Medium temperature applications, maximum internal temperature of 200°C. Electrochem VHT200C can be used, this is the cell that will be used for logging Venelle 2. The critical temperature of these cells is 210-215°C and they have a specified operational temperature range of 70-200°C. We have characterized these cells below specified operating range ($T < 70°C$), and the electronics are designed for reduced functionality below 70°C to draw a minimum amount of current. When the internal temperature rises above 70°C the system "wakes up" and full functionality is available.

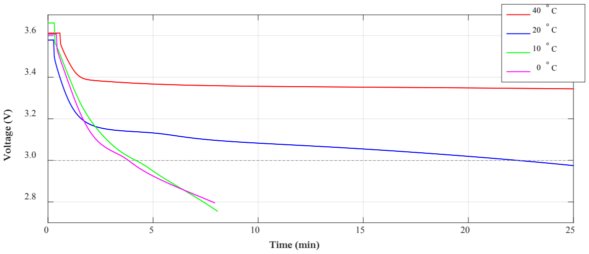

Figure 8. Characterization of the VHT200C cell outside of the specified operating temperature. Test is performed with 25mA constant current discharge (CCD) at a selection of temperatures below 70°C.

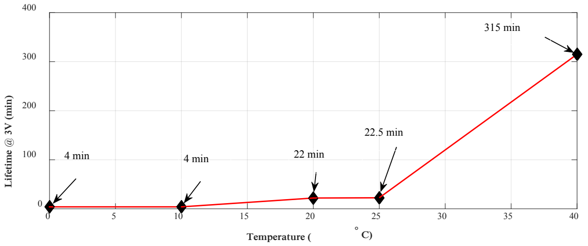

Figure 9. Lifetime of the VHT200C cell at a selection of temperatures below 70°C and a constant discharge current of 25mA. Cut-off voltage is defined at 3V.

The low available discharge current from the batteries at lower temperatures, and resulting short lifetime, is clearly illustrated in figure 8 and 9 respectively.

High temperature applications, maximum internal temperature of 225°C+. For instance, molten salt batteries can operate at high temperatures up to +400°C. But below 150°C the salt transitions to a solid state, leaving the cell inactive. For both the low and medium temperature applications the cells can be located together with the electronics inside the heat shield not seeing the full outside temperature. In high temperature application, the cells could be located outside the heat shield within the pressure housing. Either wake-up functionality or a battery heating solution could be used.

In the DESCRAMBLE project SINTEF will deliver a prototype tool which allows for use in low and medium temperature, whereas high temperature application is explored through lab testing and prototyping activities. Several novel battery solutions such as molten salt batteries and high temperature batteries with substitution of Lithium with other innovative materials, have been considered and tested. But none is found suitable within the project scope. As the batteries are the limiting factor for the system dwell time, this is one of the major improvements that could be explored more extensively in the future.

Primary lithium cells are prone to passivation and the VHT200C lithium thionyl chloride cells used in the tool are no exception. After storage over a certain amount of time (months) the cells start to passivate, meaning a layer forms on the surface of the anode preventing ions to travel through the electrolyte to the cathode. This is an inherent property that keep primary non-rechargeable cells from losing their energy, i.e. keeping the self-discharge low. Passivation increases the internal resistance R_i, thus limiting the available discharge current and resulting in a large voltage dip on load initiation. Because the cells are operated outside of spec (below 70°C) this phenomenon is especially significant as the low temperature also increases the internal resistance due to slower chemical reactions within the cell. Thus, the cells need to be de-passivated before use. This is done by discharging 1-2% of the capacity at ambient temperature with the maximum available discharge current. After the de-passivation process the cells need to regain full nominal voltage without load before use.

Results and Test Data

The tool has been extensively tested during development towards the final testing in the supercritical well Venelle 2. The following section describes the results from these tool tests.

Field-test

A field-test of the tool was performed in a geothermal well (Lumiera) at Enel Green Power's facilities in Larderello, Italy in February 2017. The test well had the following specifications:

- Liquid level 290m
- Max. temperature 250°C
- Max. pressure 53 bar
- Max. free depth 925m

The following test profile parameters were used with a total well time of 6 hours:

- Speed: 30m/min
- @500m well depth: stop for 10 minutes
- @700m well depth: stop for 10 minutes
- @ Bottom of well: stop for 4 hours
- @700m well depth: stop for 10 minutes
- @500m well depth: stop for 10 minutes

Figure 10 shows the internal temperature and the battery voltage during the test. It is clear that the batteries have a limited operating time when the internal temperature is low. Note that the electronics never entered high temperature mode as the internal temperature never exceeded the threshold of 70°C.

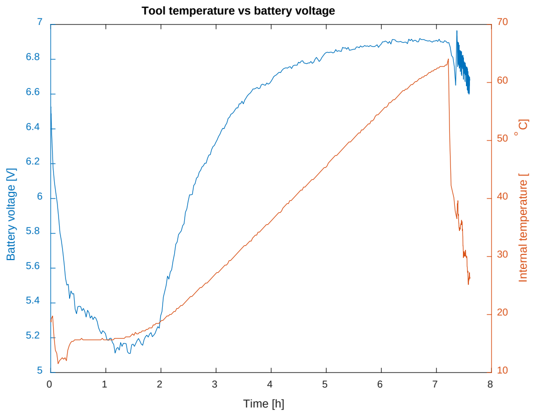

Figure 10. Internal temperature profile and the corresponding voltage when operating in low-temperature mode.

