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inliSAMP, a Modularly Designed Fluid Downhole Sampler for Deep Geothermal Applications - Proof of Concept

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ABSTRACT

The fluid sampler inliSAMP is being developed for remote controlled downhole sampling in deep geothermal boreholes. inliSAMP is designed based on the system platform for downhole tools hotToolKIT. It is a follow-up development to the inliCAM. Thus, both probes are built up from modular components of the construction kit. A new sampling and storage concept is developed and realized in a functional demonstrator (sampling volume 480 cm^3). The sampling process was tested and proven to work under laboratory conditions up to 90 bars. The demonstrator sampling system is remotely controlled via wireline using real time data. Temperature, pressure in different locations of the sample chamber, and electronic components are permanently monitored and recorded. In the design, most electronic components such as a highly efficient power supply, motor drivers and control units are placed inside a supply probe Dewar flask. The in-situ storage of the monophasic sample is being realized by an adaptive hydraulic and heating control system. The hydraulic components are developed for high dynamic loads and small installation spaces. Furthermore, the functional demonstrator fulfils the requirements of the design standard downhole logging tools (T = 200 °C, p = 60 MPa, harsh and corrosive fluids). Currently, the mechanic units such as the sample chamber, sensors, and hydraulic power pack are mounted on a socket in a demonstrator housing and are tested under realistic conditions on a test rig at the Karlsruhe Institute of Technology (KIT) in preparation for a borehole deployment. The functional tests of the sample procedure include descent of the probe, the sample intake, maintenance of sample temperature, and dispensing at changing ambient temperatures on a test rig. The focus of the research is on temperature monitoring, control, and operation management of in situ downhole sampler. This paper gives an overview over commercially available fluid sampler, the development process, a test rig for fluid samplers, explains the technical details of the complete system and presents the results of the proof of concept and the quality measure of sample temperature and pressure.

1. Introduction

This paper presents a novel fluid sampling concept for remote in-situ downhole sampling, the design of the inliSAMP probe and a proof of concept on a test rig. inliSAMP stands for "in situ live sampler". It is designed for remote-controlled sampling in deep boreholes and was developed at the Karlsruhe Institute of Technology. It is a modular build up tool based on the system platform for downhole tools hotToolKIT (Holbein et al., 2018) and a follow-up development of the video inspection probe inliCAM (in situ live camera). As a conventional downhole sampling probe, inliSAMP is lowered on a wireline in the completed borehole, and it collects a fluid sample from the borehole fluid at formation conditions. The probe stores and maintains the fluid sample nearly in situ conditions until it is transferred to a transport container at the surface.

Providing insights to downhole fluids are a crucial for the evaluation and exploitation of underground resources such hot water, crude oil, CO2 storage, and shale gas (Hsieh et al., 2021). The increasing number of projects in exploitation of geothermal energy from a reservoir or carbon storage injection of supercritical CO2 “require accurate geochemical analyses of formation water and gas samples for chemical characterization and monitoring purposes” (Wolff-Boenisch and Evans, 2014), (Lund et al., 2022), and (Ayliffe, 2022). Merely representative downhole fluid samples provide important information for aqueous chemistry, isotopic composition, and gas characterization analyses as “the physical and chemical properties of geothermal water that is at or close to equilibrium with host rocks in water-dominated reservoirs change from their initial state to the surface sampling condition during the up flow of the fluid along the wellbore” (Akın and Kargı, 2019).

The data of a downhole sample and its dissolved gases are important information for geothermal use, exploitation and research, e.g. the assessment of the operation conditions, the heat transfer and mineral scaling (Hsieh et al., 2021) and (Wolff-Boenisch and Evans, 2014). In application of mineral carbon storage, a representative sample of injection conditions is needed to evaluate the hydro-geochemical pattern and proportions of $CO2$ mineralization of the aquifer (Alfredsson et al., 2016). In another application, "dissolved gas concentrations in groundwater are useful environmental tracers that can be used to determine groundwater residence times, understand geochemical processes, monitor contamination plumes, and identify mineral, oil, and gas reserves" (Eddie W. Banks et al., 2017). Further, in the oil and gas industry, representative formation fluid analyses are essential as precipitates of paraffins and asphaltenes are examined. In groundwater studies, which also detect volatile tracers such as SF6 in samples (Wolff-Boenisch and Evans, 2014).

"The main processes that change the reservoir water chemistry in the wellbore are the boiling of water, degassing of dissolved gases and the consequences of adiabatic cooling and mineral scaling. The combined effects of the increase in dissolved species concentration (boiling), decrease in temperature, rise in pH (degassing) and redistribution of bulk compositions among species (speciation) cause mineral scaling in the wellbore" (Akın and Kargı, 2019). These effects appear due to change in the formation pressure and temperature, as the mineral saturation is further dependent on temperature (Lowenstern et al., 2012). Precipitation occurs in the sample chamber with at alterations of its environmental conditions such as pH, temperature, and pressure changes (Wolff-Boenisch and Evans, 2014).

Obtaining a representative water sample, means to preserve technically the physical conditions of the downhole reservoir in the water sample, ongoing the time the sample is collected, during transport out of the borehole until it is transferred to a transport container at the surface.

Well sampling techniques distinguish between downhole (in-situ) and uphole (ex-situ) sampling. Today, available commercial downhole samplers and specific field-tested samplers are lowered to the target depth in the borehole. A positive displacement sampler (PDS) are systems, which is described in (Wolff-Boenisch and Evans, 2014) and still state of the art, for example the Single-Phase Reservoir Sampler of Schlumberger (Schlumberger, 2020). Other in situ technologies as vacuum and flow through samplers are here not considered, as they have no pressurization of the collected sample (Conaway et al., 2016). A PDS consists in principle of a housing with cable head connected to a wireline, a sample chamber and a time-controlled valve. It works with a prefilled pressurized displacement fluid that first exerts a piston on the closure and second, when a timer sets the valve open, it controls a slow displacement while existing differential pressure to the formation. A pressurized gas such as Nitrogen can be used to keep in the sample above reservoir pressure, while cooled from outside down during uplift and transportation. "Deployment of a PDS or keeping the well over pressurised can produce a single-phase fluid, which requires the sample extraction line to be operated under overpressure with respect to the formation or the bubble point and the introduction of a well-defined sampling loop to acquire a representative sub-sample."(Wolff-Boenisch and Evans, 2014)

The following state-of-the-art examples show the variety and current usage cases: The Positive Displacement Sampler PDSshort provided by Leutert for example has a sample capacity of 600 cm^3, an operating temperature of 180 °C and a sample pressure of 1035 bars. With a preloaded pressurized chamber, it retrieves a representative sample in a single-phase condition to the surface (Leutert, 2021). The sampling of deep geothermal wells and CO_2 reservoirs with the Leutert positive displacement sampler (PDS) is well documented in many publications, for example in (Kampman et al., 2013) and (Regenspurg et al., 2010). The Armada® SPS-A Single-Phase Sampler by Halliburton operates at similar conditions and has the additional feature to preload scavenger fluid. Further, the sample chamber material is designed for detection of trace elements such as H_2S (Halliburton, 2022).

The GTFSampler is composed of a shut-in valve, maximum thermometer, a filter, check valve and a sampling cylinder with noble gas as Nitrogen. It is designed for temperatures up to 200 °C and pressures up to 77 to 226 bars. It is made for the retrieval of geothermal fluids (water, vapor, and gas) with a sampling volume of 500 cm^3 (Hsieh et al., 2021). The Multi-Temperature Fluid sampler (MTFS) is designed for fluid sample 1000 cm^3 with operation temperatures up to 190 °C, non-gas tight and to connect different probes in a row in the Deep Sea Drilling Project Hole 504B. It uses a syringe style design of the sample chamber and a "mechanical trigger that utilizes the thermal-response properties of a shape memory alloy (SMA)" (Wheat et al., 2020). The MTFS can be deployed with the elevated temperature borehole sensor (ETBS) tool in the borehole (International Ocean Discovery Program, 2022).

The downhole sampler of the project SECURe-Subsurface Evaluation of Carbon capture and storage and unconventional Risks is made for retrieval of integer fluid samples (water, oil, gas) with any contamination and leakage to the surface. The analyzation of geochemical composition of the fluid sample is done in a laboratory on site. The probe transmits measured data via the wire line (Ricroch et al.). The variation in the products is the quality of the fluid sample as pressurization sample while intake, storage, the product specification and fluid sample volume. Most of the probes have a countdown timer to open the inlet valve and use a pressurized displacement fluid and gas. Furthermore, most probes do not transmit real-time data about the status of the sample, temperature and pressure, as they operate purely mechanically. Findings from current research projects are the need of more downhole data of the sampling process (Ricroch et al.), sample pressurization and verification further reservoir information to the taken sample such as downhole pressure and temperature.

Commercially available samplers today only partially have remote control and monitoring of the sampling process as well as active control of the samples taken. This issue is to be addressed by developing a remotely controllable and monitorable sampling probe. To improve the integrity of a representative fluid sample, it is crucial to log the full sampling process. The quality of the fluid sample can be enhanced with a remotely operated opening and closing unit. Further, an adaptive control and monitor system is used to maintain the formation pressure and temperature inside the sample chamber. The quantity of samples can be increased with a shorted preparation time at the surface and faster sampling, as well as by multiple sampling at different depths. How is an automatic sampler downhole probe designed, and how is the procedure to remotely controlled collect and retrieve a fluid sample from a deep borehole at nearly in situ conditions?

