D2.1 Report on the chosen sensors

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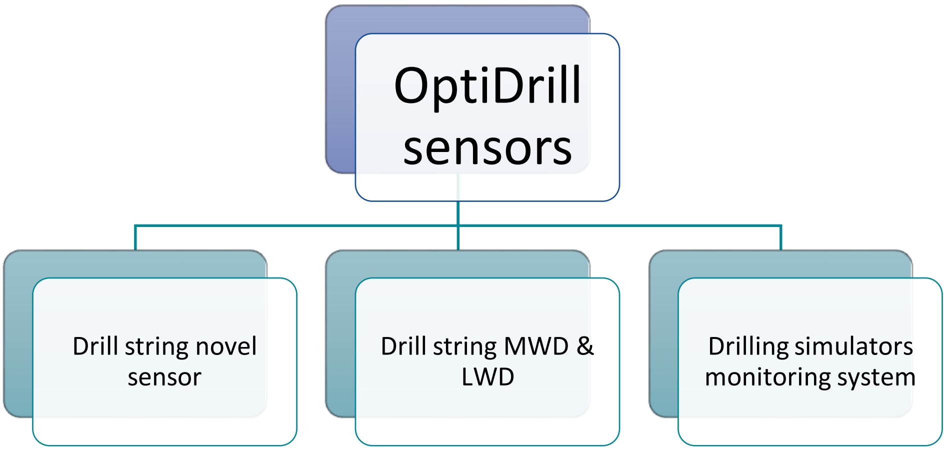
D1.2 OptiDrill Sensor selection and specifications

This report provides a comprehensive overview of the sensor selection process for the OptiDrill project, focusing on the development and integration of novel drilling measurement systems. The goal of the project is to enhance the efficiency and reduce the risks associated with geothermal drilling through the use of advanced sensors and real-time data analysis. The selected sensors include novel downhole sensors for Measurement While Drilling (MWD) and Logging While Drilling (LWD) systems, as well as the instrumentation of the IEG drilling simulators for advanced process monitoring. These systems will allow for precise measurements of key drilling parameters such as pressure, temperature, torque, vibration, and gamma radiation.



The report details the specifications and functionalities of various sensor types, including acoustic emission sensors, accelerometers, and electromagnetic sensors, which are critical for data acquisition in challenging downhole environments. The innovative sensor string developed for deep geothermal applications is designed to withstand extreme conditions while capturing high-resolution data for process optimization. Additionally, the integration of the multi-sensoric process analysis system (MoUSE) enables detailed real-time monitoring, making it possible to optimize drilling technologies and decision-making processes based on sensor data. The selected sensors will facilitate the development of a machine learning-driven drilling advisory system aimed at optimizing resource extraction and improving overall drilling performance.

1. Introduction

(Adapted from Executive Summary from User Requirement Report – Deliverable 1.1)

The success of geothermal applications has been mainly dependant on reducing the risks and costs associated with the drilling process. During the past few years, there has been a sudden improvement in analysis systems through AI applications however the success of such processes is mainly dependant on the collection, analysis, and use of data.

The main objective within the project is to develop a drilling advisory system based on machine learning methods and utilization of novel sensors to predict ROP, lithology, drilling problems, well completion and enhancement and finally to unite those methods under one system to enable drilling process optimization and intelligent decision making. The focus is set to, take advantage of the existing data and knowledge transfer, solve the existing problems, and enhance the existing methods and technologies while employing methods to acquire new sets of data through instrumentation of the drilling process through employment of sensors and monitoring techniques.

The selection and specification of the monitoring methods and the sensors which will be used in multiple stages of the OptiDrill advisory system development has been made through multiple discussions and meetings with the OptiDrill project partners to firstly identify the goals, requirements and eventually the final sensors selection.

2. OptiDrill novel drill string sensors

(adapted from D1.4 OptiDrill Sensor Specification)

The novel drill string sensors which will be developed by PVI within the OptiDrill project will be used in OPTIDRILL measurement and monitoring system development phase and also in sensor housing development to include sensor string casing package requirements, power cables selection, sensor materials for sensor string and jetting module, and micro-processing specifications based on data acquisition resolution as defined by user expectation in **task 1.1** of the project.

