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Cryogenic Cooling Enabling Increased Performance of Logging Tools Utilizing Vacuum Flasks

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ABSTRACT

Logging is performed in all phases in the life of a well, drilling, completion, production and abandonment. It is an important contributor in reducing the cost and risk, improving reservoir characterization, and optimizing production and maintenance.

Enel Green Power and HS Orka, in collaboration with Equinor, have in recent years explored geothermal wells with supercritical conditions. These wells have a potential of 5-10 fold increase in energy output compared to traditional geothermal wells, making them very attractive to explore since fewer wells need to be drilled. This represents a step-change in geothermal business since drilling operations represent the greatest cost in exploiting geothermal energy.

Currently there are no logging tools in the market capable of performing logging operations in wells with extreme supercritical conditions. Probe1 (previously Kuster) manufactures logging tools which have become an industry standard within geothermal logging with temperature ratings up to maximum 350°C at a limited operation time of 4 hours when Run In Hole (RIH) using the flasks currently available to the industry.

Extended operational time may be achieved by increasing the tool outer diameter (OD), adding more heat sink material inside the vacuum flask and use high temperature electronics and batteries, but this will result in large, heavy and expensive logging tools. Due to their large OD such tools cannot be deployed inside a drill string, forcing the geothermal drilling contractor to remove the drill string prior to logging with large OD tools, which is both time-consuming and impose a higher operational cost and risk.

The CryoFlask project is developing and demonstrating a technology which will enable significantly extended operational time for downhole logging operations and interventions in deep, supercritical geothermal wells with temperatures reaching 450°C without an extreme increase in the OD of the tool. The project utilizes a cooling technology patent by Norwegian Well, enabling a new generation of tools utilizing vacuum flasks in combination with lower temperature rated electronics, improved reliability, smaller OD and lower cost to performance ratio to be deployed in high temperature wells. This project thus represents a breakthrough in downhole logging technology for supercritical geothermal wells. The cooling technology will also give a significant increase in operational time compared to existing tools being used in geothermal wells below 350°C and HPHT O&G wells.

The CryoFlask technology uses standard flasks combined with a thermal heat sink cooled down to cryogenic temperature and a thermal valve to balance the temperature of the electronics, batteries and internal sensors, and thereby keeping these components within their rated temperature range. The project is building and demonstrating a prototype with four times increase in operational time in-well compared to existing industry standard logging tools and in addition enables logging in geothermal wells up to 450°C. The prototype is planned tested in geothermal wells in Iceland and Italy in collaboration with Equinor, HS Orka and Enel Green Power in 2021.

1. INTRODUCTION

A wide range of different logging tools measuring basically temperature (T) and pressure (P) have been used to take measurements in geothermal wells. The first logging tools for measuring temperature were maximum reading mercury meters which were lowered repeatedly into the well to create a temperature profile (Steingrímsson, 2013). In the 1930’s the American Geophysical Research Corporation developed mechanical temperature and pressure gauges for the oil Industry. Similar gauges were later produced by the Kuster Company (Kuster Pressure Gauge – KPG and Kuster Temperature Gauge – KTG). Kuster uses bourdon tube to measure the pressure and a bimetal sensor to measure the temperature. The gauges were lowered into the well using slickline, and data was recorded using a pen needle on a brass foil inside a clock driven recorder. Data was recorded at 100 m depth intervals. A limited number of data points (20-30) could be recorded in each run. The Kuster gauges has been used routinely up to 380°C (Steingrímsson, 2013).

In the 1980’s the push in the O&G industry led to the development of high temperature logging tools operated on electric wire (E-line) with real time surface readout. These type of logging tools first made its introduction to the geothermal industry in the year 2000 when the Kuster company developed an electronic P&T gauge named K10 geothermal (Steingrímsson, 2013). This tool was a memory tool with battery powered electronics and sensors to be deployed on a slickline without real time surface read out. The tool utilizes a combined pressure and a vacuum flask combined with a heat sink to keep the temperature of the internal parts (electronics, batteries and sensors) below max rated temperature. The tool 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 characterization &

exploitation" (HITI) project, it was 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 aiming 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, this system requires a Measurement While Drilling (MWD) tool rated to the same temperature. This tool will require electronics rated to 300°C (i.e., sensors, 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. The module uses custom silicon-on-insulator (SOI) integrated circuits mounted on high temperature co-fired ceramic substrate; all components rated to 300°C. 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.