The novel inliSAMP probe has remote controlled actors and sensors for intake, storage, and retrieval of the sample. A steerable hydraulic unit and a resistance heater are used as actuators for an adaptive pressure and heating system. With the developed sampling procedure, a fluid sample can be stored and maintained under nearly in situ conditions, without the need of a displacement fluid and pressurized nitrogen. The mission of the downhole fluid sampler inliSAMP is to take a sample larger than 450 cm^3 from the borehole at an arbitrary depth and retrieve a single-phase sample to the surface at in situ downhole conditions with logging data. In this research, a novel sampling procedure is being developed and implemented in a demonstrator probe inliSAMP. The demonstrator is a simplified hardware version of the borehole probe. This involves the experimental investigation of the sampling process, the temperature distribution in the sample chamber and the sample pressure during the process.

The main focus of the research is to develop a solution for keeping the sample temperature and pressure constant during the ascent at a changing ambient temperature. For this purpose, a constructive solution, extended sampling procedures and the use of a temperature control with limited heating power are combined. The demonstrator with the sampling procedure is tested on a test bench. Chemical analysis and measurement of dissolved and undissolved gases in the sample are not performed.

Moreover, inliSAMP is specially designed to meet the requirements of most geothermal boreholes in Central Europe. The main requirements are an operating temperature of 200 °C, a maximum thermal water pressure of 60 MPa, and resistance against very corrosive and harsh environments (Spatafora et al., 2019). The specifications are consolidated in the so-called hotToolKIT requirements. At the Karlsruhe Institute of Technology, within the workgroup Geothermal Energy at the Institute for Automation and Applied Informatics was developed an open-source platform for geothermal borehole tools and probes to enhance and innovate the information quality and integrity of deep geothermal applications. The hotToolKIT platform is the renaming and commercialization of the ZWERG modular system and the two downhole probes inliCAM (working title GeoKAM) and inliSAMP (working title WASAM) (Holbein et al., 2018).

hotToolKIT links the requirements of deep boreholes, electronic hard- and software, a design construction kit. Standardized testing is applied for variable uses such as a video inspection system GeoKam (Spatafora et al., 2019), a permanent cooling system (Holbein, 2019) and a new downhole sampling system (Isele et al., 2015b) and (Berentelg et al., 2020).

2. Novel fluid sampling method for deep boreholes

HotToolKIT is a modular system for design, construction, and operation of downhole tools and high-temperature applications. The general operating parameters of the environment condition for all probes are listed in Table 1. The tool and technology development are structured by applying a repetitive modular design. Development costs and the risk of errors are thus significantly minimized (Holbein et al., 2017).

The module-based probes consist of universal modules and task-specific application modules. The universal modules include all components such as a housing and thermal insulation, which each type of probe requires. The application module is developed task-specific and is made of assemblies, actuators, and sensors. Special electromechanical couplings enable the individual modules to be connected and combined (Isele et al., 2015b).

The sampling probe inliSAMP structure is build up from standards of the hottoolKIT. inliSAMP is composed of an application module: the sampling unit and various universal modules such as a hydraulic power pack, insulation, power supply unit, and a communication board. The probe consists of two sections, a high-temperature section with the sample unit and hydraulic power pack with a coupling (Holbein et al., 2017) and an insulated section for temperature sensitive electrical components. A suitable Dewar tube from hotToolKIT is used for the thermal insulation of the electronic components. Control circuits boards, as HiTES, communication electronics, and power electronics are installed to operate and monitor the probe (Dietze, 2020). The module groups are each protected by a stable housing tube which is screwed to the coupling (Spatafora et al., 2016).

The sampling unit, the application module for the task of downhole sampling and fluid storage, is a new development. It consists, in principle, of an insulated and heated pressure vessel named the sample chamber attached to a hydraulic cylinder (Berentelg et al., 2020). The hydraulic cylinder is actuated by a hydraulic power unit. The container is closed by two axially movable pistons which are directed over a rod. The distance between the pistons corresponds to the volume of the sample to be taken up in the so-called sample chamber.

The developed fluid sampling procedure is simplified by a five-phase principle: descending the probe, sample taking, closing, pressurization, temperature control, and sample dispensing. The phases are illustrated in Figure 1 showing a Pressure vessel with an Inlet hole, Heating, mechanical Stops, and a Sample piston and Valve piston. The sampling concept is based on the function of a syringe and a valve. Each piston, shown, has seals on both sides and can only be shifted axially by fluid pressure or the piston rod force:

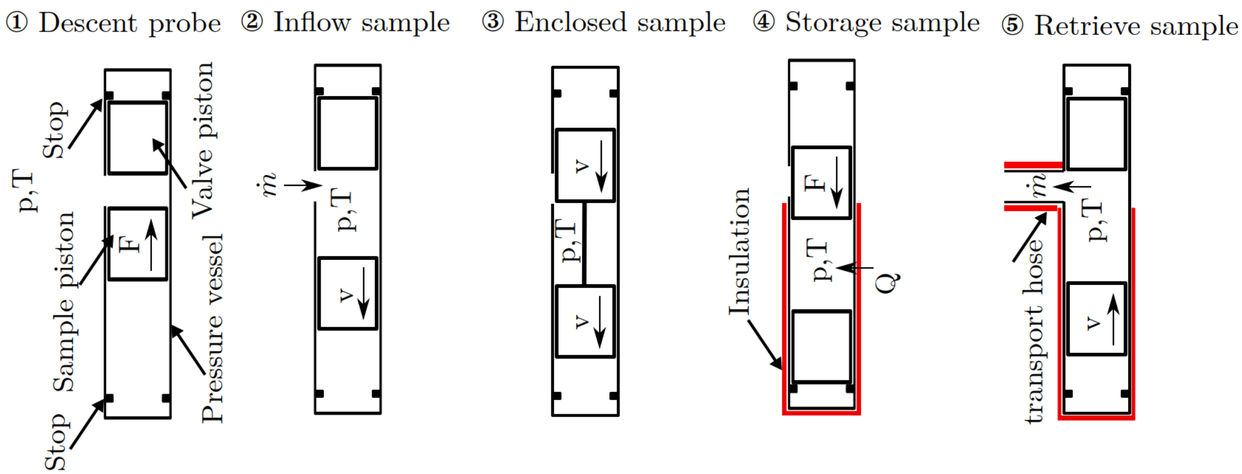

Figure 1: Fluid sample principle in five phases: ①descent probe: The probe is submerged into the borehole to a selected depth. The Sample piston is held in place as the sample container closure is open. The Valve piston pushes against a Stop. The sensor system measures temperatures outside and inside and the pressure. ② As the Sample piston is released, the fluid enters the sample chamber. ③ the defined sample volume in the sample container is enclosed by the two pistons, and everything is moved until the Valve piston closes the inlet. Then the sample is sealed. ④During emergence and at the surface, the sample pressure is controlled by the Valve piston force and the sample temperature is controlled by an electric heater. ⑤When dispensing via a hose, the Sample piston presses the Valve piston against the upper Stop and the sample is transferred to a transport container with minimal loss.

①*Descent probe*

The probe is submerged into the fluid-filled borehole to a selected depth via the wireline. The rising pressure pushes the Valve piston constantly against a Stop, and rising temperature heats up the probe slowly. The Sample piston is held in place by the piston rod force *F* as the sample container closure is open. The sensor system measures temperatures inside *T_in* and outside *T_out* and the ambient pressure *p*.

②*Inflow sample*

At the selected depth, the piston retention force is set lower than the force on the piston. As a result, the piston moves and fluid flows into the sample vessel. The inflow velocity is determined by the velocity of the piston rod.

③*Enclose sample*

The stroke of the piston rod determines the volume of the fluid sample. The collected sample is shuttled between the Sample piston and the Valve piston, and thus the system is in a state of equilibrium. Piston force is used to move the system until the Valve piston closes the inlet. Then the sample is sealed yet can still be moved axially in one direction.

④*Storage sample*

The temperature *T_in* and pressure *p* of the sealed sample are kept constant by an adaptive control of piston force and heating power. During emergence and at the surface, the ambient temperatures are lower than in the sample and the sample chamber. The sample pressure *p* is dependent on the true sample temperature and can be manually controlled by the Valve piston force.

⑤*Retrieve sample*

When dispensing via a hose, the Sample piston presses the Valve piston against the upper Stop and the sample is transferred to a transport container with minimal loss. To avoid a drop in temperature in the out flowing sample, the fittings, hose, and transport cylinder are preheated up to sample temperature.

Table 1: Environment condition and requirements for sampler and downhole probes, taken from (Spatafora et al., 2019)

Borehole depth	5 km
Diameter open hole	approx. 220 mm / 8 ½ inch
Diameter Housing tube	<95 mm
Ambient Temperature	<200 °C
Ambient pressure	<600 bar, 60 MPa
Sample Volume	> 450 cm3
Pressure keeping & record	+20 bar
Temperature maintain & record	± 5 K
single phase sample, CO2, *uGT*	slow sampling, heat control

2.1 Enhancement of temperature control

In the sampling principle, the sample chamber temperature is assumed to be equal to the ambient temperature at all times downhole. Thermal inertia, heat transfer, temperature stratification in the sample and in the sample chamber is neglected. In reality, there are temperature differences between the outside and inside the probe, as the deployment time is reduced. Generally, these differences are summarized by the Φ-factor. The Φ-factor or thermal inertia is the ratio of the mass times the heat capacity of the sample to the sample container. The closer this is to value 1, the more representative the sample is (Ekkehard, 2020). For a more representative sample in the sampler, the following procedures are recommended: Preheat the sample chamber to ambient temperature with a dummy sample. The heat transfer across the shell surface is reduced by an insulating layer. Furthermore, by forcing natural convection in the sealed fluid sample, temperature stratification is avoided.