The development of the sensors will be based on their functionality in drilling environment specifically target for deep geothermal applications. The main attributes of the material selection for such a sensor system include: chemical resistance, abrasion resistance, moisture resistance, heat resistance, pressure resistance, impact resistance, the used drilling method(bit), and the target drilling depths.

The sensor types which have been initially planned for the OptiDrill novel sensor string consist of acoustic emission and accelerometer sensors, however, in addition, PVI aims to add pressure, temperature, and strain sensors to the string to further enable the possibility to characterize and analyse the drilling process.

The position of the sensors on the drill string will be varying dependent on the drilling method and the drilling depths. Figure 2 shows an exemplary setup of the sensor string with the DTH hammer drilling method. The sensors will record the data using hardware's including microprocessors, multiplexers and demultiplexers, signal conditioners, and amplifiers and the measurements will happen either in 8 or 6-bit configuration sampling rates translating into 256 and 64 datapoints between impacts (in case of percussive drilling as is shown in Figure 2) respectively. Detailed information regarding the novel sensors can be found in OptiDrill project Deliverable 1.4 report.

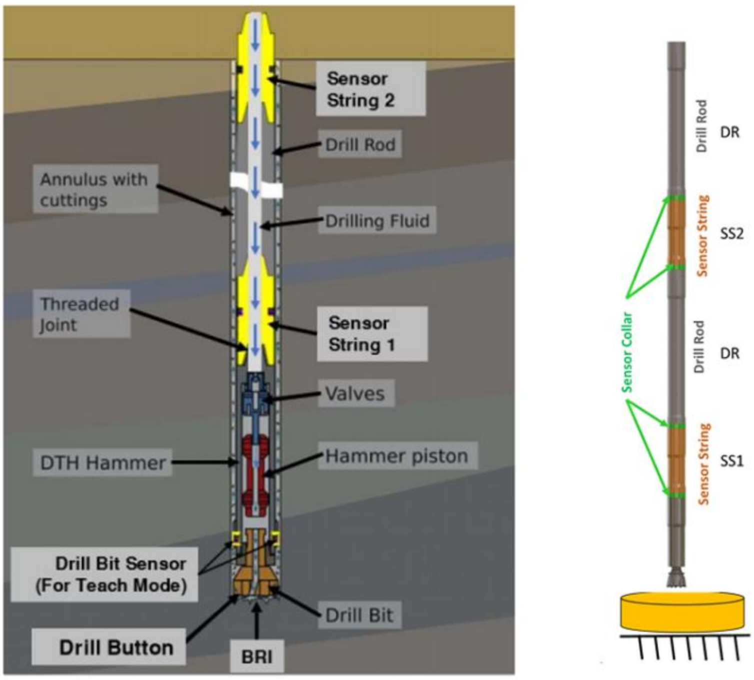


Figure 1 Traditional' percussive drill string configuration (L) and sensor string / collar locations (R)

3. Drill string MWD & LWD systems

In order to gather information about the drilling process in terms of monitoring and documentation of process parameters and downhole conditions as well as the verification of the progress made, two kinds of downhole measuring systems containing a number of different sensors are commonly used in drilling operations. These systems are generally known as Measurement While Drilling (MWD) systems and are located in the bottom hole assembly (BHA). Depending on the properties that are measured these systems can be distinguished in MWD and Logging While Drilling (LWD) systems, where MWD systems measure properties like wellbore trajectory, downhole pressure or temperature and LWD systems measure parameters describing the formation being penetrated. Apart from the measurements taken downhole, there are other measurement tools used to measure process parameters and properties at the surface of the drilling site.

Both MWD and LWD systems consist of three basic components: a system providing the power supply, a telemetry system for the transmission of the acquired data and the sensors used for the measurements. The power system is realized using either a battery or a turbine (mud motor), or as in most systems a combination of both. The combination of both a turbine and a battery has the advantage that the power supply is not interrupted when there is no circulating drilling fluid driving the turbine.

