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High Temperature 300°C Measurement While Drilling (MWD)

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ABSTRACT

Many countries around the world, including the USA, have untapped geothermal energy potential. Enhanced Geothermal Systems (EGS) technology is needed to economically utilize this resource. Temperatures in some EGS reservoirs can exceed 300°C. To effectively utilize EGS resources, an array of injection and production wells must be accurately placed in the formation fracture network. Therefore, EGS can greatly benefit from a high temperature directional drilling system. Most commercial services for directional drilling systems are rated for 175°C while geothermal wells require operation at much higher temperatures. Two U.S. Department of Energy (DOE) Geothermal Technologies Office (GTO) projects have been initiated to develop a 300°C capable directional drilling system, the first developing a drill bit, directional motor, and drilling fluid (award number DE-EE0002782), and the second adding navigation and telemetry systems. This report is for the second project, "High Temperature 300°C Measurement While Drilling System", award number DE-EE0005505.

The "High Temperature 300°C Measurement While Drilling (MWD)" system complements the already developed drilling system with real time navigation capability. It is comprised of 175°C directional measurement electronics including the required sensors for measuring inclination and azimuth in 3 axes. It is embedded in a cooling and temperature isolation system to protect the electronics and sensors from the higher temperature outside the system, which can reach 300°C. Building the cooling and isolation system from non-magnetic materials and keeping a required distance to any magnetic component, such as alternator parts, ensures a high quality measurement of the earth's magnetic field. This is required to achieve the specified navigation accuracy. The MWD system has a turbine driven alternator that is capable of delivering the required electrical energy to the electronic system at a 300°C borehole temperature. Measured data will be communicated to the surface by mud-pulse-telemetry. For this purpose the tool has a mud-pulse-valve that is controlled by the measurement electronics to establish a serial data communication via the mud stream. The mud-pulse-valve is also built to operate under 300°C borehole conditions.

Three prototypes of the 300°C MWD were built and tested. These systems are available for a joint application with the previously developed 300°C drilling system, in a geothermal well.

ACKNOWLEDGEMENT

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2. Executive summary

The Geothermal Technologies Office (GTO) of the United States Department of Energy (DOE) awarded Baker Hughes a project with award number DE-EE0005505 for the development of a "High Temperature 300°C Measurement While Drilling System". The objective of this project was to develop a prototype of a Measurement While Drilling (MWD) system to add real time navigation capability to the already developed drilling system for the creation of wellbores for Enhanced Geothermal Systems (EGS). The MWD system was to provide optimum performance for at least 50 hours in temperatures up to 300°C (572°F) in hard rock formations, and under the high pressures encountered in boreholes at depths of up to 10,000 meters.

The task was to design MWD technology for 300°C including the required electrical power supply and the mud pulse telemetry system. The MWD system should provide the same state of the art measurement accuracy and precision, as is generally accepted in oil field applications, to EGS wells.

We have developed and built three prototypes of an MWD system that can be applied in high temperature geothermal wells for at least 50 hours under the extreme temperature of 300°C. The system was successfully tested under drilling conditions in a test well at Baker Hughes' Experimental Test Area (BETA) near Beggs, Oklahoma. The cooling and temperature isolation system was extensively temperature tested on a 300°C test bench in Celle, Germany. During these tests the MWD system showed that it can run under 300°C for at least 50 hours and that it can protect the measurement electronics from the extremely high ambient temperature by maintaining the temperature in the electronics compartment at 170°C while the outside temperature was 300°C. Development and testing highlights are:

1. <u>BETA test:</u> The complete 6 ¾" MWD system was tested in the Baker-Hughes test-well in Oklahoma (BETA) in December 2017. The MWD system was used on top of a standard directional drilling motor. It provided high quality survey data from the wellbore. In addition it transmitted the tool-face direction of the directional drilling motor in real time to support steering activities on the surface. The transmission rate of the special 300°C mud pulse telemetry system was in the range of fast data rate capabilities of known standard oil-field data transmission systems.
2. <u>High temperature lab test of alternator system:</u> The alternator that is required to provide electrical energy to the measurement electronics and to the mud pulse data transmission system was extensively tested under 300°C in a dedicated test stand. It was mechanically driven from outside of an oven by a shaft transmitting the rotation through the wall of the oven, and electrically loaded to simulate the load of the Electronics and the mud-pulse telemetry system. The actual temperature of the alternator exceeded 300°C due to electric and magnetic losses during operation.
3. <u>High temperature lab test of the electronics and cooling system:</u> The measurement electronics was tested in combination with the isolation and active cooling system in a test at various temperatures, including 300°C. The system showed that it can protect the measurement electronics from high temperature external influences. A cooling control system was used to maintain the temperature inside the temperature isolated area at maximum of 170°C while the outside temperature was much higher and reached the required 300°C. To monitor the system a mud pulse control valve was placed inside the oven but outside the temperature isolated area of

the electronics (i.e., under high temperature). It was electrically connected to the electronics and mechanically loaded to simulate mud pressure.

4. Flow loop test performed with the entire MWD system: A flow loop test was performed with the entire system. The purpose of this test was to prove that the system can operate in the required flow rate range and that the mud pulses of the pulse valve can be decoded with the standard Baker Hughes surface system.

Unfortunately, at the end of the project, the unavailability of a geothermal well led to an inability to complete field testing of the MWD system. We have attempted to organize a field trial but so far have not found an operator ready to drill the appropriate hole. However, Baker Hughes intends to complete the field trial of the entire directional drilling system in an EGS well. In addition to geothermal wells, we are open to field tests in high temperature oil and gas wells.

Baker Hughes would like to thank the U.S. Department of Energy for its collaborative funding of this project, which has demonstrated that high temperature components for directional drilling the most challenging EGS wells can be designed and manufactured. It remains to be demonstrated that these components can be built in a commercial environment – but the results of this R&D project is a very promising first step and one that would not have been accomplished without U.S. DOE funding.

3. Introduction

The drilling of geothermal wells for Enhanced Geothermal Systems (EGS) requires precise placement of injection and production wells [1]. If there is any direct pathway from the injection to production well then there will be insufficient heat exchange. On the other hand, if heat exchange impedance is too high, that is if the wells are too far apart without sufficient fractures between wells, flow would be poor and heat exchange would still be insufficient. Important steps in geothermal well development are illustrated in Fig. 1 [taken from reference 1]. Precise well positioning will achieve maximum heat exchange and shall render EGS economical. This precise placement can only be done with a directional drilling system (DDS) and precise measurement-while-drilling (MWD) system. There is no DDS directional drilling system in the industry capable of surviving the 300°C temperatures encountered in typical EGS wells.

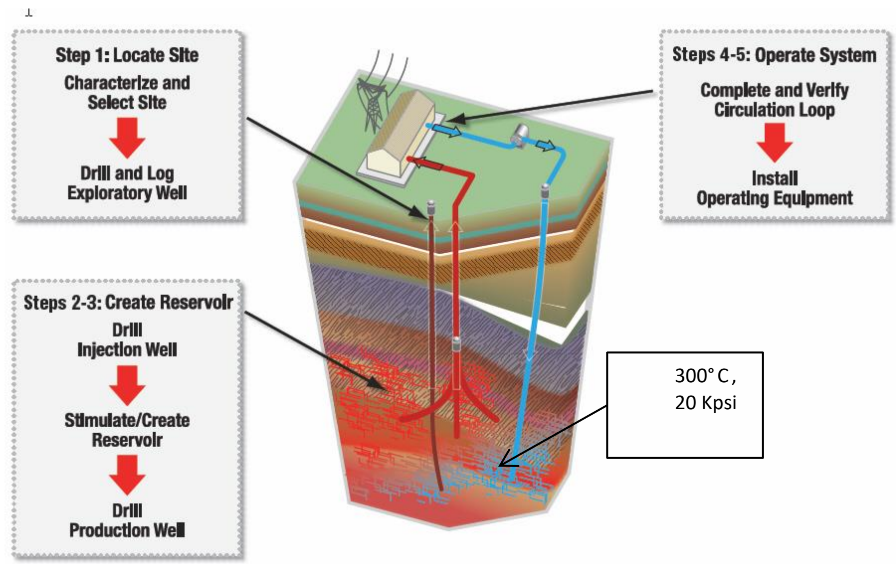


Figure 1 Typical production and injection well in a geothermal system [1]

Development of a directional drilling system for geothermal applications capable of drilling hard rock at depths to 10 km, at temperatures as high as 300°C is seen as a necessary step in making EGS technology economical and efficient. This project, DE-EE0005505, produced 3 prototypes of Measurement While Drilling (MWD) systems capable of navigating in EGS environments. Further, this high temperature MWD system is designed to operate with the directional drilling system that was developed in a separate project, DE-EE0002782. The directional drilling system is shown in **Figure 2**. The MWD system is placed on top of a steerable motor.