In the DESCRAMBLE project, SINTEF developed a P&T memory logging tool with a maximum temperature rating of 450°C for 8 hours (Vedum et al. 2017). The tool was tested in the Venelle 2 well deepened down to a depth of 3000 m. The SINTEF P&T tool had a mechanical design similar to earlier developed high temperature logging tools (Halladay et al. 2010), (Ásmundsson et al. 2014), (Halladay 1997) and (Halladay and Manning 1995). The max temperature measured during logging with this tool was 443.6°C (Bertani et al. 2018).

Common for all the tools utilizing vacuum flasks is that their performance at high temperature mainly has been determined by the amount of heat sink that is incorporated in the tool. There have been small improvements in operation time by using high temperature electronics and high temperature batteries. But, still the limited availability of different high temperature components and their max temperature rating (typically 225-250°C) is making it difficult for the geothermal industry to take advantage of the logging tools that today exist in the O&G industry.

2. CRYOFLASK – SYSTEM DESCRIPTION

The CryoFlask technology utilizes a cooling technology patent by Norwegian Well. The inventions relate to a device for transfer of heat energy in a well logging tool, where a variable heat flow from a chamber for electronics via a thermal valve is transferred into a heat sink consisting of cooled metal, thereby establishing an approximately constant temperature in the chamber for electronics.

2.1 Traditional design of a geothermal logging tool using electronic sensors

Figure 1 shows a principal way of building an electronic logging tool for hot wells. Electronic components (integrated circuits, printed circuit boards, wires, connectors, batteries and sensors) typically have temperature ratings up to 125, 150, 175/177 or 200°C. Above these temperatures the components will stop functioning or at worst break down. Also, exposing electronic components to temperatures close to their max rating will reduce the lifetime of the components. Electronic components with higher temperature ratings have higher cost and the component selection is less, which is restricting the electronics designs. Logging tools in the market typically use electronics rated to 150°C or 175/177°C since these temperature ratings give a good tradeoff between component availability, selection and cost. Geothermal wells which are used for production of electricity by turbines, typically have temperatures from about 200°C and above and a few are even above 400°C (Venelle 2 in Italy and IDDP-1 and IDDP-2 in Iceland).

To survive these high temperatures, the electronic components of a logging tool are placed inside a vacuum flask which consists of two thin-walled tubes with high vacuum in the anulus to reduce the heat flux from the hot well/formation. The space inside the vacuum flask is filled with a thermal heat sink, normally a metal with high heat capacity like stainless steel, aluminum or copper. The electronic components are mounted to this thermal heat sink. The purpose of the heat sink is to store the heat flux penetrating the vacuum flask and heat stopper, absorb the internal heat generated by the electronics and thereby slow down the heat-up of the internal parts (payload).

The heat sink is connected via a heat stopper tube – a thin-walled stainless steel pipe – to the bottom connection which in Figure 1 is equipped with a plug. The bottom connection, and in this case the plug, is exposed to the full wellbore temperature. If external sensors (temperature, flow, etc.) are used, these are attached to the bottom connection and thereby replacing the plug shown in Figure 1. Outside the vacuum flask a pressure shield protects the fragile parts (vacuum flask and electronics components) from the pressure in the wellbore. Heat sink, vacuum flask and pressure shield are all mechanically fixed only to the bottom connection allowing for different thermal expansion between the parts. Between the bottom connection and the pressure shield O-rings, metal to metal seals or a combination of them, are used to create a hermetically sealed and controlled environment for the payload.

By unscrewing the bottom connection from the heat shield, the internal parts of the tools can be accessed allowing the operator to start and stop the tool, download data, setting logging parameters, swapping batteries and maintenance. The pressure shield and the vacuum flask can be combined into one part by replacing the outer thin wall tube of the vacuum flask with the pressure shield itself. This simplifies the design of the bottom connection and decreases slightly the outer diameter of the tool. Vacuum flasks can be produced with openings in both ends enabling easier routing of wires (typically used in E-line logging).

The maximum operational time of a logging tool in a hot well is defined by the performance of the vacuum flask, heat stopper tube, the amount of heat that can be stored in the heat sink and the maximum temperature rating of the payload. The maximum temperature rating of a logging tool is given by the seals used (O-rings can be used up to 330°C, above this temperature metal to metal seals must be used), temperature rating of the external sensors and the vacuum flask.

