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

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ABSTRACT

Exploitation of super-critical geothermal resources demands novel downhole logging tools, which are important for evaluating the formation properties, inspection of the well completion and for optimizing production and maintenance. For deep wells with temperatures above 350°C, state-of -the-art electronic logging tools lack the performance to operate reliably. Currently, the operator is limited to coarse temperature measurements using mechanical tools based on bourdon tubes or observation of physical processes such as melting.

In this work, we describe the development status and main research areas in developing a pressure and temperature logging tool for the ongoing H2020 DESCRAMBLE (Drilling in dEep, Super-CRitical AMBients of continentaL Europe) project. Our target specification for the autonomous tool is 8 hours operation time at 450°C/450 bar. We expect such performance to be necessary in order to log a 4km deep well with maximum temperature of 450°C. The tool consists of a high performance heat and pressure shield that protects a high temperature electronics platform that can operate and store data at a minimum of 200°C, targeting 300°C. More specifically, we describe the design choices made for the mechanical sealing, heat shield, high temperature electronics and sensors, and battery technology. In addition, we will present some preliminary lab test results.

1. 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 3-3.5km. The reservoir is expected to contain water at super-critical conditions (>374°C, >220bar) with a maximum temperature of 450°C. The estimated maximum pressure is more uncertain but a maximum pressure of 450 bar has been specified. As the well temperature and pressure profiles are important parameters for evaluating the formation properties, inspection of the well completion and for optimizing production there is a need for a logging tool to measure these parameters. However, it is not possible to measure the well temperature and pressure at the expected reservoir conditions using commercially available P&T logging tools. One example is the electronic K10 P&T logging tool, from Kuster (Kuster Co., 2016) which has a maximum temperature rating of 350°C for 4 hours.

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), (Halladay et al. 2010), (Ásmundsson et al. 2014). The U.S. department of Energy has supported several projects that aim at developing a 300°C capable directional drilling system. Dick et. al, (2013) describes progress in the development of a 300°C directional drilling system for Enhanced Geothermal Systems (EGS) . In order to navigate the system requires an 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). MacGugan (2013) 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 (Isele 2015), (Isele 2013) 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 is scheduled to be tested both in offline wells at lower temperatures (<350°C) and in the Venelle 2 well at up to 450°C. In order to accelerate the development, DESCRAMBLE builds on experiences from earlier projects by basing the mechanical design of the tool on earlier developed high temperature logging tools (Halladay et al. 2010), (Ásmundsson et al. 2014), (Halladay 1997) and (Halladay and Manning 1995). The tool is memory based with battery power, as there are no wireline cables rated to 450°C.

2. DESIGN SPECIFICATION AND SYSTEM DESCRIPTION

2.1 Design specifications

Table 1 shows the operational design specifications, while Table 2 shows the measurement design specifications. The specifications are named "design" as we expect some adjustments as we manufacture and test the tool.

The specifications are a compromise between operational constraints, availability of components (e.g. seals and heat shield) their performance and requirements. Throughout the project we aim at gaining knowledge of the design trade-offs so that we can better optimize the design in future tools.

Table 1: Operational design specifications.

Max External Temperature	450 °C
Max External Pressure	450 bar
Outer Diameter	76.2mm (3")
Tool length (without centralizers)	260 cm
Tool Weight (without centralizers)	50 kg
Max Tool Running Time @450°C	8 hours

Table 2: Measurement design specifications.

Pressure accuracy	0.5 bar (including temperature variations, hysteresis and linearity)
Pressure resolution	0.125 bar (limited by A/D converter)
Temp. accuracy	Better than 5°C
Temp. resolution	0.125 °C
Sampling rate	0.1-10 Hz
Storage	36000 datapoints x 3 (P,T,time)

2.1 System description

Figure 1 shows a simplified schematic of the main tool components. From the left we see the bulkhead, which can be detached to extract the payload. A tube transfers pressure to the pressure sensor located in the payload. A pt1000 sensor located at the "nose" of the tool measures the temperature. This sensor is connected to the electronics via wires passing through the bulkhead. A heat shield located inside the pressure housing protects the payload from the ambient temperature. The payload consists of heat sinks, electronics and batteries

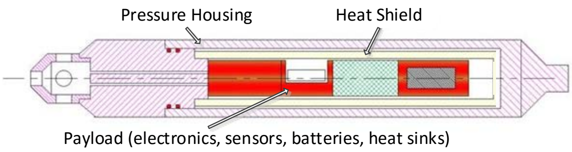

Figure 1: Simplified schematic of the tool.