The telemetry system transmits the collected data from the bottom hole assembly up to the drilling site most commonly by sending pulses, which can be either positive, negative or continuous, through the drilling fluid.

In the following sections the third component of the described systems, the sensors used to measure the respective drilling parameters and downhole and formation properties, are described. The devices described in this section are current state of the art sensors which are also mainly going to be used for the collection of the data within the OptiDrill project with minor changes in the design and specifics while each rig will be equipped with a slightly MWD and LWD system design, however the general characteristics of the systems remains the same.

3.1 Existing Sensors in Measurement While Drilling Systems

MWD systems are used for the real-time measurement of a number of different drilling parameters including directional information on one hand and drilling process information on the other hand. Directional information primarily includes the inclination and the azimuth of the wellbore, which are used to calculate and monitor the trajectory on the well. The real-time acquisition of directional information has special importance in directional drilling and is used to steer, verify and correct the path of the wellbore. Drilling dynamics information includes data like the rotational speed of the BHA, vibrations, downhole temperature and mud pressure, torque and weight on bit. Some MWD systems as the one shown in Figure 2 also measure gamma ray which can be used to interpret the type of the formation being penetrated.

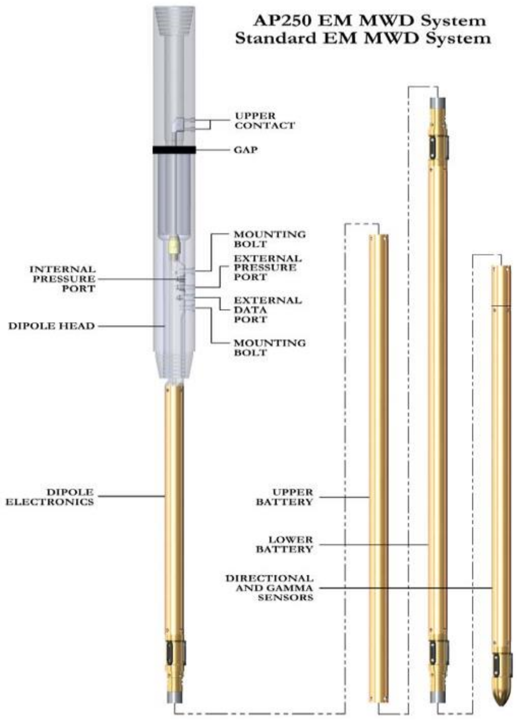


Figure 2: MWD system by "Applied Physics Systems" [5]

3.1.1 Directional Sensors

For the gathering of directional data like inclination and azimuth a combination of orthogonally mounted fluxgate magnetometers and accelerometers is used in modern systems. The sensors are mounted in arrays of three and the arrangement can be seen in Figure 3. The magnetometers are used to measure the azimuth and the accelerometers are used for the measurement of the inclination. For simpler applications with lower accuracy requirements on the measurement data normal directional sensors are also being used. It is important to mention that the employed sensors have to face very harsh conditions in the bottom hole environment and have to withstand high temperatures (approximately up to 175°C and higher) as well as high vibration and shock.

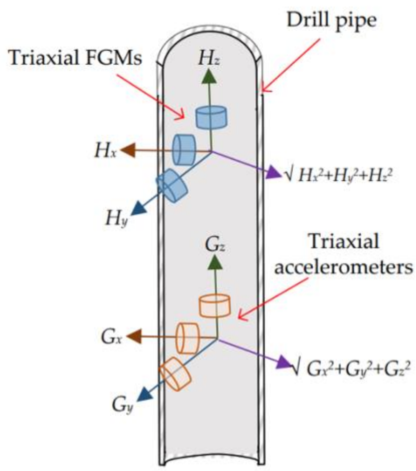


Figure 3: Arrangement of FGMs and accelerometers [6]

3.1.2 Gamma Ray Sensors

For the measurement of the naturally occurring gamma radiation in the wellbore detectors based on solid-state scintillation crystals are being applied. Gamma rays striking the crystals located in the detector cause the crystals to emit light which can be sensed and converted into an electrical pulse. The pulses can be counted and the value of the count represents the raw data being measured. The location of a gamma ray sensor in an MWD system by “Scientific Drilling” is depicted in Figure 4.