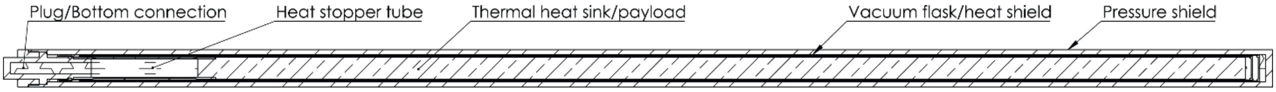

Figure 1. Traditional design of a geothermal logging tool.

2.2 CryoFlask design

The CryoFlask technology is similar to the traditional way of building logging tools for high temperature applications, but by adding a thermal valve dividing the heat sink into two separate compartments, the heat sink not containing electronic components, can be cooled down to cryogenic temperature (below -180°C). This part is defined as the cryogenic heat sink. The part of the heat sink that is not cooled down to cryogenic temperature is in the section of the tool which contains the electronics components. This part is defined as the payload section of the tool.

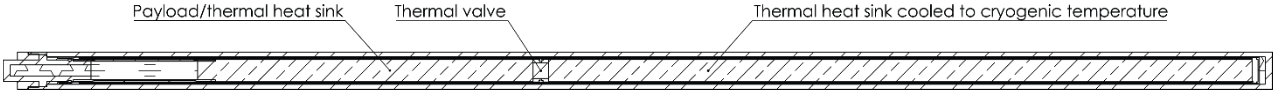

Figure 2. Geothermal logging tool utilizing CryoFlask technology.

Prior to deployment in the well, the cryogenic heat sink is cooled by liquid nitrogen (boiling point –196°C). During logging in the well, the payload will increase in temperature due to heat flux entering the tool from the wellbore through the vacuum flask and the heat stopper, and also due to heat generated by the electronics itself. When reaching a defined temperature in the payload, the thermal valve will thermally connect the payload section to the cryogenic heat sink which is cooled down to cryogenic temperature. The payload will be cooled down to a set temperature until the thermal valve disconnects from the cryogenic heat sink. This will enable a stable temperature in the payload section until the cryogenic heat sink reaches the same temperature as the payload. In total the CryoFlask enables several advantages compared to the traditional design:

- Longer operation time in the well.
- Stable and lower temperature of payload components during logging.

Longer operation time in the well will enable:

- Longer sampling time of low frequency transient parameters in the well (e.g., temperature, pressure).
- No need to have multiple runs in the well since all measurements can be performed in one operation, lowering the risk of getting stuck in well etc.
- Performing logging operation in hot wells previously not possible.

A stable temperature of payload components during logging will enable:

- Improved sensor readings.
- The use of components rated to industrial temperature ranges (85°C, 105°C and 125°C) lowering the cost of electronics and taking advantage of the much larger availability of components in this temperature range.

3. HEAT TRANSFER IN A LOGGING TOOL UTILIZING VACUUM FLASK

When building high temperature logging tools utilizing vacuum flasks it is important to have a good understanding of the heat transfer paths and how to minimize this to have as low as possible temperature increase inside the payload section of the tool. There are three ways heat is transferred:

- *Convective heat transfer:* Transfer of heat from one place to another by the movement of fluids (liquids and gases).
- *Conductive heat transfer:* Thermal conduction is the transfer of internal energy by microscopic collisions of particles and movement of electrons within a body.
- *Thermal radiation:* Thermal radiation is the emission of electromagnetic waves from all matter that has a temperature greater than absolute zero.

3.1 Convective heat transfer

Convection currents are set up in fluids because in general the hotter part of fluids is not as dense as the cooler part, hence there is an upward buoyant force on the hotter fluid, making it rise, while the cooler, denser, fluid sinks. Inside high temperature logging tools open spaces, gaps etc. are filled with air. To reduce the convective heat transfer of air circulation because of surfaces inside the tool have different temperatures, the tool manufacturer in general makes the gaps as small as possible or fills the open spaces with heat sink material. If an open space cannot be filled with heat sink material, as is the case for the space inside the heat stopper tube, this space is filled with glass wool or similar high temperature material with low heat conductivity stopping the air from circulating. In the simulations results referred to in this paper, the convective heat transfer has not been included since this part is minimal compared to conductive and thermal radiation.