3. PRESSURE HOUSING AND SEALS

We have modelled the pressure housing and internal assembly in SolidWorks™. Figure 2 shows one end of the pressure housing and illustrates its main components:

- A main cylinder body with one end closed.
- Threaded collar and bulkhead.
- Seals.

Inconel 718 was selected for the pressure housing material due to its chemical resistance and strength properties. As figure 2 shows, the bulkhead is secured in place by a threaded collar that locates it into the pressure housing. The bulkhead material is also Inconel 718 while the threaded collar material is Aluminium Bronze (BS EN 12163) to avoid galling of the threads.

In order to allow for flexibility and redundancy we have chosen to design the tool with three different seal types. As shown in figure 2 the design allows for the use of two O-rings, two polymer seals and one metal seal. The seal types complement each other as described below:

O-rings: easy to use, reasonably tolerant to "dirty surfaces", a good all-round seal.
Polymer: Good chemical resistance but harder to install.
Metal: 100% gas tight, excellent chemical resistance, requires a very clean surface and strict machining requirements. The only seal type rated to >450°C

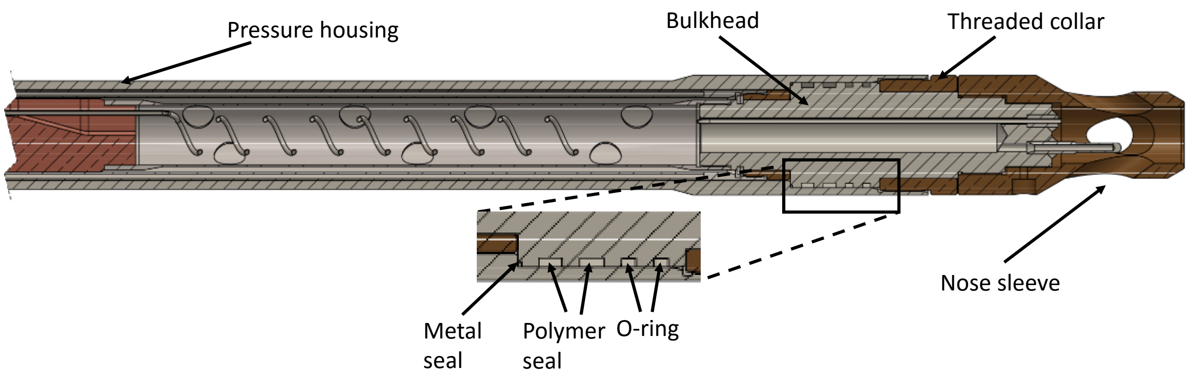

Figure 2: The pressure housing consists of a main tube body with one end closed, a threaded collar that secures the bulkhead and seals.

When logging a well with a temperature below approximately 350°C the tool can be used without the metal seal. At higher temperatures both the O-rings and the polymer seals are expected to fail after some time (minutes to hours depending on the temperature). In order to validate the seal design, and to determine more exact limitations (lifetime and temperature) for the O-rings and polymer seals, we are currently conducting tests. Figure 5 shows an example of an O-ring tested to failure. It shows that the O-ring fails after 10-20 minutes at approximately 350°C after over.

4. HEAT SHIELD

The heat shield consists of a vacuum flask (Dewar flask) with insulating foils placed between the walls in a vacuum. In order to ensure a sufficient vacuum at the high temperatures expected, the vacuuming is done at high temperatures (>400°C). A heat stopper consisting of a thin walled tube filled with mineral wool is used to plug the flask opening. Wires from the temperature sensor and a tube from the pressure sensor pass through the heat stopper in a spiralling manner to minimize the heat transfer.