3. Design demonstrator probe inliSAMP and sampling procedures

3.1 Design and layout of mechanical components inliSAMP

The proof of concept demonstrated the implementation of the novel sampling method, illustrated in Figure 1. The inliSAMP probe was engineered and constructed as a demonstrator for this purpose. A specific sampling procedure was developed for inliSAMP, which was then deployed on a borehole test rig under laboratory conditions. The sampling procedure was successfully tested with the demonstrator. The demonstrator inliSAMP is built according to the hottoolKIT standards. It consists of two high-temperature modules: the task specific sampling unit and a universal hydraulic power pack. The two modules are built up and installed in a housing tube, see Figure 2. The electronics boards required for the remote operation of the demonstrator are outside the housing tube and are supplied by laboratory power supplies. The setup is shown schematically in yellow on Figure 3. Components and assemblies used from the modular system and new designed parts for the borehole probes, are at different stages of product readiness and have different material requirements. For the sample unit, mainly stainless steel 1.4313 QT900, 1.4307, and 2.468 (Inconel® Alloy 718) were selected.

3.1.1 Hydraulic power pack

The hydraulic power pack is a module from the construction kit (Holbein et al., 2017) for down-hole tools. The hydraulic power pack consists of a 4-3-way valve, a high temperature pump, a high temperature motor, an oil tank and a lowering brake valve on the secondary side. Table 2 lists all purchased parts that were used. Figure 3 shows the hydraulic circuit diagram.

Table 2: Used purchased parts in the demonstrator inliSAMP

Item	Product	Producer
Electric Motor	EC-4pole 32 brushless 480 Watt | Heavy Duty	Maxon motor AG
Motor control board	EPOS4 CoMPact 50/8 CAN	Maxon motor AG
Fixed displacement micropumps	PB33	Hydro Leduc
4/3 Directional spool valve solenoid operated	WK06E-01	Tries GmbH & Co. KG
Lowering brake valve	SJ 00 G	HAWE Hydraulik SE
Heating mat	RS Pro Silicon Heater Mat, 80 W, 200 x 400mm, 12 V dc	RS Components GmbH
Pressure sensor	Series 7 LHP Inconel®Alloy 718	KELLER AG
Temperature sensor	PT 1000 Class B 1.0 x 3.0 mm	Farnell GmbH
Temperature sensor	PT 1000 Class B 1.7 x 1.7 mm	RS Components GmbH
Hydraulic fluid (fire resistant)	AeroShell Fluid 31	Shell Deutschland GmbH

3.1.2 Sampling unit

The sampling module comprises a sample chamber and two double-acting hydraulic cylinders arranged in tandem, as shown in enlargement in Figure 2. Connecting the hydraulic cylinders in parallel increases the piston rod force for both extension and retraction strokes. Both cylinders are equipped with a pressure sensor to monitor the force transmission over the piston rod. Pressure sensor P 3 measures the extension pressure (PUSH) and P 2 measures the retraction pressure (PULL) refers to Figure 3. The hydraulic fluid pressure data is crucial to operate and control the sampling process remotely. The measured pressure rise in the cylinder tube is important information for determining the piston position in the sample chamber.

The sample chamber is a heatable pressure vessel insulated over the circumferential surface, see Figure 2. The connection between the housing tube and the sample chamber is implemented with a small inlet flange and bushing. This is radially connected to an axially and radially movable sleeve, which is around the inlet bore of the sample chamber (Berentelg et al., 2020). The sample chamber tube has an inner diameter of 55 mm and a stroke of 305 mm; thus, the sample volume is approximately 480 cm^3. The sample volume can be easily increased by using a longer stroke and longer tubes. The piston rod diameter is 20 mm in the sample chamber and 22 mm in the hydraulic cylinder due to buckling. Standard fine pitch threads of M20 X 1.5 are used for coupling and end stop. The assemblies are connected by a special gland and a multi-part piston rod.

As shown in the concept in Figure 1, the water sample is taken between the Sample piston and the Valve piston. In the design shown in Figure 2, both pistons are axially mounted movable on a piston rod. The piston movement is controlled between both stops. They are equipped with O-rings (material Fluorocarbon (FKM)), back-up rings (material Polytetrafluoroethylene (PTFE)) and guide rings (material PTFE with bronze) on the piston seal and rod seal. The sealing clearance between the tube and the piston is approximately 2/10 mm.

Technical cleanliness in the sample chamber is provided through the design, preparation, and the sampling process. At the beginning of sampling, when the cleaned probe is lowered, the two pistons are in contact on the face and the inlet port is filled with demineralized water. Due to the vertical position of the hole of the inlet and length and small diameter of the pipe, little substance exchange takes place through the water inside and outside. This could be further reduced by the use of a push-off cap. Due to the small axial stroke of 65 mm at sample termination, it is feasible to equip the moving piston with a pressure sensor and a short and a long resistance temperature sensor probe using flexible, high temperature pre-bent wires. The pressure sensor records the ambient pressure in the borehole and, after closure, the sample pressure in the sample chamber. Two immersion temperature sensors measure the temperatures in the sample chamber. A longer temperature sensor (immersion depth 20 mm) measures the sample temperature, defined *T1*. while the short sensor (immersion depth 1 mm) measures the boundary layer temperature between sample and piston, defined *T2*. Furthermore, the borehole temperature and the outside temperature are recorded with an external temperature sensor, defined as T inlet flange *T_IF* on the nose of the probe. When the probe is lowered downhole (descent probe), the water pressure pushes the Sample piston (lower piston) on the piston rod against a Nut, the lower Stop. The upper Stop for the Valve piston is a short, thick-walled pipe. The hydraulic valve is closed, and the pump is at a standstill, hence the retention force from the Sample piston is transferred to the hydraulic cylinder via the piston rod.

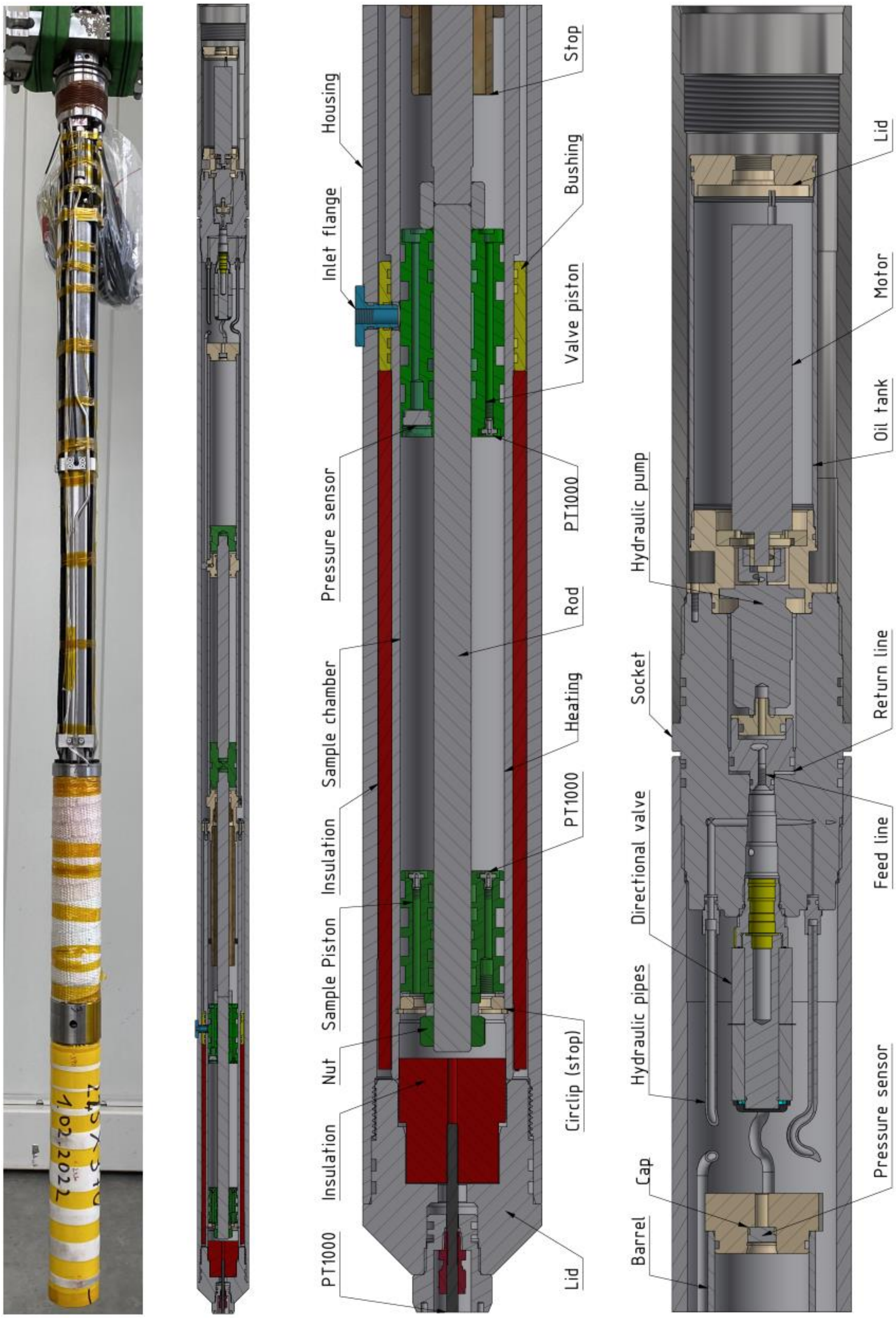

Figure 2: Left to right: photo of demonstrator inliSAMP used in test rig, CAD model borehole probe inliSAMP, enlargement: sample chamber, hydraulic power pack.