3.2 Conductive heat transfer

Conductive heat transfer will exist in all parts of the tool except where there is vacuum. In conduction, the heat flow is within and through the parts. Local heat flux density, $\mathbf{q}$, is equal to the product of thermal conductivity, $\mathbf{k}$, and the negative local temperature gradient, $-\nabla \mathbf{T}$:

$$q = -k\nabla T$$

For a homogeneous material of 1-D geometry between two endpoints at constant temperature, the heat flow rate Q is:

$$\frac{Q}{\Delta t} = -kA\frac{\Delta T}{\Delta x}$$

Where **Δt** is the time interval during which the amount of heat **Q** flows through a cross section of the material. **A** is the cross-sectional surface area, **ΔT** is the temperature difference between the ends, **Δx** is the distance between the ends. To reduce the conductive heat flux, critical parts are made with low cross-sectional area, large distance between the ends and of metals with low thermal conductivity. The heat stopper is a good example of how this can be implemented to reduce the heat flux between the plug, which is exposed to the full wellbore temperature and the payload/heat sink inside the vacuum flask.

3.3 Thermal radiation

The most effective way of reducing the heat flux from the hot environment in a geothermal well into the payload section of a logging tool is by eliminating convective and conductive heat transfer. This is done by utilizing a vacuum flask built by two tubes with a high vacuum in the anulus. Only thermal radiation remains. Thermal radiation is electromagnetic radiation generated by the thermal motion of particles in matters. All matters with a temperature greater than absolute zero emit thermal radiation. A vacuum flask is like the everyday vacuum flask people use for storing hot fluids. A vacuum flask can also be referred to as heat shield, thermoshield, thermos, Dewar flask or Dewar bottle. In a vacuum flask the main component for heat flux is thermal radiation which is given by this equation using Kirchhoff's Law for gray surfaces:

$$q_{1\ to\ 2} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

Where **σ** is the Stefan–Boltzmann constant, **T_1** and **T_2** the temperature and **ε_1** and **ε_2** the emissivity of the of the outer and inner wall. By decreasing the emissivity of the surfaces of the outer and inner wall of the vacuum flask, thermal radiation is reduced. Furthermore, the thermal radiation can be reduced even more by adding thin layers of reflective metal foil in the vacuum between the outer and inner wall, this technique is named Multi-layer insulation (MLI). The performance of a vacuum flask utilizing MLI can be quantified in terms of its overall heat transfer coefficient **U**, which can be expressed in the following equation assuming the same emissivity for all layers:

$$U = A\frac{\sigma(T_1^4 - T_2^4)}{N(2/\varepsilon - 1) + 1}$$

Where **N** is the number of MLI layers and **A** is the area. Increasing the number of layers and decreasing the emissivity lowers the heat transfer coefficient resulting in less heat flux caused by thermal radiation through the vacuum flask over time.

4. PERFORMANCE OF CRYOFLASK TECHNOLOGY VERSUS TRADITIONAL DESIGN

Finite Element simulations have been performed to visualize the performance of the CryoFlask technology compared with the traditional design. The simulation tool used is COMSOL with the thermal module. The parameters for the simulations are:

- Time = 0-1 hour, tool waiting at wellhead. If tool has CryoFlask technology the heat sink is cooled to –196°C in this period. Ambient temperature at wellhead 20°C.
- Time = 1-2 hour, tool lowered into hole/wellbore reaching target depth and target temperature of 350°C. Assuming linear increase in temperature.
- Time = 2-> hour, tool stationary at target depth of 350°C.

Simulations in Figure 3 and Figure 4 show the temperature profile of a traditional design of outer diameter Ø52 mm, payload diameter of Ø32 mm and total length of 1785 mm compared with equal sized CryoFlask design at t = 5 hours, i.e. operation time in well after 4 hours. Simulations have been done with copper as heat sink and the same performance of the vacuum flask is used in both simulations.

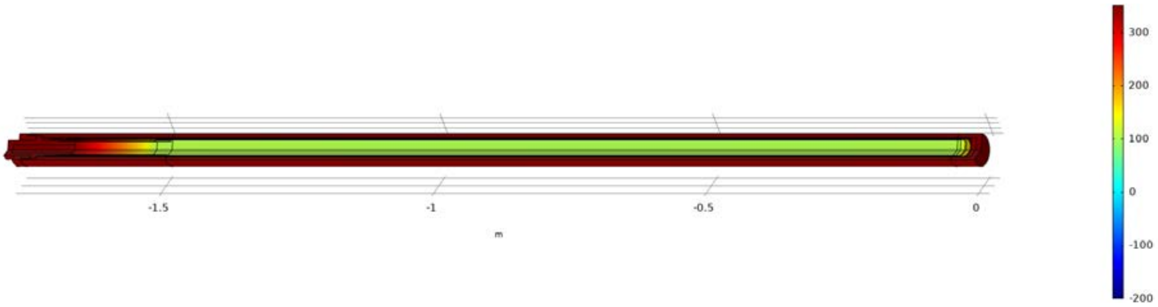

Figure 3. FEM simulation of traditional design. Temperature of tool at t = 5 hour.