There is an option of adding a feed-through feature at the closed end of the heat shield. Such a feed-through can be used for wires if the tool is powered by wireline, or if it is powered from a separate battery pack outside of the electronics heat shield. For the first version of this tool neither of these options are used and we have omitted the feed-through in order to lower the cost and complexity.

5. PAYLOAD

The payload consists of various sensors, analogue front-end electronics, digital electronics for processing and storage and a battery and power supply as shown in figure 4 and figure 7. In addition two copper heat sinks are added to increase the thermal mass (and thus the dwell time) of the tool. The electronics contains only components that can operate reliably up to or above 225°C. A strict limitation is the existing commercially available battery technology based on lithium thionyl chloride as it limits the operating temperature of the payload to 200°C. .

5.1 Sensors

Based on an evaluation of several sensors from Kulite, EFE, ESI Technology and Omega Engineering we chose the Kulite HEM-375 pressure sensor due to its availability, cost and proved performance. The sensor uses a piezoresistive sensing principle and is rated to 232°C. A spiralled grease filled tube that runs from the outside of the bulkhead through the heat stopper transmits the well pressure to the sensor.

Figure 3 shows the temperature sensor. It is an RTD sensor with a PT1000 element encased in a steel probe with mineral insulated wires inside. The specific model was chosen based on earlier experience, the possibility of bending the metal probe into a spiral to reduce heat transfer and the high temperature rating.

Figure 3: Temperature sensor probe

Although not part of the original specification, there is an option of adding a casing collar locator (CCL). This sensor is custom made and consists of a coil and magnets. When the sensor passes a casing collar, the metal induces a current in the coil that is measured by the front-end electronics. The CCL is thus used to measure the position/depth of the tool in cased sections of the well.

5.2 Analogue front-end

As illustrated in figure 7 the analogue front-end amplifies and conditions the sensor signals before they are read by the A/D converter (ADC). The design consists of standard bridges, protection, buffers/amplifiers and filters. The specified operating temperature of at least 200 °C imposes severe limitations on the choice of components. Op-amps with auto-zeroing techniques are used to compensate for temperature voltage offset drift. Only silicon-on-insulator components are used.

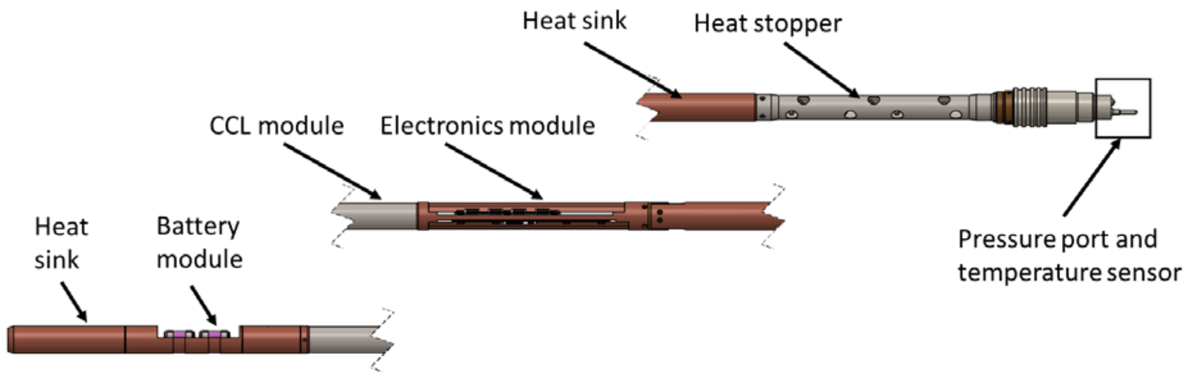

Figure 4: Payload components

5.3 Digital system

The digital system performs the following tasks:

- Read ADC, buffer and store measured data in memory.
- Measure time (clock).
- Basic system monitoring logic to decide when to sleep/wake, when to store data.