To initiate the inflow sample under load (inflow sample), the valve opens the retraction cylinder and hydraulic oil flows through a lowering brake valve to the tank. The lowering brake valve enables a set constant flow rate, largely disengaged of the load, and is used to adjust the sampling time according to the application requirements. Simultaneously, the pump transports oil on the extension side without back pressure. The process is terminated by contact between the Valve piston and the collar on the tie rod at the end of the stroke. A force equilibrium (enclosed sample) is created, and the movement of the Sample piston stops immediately. Thus, only little fluid power is required to move the Sample piston, the fluid sample and the Valve piston to the lower Stop, a heavy retaining ring. The retaining ring is seated in a groove in the pressure vessel tube and the exact position is adjusted by spacers.

The sample is sealed when the lower O-ring of the Valve piston has passed over the inlet bore. This initiates the storage phase, in which pressure and temperature are kept constant. The pressure in the sealed hot sample is temperature-dependent and must not fall below the borehole pressure. The pressure can be increased or decreased by changing the heating power, or more precisely, changing the global sample chamber temperature.

In case of leakage, deviation, or temperature drops, the sample pressure can be manually increased as required by fluid power through the piston rod and the Valve piston without changing the sample temperature. The heating of the sample chamber carries out three functions, heating the sample chamber and dummy sample before sampling in a hotter environment, keeping the temperature of the sample constant at colder outside temperature and to avoid shrinkage of assemblies. The resistance heating mat is glued onto the sample chamber up to the bushing and insulated towards the outside (see Figure 2 left). During storage phase, the outside temperatures are below the sample temperature and required heating power depends on the outside temperature.

The heating and insulation design of the sample unit is adapted from everyday objects such as an electric kettle. During storage phase, the heat source is at the bottom and the heat sink, the coldest point, is at the top. Thus, the different density of the fluid creates a static buoyancy. Natural convection leads to a homogeneous permeability and temperature distribution in the sample chamber. Before sample dispensing (retrieve sample), the inlet flange and outer housing is heated externally with a heating jacket (Leutert, 2021). In addition, the lower Nut on the piston rod must be manually readjusted. This reduces the pressure drop during sample dispensing.

3.2 Wireline power supply unit, control and communication board

3.2.1 Power supply requirements and layout for inliSAMP

The probe is powered by a DC power supply. Unlike the inspection tools such as the inliCAM probe, the expected consumption of the probe is much higher (Dietze, 2020). The embedded system and the communication systems are using about 10 W. The expected power consumption for the heat and motor control is approximately 400 W. In addition, the valves require 10 watts, and the maximum power is calculated as 420 W. It is recommended to use the theoretical maximum power transfer at the impedance matching point, where the output voltage is the same as the voltage over the cable and thus the probe voltage is half of the supply. For the coax cable of inliCAM, about 4.2 km long, and including a higher cable resistance to heat, a power supply with 520 Volt DC is needed. When less power is needed, nearly the maximal voltage applies to the entrance of the DC-DC converters at the probe. Therefore, special DC-DC converters operating at high volt are needed. For inliSAMP an additional circuit converter for use of long cables and storage functionality was invented. It operates in a Dewar flask with cooling reservoir (Dietze, 2020). Alternatively, a larger cable diameter with more copper can be used, but this will increase the weight and require larger winding equipment. A coaxial cable is usually very heavy in itself. The maximum length should be short enough with a reserve, before tearing itself off from weight. For example, the inliCAM cable weighs 1125.6 kg (in air), which is about 25% of the cable strength. Holding a probe with additional 150 kg is acceptable in water (RochesterWireCable., 2012).

3.2.2 Communication and embedded system

Communication, modems, and processing system were designed and developed for a universal use in borehole probes (Holbein et al., 2018). The main board of the embedded system, High Temperature Embedded System (HiTES), has as main chip a Field Programming Array (FPGA), which allows an implementation of algorithms for data modulation and demodulation in a suitable flexible way.

The wireline cable communication system was developed by an external partner and is presented in (Schubert et al., 2015) The communication system consists of plug & play software and hardware and further a Softcore-CPU for control and monitoring. The whole communication system is the same as the one successfully used for the inliCAM project, including the filter amplifier boards. The host modem, which is connected to the host PC via Ethernet, is a HiTES - system too, identical as for all wireline connected probes.

3.2.3 Electronics for measurement and control technology

To get access to the peripheral sensor and actors of inliSAMP, an IO-plugon-Board for HiTES has been developed, handling several measurement inputs and digital outputs. A motor control board for the hydraulic motor with a suitable size for the probe Dewar (Spatafora et al., 2016) was obtainable from Maxon™ (EPOS4 CoMPact 50/8 CAN, see Table 2). A Power IO board (PIO), which enables control of valves and heaters, as well as inputs for temperature sensors (Resistance thermometer, PT1000) and pressure sensors (piezoresistive pressure transducers), was built and installed. The layout of the circuit fits the mounting bars of the main board in the Dewar tube.

3.2.4 Information management

The host-PC software from hotToolKIT (Isele et al., 2015a), named “GeoGUI” is a workbench where forms can be composed with gadgets, which are connected to values to the probe or sending commands. InliSAMP has several forms and is designed with a GUI for full live control of the system. GeoGUI is connected to an SQL database and for example has the ability to replay a session at different speeds. Additional database export features were implemented for InliSAMP: Sensor data, valve position, motor control values, please refer to Figure 3.

3.2.4 *Control and monitoring of pressure and temperature in the sample chamber*

For the operation, partly automatized procedures have been implemented to HiTES Firmware to make remote control easier: To handle pressure, a "Wait-until-P_set-raise" and "maintain-P_set", where P_set is selectable out of the measured pressures in the inliSAMP. The procedures compare the measured P_set with a demand pressure and, if necessary, drives the motor of the hydraulic pump with a demand velocity. Heating of the probe is done by supplying the heat mat with 28 Volt and up to 18 Ampere.

Table 3: Sampling procedure: actions, monitoring, and measurements as positions of sensors are in Figure 3 and Figure 4.

operation	Phase principle	environment borehole test rig	Function for the probe operator or computer	Monitoring Measuring data in the probe
descent	① descent probe	p increase TIF increase	valve CLOSED preheat sample chamber motor 0 rpm.	P1 increase TIF; T1 increase P2, P3 = 1 bar
dummyIN	② inflow probe	p const TIF const	valve Port PUSH (B) heat sample chamber motor 4500 rpm	P1 const T1 increase P2 increase, as a braking element
dummyOUT	⑤ outflow probe	p const TIF const	valve Port PULL (A) heat sample chamber motor 2500 rpm	P1 const T1 const P2 increase
sampleIN	② inflow probe	p const TIF const	valve Port PUSH (B) keep heat sample chamber motor 4500 rpm	P1 const T1 const P2 increase, as a braking element
enclose	③ enclose probe	p const TIF const	valve Port PUSH (B) control heat sample chamber motor 2500 rpm	P1 const T1 const P2 and P3, decrease to balance
storage	④ storage sample	p decrease TIF decrease	valve Port PUSH (B) control heat sample chamber motor 1500 rpm	P1 const T1 const P3 increase
sampleOUT	⑤ retrieve sample	p = 1 bar T air = 14 °C	valve Port PULL (A) control heat sample chamber motor 2500 rpm	P1 const T1 const P2 increase

The use of a software of pulse-width modulation (PWM) with a cycle of two seconds and a minimal time slot of 20 milli seconds results in a demand of X % PWM of the maximal power of 504 watts. To heat up the sample chamber (demand temperature T_{demand} increase of the water sample), the nominal power is approximately 400 watts, this is defined for 100 % PWM heating power. For temperature control, a PI-Algorithm is provided with a cycle period of 100 milli seconds: The bias X of demand and curing temperature T_{cur} is calculated in Equation 1.

$$x_d(t) = T_{demand} - T_{cur}(t) \qquad (Equation\ 1)$$

$$x_{sum}(t) = k_{s0}x_{sum}(t-1) + k_{s1}x_d(t) \qquad (Equation\ 2)$$

$$y(t) = k_p x_d(t) + k_i x_{sum}(t) \qquad (Equation\ 3)$$

The sum for integral part is done in Equation 2. But additionally, because of the lack of negative output, there is no cooling possible, the integral sum is kept positive or set to zero. The vanish factor k_{s0} should be greater than zero and less than 1.0. Equation 3 shows the addition of the P-and the I-Part creating the output y. For example, the P-factor k_p is default set to 5.9. With ignoring the I-Part the maximum y = 100 % PWM is then reached when T_{cur} < $T_{demand} - 17$ K and defines a linear working range of 17 K below the demand temperature.

3.3 Sampling procedure

The sampling procedures are the sequences of operations the operator or the program runs through. It includes 7 operations steps and is listed in Table 3. These are the execution of the 5 different fluid sample principles, see Figure 1. The function at system level is not explained. It involves the operation of the control elements in sequence as given in the Table 3 and observation of the measurement data by the operator or a program. Below are listed the controls and measuring sensors for the execution and monitoring of the fluid sampling. The positions of the sensors and actuators are shown in Figure 3 and Figure 4.

- Control element:
  - hydraulic directional valve, status flow: Port PULL (A); CLOSED; Port PUSH (B)
  - electric motor rpm, user selectable: 1500 to 6000 rpm
  - heating, user selectable or controller max. 400 watts: 0 to 100 % PWM heat power
- Monitoring system
  - sample chamber temperature, Valve piston: T1, T2; Sample piston: T3.
  - borehole environment temperature outside inliSAMP: TIF
  - sample pressure: P1; pressure hydraulic pull; P2 pressure hydraulic push: P3.