A direct comparison of the internal temperature to the Kuster K10 P&T tool, which was used for logging in the same well a few weeks earlier, is shown in figure 11. The DESCRAMBLE tool has a lower internal temperature gradient than the Kuster K10 tool. Even with a higher starting temperature the DESCRAMBLE tool also has a lower maximum internal temperature of approx. 64°C. In reality, the temperature is slightly lower as the temperature peak occurs when removing the payload out of the dewar which has a higher temperature causing it to heat up the temperature sensor.

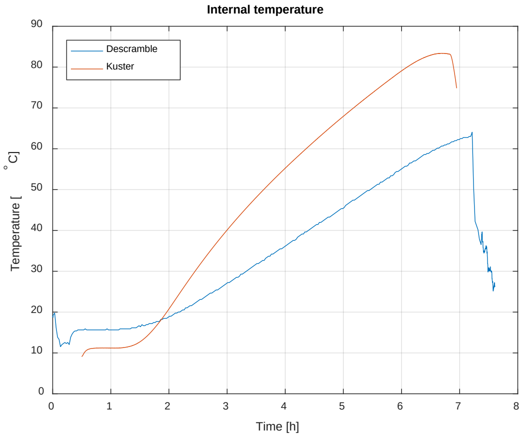

Figure 11. Internal temperature of the DESCRAMBLE and the Kuster K10 tool.

A depth plot from the test well comparing both DESCRAMBLE and Kuster K10 tool is shown in figure 12. The pressure deviations going down arise from the initial high viscosity of the grease barrier in the pressure tube, while the upwards temperature deviation arise from the internal heat capacity of the tool when leaving the water table at 367m.

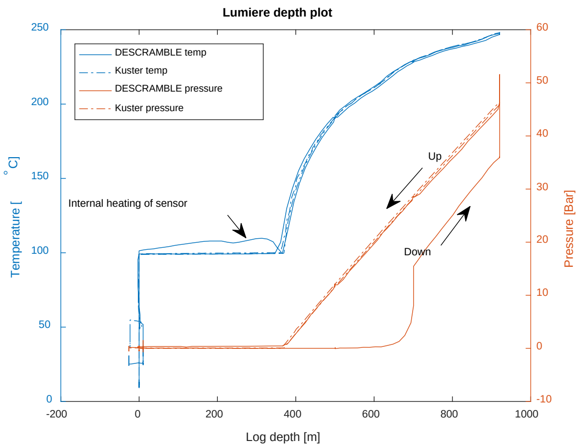

Figure 12. Depth plot of two runs (DESCRAMBLE and Kuster K10) for benchmarking and testing in the Lumiera well.

In-House testing

The thermal performance of the tool was tested in a large industrial oven at SINTEF, Raufoss Manufacturing branch, in Norway. Here the tool was exposed directly to the estimated 450°C temperature of Venelle 2 and kept there for approx. 3 hours. Using linear extrapolation, the tool has a dwell time of 6 hours at 450°C before reaching the internal temperature limit of the batteries (200°C).

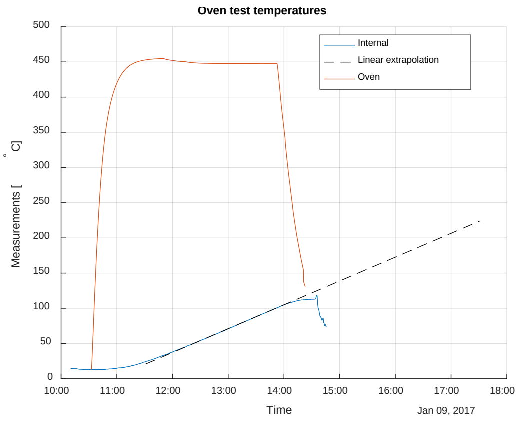

Figure 13. Internal temperature versus the maximum rated environment temperature (450°C). A linear extrapolation is shown dashed up to an internal temperature of 225°C

Future plans and improvements

Drilling of the DESCRAMBLE test well, Venelle 2, started 28th of April 2017 and are currently ongoing while this paper is written. Further testing of the DESCRAMBLE tool will continue when the drilling process are reaching the critical depth of supercritical conditions. Results from these tests will be published in a subsequent paper.

One of the main limitations of the current tool is its size due to the necessary heat sink volume to achieve the required dwell time for operating in supercritical wells. A smaller tool will enable logging inside the drill string which is a preferred option. To enable this the technology needs to be improved in one or more ways:

- Reduced heat sink volume using active cooling technologies.
- Higher temperature rating of components in the payload:
    - Batteries (today limited to 200°C)
    - Electronics (today limited to 225°C)
- Improved performance of the heat shield.

In addition, usability of the tool will be improved by booting from internal non-volatile memory.

Conclusion

In this paper, we have presented a prototype high temperature logging tool for supercritical conditions, enabled by use of high temperature electronics and efficient heat shielding.

Innovative use of high temperature components in combination with high temperature batteries and firmware enable higher internal payload temperature of heat shield operated logging tools.

The performance of the tool and its operability has been verified in lab and field tests.

Acknowledgements

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