In the screening phase of available components, three high temperature microcontrollers were identified:

- RelChip RC10001
- Honeywell HT83C51
- Texas Instruments SM470R1B1MHFQS

CMOS devices, such as the one manufactured by Texas Instruments (TI), are based on a process that lacks the ability to operate in temperatures above 220°C. While the TI processor has excellent functionality specifications, higher temperatures induces higher current leakages in the CPU's transistors and limits the device operation. Choosing a processor capable of temperatures approaching 300°C provides flexibility in future tool developments, as we can allow for a higher maximum temperature inside the heat shield. The Honeywell processor is a proven candidate, but has limitations on the selection of peripherals and speed, which complicates other parts of the electronics design. The novel RelChip RC10001 is our choice and it has the following main features:

- Silicon-on-insulator technology
- Temperature range -55ºC to 300ºC.
- ARM® 32-bit Cortex™-M0 Core. (Small, modern controller-optimized architecture)
- 4 kB internal SRAM.
- Four timer/counters (2x 16-bit, 2x 32-bit)
- Single SPI interface
- Single UART

The RelChip stores data in the Honeywell HTEE25608 EEPROM rated to 250°C (the EEPROM includes a memory refresh function required for long-term data retention at high temperature), and in the RelChip RC2110836 SRAM rated to 300°C.

5.4 Power

As it is not possible to power the tool using a wireline cable, we need to use batteries. We have chosen to divide our application domain into three temperature ranges with optimized battery solutions for the three ranges

Low temperature applications, maximum internal temperature below 150°C, use commercial batteries with range 0-150°C. (e.g. PMX150 from Electrochem).

Medium temperature applications, maximum internal temperature below 200°C, use commercial batteries with range 70-200°C (VHT200 from Electrochem). Below approximately 70°C the electronics will stay in low power mode and only draw a small amount of current. As the battery temperature reaches approximately 70°C the electronics will wake-up (and have full functionality).

High temperature applications, maximum internal temperature below 225°C or possibly higher, use non-commercial batteries with ranges from i.e. 150°C to 300°C, or 200°C to 400°C. Either use a wake-up functionality or use a battery heating functionality.

For both the low and medium temperature application, the batteries may be co-located with the electronics inside the heat shield. For the high temperature application, the batteries may be co-located with the electronics or located in a separate heat shield.

In the *medium temperature application,* we will run the electronics in low power mode as long as the battery temperature is lower than approximately 70°C. We have tested the VHT200 cells (AA size) and found that the cells can deliver at least 3-5mA at room temperature. Figure 6 shows a test where we have found that the cell can deliver 5mA for at least 7 hours at room temperature. By reducing the sampling rate to a minimum and turning down the clock speed we are able to power the electronics with this small current.

In the DESCRAMBLE project we will deliver a prototype tool which allows for use in *low and medium* temperature applications while the *high* temperature application is explored through lab testing of prototype batteries. Depending on the experience gained such batteries may be incorporated in a later version of the tool.

5. CONCLUSION

There are currently no downhole logging tools that can operate in wells with super-critical conditions (>374°C, >220bar). We have described the development of such a tool within the ongoing DESCRAMBLE project. The tool will allow for operation of at least 8 hours at 450°C.