The sampling procedure listed in Table 3 and actions are started and ended by predefined measured values and predefined states. Before sampling or testing, the preparation includes a surface pressure test, use of clean and rinsed equipment, connection check, and power supply review. At "**descent**" of the probe in the borehole the ambient pressure P1 and temperatures TIF, T1 increases with depth, the sample chamber is empty and heated up in accordance to TIF. The valve is at status CLOSED and motor on stop. At planned depth, temperature, formation pressure or some other point, the operation **dummyIN** starts, the hydraulic valve opens Port PUSH (B) and the motor set to 4500 rpm. It is finished when P2 decreases. Then the full sample chamber with T1 is heated up to TIF. In the next operation **dummyOUT** the hydraulic valve opens Port PULL (A) and the motor set to 2500 rpm, and it dispenses the dummy sample. It is finished when P1 rises up. The sample chamber temperature T1 is kept constant at TIF using the heating. At sampleIN the hydraulic valve opens Port PUSH (B) and the motor set to 4500 rpm. The sample is taken and the chamber temperature T1 is heated up again to TIF if necessary. It is finished when P2 decreases. To enclose the fluid sample, the hydraulic valve again opens Port PUSH (B) and the motor set to 2500 rpm. It is finished when P1 rises a little up the hydraulic cylinder are in equilibrium as the sample is confined between Sample valve and Piston valve. The sample chamber temperature is kept to T1. To store the fluid sample, the hydraulic valve opens Port PUSH (B) and the motor set intermittent to 1500 rpm and finished when P1 rises up a little in a hysteresis loop. The control of the chamber temperature and pressure is achieved via the T1 control. This may be used as an alternative method. At surface conditions, the sample dispensed "sampleOUT" with hydraulic valve opens Port PULL (A) and the motor set to 2500 rpm. At first, the system is in balance, hence only small force is required. When the sample chamber is connected to the transport cylinder, the full mechanic load has to be applied. The heat control heats the sample chamber to T1. The operation is completed when P1 rises up. The procedure was carried out in the proof of concept experiment in section 5. A detailed protocol of the experimental demonstration can be sent on request.

4. Setup test environment demonstrator inliSAMP

4.1 Test rig characteristics for fluid sampling

The functioning of sampling procedure and quality of measurements outputs of the demonstrator inliSAMP are evaluated on a test rig under laboratory conditions. The test rig simulates the environmental conditions in the borehole at a specific depth. Only demineralized water in the liquid state is used as downhole fluid. By varying the parameters of pressure and temperature of the water, different virtual depths can be reached. Heating and cooling sequences simulate the descent and ascent of the probe. This is essential for mapping the heating and cooling processes inside the probe. The test rig delivers a flow of water at a constant temperature and pressure. The sample is taken from a heated pressure vessel (preheater). In a real downhole application, the sample from the borehole is dispensed into a transport cylinder (Leutert, 2021). In this test rig, the sample is returned to the preheater at the end of the sampling procedure. The probe mechanism sets the flow rate. To maintain the aggregate condition of the water, the design of the test rig has to be failure safe. To fulfil the boundary conditions of taking samples up to 200 °C, all components have to be temperature rated. For safety measures, the sample pressure is scaled from 600 bars to 60 bars. This is possible as the isobars are adequately close to each other in the liquid state (Huber et al.). Demineralized water is used to prevent rust.

4.2 Test environment for hot water deep borehole

The test rig is shown in Figure 3 for the execution and monitoring of the fluid sampling procedure described in subsection 3.3. The demonstrator inliSAMP stands upright on a support and is permanently connected to the test rig. The test rig consists of a commercial standard hydraulic double-acting cylinder (DAC) with fastenings, a heatable pressure vessel (preheater) and a heating hose. The DAC is grabbed by a lifting hook at the head. Test weights (2.1 t) equivalent to 88 bars are attached to the rod of DAC. The retracting port of the DAC is connected with a hose via a check ball valve to the lower port of the preheater. A commercial flexible heating hose connects the upper port of the preheater to the inlet flange of the demonstrator inliSAMP. The demonstrator inliSAMP and the preheater are mounted vertically to obtain convection in the vessels. Tap water is used to cool the outer housing tube of the demonstrator. A pressure gauge and transmitter, and a lower and upper thermocouples type K monitor the pressure. Pressure P 4 and temperature, *T_Ph* and *T_IF* are logged by a computer. All hot hoses and connections are insulated and heated externally. The laboratory power supply units for the heaters are regulated manually. For testing, the demonstrator inliSAMP is equipped with additional temperature sensors that provide information about the operation of the probe and help gain a better understanding of the sampling processes and effects in the probe. For easier handling in test operation, the lower lid is also not used, see Figure 4. Hence, temperature *T_Ph* and *T_IF* represents the borehole temperature in the test rig. The outer temperature sensor *T_IF* is mounted on the inlet flange to the sample

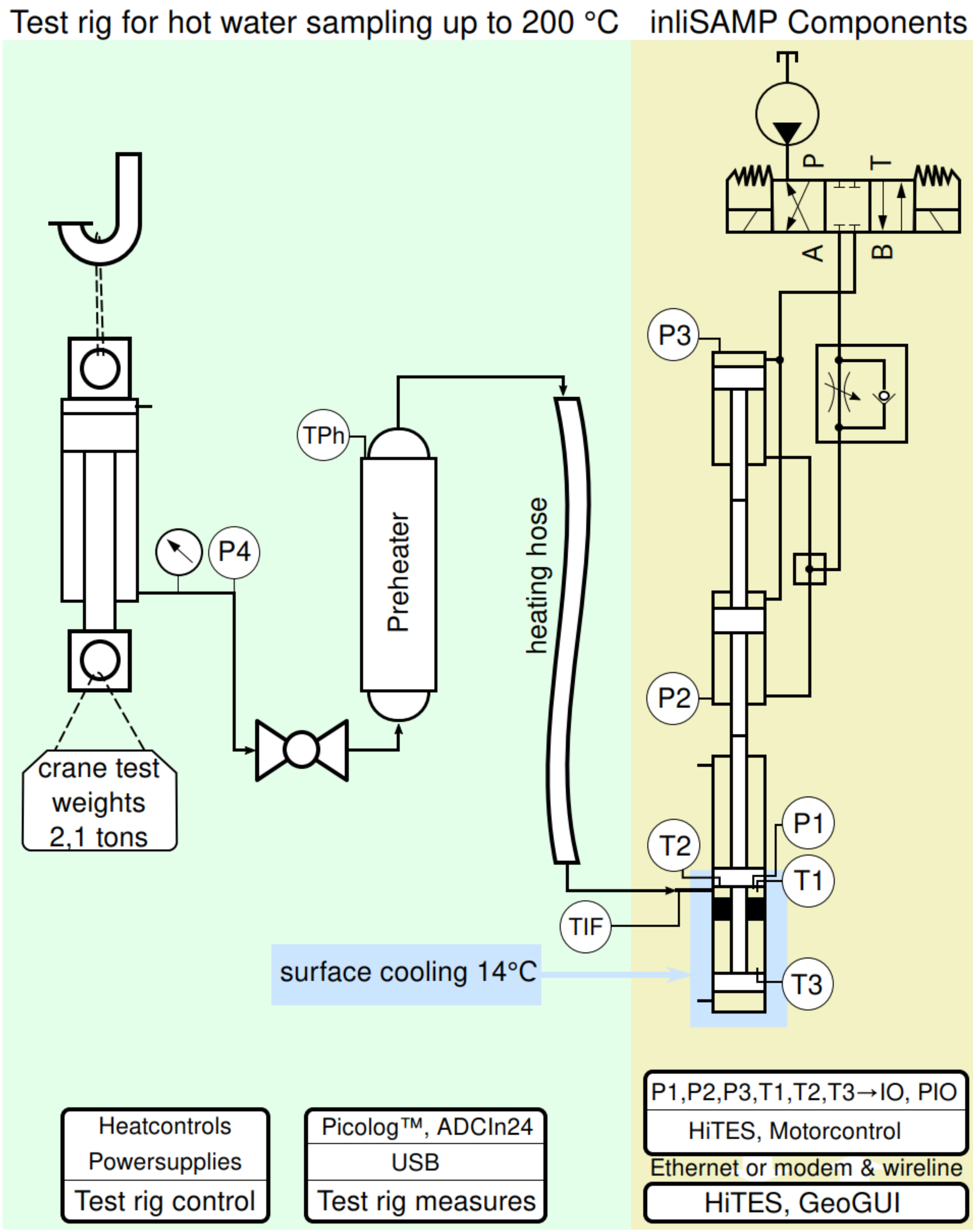

Figure 3: Green: Test rig for hot water sampling up to 200 °C; yellow: hydraulic circuit diagram of fluid demonstrator inliSAMP.

chamber and important during the **descent** and **storage** operations as well while dispensing the sample. On the probe *T_HM* is on the internal heating mat. It monitors the maximum heating temperature placed on the tube at a lower heat flux. *T_SC*2 is positioned in the centre of the sample chamber tube and provides information about the heat transfer to the housing and the sample chamber. *T_SC*2 is near the inlet flange and bushing, it monitors the heat flux over the thermal bridge of the demonstrator. The immersion temperature sensor *T*3 in the Sample piston, together with temperature sensors *T*1 and *T2*, monitors the temperature stratification in the fluid sample over the height of the sample chamber.