The measurement of the natural gamma ray gives information about the formation properties and is often also part of the LWD system.

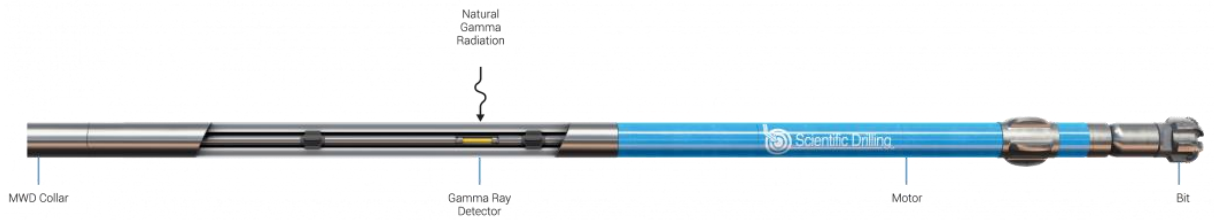


Figure 4: Location of the Gamma Ray Sensor in the MWD System [8]

3.1.3 Other Sensors

Other sensors employed in MWD systems include shock sensors, temperature and pressure sensors as well as force sensors.

3.2 Existing Sensors in Logging While Drilling Systems

LWD systems are used for the real-time measurement of the properties of the formation that is being drilled. These properties include density, porosity, resistivity, magnetic resonance and formation pressure. While all of these measurements can also be carried out by wireline logging the deployment of an LWD system can be advantageous since it delivers measurements before the formation is being deeply pervaded by the drilling fluid and especially in wells with high deviation where wireline logging might not be possible. An example on an LWD log file displaying the measurement of different formation properties is shown in Figure 5.

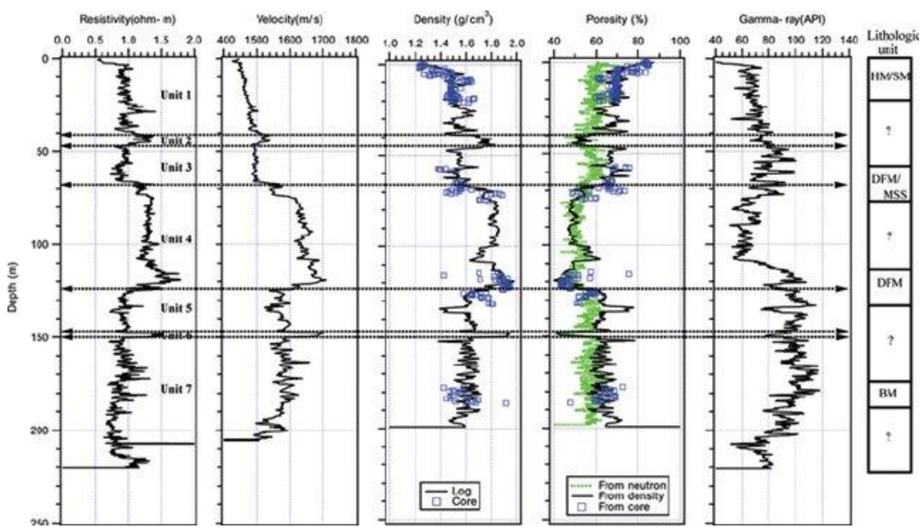


Figure 5: Example of an LWD log showing resistivity, P-wave velocity, density, porosity and gamma ray [9]

3.2.1 Electromagnetic Sensors

For electromagnetic measurements concerning the resistivity of the drilled formation the electromagnetic-wave resistivity tool (EWR) has become the established standard. The tool consists of a loop antenna that is mounted on the outer diameter of the drill collar and a pair of receivers. The antenna emits electromagnetic waves which travel through the surrounding wellbore and back to the receivers where the measured signals are converted into resistivity values.