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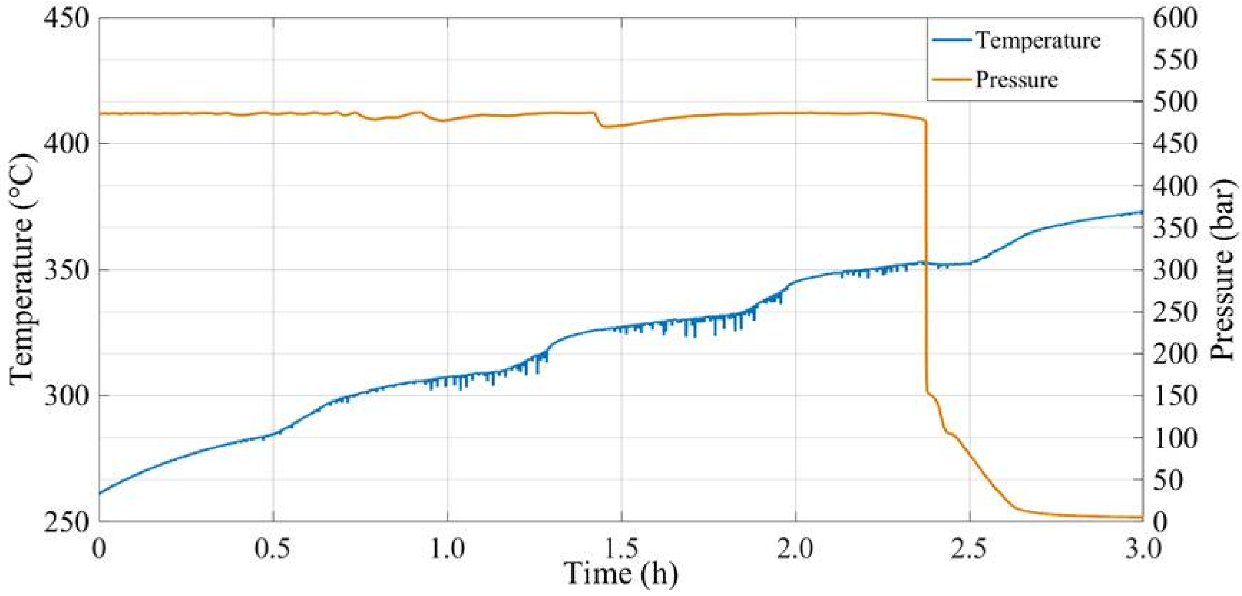

Figure 5: Test of o-ring at high temperature. The abrupt pressure drop just before 2.5 hours shows that the seal failed after a short time (10-20 min) at 350°C.

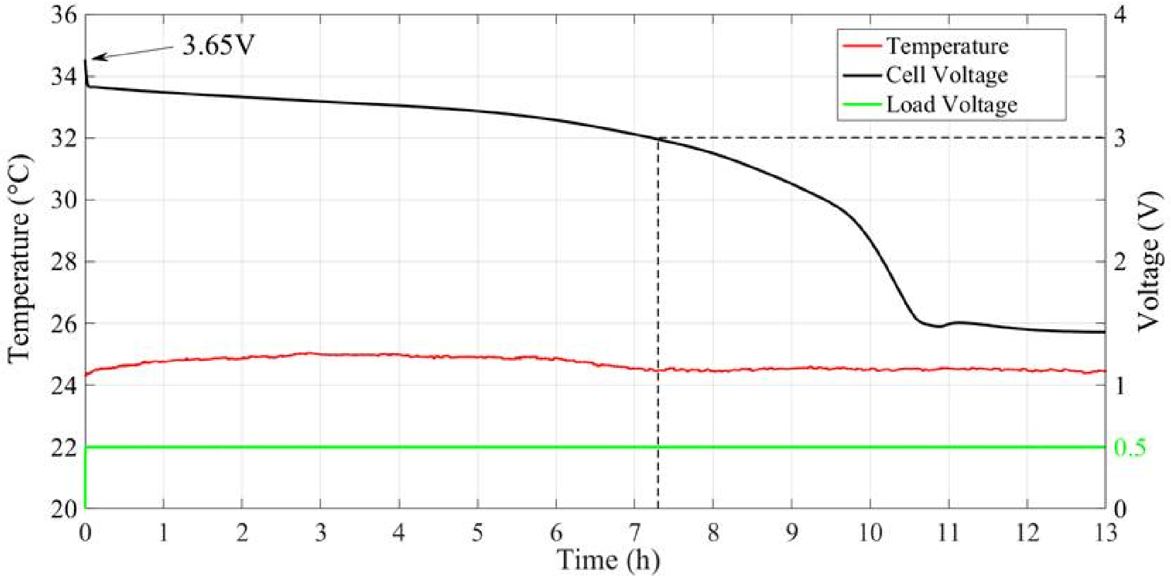

Figure 6: Test of the VHT200 cell at room temperature with 5mA current draw. We can see that the cell voltage remains above 3V for at least 7 hours.