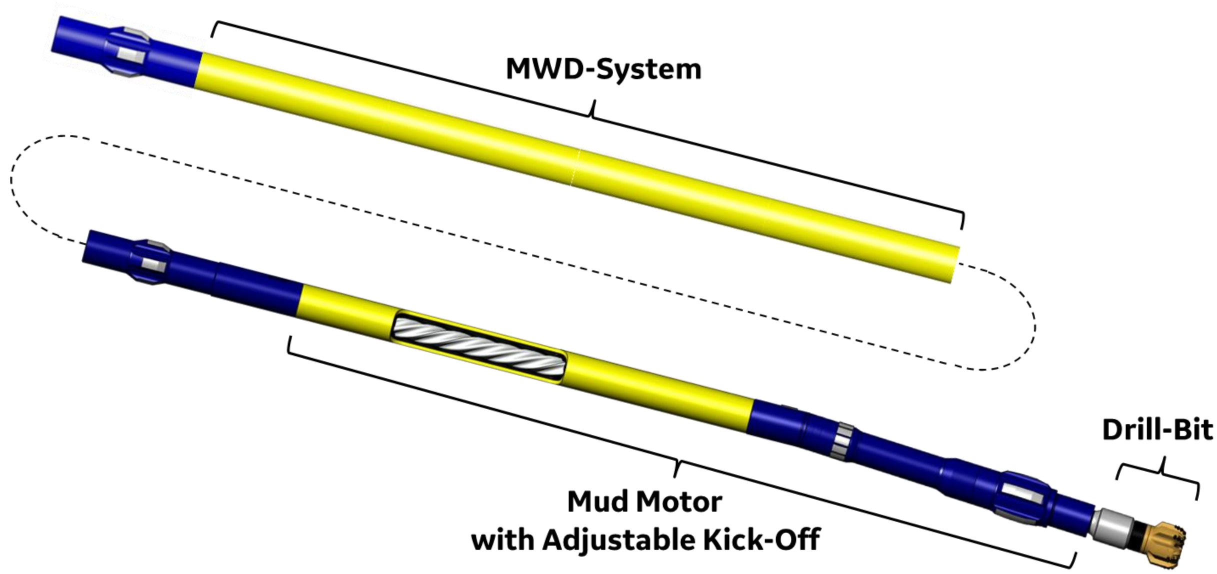


Figure 2 Typical MWD system comprising of Drill Bit, Mud Motor with Adjustable Kick-Off Sub and MWD

The task is to develop measurement electronics and sensors that cannot only survive the 300°C temperature, but that should also provide the required measurement accuracy and precision in this high-temperature, high-vibration, high-pressure environment. In addition an electrical power source was required and a system to provide reliable real-time data communication from the hot borehole to the surface system at the drilling rig. The project team members were organized into closely coordinated groups, each working on the deliverables, to assure smooth integration.

In order to design the MWD system many components were individually tested to finally create the concept and design the subsystems.

Earlier feasibility tests did not yield promising results that could justify an application of certain components and sub-systems. For example it was found to be impossible to build an entire MWD-electronics that could survive drilling vibrations under 300°C temperature. There are several components feasible to operate under 300°C but connection technology and high integrated electronic circuitry was not available at the time the system was designed. In addition there were no high temperature batteries available that could be operated under EGS drilling conditions. Many deviations from the original concept were needed to finally build a system that could be applied for drilling at 300°C.

The final design of the MWD system consists of a 300° mud-pulse telemetry transmitter (Pulser), a 300°C turbine driven alternator, and electronics with sensor package inside an active cooling system. The individual components are described in the following chapters.

4. MWD electronics and sensors

The core module of the MWD electronics system is an electronics and sensor package which is designed and built for 175°C. The module has three accelerometers to measure the gravity field in three axes to determine the inclination and to derive the tool-face orientation for steering the drilling system. An additional three-axis magnetometer package is used to measure the azimuthal direction of the tool. Using the earth magnetic field for determining azimuth requires building all components in the proximity of the sensors from non-magnetic materials. This poses an additional challenge for the design of the 300°C MWD.

Figure 3 shows the concept of the active cooling system that protects the measurement electronics from temperatures exceeding 175°C, which is the maximum temperature the electronics and sensors can operate under while taking high quality measurements.

The electronics are housed in a Dewar- or Thermos flask. It is assembled on an aluminum frame that carries a water evaporator and a control valve to supply the correct amount of liquid water to the evaporator. The evaporation valve is controlled by a cooling controller electronics that compares the inside temperature of the Dewar flask with the maximum temperature that is required to keep the electronics safely under the 175°C limit. The water that is needed for evaporation is stored outside the Dewar flask in a pressure tight container. In order to avoid evaporation of the water outside the Dewar flask a pre-pressure is needed that keeps the pressure inside the water container always above the steam-pressure of water at 300°C. This pre-pressure is created by a Nitrogen buffer that is pumped into the water container.

After evaporation the water vapor is stored in a Zeolite bed by an adsorption process. The specially selected Zeolite is capable of storing water even under 300°C. The water container and Zeolite reservoir are outside the Dewar Flask at high borehole temperatures but protected against high borehole pressure by pressure barrels.

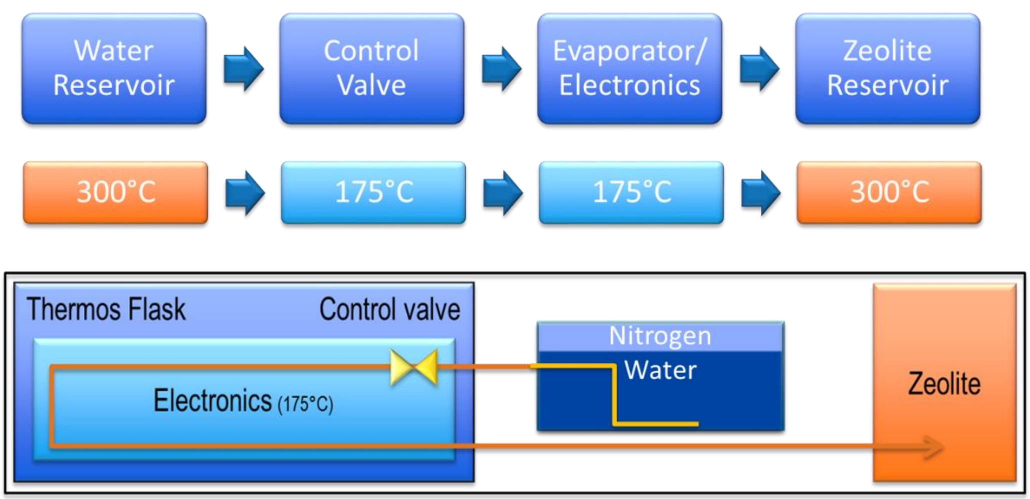


Figure 3 Active cooling system for the 300°C MWD system using water evaporation and steam adsorption in Zeolite

Figure 4 shows the technical embodiment of the described concept. The biggest portion of the system is occupied by the Zeolite Reservoir. Between the magnetic field sensors and magnetic components of the drill-string is a certain distance (non-mag spacing) required to avoid magnetic interference of the measurement of the earth's magnetic field. In order to provide this non-mag spacing in the 300°C MWD system, the water container and the Zeolite-reservoir were built from non-magnetic material and placed in-between the sensor section and the magnetic steel of the drilling motor.

The entire MWD system is little more than 10 m long. This allows for handling and transportation of the entire system in one piece.

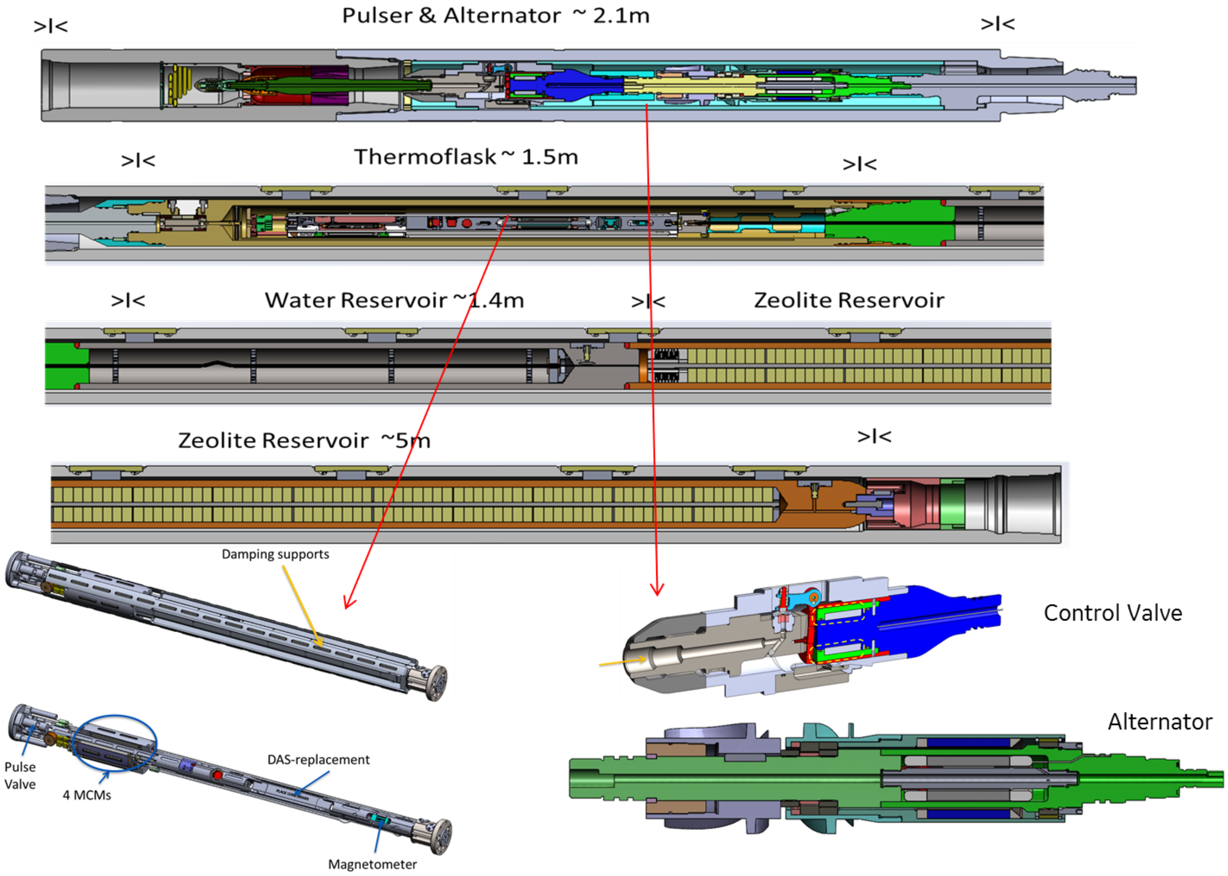


Figure 4 MWD system with pulser and alternator at environmental temperature, and with electronics and directional sensors inside an active cooling system

5. Electronics System

Figure 5 shows a block diagram of the electronics system. Except for the pulser control valve and the alternator, all electronics components are inside the Dewar flask.