3.2.2 Acoustic Sensors

In order to obtain acoustic-velocity data, which is important in terms of lithology interpretation and seismic information, acoustic measuring devices are used. Such devices can basically be realized by using at least one transmitter and two or more receivers, which are mounted in a certain distance from the location of the transmitter. The more transmitters and receivers the system contains the better the accuracy and reliability of the collected data. The transmitters as well as the receivers are piezoelectric stacks operating at frequencies that are higher than those of ordinary noises from the drilling operation

3.2.3 Nuclear Sensors

The gamma ray logging device which is also part of most LWD systems is already described in section 1.1.2. Apart from the gamma ray measurement there are other nuclear sensors deployed for measuring neutron porosity and bulk-density which are often combined in one module. The sensors used for these measurements often consist of a gamma ray source, e.g. Cesium or American Beryllium, and two detectors. One of the detectors is located close to the source, while the other one is located farther away. For the measurement the gamma ray, counts for both detectors are evaluated. The basic design of a neutron tool is illustrated in Figure 6.

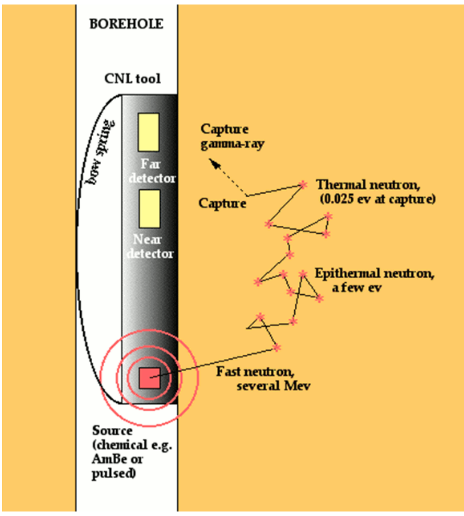


Figure 6: Basic design of a neutron tool [10]

3.2.4 Magnetic-Resonance Image Logging

In magnetic-resonance image logging the principle of magnetic relaxation is being used to measure petrophysical properties of a formation like effective porosity, permeability and irreducible water saturation among others.

4. Drilling simulators monitoring system

The drilling simulators at Fraunhofer IEG are part of multi system modular simulator system called match.BOGS. The monitoring system implemented in each system varies depending on the application, however, in case the Acoustic emission measurements are required, the IEG multi-sensoric process analysis system (MoUSE), as is described in the following section, will be used to do the monitoring of the process.

4.1 match.BOGS

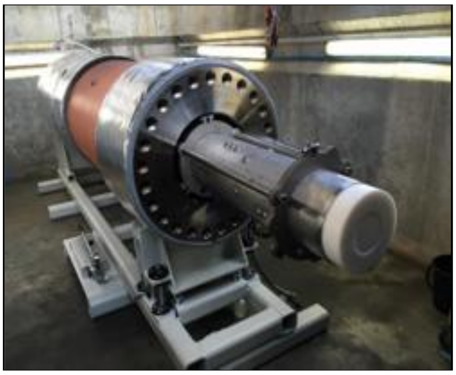
A fundamental problem in the investigation of processes related to the provision and exploitation of deep and ultra-deep reservoirs is the fact that a significant part of these processes takes place in conditions that may allow no or only indirect measurement methods. The main challenges include encountering aggressive geo-fluids, high temperatures, and high pressures. A new type of test bench called match.BOGS has been developed at Fraunhofer IEG in order to help overcome those challenges and gain an understanding of processes under reservoir type conditions.

The match.BOGS enables field research in a laboratory environment and consists of three main modules including i.BOGS, Drill.BOGS and fluid.BOGS, as can be seen in Figure. 7. Each of the modules can be independently operated as well as linked together based on the requirements of each research project enabling the testing of actual rock cores / samples, any materials, or even machinery / equipment such as casing, cement, pumps, BHAs, drill tooling, and fluid flows under pre-defined borehole conditions at various simulated depths.

Figure 7: The complete Match.bogs system overview

4.2 i.BOGS

The i.BOGS is an autoclave system that can simulate HT and HP conditions at reservoir depths down to 5.000 meters (Figure. 8). The main governing parameters include confinement pressure, sample pore pressure, temperature, and drilling fluid / mud circulation (see also Table. 1). Further, a multi-sensor parameter analysis system, consisting of fluid, acoustical, optical, pressure, thermal, seismic, gamma sensors, has also been integrated into the system to be able to monitor, control and evaluate all the experiments.