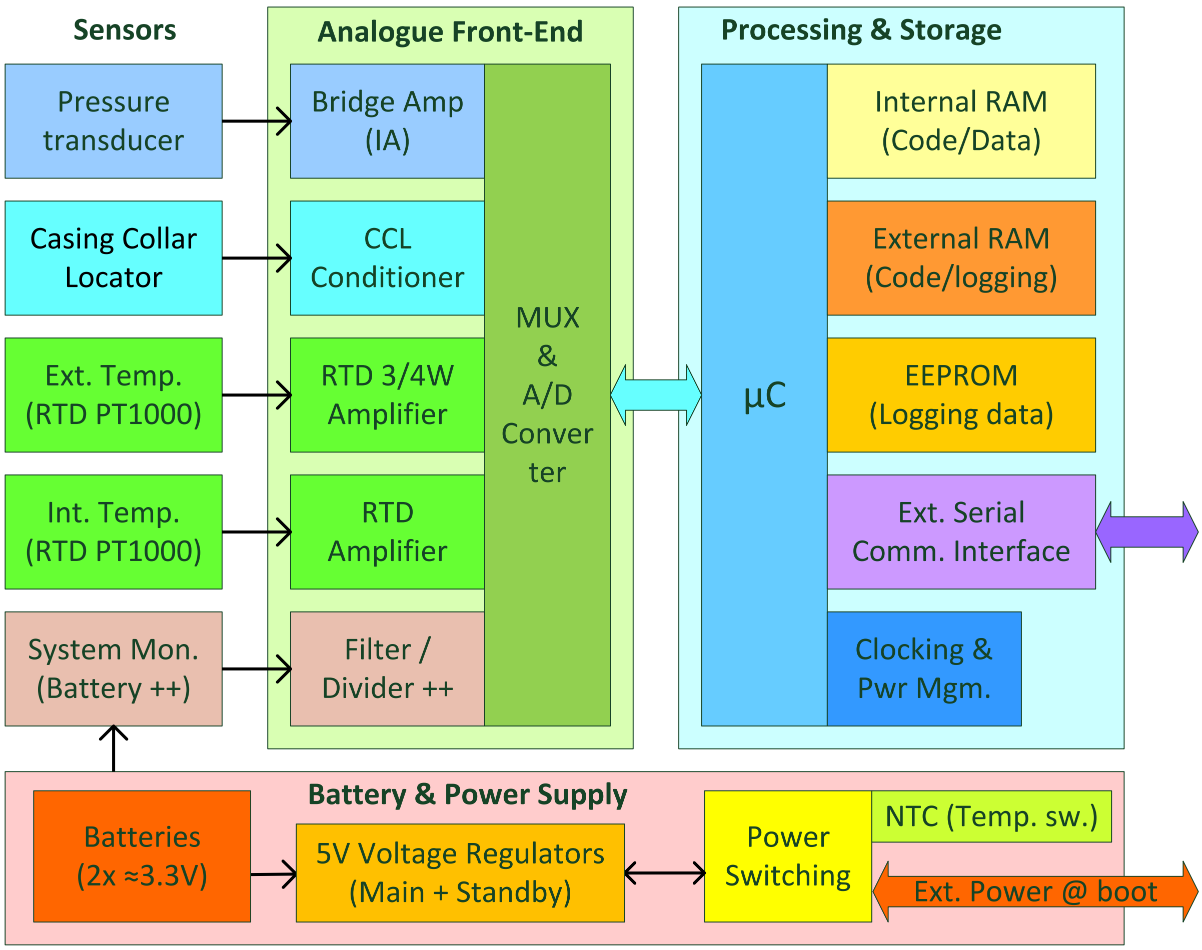

Figure 7: Payload components