The directional unit takes raw data from all sensors, three axis magnetic field and three axis gravity field. Based on these sensor readings it calculates the inclination, the azimuth, and the tool-face. It performs mathematical operations and applies necessary temperature corrections. It has a separate low-voltage power supply for feeding electrical power to all components of the directional unit. In addition the system has an alternator high voltage power supply, cooling controller electronics and a solenoid driver for controlling the mud pulse telemetry.

The high voltage power supply rectifies and regulates the alternator AC voltage. Since the alternator voltage depends on the speed of the turbine which depends on the flow-rate, the high-voltage power supply has to operate with any voltage between 60 and 160 V.

The temperature controller is designed as a two point controller. It measures the inside temperature of the Dewar flask, and compares the measured value with a set-point and controls the evaporation control valve accordingly. The control characteristics of a two point controller is sufficient for the 300°C MWD system. The deviation from the set-point is low and the time constants of the cooling process are sufficiently long.

The solenoid driver takes the control signals from the directional unit and translates them into sufficient electrical power to actuate the solenoid inside the pulse-control valve.

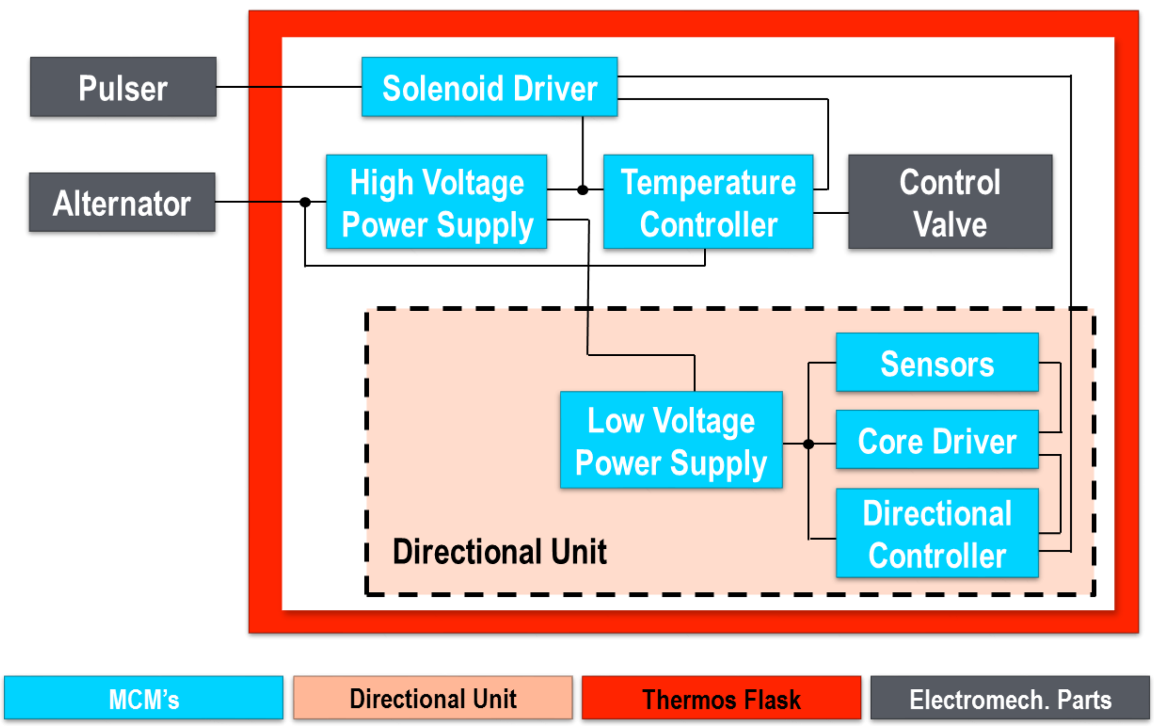


Figure 5 Concept block diagram of 300°C MWD

Figure 6 shows an assembled electronics frame with water evaporation system and the connection to the water container and Zeolite reservoir. This frame was used later for the high temperature tests of the entire system to verify the functionality of the cooling at 300°C.

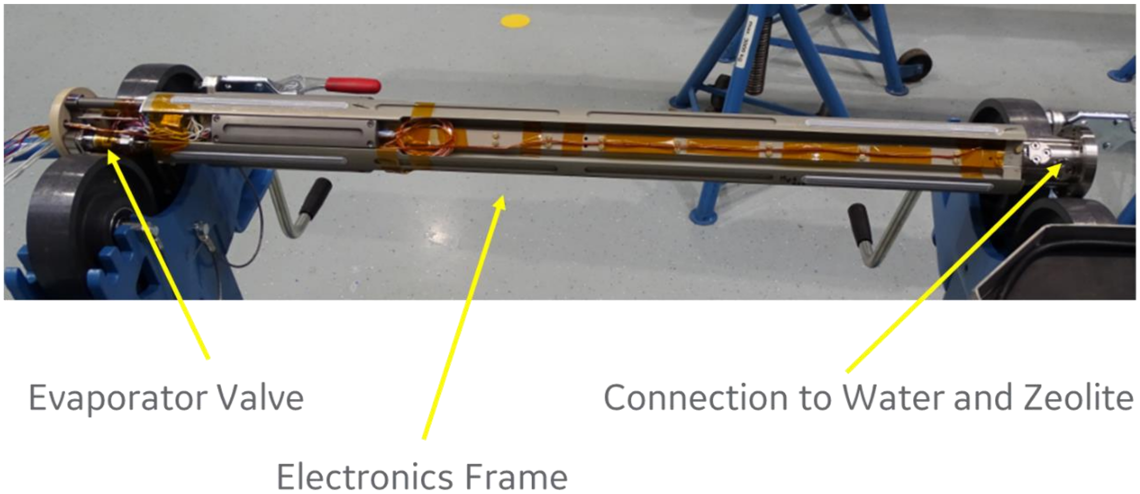


Figure 6 Assembled electronics frame with water evaporation cooling

6. Active cooling of electronics and sensors

The active cooling system uses liquid water that is evaporated to cool the electronics modules inside the Dewar flask. The Dewar flask is a fundamental component of the cooling system. It limits the amount of heat that migrates from the outside into the electronics area. Since the system will be applied under drilling conditions, it has to withstand drilling vibrations and the shock load associated with handling and operations at the rig-site and in the well. A special support structure is used to maintain the integrity of the flask, including the vacuum super insulation inside the Dewar flask, and supports the electronics frame rigidly enough to maintain its position. The Dewar flask has a cable conduit on the upper side in order to connect alternator and pulser. On the lower side it has a special support structure to connect the electronics frame to the mechanical components outside the flask. This structure has to combine low thermal conductivity with high mechanical strength and stiffness. A concentric tube connects the water container and the Zeolite reservoir to the evaporator inside the flask. It carries the water on a bigger tube into the Evaporation system and delivers the steam on a smaller tube inside the bigger water tube to the Zeolite.

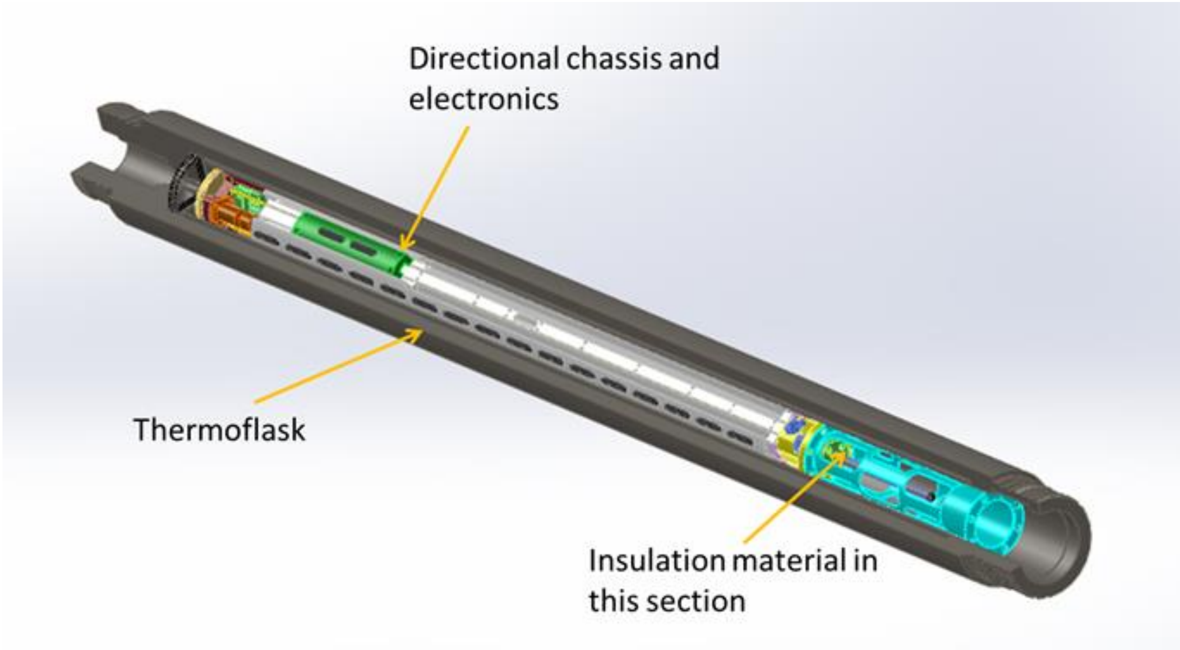


Figure 7 Electronics frame inside of the Dewar flask

Figure 7 shows the Dewar flask and the components inside. The outer wall of the flask has been designed strong enough to carry the high geostatic pressure inside the borehole.