4.3 Test run fluid sampling procedures

The planned tests involve going through the full sampling procedure (see Table 3) using the test rig and the demonstrator inliSAMP. The objective is to test the sampling process applied with the demonstrator and evaluate the temperature curves and pressure maintenance over the full sampling procedure. The sampling history data are proof for the quality of the water sample. In addition, the following issues are to be answered by the experiment: Required heating power during different operations and in transition, heat up and temperature regulation in a cold environment, stability of pressure and temperature of the sealed sample, temperature stratification and natural convection in the sample, behaviour of the temperature curve, during sample taking and dispensing.

5. Results proof of concept demonstrator

5.1 Test execution Sampling procedure

In the **descent** probe operation, the probe housing tube was heated up to 200 °C with a detachable heating band, as well as the test rig components such as the water-filled preheater, and the heating hose. Inside, the PWM heating power preheated the empty sample chamber to 200 °C. The sample pressure was set by the ambient pressure at approximately 88 bars (see Figure 4). A heated fluid sample was taken in the sample chamber. After **dummyIN** operation, the dummy sample was deliberately overheated by the PWM heating power up to 204 °C, to avoid a temperature drop in the next operation. The other temperatures were manually controlled to be constant at about 200 °C. While dispensing the dummy sample at **dummyOUT** the PWM heating power was maintained in the sample chamber temperature. After short stabilization of the reference temperature, at **sampleIN** the final sample was taken at 200 °C. During **enclose** the sample was enclosed by the moving Sample piston and Valve piston and was heated up with the PWM heating power to 200 °C. Briefly, after sealing the sample at **storage**, the external heaters are switched off and only the PWM heating power was used to maintain the sample temperature. The heating hose is removed. The housing tube and the inlet flange are cooled down to 14 °C with faucet water. The PWM heating power is used to maintain the sample temperature and pressure remotely. The hydraulic system was being additionally used to manually increase the pressure. For the retrieval of the sample into the preheater at **sampleOUT**, the heating hose was reconnected to the inlet flange and the heating band heats up the housing tube. The PWM heating power was reduced to avoid overheating and overpressure while heating from outside. At constant temperatures at the inner and outer vessels, the sample is dispensed to the preheater.

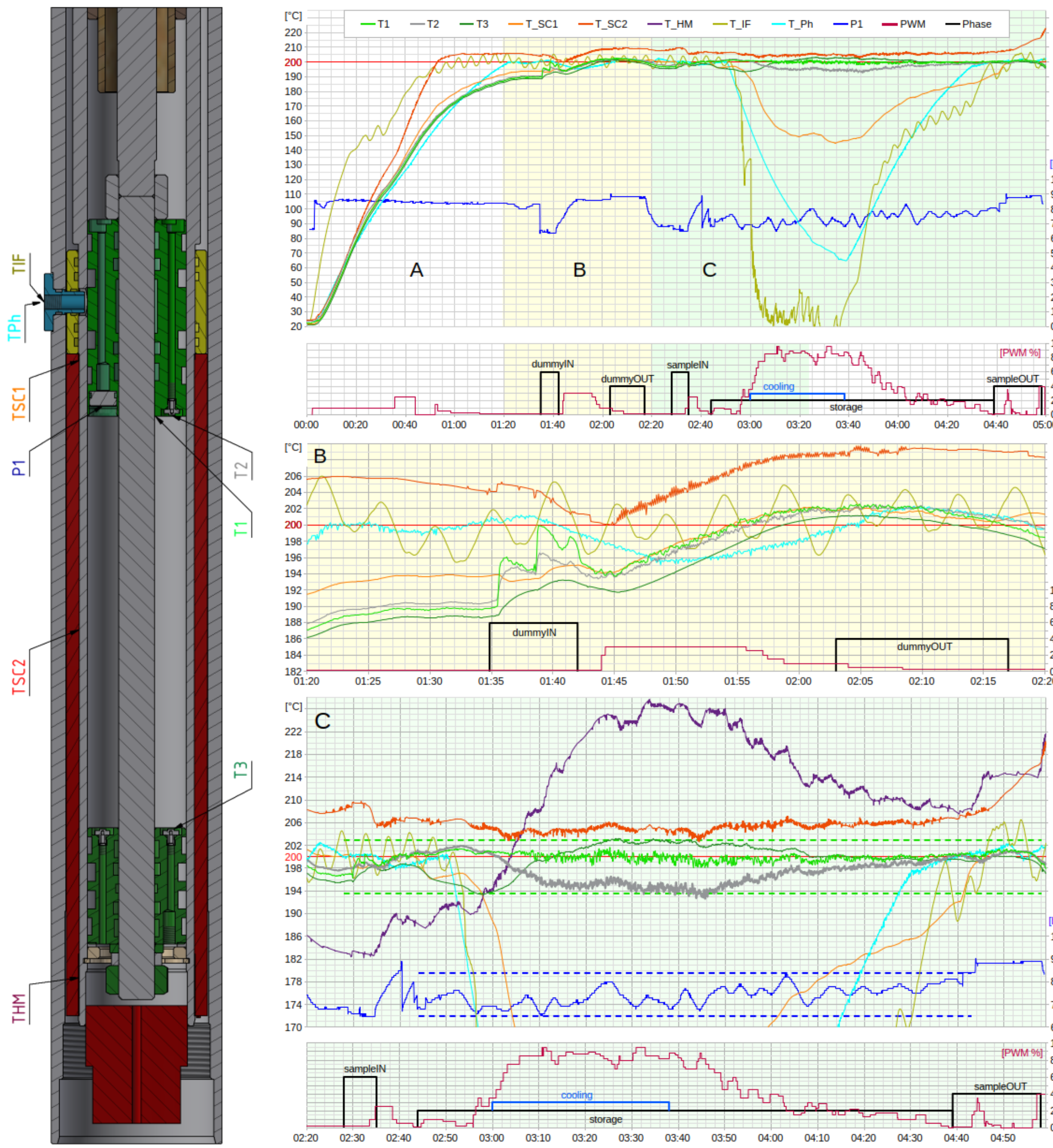

Figure 4: Left: sample chamber with temperature measuring points and pressure sensor (P1). Right: Data of test run with a dummy sample and representative water sample. The upper diagram is an overview of all measured values and operations. Section B shows dummy sample inflow (dummyIN), heat up and stabilize, dummy sample output (dummyOUT), Section C shows sample inflow (sampleIN), heat up and stabilize, sample output retrieval (sampleOUT).

5.2 Results and data of the demonstration run

The measured values of the sensors from the test are shown in Figure 4. The upper section is the overview of all data and performed operations over a demonstration run. The temperature data is shown on the left ordinate and the pressure data is shown on the right ordinate. On the abscissa, the time of experiment and additionally the steps of sampling procedure and PWM heating power of heating are listed. Section B shows the intake, heat up and dispensing of the dummy sample, and section C shows the intake, storage and dispensing of the representative sample in greatly enlarged form. The accurate representation of the data is intended to facilitate the presentation of thermodynamic effects of the different operations and to show the quality of the equipment.

5.2.1 Result descent probe: heat up and pressure monitor in Figure 4 section A

During heat up, the temperatures *T1*, *T*2, *T*3 and *T_SC*1 increased slower than the middle outer sample chamber temperature *T_SC*2. At 01:00 *T_SC*2 stabilized with 205 °C, at a utilization rate of 14% PWM heating power, illustrated in the upper Figure 4 section A. At the end of this operation the curve of *T1*, *T*2, *T*3 and *T_SC*1 flattened, and they have reached a plateau at 190 °C, the temperature difference is 3 K. Temperatures *T_IF* and *T_Ph* showed oscillations and were on average about 200 °C hot. As the fluid sample was open until the **storage** operation, the surrounding pressure was dependent on the test rig. First, the surrounding pressure *P*1 was above 65 bars. During the heating period, the pressure increased to 88 bars due to thermal expansion and the resulting static friction forces in the cylinder. These can be explained by the design of the test setup. The temperature data showed that the heat transfer from the outer housing tube to the sample chamber varies in vertical (axial) direction. In the area from the inlet flange the heat transfer is high, and at the lower part of the sample chamber vessel to the piston it is low. It is limited by the maximum operation temperature of the heating mat and sealing. It is monitored with *T _HM* in section C. Therefore, the empty sample chamber can only be slowly preheated from the outside and inside.

5.2.2 Result dummy sample: inflow, heat up and outflow in Figure 4 section B

During the inflow of the hot sample (*T_Ph*=201 °C), temperatures *T1*, *T*2, and *T3* increased immediately at 01:35 shown in Figure 4 section B. After taking the sample, *T_SC*2 decreased from 205 to 200 °C at 01:45 evenly. Due to thermal inertia and thermal gradients, the taken sample temperature *T1*, *T*2, was 194 °C, 5 K below the reference temperature of 200 °C. The reference temperature *T_Ph* decreased after the sampling as cold-water flows into the preheater, this does not affect the demonstration. With 30% PWM heating power from 1:45 to 1:55, the dummy sample was overheated *T_SC*2 at 210 °C, so fluid temperatures *T1*, *T*2 increased to 202 °C, with *T3* reached only 201 °C at 02:05. After dispensing the dummy sample, *T1* decreased to 197 °C, whereas *T2* was approximately 1 K above. Temperature *T*3 decreased to 195 °C at 2:20. Despite minimal PWM heating power, *T_SC*2 remained at 210 °C.

As a finding, the 200 °C hot water dummy sample from the preheater heats up the upper part of the sample chamber and the pistons. In summary, the fluid sample becomes slightly colder, as the heat is distributed in the probe. Due to the increased heat transfer in a fluid loaded sample chamber, the system can be PWM power heated more homogeneously and faster to reach equilibrium with the reference temperature.