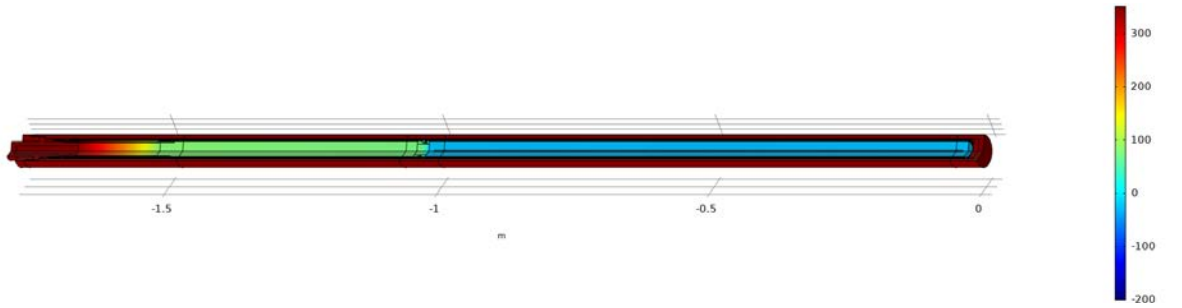

Figure 4. FEM simulation of logging tool using CryoFlask technology. Temperature of tool at t = 5 hour.

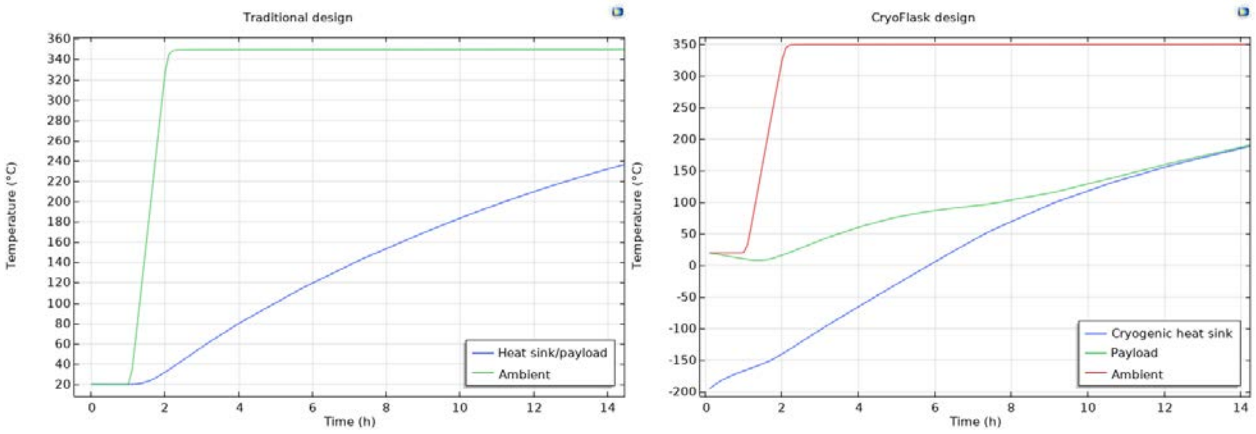

Figure 5. Temperature profile of traditional design compared with CryoFlask design in a 350°C well. Note: The x-scale show time after FEM simulation start.

Graphs in Figure 5 show the performance of the CryoFlask and traditional design in a 350°C well. The traditional design reaches 150°C internal temperature after 6.8 hours operations time in the well while the CryoFlask design reaches 150°C at 10.4 hours operation time in the same well – a significant increase in operation time of 65 %. This number will increase if the amount of heat sink cooled down to cryogenic temperature is increased.

Several FEM simulations for different CryoFlask sizes have been simulated to find the optimum trade-off between size and performance. A chart has been created (Figure 6) mapping the data from these simulations. In these simulations 5 W of heat generated by the payload has been included.