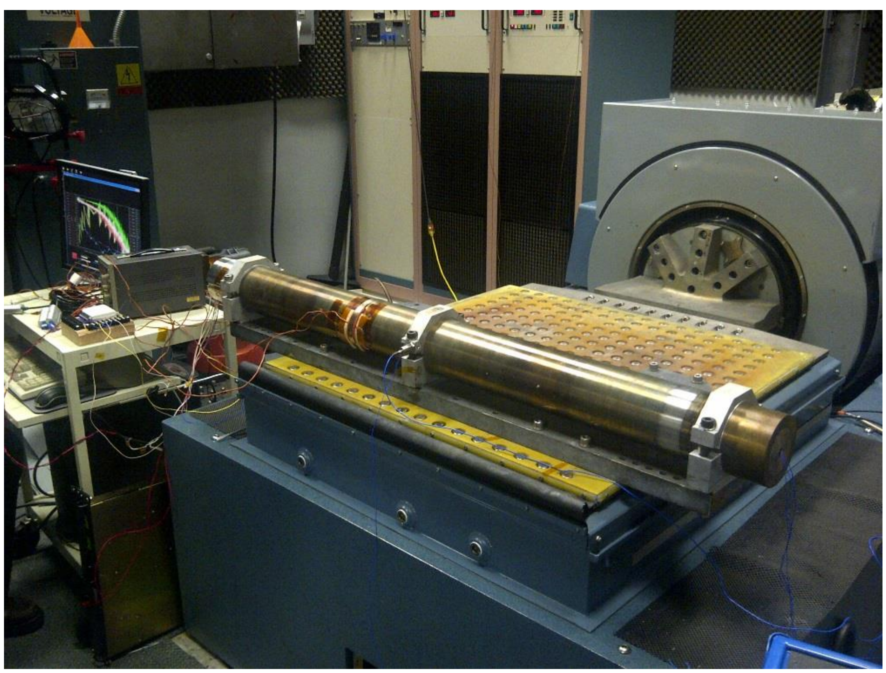


Figure 8 Dewar flask for the active cooling system with high pressure resistant housing on a shaker table to verify vibration resistance

In order to prove the shock and vibration resistance of the Dewar flask an extensive test program was carried out. After a further design iteration the Flask survived the test procedure. The final design was used for the built prototype. **Figure 8** shows a test flask on a shaker table during a vibration test in the lateral orientation.

The thermos flask is connected to a water container by a lock nut connection. This type of connection is used in the 300°C MWD to avoid rotation of metallic O-ring seals during assembly. Metallic O-rings are used since elastomeric O-rings will not survive the 300°C temperature in combination with high hydrostatic pressure. Therefore all seals sealing against borehole mud are designed as metallic O-rings. The water container is filled with about 3.7 liter of distilled water. In order to avoid any evaporation of the water outside the Dewar flask, the water container is, in addition, filled with Nitrogen. The Nitrogen increases the pressure inside the container to about 5 bars above the vapor pressure. This ensures that water is kept liquid even at the 300°C temperature.

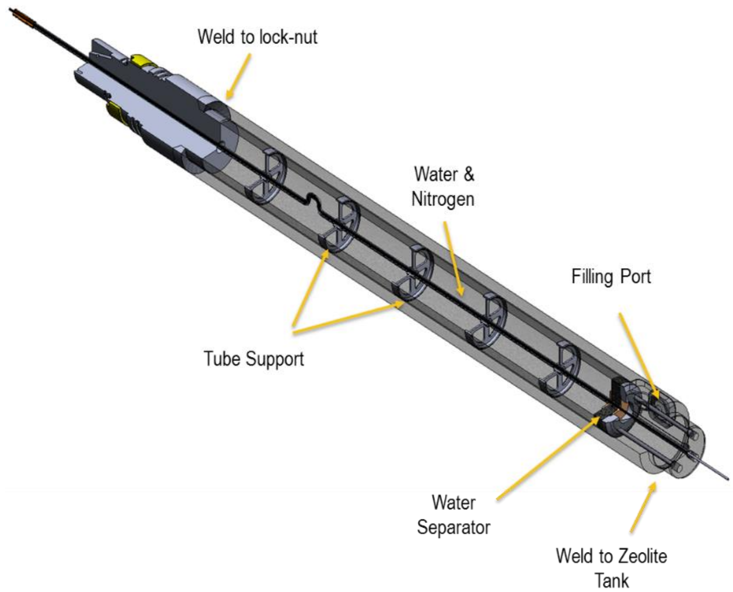


Figure 9 Assembly of the water tank with water separator to extract water w/o Nitrogen

In order to extract only water for evaporative cooling a separation device is needed to leave the Nitrogen in the container and let only the water flow out. This separation is realized by an iron sponge. This sponge draws the water out of the liquid gas mixture inside the water container by capillary forces. On the outlet side of the sponge a tube delivers the water to the electronics frame inside the thermos-flask.

Figure 9 shows a drawing of the water container, along with separator and support wheels for the concentric tube delivering water and steam.

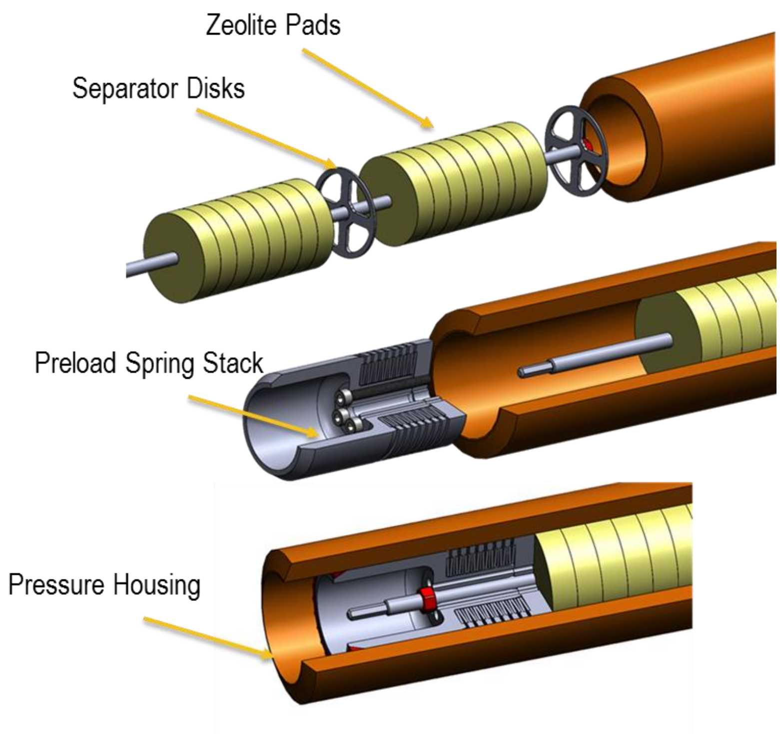


Figure 10 Zeolite reservoir with spring pack to preload and compensate different thermal expansion

The inner tube of the concentric tube is connected to the Zeolite reservoir that has to store the evaporated water. Zeolite is a microporous aluminosilicate material. The type of Zeolite that is used in the 300°C MWD is specially designed to maximize water adsorption under higher temperatures. It is manufactured in disk shaped bodies that fit into one of the tool elements. A length of about 4.5 m is filled with these Zeolite disks.

Figure 10 shows the general design of the Zeolite reservoir. A tension rod in combination with a Bellville spring package holds the disks together. This is necessary to compensate for the different thermal expansion of Zeolite and metallic material of the pressure housing, and to avoid destruction of the Zeolite material under vibration and shock.

Zeolite that has been used during drilling for cooling of the electronics can be dried and refurbished for the next application. Drying is done preferably at an elevated temperature with support of a vacuum pump connected to the Zeolite reservoir.

7. 300°C Alternator

The 300°C MWD tool needs electrical energy to perform the downhole measurements. There was no battery technology available that could safely operate in a temperature range from 20°C during surface testing, to the 300°C during downhole application. Therefore, a high temperature turbine-driven alternator was developed.

In order to avoid elastomer seals and pressure compensation areas, a special design was conceived. This uses an outside rotor which carries permanent magnets, and an inner stator having a high temperature resistant winding package. **Figure 11** shows the alternator with a one stage turbine

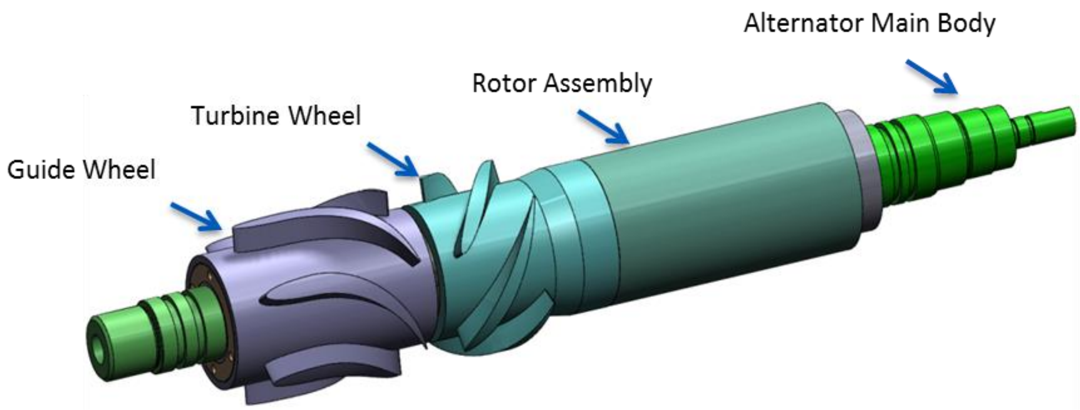


Figure 11 Alternator with guide- and turbine wheel

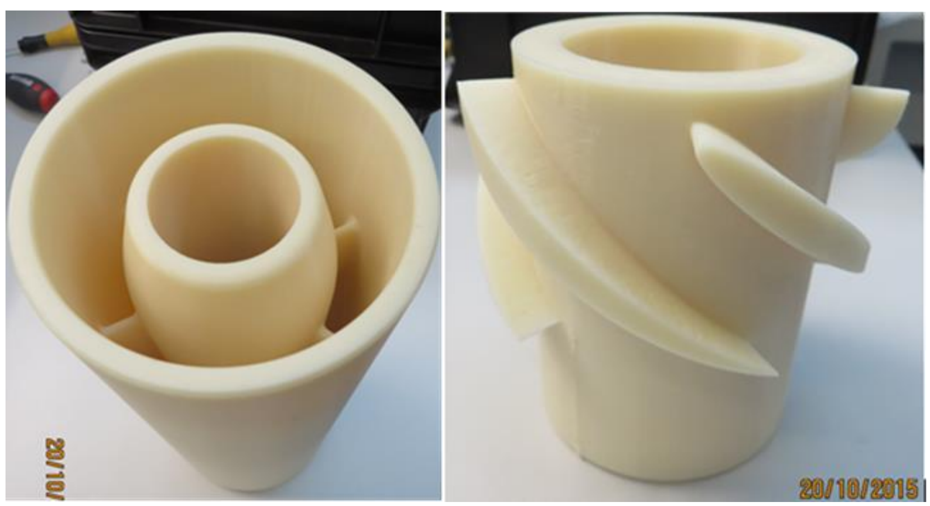


Figure 12 Alternator guide- and turbine wheel for concept testing on a water flow line

Figure 12 shows pictures of the guide wheel and the turbine wheel that were for test purposes, built from plastic material. These test parts are a good way to test flow properties before building the real steel parts. **Figure 13** shows the speed versus flow rate characterization for the alternator using the rapid prototyping plastic turbine parts. There is only a low load sensitivity in the turbine speed, and the turbine covers the required flow rate range perfectly.