5.2.3 Results sample: inflow, heat up, storage and retrieval, sampleOUT in Figure 4 section C

After preheating with the dummy sample at 2:20, the temperatures at the different temperature measuring points are much closer to each other. At the beginning of the operation Temperatures **sampleIN** at 2:30 *T3*, *T1*, *T2* were at 196 °C to 198 °C represented in the Figure 4 section C. The

PWM heating power with 10 to 20% was used to maintain the taken sample *T1* and *T2* at 200 °C at 02:40, however, temperature *T3* did not increase consider-ably. Before the sample is drawn and enclosed the heating controller starts maintaining the sample temperature, represented by a dashed green line in Figure 4 section C. Since the pressure in the sample *P* 1 was dependent on the total fluid temperature, it also ramps up until 90 bars.

At 02:44 after the **enclose** operation the fluid sample was sealed and thus the sample probe is disconnected from the test rig. The operation **storage** has been started and can be controlled by the operator. From this moment, the fluid sample in the sample chamber was separated from the pressure compensation of the test rig. Due to the closed sample chamber, the pressure *P*1 was directly dependent on the actual temperature. This state is marked by a dashed blue line. Furthermore, the dashed line blue and green represent the range of minimum and maximum values of pressure and temperature in the **storage** operation. Small temperature changes of the inert mass of fluid sample and sample chamber result in large pressure changes, as the pressure values went up and down. It had the lower boundary at inlet pressure 65 bars and upper boundary at 83 bars (blue dashed line), as the given procedure allows only positive elevations.

At 02:50 all external heaters were disabled, and *T_Ph* began to decrease slowly to 65 °C. The housing tube and inlet hole *T_IF* were cooled below 20 °C, first with air and then with faucet water. Hence, the temperature at the inlet flange *T_SC*1 decreased to 145 °C, simultaneously *T1*, *T*2 decreased and stabilized at 201 °C at 02:56. Temperature *T3* dropped to 194 °C, the lower boundary of the temperature range.

Next, the PWM heating power was ramped-up to 90% to maintain *T1* at a constant value. At 02:58 at temperature lines intersection point the lower piston temperature *T3* and *T_SC*1 started to rise and stabilized to 203 °C at 03:26 the upper boundary value. Concurrent *T2* over time decrease to 194°C with small aberration. As well, *T1* wobbled around the target temperature with ± 1 K difference.

During the **storage** operation and extensive *cooling*, temperature *T_SC*2 decrease evenly to a minimum of 204 °C, although the PWM heating load was at peak. Further, the curve *T_HM* showed a maximum temperature of 227 °C at 03:40, indicating the activity of the internal heat mat. At 03:40 the detachable heating band, preheater and heating hose were set back and heated up to a reference temperature of 200 °C of the test rig. The PWM heating power was reduced accordingly. The fluid sample temperatures *T1*, *T*2, and *T3* slowly converge nearly to 200 °C, beginning at 03:45 until 04:39. When the sample was half retrieved *T1*, *T*2 rose to 201 °C. After sample dispensing *sampleOUT*, the *T1*, *T*2, *T*3 dropped to a minimum of 198 °C, while *T_IF* and *T_Ph* fluctuated slightly. During sample dispensing, the pressure increases to 88 bars to overcome the frictional forces in the cylinders.

The results and data show that after dispensing the dummy sample, temperatures in the sample chamber dropped 2 K because of cooling effects in the sample chamber. This small value indicates that the temperature is evenly distributed. Next, the incoming hotter sample heats up slightly the sample chamber, as *T*1 and *T2* rose. After the additional heating with the PWM heating of the chamber, there was subsequently a temperature stratification due to cooling processes and an inhomogeneous temperature distribution in the sample chamber. During the **storage** operation and cooling stage, the top of the sample chamber and inlet flange is colder as the bottom (see design of the probe Figure 2). As shown in the measurement data applying the heating power to the lower part of the sample chamber, leads to a reversal of the thermodynamic system and the temperature stratification dissolved (follow *T3* from 2:56 to 3:35). This result is an inversion of the temperatures. At the lower Sample piston, the highest temperatures are measured, and at the boundary layer at the Valve piston the lowest. The temperature *T1* immersed in the fluid remained approximately constant but gets many small jumps. In addition, the sample chamber wall temperature *T_SC*2 decreased while heating power is high. The effect can be explained by the occurrence of natural convection, as the chamber is cooled at the top and heated at the bottom. The coincident heating and cooling of the sample chamber leads to vertically different temperatures in the fluid sample. Thus, a flow is created by different temperatures of layers, which affects the density. This leads to a steady temperature exchange, increased cooling of the sample chamber tube, and mixing of the sample.

After the water cooling was disabled, the heating power was reduced accordingly. Simultaneously, the vertical temperature difference in the sample decreased. Due to the homogeneous temperature distribution in the sample chamber and the successful mixing of the sample, the temperatures converged towards 200 °C.

As the experiment shows, an electrical heating power of 400 watts, insulation and good design of the sample chamber is sufficient to maintain the temperature in the sample chamber permanently. Furthermore, the seals (O-ring) kept the pressure in the sampling process without leakage on the demonstration run. Materials FKM and FFKM were used. The experience with these materials under the given conditions at 200 °C and 60 to 100 bars is the failure of the O-ring after passing through the radial inlet bore several times. A revision of the design is necessary here.

Furthermore, the housing tube of the demonstrator housing is made of steel. A housing tube of the same dimension made of Inconel® Alloy 718 has a lower thermal conductivity, and the system would be cooled and heated more slowly by the environment.

6. Discussion

The findings from the experiment show that, under laboratory conditions, a fluid sample can be taken, stored and dispensed using the demonstrator inliSAMP in the test rig. The quantitative results from the experiment show that with the execution of the fluid sampling procedure, the sample temperature and pressure in the sample chamber deviates only slightly from reference fluid in the preheater. Thus, proof of concept has shown that a fluid sample can be collected and stored in the inliSAMP demonstrator under nearly in-situ conditions.

First, a water dummy sample with 200 °C and 65 bars was taken from the preheater. In the cold sample chamber inside the probe, it was heated up to the target temperature of 200 °C and dispensed back in the preheater. Second, the actual sample was taken from the preheater and stored in a clean, warmed-up sample chamber. When the sample was stored in the demonstrator, the heating hose was disconnected. The outer housing was cooled down to 14 °C. The sample temperature and pressure were maintained by the sample chamber heater control and hydraulic piston force. Only small pressure overshoots were allowed. Natural convection is used to keep a homogeneous sample. At the end, the sample was dispensed into the preheater at nearly 200 °C and 88 bars.

The inliSAMP demonstrator consists of a stable housing with the sample unit and a hydraulic power pack and electric supply. The parts are developed accordance to the HottoolKIT standards and taken from the modular system. The sample unit was developed for undisturbed and pressure-constant sample collection, storage, and dispensing. The high-performance hydraulic unit was engineered for high temperature operation and for usage in very small, round installation spaces. The associated communication and power supply was provided via a high temperature circuit board HiTES and power supply units in the laboratory.

The sampling procedure was developed for the inliSAMP demonstrator with the aim of obtaining a representative fluid. A key feature is the preheating of the sample chamber by a dummy sample, mixing and adaptive temperature control of the sealed sample during uplift and transportation. The test rig provides preheated water with a permanent pressure control. Also heating jackets and a heating band for thermal simulation of a borehole environment. The total power consumption of the demonstrator was also derived from the experiment. The power requirement is approximately 470 Watts for inliSAMP (see section 3.2), 400 Watts for heating at an ambient temperature of 14 °C in water, 50 Watts for the electric hydraulic motor, 10 Watts for the alternately powered valve and 10 Watts for permanent power for embedded and communication. Thus, for industrial available cables, the maximum cable length or operation depth can be calculated. A coax cable of 5 km length and 500 V DC capable, with a bit thicker wire than the cable of video probe inliCAM is required.

The quality of the fluid sample taken with the demonstrator has been assured by various technical measures such as the use of an adaptive intake and sealing mechanism, temperature controllers and temperature monitoring. Sample temperature and pressure, and sample status can be directly monitored and logged. Before the storage operation the temperature can be increased manually by the operator. The sample pressure can be increased manually as often and as high as desired during storage.

The temperature distribution in the sample is monitored at three measuring points and adjusted by an internal heating control according to the predefined procedure. The temperature gap between the sample chamber and the borehole is reduced by preheating. With a dummy sample, the temperature difference is reduced to 6 K at 200 °C during 3 hr testing. Convection dissolves the temperature stratification and permanently mixes the sample in the storage operation. Processes such as over heating, cooling, degassing, mineral perception which result in an alteration of the sample are suppressed by these measures. The pressure in the sample chamber is identical to the formation pressure until sealing. Moreover, the sample is collected slowly, independent of the load. Due to the simple sealing mechanism, the formation pressure or a higher adjustable sample pressure is in the sample chamber. Hence, there are no pressure differences and processes such as flashing and adiabatic cooling does not occur. The overpressure is to ensure no alteration of the sample, the maximum range value is 20 bars plus, due to thermal expansion.

Similar temperatures to the test bed and demonstrator at 190 – 197.5 °C were measured downhole in geothermal wells using the GTFSampler (Hsieh et al., 2021). After the probe has cooled down to about 20 °C, the sample pressure is 25 bars, The aqueous composition of the sample is verified by a simulation and the geochemical characteristics provides knowledge about the geothermal reservoir. Hence, downhole procedure of full pressurization at formation pressure and pressurization above dissolved gas pressure should be further investigated. A similar result is provided by the in-situ sampling (150 °C, 45 MPa) in Groß Schönebeck, Germany with the Leutert system (Regenspurg et al., 2010) from the borehole. Here, no results of the measurement of pressure and temperature at the surface are measured, as only downhole fluid from the borehole analysis is existent. In addition, the inliSAMP demonstrator could provide temperature and pressure data over the wireline.