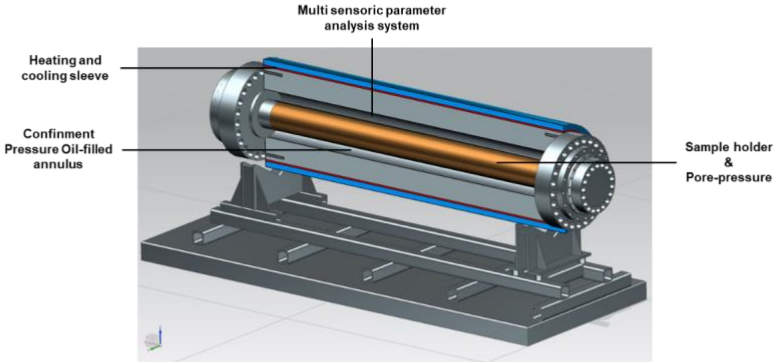


Figure 8: The i.BOG autoclave system and (right) the CAD model schematical overview

Table 1: The main sensors and their respective parameters within the i.BOGS module

Parameter	Range	Type
Confining pressure	0-1250 bar	Pressure transducer
Pore pressure	0-1250 bar	Pressure transducer
Temperature	-10 – 180 °C	Thermocouple
Sample deformation	0-25 mm	Circumferential extensiometer
Acustic emission	20 MHz sampling rate	AE System

4.3 Drill.BOGS

The Drill.BOGS, (Figure. 9) is a complete, vertical high-precision drill rig, enabling automated drilling operations inside the autoclave i.BOGS under reservoir type conditions using any drilling type tools. Its modern measuring, monitoring and control technology allows for precise evaluation of the complex rock breaking and drilling processes, much like having a fully automated drilling system. drilling-related parameters of the Drill.BOGS which will be monitored through multiple sensor and monitoring systems can be found in Table. 2.

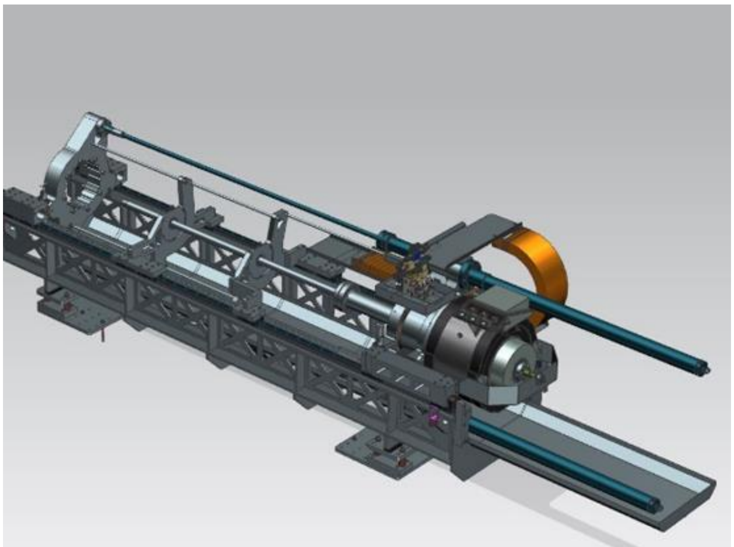


Figure 9: Drill.Bogs module overview schematics

Table 2 Drill.BOGS module drilling related parameter capabilities

Parameter	Range	Type
Torque	0-13,000 Nm	Electric motor controller
RPM	0-330 1/min	Electric motor controller
WOB	0-400,000 N	Load cell
Flowrate drill mud	0-600 l/min	Pump controller
Pressure drill mud	0-800 bar	Pressure transducer

4.4 Multi-sensoric process analysis system (MoUSE) system

The multi-sensoric process analysis system (MoUSE) is a complete measurement system for active and passive detection, transmission, and analysis of multi-type sensor system such as acoustic emission, temperature, mechanical forces, etc.