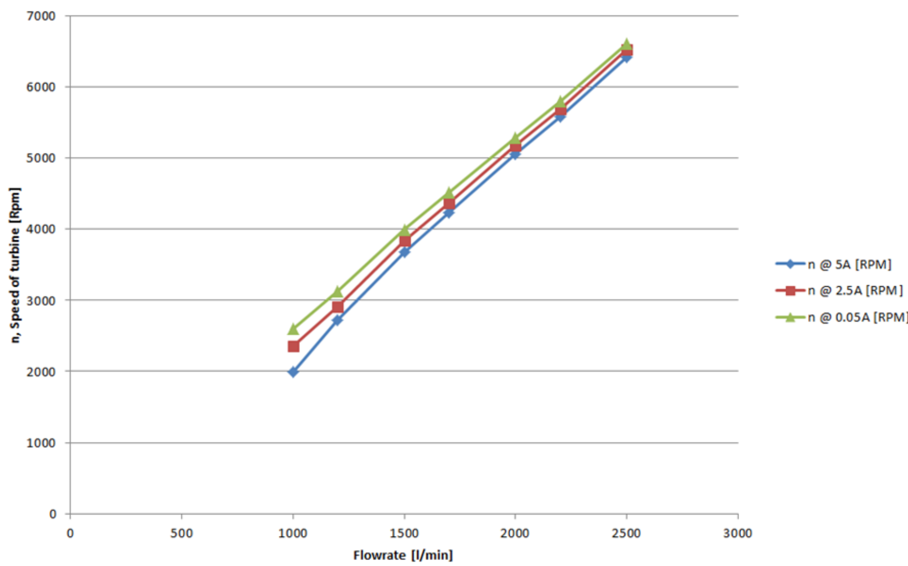


Figure 13 Test results showing alternator rpm vs. flow rate

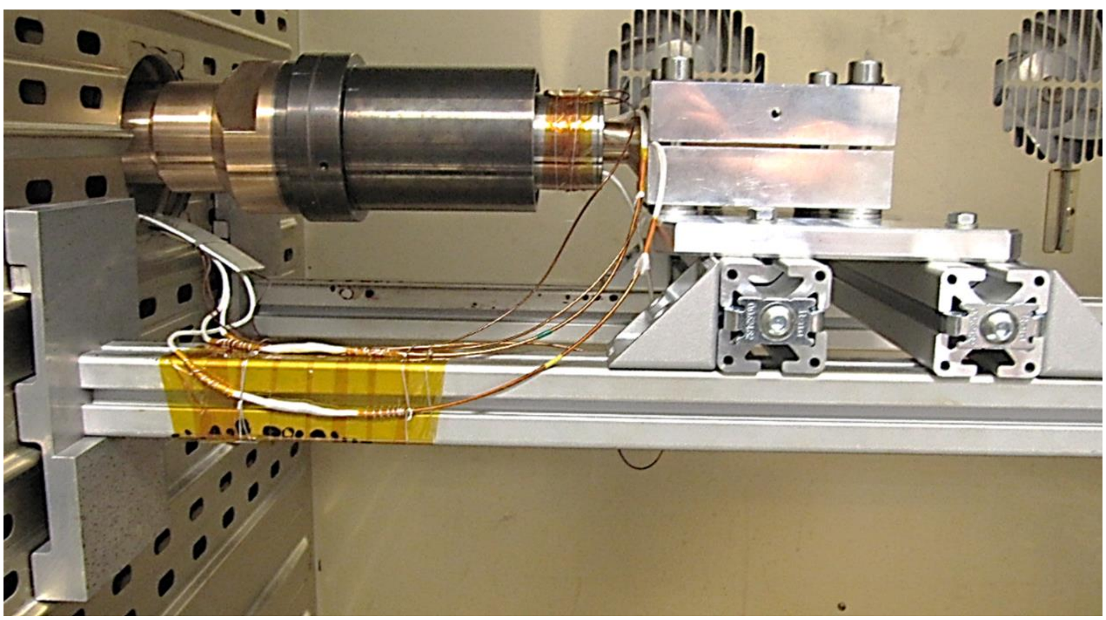


Figure 14 Alternator test set-up in a 300°C oven

In order to test the alternator performance, an oven test was devised. **Figure 14** shows the inside of a 300°C oven that was used for this test. The alternator was driven from the outside and a shaft delivered rotation into the oven. Test conditions were harder than they would be later in a real downhole situation, because the heat created by the losses of the alternator cannot efficiently be dissipated in air during oven testing. However, with both tests it was possible to define a safe operating range for the alternator. In a real application, drilling mud will absorb the heat loss of the alternator winding and will lubricate the turbine bearings.

8. 300°C Pulser

Mud pulse telemetry is essential in measurement-while-drilling applications to establish real time data communication to the surface. This is done by encoding data in pressure pulses inside the bore of the drill string. The pulse valve that creates pressure pulses downhole consists of a main valve assembly (MVA) and a control valve assembly (CVA).

Figure 15 shows the general concept of the developed pulse valve. The main valve has a valve body that is mud hydraulically activated and can slide into a valve seat. The valve seat can be replaced, during assembly of the system, by another seat with different diameter to deliver a certain flow-rate range. The activation pressure for the valve body is taken trough a mesh from an area before the valve seat. This design is characterized by a self-energized valve action. The hydraulic activation area of the main valve is in the low pressure stage of the pulser vented to an area below the main valve. Thus the valve body is in a retracted position and there is a low pressure created over the valve. If the control valve closes the venting port, the area below the valve body is filled with the pressure that exists in front of the main valve. As a consequence the valve body slides further into the valve seat creating a higher pulse pressure up to the point of equilibrium.

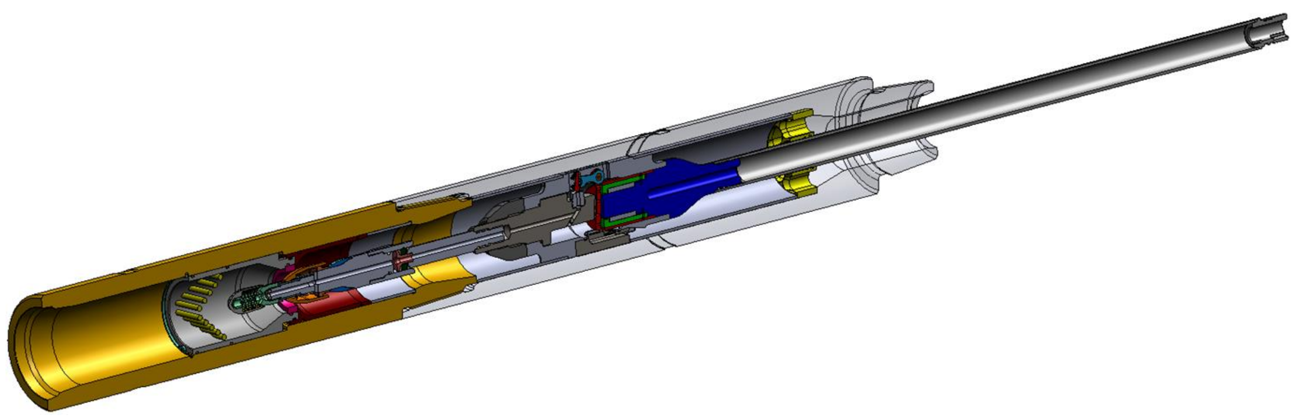


Figure 15 300°C Pulse Valve

Figure 16 shows the control valve which is built without high pressure elastomeric seals and without pressure compensation areas. The Valve is energized by a solenoid that is embedded in a pressure tight structure. The magnetic flux that is created by the solenoid is guided out of the pressure sealed area and acts on a soft-magnetic plate that pivots about an axis and closes a valve in the mud-flow.

Figure 17 shows the soft magnetic plate that is used in the control valve. It has holes in the plate to cope with the mud gap that exists between plate and solenoid and needs to be replaced when the valve closes.