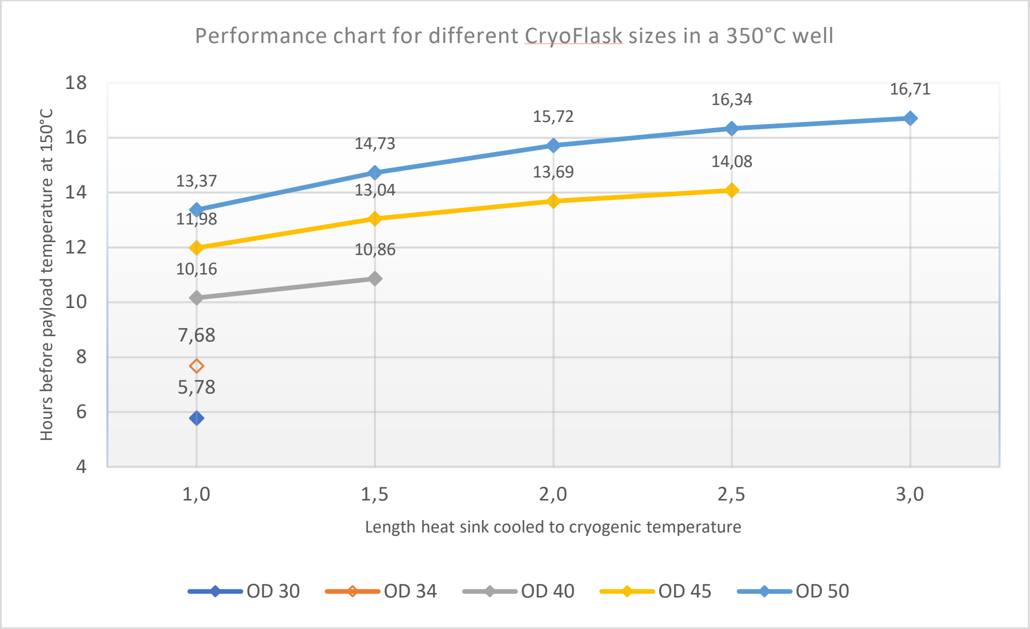

Figure 6. Chart showing performance of different CryoFlask sizes. All simulations have been performed with the same payload size and length. Simulation with outer diameter (OD) 30 mm of payload is without CryoFlask technology for reference.

The chart in Figure 6 shows several parameters. Along the x-axis is shown the length of the heat sink cooled down to cryogenic temperature (-196°C). Along y-axis the number of hours before the payload reaches 150°C is plotted. OD denotes outer diameter of the payload and cryogenic heat sink section. This diameter does not include vacuum flask and pressure housing. The reason for not including these components is that the total outer diameter would then depend on the configuration of the vacuum flask and pressure shield used (thin wall flask – separate vacuum flask and pressure shield, or thermohousing – vacuum flask and pressure shield combined into one piece), and also the thickness of material in the pressure shield and pressure rating of the tool. These components have very little influence on the thermal performance of the tool. In the simulations we have used the same parameters for the vacuum flask throughout all simulations, hence the simulation results only depend on length and OD which enable us to directly compare the simulation results of each case. A traditional design with payload OD of 30 mm has been included in the chart for reference.

As a general result of the simulations, we see the two following overall results:

- Larger outer diameter (OD) gives the largest increase in operation time.
- Longer heat sink cooled down to cryogenic temperature also increase operation time, but this effect will fade with length.

These results in general also apply to traditional designs.

4. PRELIMINARY TESTING OF CENTRAL PARTS OF CRYOFLASK

4.1 Thermal valve function

An early prototype of the thermal valve has been built to test functionality and performance. By adding heat wire around the housing of the thermal valve we simulate the process of heat flux into the payload of the tool. At a defined temperature – in this test about 48°C – the thermal valve will connect with the heat sink with low temperature. In our test we used a square copper bar placed in ice-water to simulate the cryogenic heat sink. Test results is shown in Figure 7. The chart shows the following stages:

- At time 0 minutes: Heat wire around payload is powered up, heating up the payload. Ice water is added to the heat sink to cool down the square copper bar acting as the cryogenic heat sink.
- At time 35 minutes: Thermal valve is thermally connecting the payload with the heat sink in the ice water. This stops the increase in temperature of the payload and stabilize it around 50°C.
- From 35 to 315 minutes: Payload temperature is kept stable at around 50°C and slowly increasing when the heat sink temperature is increasing. In this period the thermal valve´s heat conductivity increases to compensate the temperature increase in the payload to keep the payload as close as possible to 50°C.
- At time 315 minutes: Heat wire around payload turned off. The temperature of the payload is decreasing, and the thermal valve is no longer thermally connecting the payload with the heat sink.