MoUSE can be used as a non-destructive technique for accurately determine material and rock properties and examine behavioural changes under various load, confining pressure, pore pressure and temperature changes. Passive methods, i.e. acoustic emission analysis, are suitable for recording signals generated by the material itself in a time-dependent manner.

As a rule, this is characterized by the formation of micro-cracks due to any load (thermo-, chemo-, hydro-mechanical) which their frequency and locality are characterized as a function of the intensity of the load.

Analysis of the generated acoustic emissions provides a mean to monitor and evaluate the evolving damage and the fracture of rocks from very small to large scale. Active ultrasonic measurements are also used to determine basic rock properties that, on the one hand, allow conclusions to be drawn about the static elastic deformation behaviour of the rocks and on the other hand, enables characterization of the seismic wave propagation properties in the subsoil environment.

4.4.1 Sensors

Acoustic sensors form the first part in the acoustic emission measurement chain, and they are of particular importance. The AE-sensor converts the surface movement caused by an elastic wave into an electrical signal which can be recorded and processed by the measurement data acquisition system. The piezoelectric element of the AE-sensor picks up the slightest surface movement by having high sensitivity and convert it, most efficiently, to an electrical voltage.

various designs of AE-sensors have been developed in Fraunhofer IEG with a variety of sensitivities and broad frequency responses (broad band-specific resonance frequency). Built for purpose special AE-sensors, e.g. high temperature / high pressure sensors, may also be used depending on the application.

In drilling and stimulation processes, the sensors may be installed on various locations, including drilling equipment, bottom hole assembly (BHA) and along the length of well-bore using DAS, to be able to record the AE activity of each specific process.

A housing, such as a lower sub, may be used to mount the sensors between the drill bit and the drill pipe, in order to pick up the AE activities generated on the rock-bit interface. A distributed acoustic sensing (DAS) sensor will be also used to measure the properties in the fluid flow, well-bore and reservoir formation region. Drilling equipment monitoring will also be done by mounting sensors on the drilling rig.

4.4.2 Measurement and analysis

The Acoustic Emission (AE) technique is based on the detection and conversion of high frequency elastic waves into electrical signals. This is accomplished by coupling piezoelectric transducers on the surface of the specimen. The output of each coupled sensor is amplified through a low-noise preamplifier, filtered to remove any extraneous noise, and furthered processed by suitable digital means. Complete system consists of 18-channel measurement arrangement. The 18 channels are ideally connected with 18 coaxial cables. Specially designed preamplifier amplifies, adjusts, and adopts the very small-generated charge signal of the sensors to the impedance of the measuring cables and measuring instrument. The consequent gain is 30 dB and the frequency response ranges from 1 Hz to about 2 MHz There exists also an amplification by 10 or 20 dB (Adjustable) and optional high-pass, low-pass and band-pass filtering at disposal. Each channel has maximum 20 MHz sampling rate, 14-bit resolution, its own analogue-to-digital converter, its own trigger logic and an own input amplifier. Transmission signal may be sent via each channel automatically with frequency range of 1 MHz to 2 MHz in periods of maximum 100 milliseconds depending on the size of the sample. The high sampling rate of AE events measurement results to record of up to 10,000 AE events per second. The recorded events are used after a run-time measurement for extensive analyses such as frequency, amplitude, energy, etc. studies.

The active ultrasonic measurement system is capable of generating pulses with a frequency between 0.1 MHz and 50 MHz and low-amplitude (up to 2 V) arbitrary signals and high amplitude (400 V) spikes. Ultrasonic probes are used for the investigation of longitudinal and transverse waves (P and S waves) in the kHz and MHz frequency range for different sample sizes. Data is collected via 4-channel measurement arrangement with a bandwidth of 200 MHz and a maximum sampling rate of 1 GB/s for maximum uninfluenced data acquisition. The pulse generator is capable of generating output amplitudes in the form of a square-wave signal, which, because of their intensity, allows examining samples of different sizes and compositions, e.g. high-porosity foams or rock samples.

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