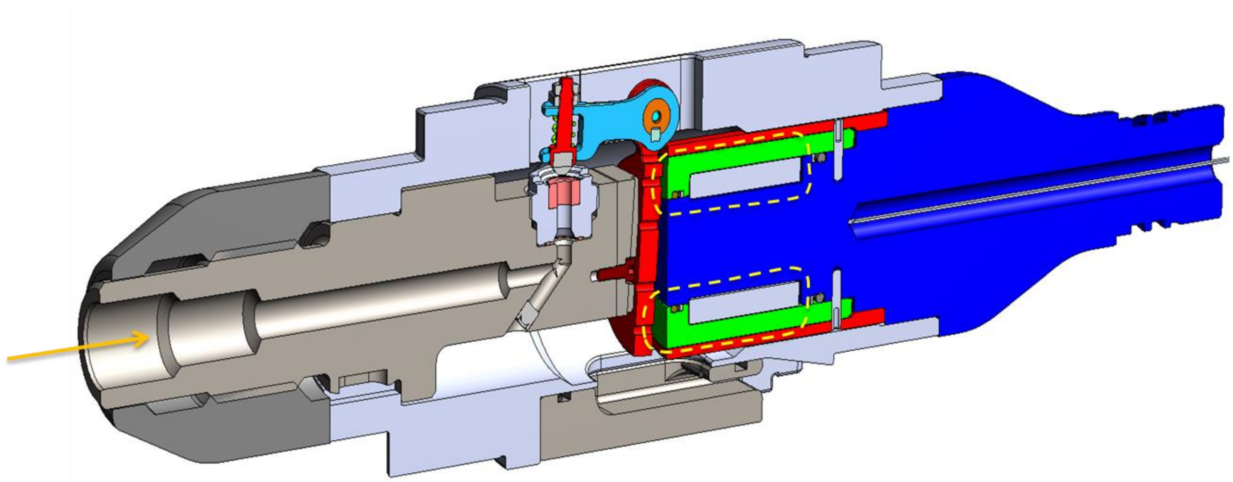


Figure 16 Control valve assembly (CVA)

Figure 17 Control valve assembly (CVA)

The entire pulser was tested in a flow loop to characterize the idle- and the pulse pressure. In addition a mud test sequence was carried out to verify that the system works under real mud conditions and that the mechanical systems will not experience any blockage caused by the high solid content of the mud.

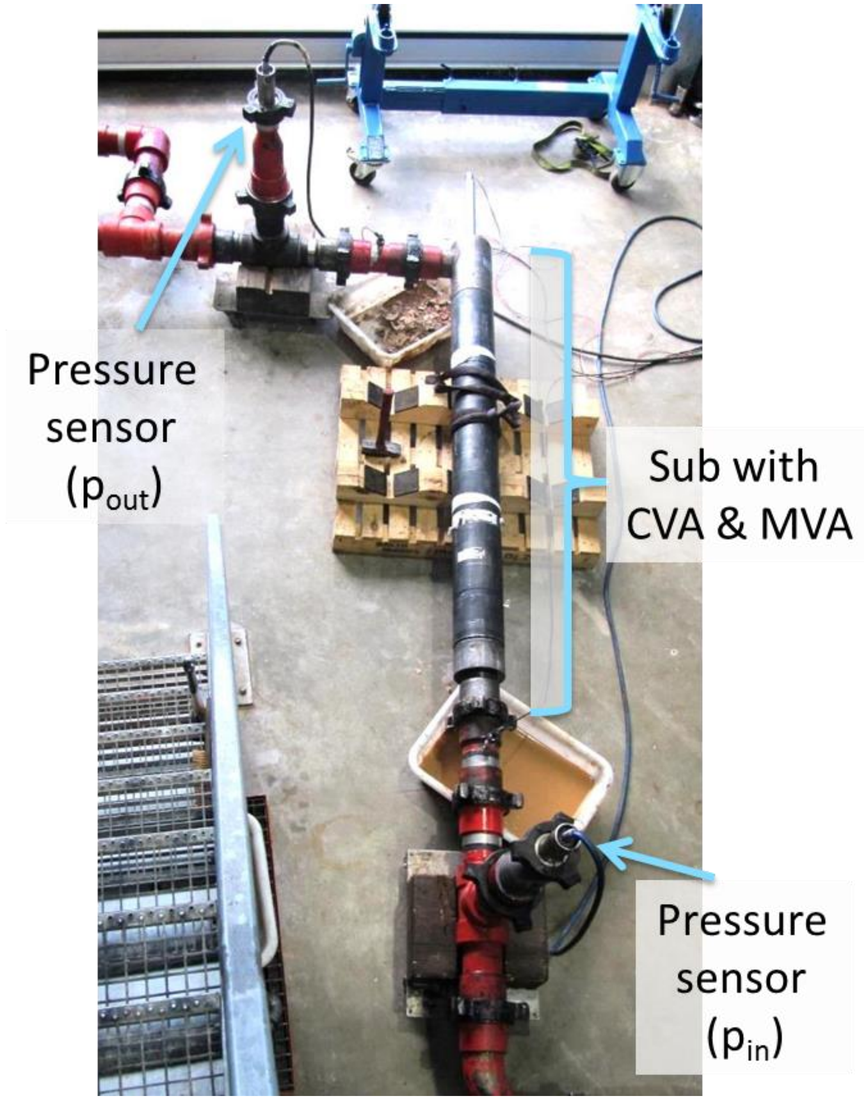


Figure 18 Control valve assembly (CVA) and main valve assembly (MVA) in a flow loop test to characterize it and prove functionality under mud conditions

Figure 18 shows the test set-up with flow line and points of pressure measurements. In order to avoid cavitation the test was performed with a pre-pressure at the return line of the mud flow.

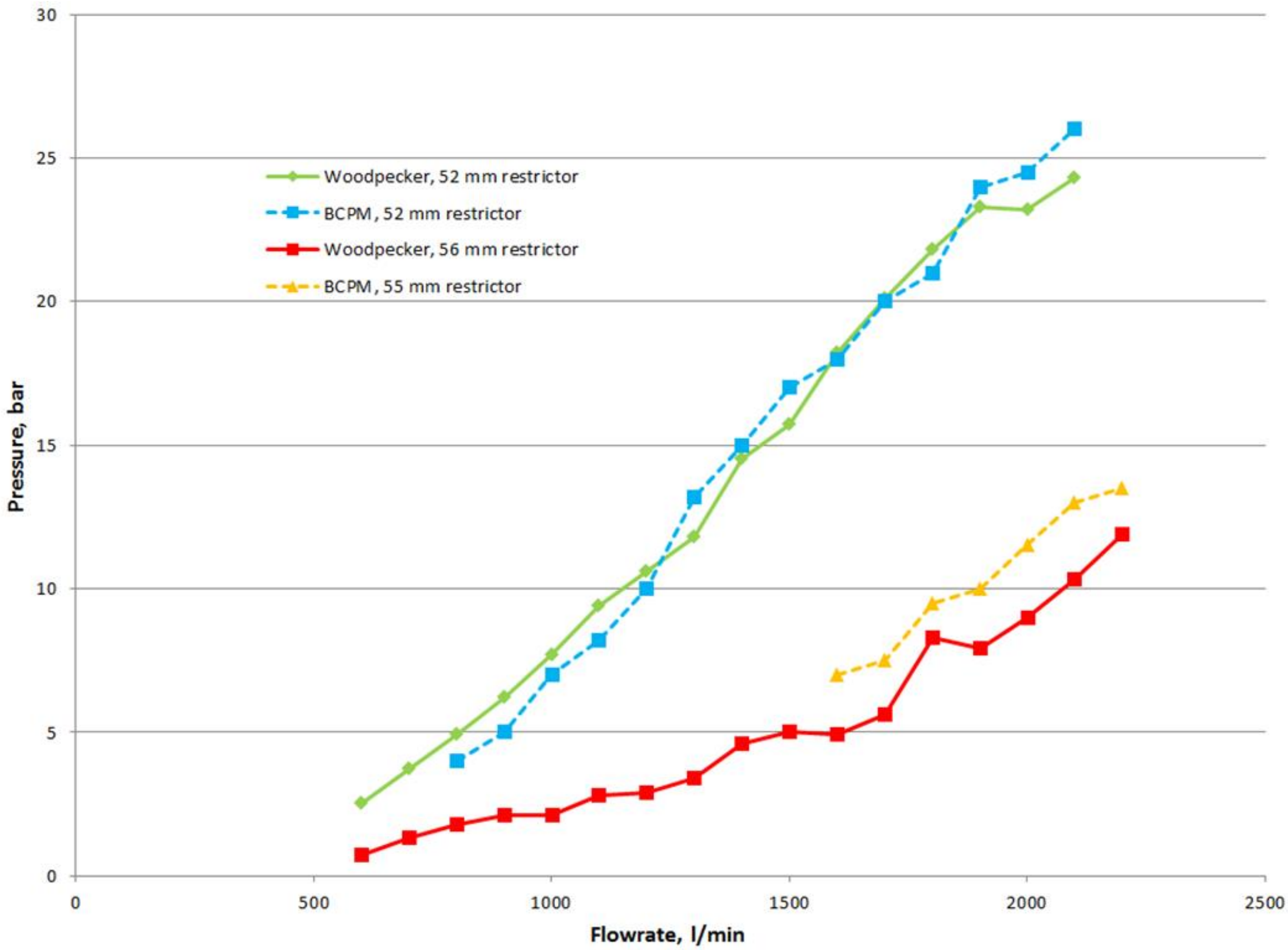


Figure 19 Pulse pressure with different Flow rates and different valve seat diameters in comparison to the standard pulser (BCPM) for oil field applications

Figure 19 shows a comparison of pulse pressures versus flow-rates of two different pulser types. The 300°C pulser (Woodpecker) is compared to the standard oil field pulser (BCPM). Different valve seat sizes are used to show an option to adjust the pulse pressure with different flow rate ranges. At higher flow rates, one would choose a valve seat of 56mm in diameter in order to avoid excessive pressure drops.

9. MWD flow loop test

Low temperature flow loop testing of a 6.75” 300°C MWD was carried out in order to prove the functionality of all components before shipping the system to the Baker Hughes Experimental Test Area (BETA) in Oklahoma.

Figure 20 Low temperature flow loop testing of the assembly prior to shipment for field testing

Flow Rate range for flow loop testing was between 900 and 2500 liters per minute. Pulse data communication was checked and the data decoding was tested to assure a flawless data communication later in the field test. After the successful flow loop testing of about 6 hours the system was cleaned, boxed up and was ready for shipment.

10. BETA test

Field testing of a complete drilling system was performed at the Baker Hughes Experimental Testing Area (BETA) site in Oklahoma in the BH-J-20 well, during December of 2017, as seen in Fig. 23. The geology of the site has been well characterized over the years, with the top of the granitic basement occurring at 4,430 feet, at a temperature not exceeding 160°F.