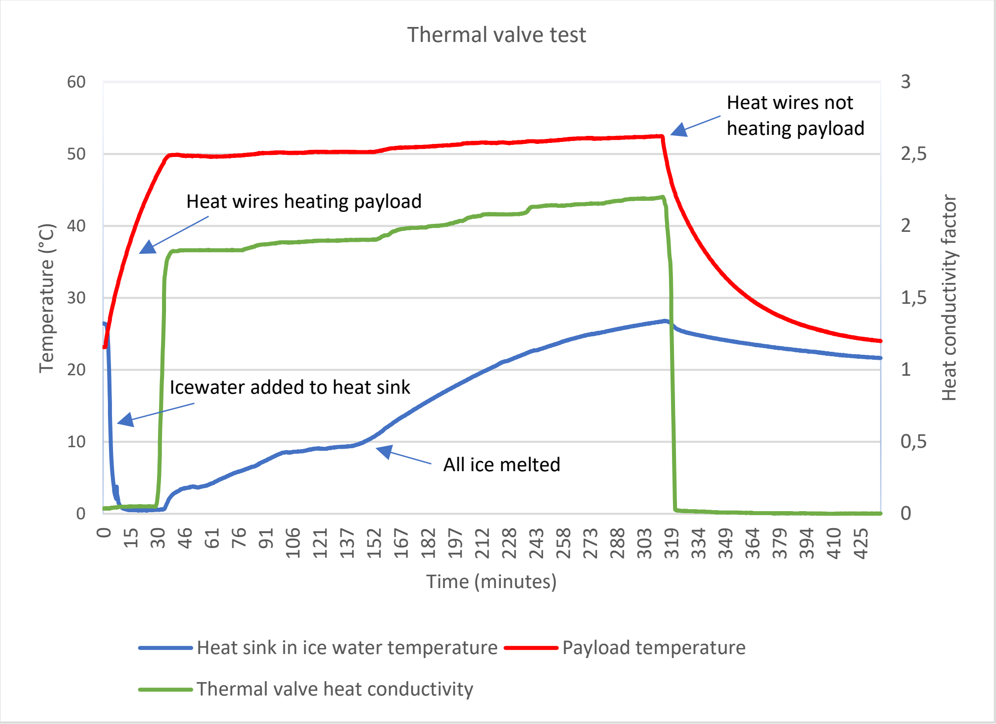

Figure 7. Results from thermal valve test. The thermal valve connects the payload with the heat sink in ice water when the payload reaches 48°C.

The thermal valve is a fully passive design not being controlled by electronics, motors and batteries. This enables less risk of failure during logging operations. The thermal valve can be designed to be activated in the range from as low as 4°C to 100°C.

4.2 Cooling of heat sink to –196°C using pipes and liquid nitrogen

Initial tests have been performed to verify cooling of the cryogenic heat sink to cryogenic temperatures. In this test a copper bar of diameter Ø50 mm and length 1.1 m with cooling pipes has been tested (Figure 8).