Figure 21 Baker Experimental Testing Area Test Facility BH-J-20 Well

The aim of the field test at BETA was primarily to demonstrate the operating capability of the directional MWD System in a downhole environment. It was not possible to test the active cooling system as the formation at BETA has low temperature, which is not high enough to activate the cooling system.

The surveys were checked for quality by using the MSA (multiple station analysis) method which required at least 15 surveys. In this case we acquired 24 good surveys for the analysis in the hole-section that was drilled by this tool. The surveys acquired on the test passed the MSA analysis which was performed by the global positioning group of BHGE. This proves the high quality of the directional measurement of this tool which is comparable to a standard oilfield MWD system. No magnetic interference was observed.

The mud pulse data transmission from the tool was reliable with decoding of 100% for both 1.5 and 0.5 bits-per-second data rates and at a flow rate of 400gpm. The minimum flow rate for the assembly in this test was 400gpm, the maximum flow rate was limited to 500gpm.

Initially the data rate was set to 0.5 bps in the tool by programming in the work shop. Towards the end of the testing the data rate was changed to 1.5 bps by rotary downlinking and the tool continued to provide 100% decoding.

The DOE 300 directional MWD system performed as required. The success of the faster data rate will help improve the overall performance of the tool, giving a range of data rates between 0.5 and 1.5 bps, which can easily be changed downhole due to the success of the rotary downlinking. This data rate is more than sufficient for directional drilling.

The MWD tool is compatible not only with the standard BHGE surface equipment but also with BHGE operations procedures.

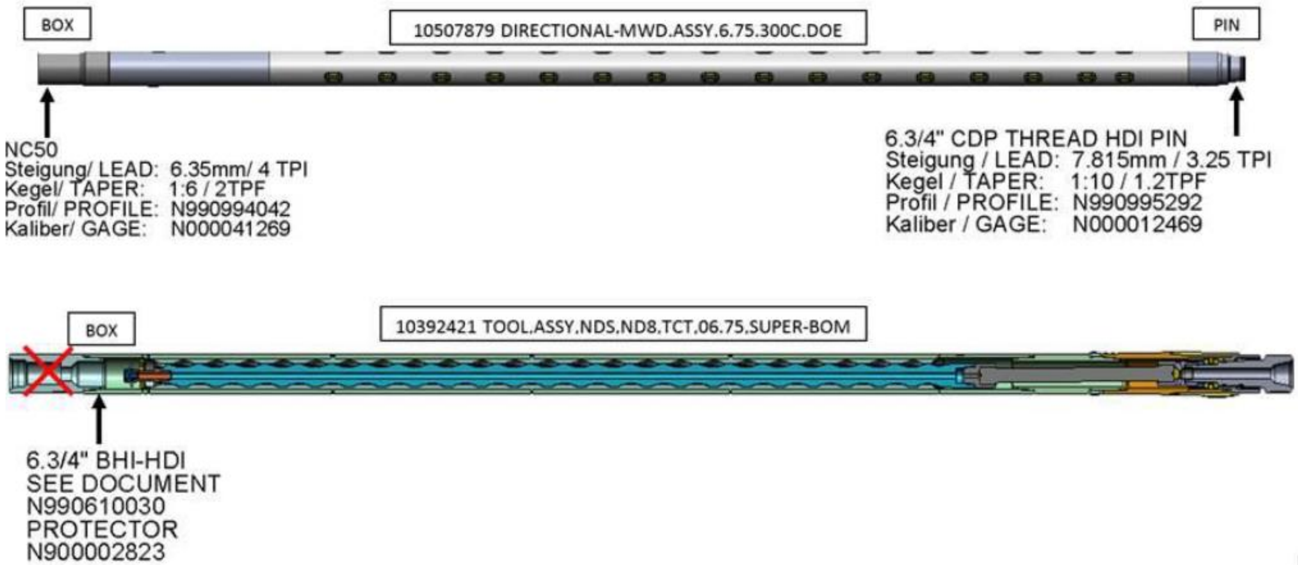
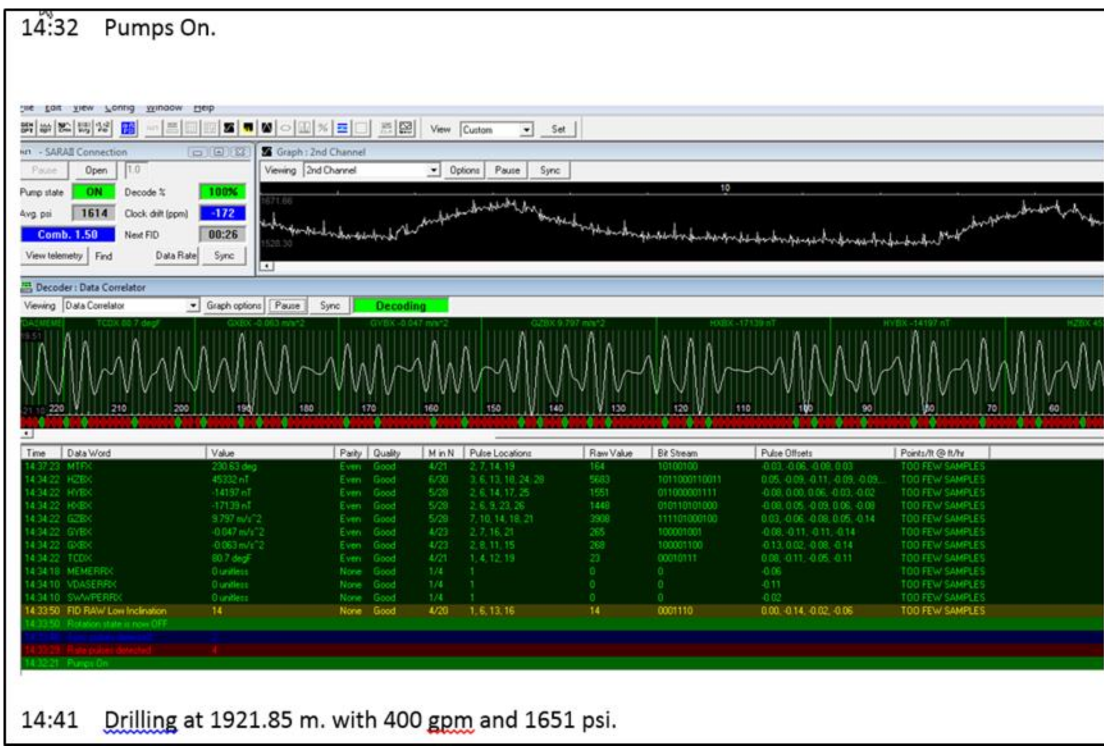


Figure 22 Bottom hole Assembly used in BH-J-20 Well comprising Drill Bit, Drilling Motor and 300°C



Two

Figure 23 Screen of the surface system showing flaw-less pulse data communication of the 300°C MWD used in BH-J-20 Well

In **Figure 23** an example of the surface system screen is shown. It shows the mud pressure pulses and the subsequent decoding of data.

Table 1: Test parameter summary of the drilling test. The systems drilled 285 feet in BH-J-20.

Hole Size:	8.5/216	inch / mm
Rate of Penetration:	50 – 80 / 15 – 24	ft/hr / m/hr
Rotary Speed	90 – 100	RPM
Flow Rate:	400 – 500/1514 - 1893	gpm / lpm
WOB:	5 – 10 / 2 – 4.5	k.lbs / tons
Standpipe Pressure:	1680 / 116	psi / bar
Downhole Pressure:	-	psi / bar
Overbalance Pressure:	-	psi / bar
Downhole Temperature:	135/ 57	°F / °C
Mud Properties:	9.2/1.10 WBM	ppg / sg, WBM / OBM
Mud Resistivity	-	ohm-m
Mud Chlorides	4500	mg/L
Circulation hrs:	20.2	hrs
Drilling hrs:	9.3	hrs
Inclination (max):	1.44	°
Azimuth (max):	167.9	°
Dogleg severity (max):	-	°/ 100 Feet / °/ 30 Meters
Depth In (MD/TVD):	1903/580	Feet / Meters
Depth Out (MD/TVD):	2188/667	Feet / Meters
Number of Runs:	1	
Drilled Formations:	Shale with sandstone beds	
Bit Type:	PDC	

Table 1 gives and overview on the test parameters used during the drilling test.

11. High temperature lab test of cooling system

A high temperature test stand was designed and set up to accommodate the inner probe of the MWD consisting of Dewar flask with electronics and sensors, water container and Zeolite reservoir. The system was completed by a CVA to realistically load the electronics with an actuator of the pulse valve. **Figure 24** shows the final step of probe assembly. In order to test the entire probe with about 8 m length a special oven was used. The oven (Fig. 26) can apply 300°C and provides a uniform temperature distribution over the entire volume.

Figure 24 Assembly of the probe comprising Dewar flask, water container and Zeolite reservoir

Before setting up the oven test, the water reservoir was filled with 2.7 l water (**Figure 25**) and pressurized with 5 bar Nitrogen. In addition, it was necessary to dry the Zeolite which was done by heating the system and evacuating the zeolite reservoir at the same time.

Figure 25 Preparation of the high temperature test of the active cooling system by filling 2.7 l water into the water tank

The MWD electronics was electrically connected to a Control Valve Assembly (CVA) (**Figure. 26**) in order to have a realistic electrical load on the solenoid driver electronics. Since it is important to see whether the CVA would create sufficient force under high temperature, the CVA was mechanically loaded with force from the outside of the oven by a steel wire connecting the armature plate with a spring system. The steel wire was guided through a hole in the wall of the oven. The actuation of the solenoid control valve was recorded. After the test a decoding routine was used to simulate mud-pulse decoding of the recorded data. The system in the oven was powered by a three-phase AC power supply system that mimicked the turbine alternator during this test.

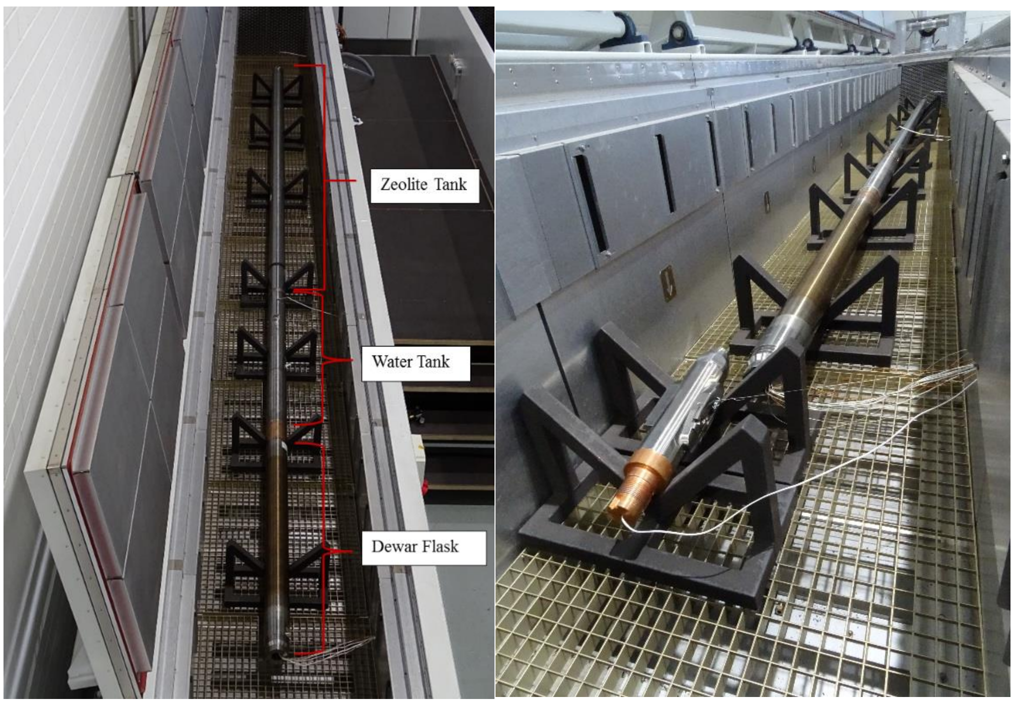


Figure 26 300°C MWD probe with active cooling system inside the oven test electrically connected to the Control Valve Assembly. A steel wire is used to load the solenoid actuator of the CVA with force from the outside of the oven.

Figure 27 shows the results of one of one oven test session. It shows two measured temperatures: one is the oven-temperature (blue line) and the other the electronics temperature (purple line). The oven was heated to 190°C during the first 5 hours. While the oven was already at 190°C, the electronics, which were inside the Dewar flask, follow the temperature increase with a much slower time constant.

After 68 hours the electronics was powered-on. This is shown by the red line jumping to the on position. The powered electronics initiated the cooling electronics, and the water evaporation inside the Dewar flask cooled the electronics to about 170°C. After 69 hours the oven temperature was increased to 300°C, while the control module on the cooling system automatically maintained the electronics temperature below 170°C. During the next few days of testing, the temperature was always decreased to

190°C overnight in order to be in a safe temperature area for the electronics in case the system ran unexpectedly out of water.

After 146 hours the cooling stopped because the water reservoir ran empty. This can be clearly seen since the electronics temperature increases above 200°C. As soon as the uncontrolled increase of the electronics temperature was detected, the power supply was switched off and the oven was cooled down to avoid damaging the components of the electronics system.

A simulation of the cooling was performed to fully understand the process and to predict water consumption, which cannot be measured downhole. The green line shows the calculated electronics temperature as a result of the simulation. It matches well with the measured temperature. The light blue line represents the water consumption of the cooling process. It indicates exactly the time when the system stops cooling because the water container was empty.

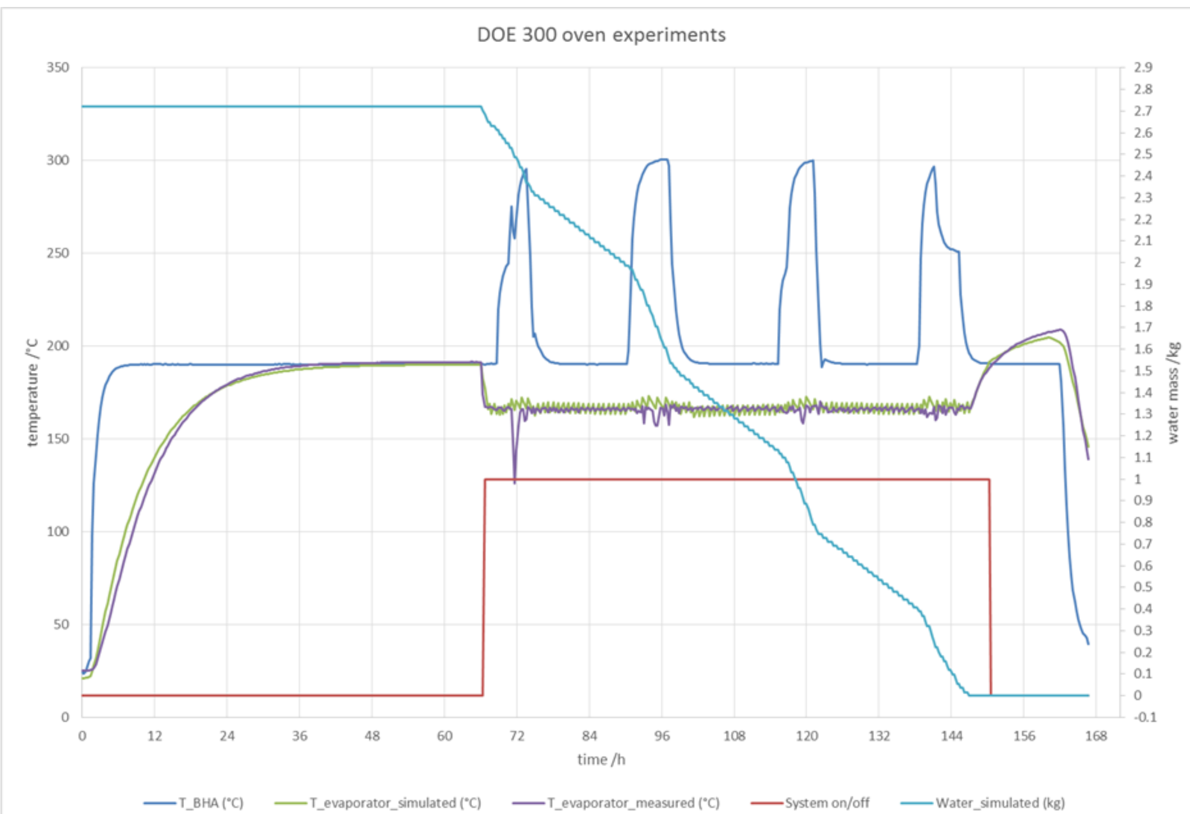


Figure 27 300°C MWD probe with active cooling system electrically connected to the Control Valve Assembly a steel wire is used to load the solenoid actuator of the CVA with force from the outside of the oven

12. Conclusions and Discussion

To summarize: the tests performed at both the Baker Hughes Experimental Test Facility in Oklahoma and the engineering lab in Celle, show that the developed 300°C MWD with active cooling system can be utilized to perform high quality directional measurements on top of a geothermal directional drilling system. This gives us the opportunity to efficiently drill geothermal wells.

The next step should be a test of the entire directional drilling system, drill bit, steerable drilling motor and 300°C MWD system in a hot well. Such a test can be performed best on a geothermal drilling site in collaboration with a company planning to establish an EGS system. The requirements would be a maximum bottomhole temperature of 300°C, and borehole sizes compatible with the 6-3/4" tool design. The large range of drill bits available can be tailored to provide optimal performance in the target lithology.

Several challenges were overcome during the development project:

1. How to provide measurement electronics for directional data while drilling a well with extreme temperatures: It was found that current high temperature electronics technology is not ready to provide highly integrated electronic circuits. Simple electronics can be built to operate at 300°C but the complexity level is not sufficient for the highly complex measurement tasks required for MWD applications. Active cooling provides a viable means for using complex electronics at a 300°C well temperature.
2. How to build an active cooling system to operate at 300°C and cool electronics and sensors so that they can operate: Water evaporation provides, even under 300°C, enough enthalpy to permit active cooling of electronics. Steam adsorption was found to be a usable process to store the evaporated water downhole. Relieving the steam into the wellbore was impractical because of the high pressure in the wellbore. A compressor to compress the steam and condense it back to water was found to be unreliable because of the extreme temperatures at the compressor.
3. Can a vacuum super isolation be applied under high temperature drilling conditions? After several approaches it was possible to build a Dewar vessel with vacuum super isolation that survived drilling at BETA and the vibration test in the lab.
4. Power supply for a 300°C MWD tool: The first approach was to acquire Batteries that can be applied at 300°C. While it is possible to get battery technology for 300°C, it is not possible to get batteries that can provide sufficient power in a temperature range from 25°C up to 300°C. Additionally it was not feasible to have batteries that could provide power during several temperature cycles as could happen during operation of a downhole tool. A mud turbine driven alternator with mud lubricated bearings and without any elastomeric seals was a good solution. Since the rectifier and the power regulation electronics was in the actively cooled area, it was possible to run the alternator in a flow rate range resulting in a manageable voltage fluctuation.
5. How can a telemetry of MWD data be achieved at 300°C wellbore temperature? The first approach was to develop an electromagnetic data link from downhole to surface. While this approach appears to be feasible it has some strong disadvantages. EM telemetry does not bridge the long distances that can be required during drilling of an EGS well.
6. How to solve the problem that elastomeric seal rings do not work at 300°C and 20000psi? During the project it was found that elastomer O-ring seals do not work under these conditions. While it is feasible to apply elastomers at 300°C, they lose strength and the ability to act elastically after some hours exposure in water based fluids such as drilling mud. So, they cannot be applied in a high pressure seal. Metallic seal rings were found to be the only viable solution. Unfortunately

they require a fundamentally different design. They require an extremely smooth surface and they must not be rotated during assembly and during application.

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