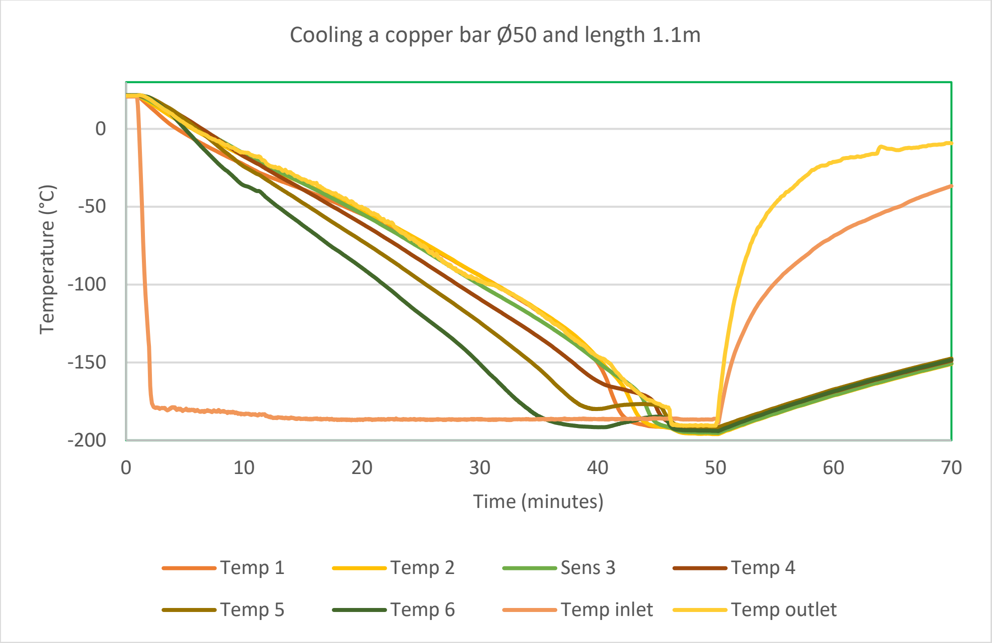

Figure 8. Results from cooling of copper rod with liquid nitrogen to –196°C.

Liquid nitrogen is flushed through the cooling pipes. Temperature sensors are attached to the copper bar, inlet and outlet pipes. Temp 1 sensor is attached close to the inlet/outlet of the bar and Temp 6 sensor is attached close to the opposite end of the copper bar. In this test the copper bar was exposed to air and not thermally isolated inside a vacuum flask as it will be when mounted in the CryoFlask setup.

Test graphs in Figure 8 show the cooling of the copper bar. The cooling period was about 45 minutes before the full copper bar was cooled down to –196°C. This cooling time will be shorter when the copper is placed inside a vacuum flask.

5. CRYOFLASK PROTOTYPES

The project will build two prototypes of different lengths utilizing the CryoFlask technology. The project does not include building the payload components containing electronics and sensors but will instead use electronics and sensors (payload) from existing tools in the market. The project will specifically adapt the payload section of the CryoFlask prototypes to fit the payload of the Probe1 Protherma tool, Memory tool (for memory recording when using Protherma on slickline) and the K10 tool (Kuster K10). No modifications are needed to the payloads of Protherma, Memory and K10 tools.

The two CryoFlask prototypes can easily be adapted to other payloads with different OD sizes and lengths by only changing two parts in the CryoFlask payload section. Both prototypes can be operated as single logging tools either on slickline with logging in memory mode or on E-line with power and data communication to surface. The two prototypes can also be connected in one tool string enabling several CryoFlasks logging tools on the same string carrying different payloads.

5.1 Specification of prototypes

The two prototypes built in this project will have the following specifications:

Parameter	**CryoFlask 1**	**CryoFlask 2**
Max operation temperature	450°C	450°C
Max pressure	10 000 psi	10 000 psi
Length	4.8 m	3.3 m
Outer diameter	69.85 mm (2.75")	69.85 mm (2.75")
Length payload section	1.86 m	1.21 m
Operational time in a 350°C well before payload reaches 150°C	17.5 hours (16 hours*)	15 hours

* Operational time simulated with 5 W internal heat generated from payload.

6. CONCLUSION

Finite element simulations show that by cooling the heat sink to cryogenic temperature (below -180°C, ref. National Institute of Standards and Technology) a significant increase in operation time for logging tools in geothermal wells can be achieved by utilizing the technology patented by Norwegian Well – CryoFlask.

Finite element simulations show in addition that by introducing a thermal valve in combination with a heat sink cooled down to cryogenic temperature, the payload temperature can be held low and stable during the operation time in the well.

The CryoFlask technology enables longer operation time in wells with use of high temperature rated electronic components (175/177°C) and/or also low temperature rated electronics (150°C) in high temperature geothermal wells.

The CryoFlask technology also enables tool manufacturers to use high quality, but far cheaper and much more readily available electronic components (85°C for industrial applications, and 125°C for military applications) in their future tool design for high temperature geothermal wells. In fact, the CryoFlask technology also enables future tools for geothermal wells to be designed using high quality, cheap and readily available consumer electronics components with a temperature rating of 70°C.

Currently two prototypes are under production. In the near future (2021) these prototypes will be tested in geothermal wells to demonstrate the CryoFlask technology in a real geothermal wellbore environment.

The project has solved several technological challenges of implementing this technology by building and testing critical components enabling this technology.

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