The integrity of the fluid sampler inliSAMP demonstrator is maintained by a representative fluid sample, a measurement log of the entire sample process history, real-time monitoring and remote control. The log contains data from the sample chamber (fluid temperature and pressure), borehole temperature, and operating data from the hydraulic power pack. The operating data provides important information about the status of every operation of the sampling procedure, the sampling time and the success of the sampling. In the SECURe project the sampler provides temperature and pressure data from downhole and volume. In the deployment, a pressure of 41.5 to 42 bars is measured, which is in the same magnitude to the experiment. Temperature and pressure are not maintained, so that no data is available during uplift to the measuring station (Ricroch et al.). However, it would be interesting to compare the sensor data accuracy and sample function with the inliSAMP demonstrator, as both probes can transfer real time data to the operator.

The inliSAMP demonstrator reduces the sampling time in the borehole, since no displacement fluid and pressurization fluid are required. Furthermore, repeatability of the sampling procedure is easily possible with the electrical and mechanical components. In the future, this will also include sampling with several probes or sample chambers. As preparation at site, a rinsing of the sample camber, check of the functions and filling of demineralized water is required. To obtain a representative sample from the borehole, the following fundamental requirements for temperature and pressure management as well as cleanliness of the sampling procedure and design were met. The experimental results and findings on the behaviour of the developed sampling procedure and inliSAMP demonstrator show progress in the field of in situ sampling tool development.

7. Conclusion

Extensive investigations have been carried out for the development of a novel sampling procedure, the sample chamber design and the implementation of a sampling module in the inliSAMP demonstrator. The overall objective was to develop a sample unit with controls and actors to retrieve a representative sample from downhole to surface with monitoring and control in real time data. The sampling module was mounted in a demonstrator housing and the developed sampling procedure was performed on a test bed under laboratory conditions. The investigations were mainly focused on design calculations of the sample chamber, the sample intake, and closing mechanism plus the sampling procedure with a minor temperature distribution in the sampler and a permanent pressure maintenance. Standards, experience with materials, and component developments were adopted and/or further enhanced from the hotToolKIT construction kit.

The main investigations and results of the proof of concept test showed:

- With the sampling procedure the fluid sample is taken, stored and delivered near in-situ downhole conditions.
- With a two-piston mechanism and operation hydraulic force, the sample is taken up without flashing, sealed without pressure change, recompressed if required and released again. Pressure change occurs during the storage and dispensing of the sample.

- In the sample chamber, the temperature distribution in the sample is monitored and logged over time at three positions. A tube heating mat is used to preheat the sample chamber, maintaining the temperature of the fluid sample and mix the sample due convection flows. Small deviations occur when the sample is let in and out.
- The inliSAMP demonstrator is monitored, supplied and operated with real time data via the wireline. Thus, a free choice of operations is possible. Additional operations could be performed such as sampling repetition, dispensing of any fluid downhole, multiple sampling and extended measurements.

During the proof of concept demonstration run and previous runs of the test rig, the pressure range is plus 20 bars in the storage operation during uplift and the temperature range is about 6 K during the sample intake in a preheated sample chamber. Thus, the in-situ conditions of the formation fluid a nearly maintained. The pressure increase could be reduced by improved automatized control of the temperature. For each process operation, a controller should also be developed to simplify remote operation by the operator and to partially automate sampling. A further test would be of importance with brine including dissolved gases in the test rig and a subsequent fluid and gas analysis. Furthermore, a revision of the design of the inlet hole and the seal is necessary to increase the lifetime of the sealings. For deployment of a prototype probe in the borehole, electronic components such as a power management system and power supply are under development. Many existing solutions such as the Dewar tube, cold reservoir and communication unit can be adopted from the inliCAM. This research on the inliSAMP probe has focused intensively on the sampling process and the maintenance of in situ downhole conditions in the sample chamber, as well as the enhancement of the integrity of the sampling data.

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REFERENCES

Akın, T., Kargı, H., 2019. Modelling the geochemical evolution of fluids in geothermal wells and its implication for sustainable energy production. Geothermics 77, 115–129. doi:10.1016/j.geothermics. 2018.09.003.

Alfredsson, H.A., Mesfin, K.G., Wolff-Boenisch, D., 2016. The syringe sampler: An inexpensive alternative borehole sampling technique for co 2 -rich fluids during mineral carbon storage. Greenhouse Gases: Science and Technology 6, 167–177. doi:10.1002/ghg.1543.

Ayliffe, C., 2022. 25.5.2022 Geothermal Energy Production Utilisation. ThinkGeoEnergy URL: https://www.thinkgeoenergy.com/geothermal/geothermal-energy-production-utilisation/.

Berentelg, G., Spatafora, L., Hagenmeyer, V., 2020. Wasam, a modularly designed fluid downhole sampler for deep geothermal applications. Geothermal Resources Council (GRC) doi: 10.5445/IR/1000127866.

Conaway, C.H., Thordsen, J.J., Manning, M.A., Cook, P.J., Trautz, R.C., Thomas, B., Kharaka, Y.K., 2016. Comparison of geochemical data obtained using four brine sampling methods at the secarb phase iii anthropogenic test co2 injection site, citronelle oil field, alabama. International Journal of Coal Geology 162, 85–95. doi:10.1016/j.coal.2016.06.001.

Dietze, S., 2020. Control and communication technologies of cable-based borehole probe - final GRC Transactions, Vol. 44. URL: https://publikationen.bibliothek.kit.edu/1000131541.

Eddie W. Banks, Stanley D. Smith, Michael Hatch, Lawrence Burk, and Axel Suckow, 2017. Sampling Dissolved Gases in Groundwater at in Situ Pressure: A Simple Method for Reducing Uncertainty in Hydrogeological Studies of Coal Seam Gas Exploration. doi: 10.1021/acs.estlett.7b00457.

Ekkehard, F., 2020. 16/08/2022. AN 134_VariPhi The Patented Immersion Heater Thermal Runaway Tests URL: https://analyzing-testing.netzsch.com/_Resources/Persistent/0/4/3/a/043ad64fd7dd71a1ea0ca5764f5359e9acb70b65/AN%20134_VariPhi%20The%20Patented%20Immersion%20Heater%20Thermal%20Runaway%20Tests.pdf .

Halliburton, 2022. Armada®sps-a single-phase sampler: Downhole collection of reservoir fluid samples for pressure-volume-temperature (pvt) analysis URL: https://cdn.brandfolder.io/G1R8FA5S/as/q5uwqk-1jkrs0-5z1vcv/H012196-ArmadaSPSA.pdf.

Holbein, B., 2019. Theoretische und Experimentelle Kältemittel- und Dichtungsauswahl und Komponentenentwicklung zur Langzeitkühlung von Elektronik in Untertagewerkzeugen. Karlsruher Institut für Technologie (KIT). doi:10.5445/IR/1000094597.

Holbein, B., Dietze, S., Hurst, F., Isele, J., Spatafora, L., Wiegel, F., Hagenmeyer, V., 2018. Quality management and improvement for geothermal energy projects using the platform-based tool development technology - ZWERG. Geothermics 71, 320–330. doi:10.1016/j.geothermics.2017.10.010.

Holbein, B., Isele, J., Spatafora, L., 2017. New downhole tool designs for EGS based on platform development approach, in: Geothermal Resources Council Annual Meeting and GEA GeoExpo+, Salt Lake City, Utah, October 1-4, 2017, Geothermal Research Council. pp. 2453–2469. URL:https://publikationen.bibliothek.kit.edu/1000076978.

Hsieh, P.S., Lin, C.K., Chang, Y.T., Lu, H.Y., Yang, T.F., 2021. The GTFSampler: A new downhole equipment for geothermal fluid sampling and its testing results in the Chingshiu geothermal field, Ilan, Taiwan. Geothermics 94, 102077. doi:10.1016/j.geothermics.2021.102077.

Huber, M., Harvey, A., Lemmon, E., Hardin, G., Bell, I., McLinden, M., . Nist reference fluid thermodynamic and transport properties database (refprop) version 10 - srd 23. doi:10.18434/T4/1502528.

International Ocean Discovery Program, 2022. 10.08.2022. iodp jrso • downhole logging tools. URL: https://iodp.tamu.edu/tools/logging/index.html .

Isele, J., Bauer, C., Dietze, S., Holbein, B., Spatafora, L., 2015a. The zwerg project: a platform for innovative logging tools, in: Proceedings of the World Geothermal Congress 2015, Melbourne, Australia. URL: https://publikationen.bibliothek.kit.edu/240100881.

Isele, J., Spatafora, L., Wiegel, F., Holbein, B., 2015b. Kamerainspektionssystem für tiefe Geothermie Brunnen (GeoKAM): Abschlussbericht: Forschungsvorhaben: 0325580. Karlsruhe Institute of Technology.

Kampman, N., Maskell, A., Bickle, M.J., Evans, J.P., Schaller, M., Purser, G., Zhou, Z., Gattacceca, J., Peitre, E.S., Rochelle, C.A., 2013. Scientific drilling and downhole fluid sampling of a natural CO_2 reservoir, green river, Utah. Scientific Drilling 16, 33–43. doi:10.5194/sd-16-33-2013.

Leutert, 2021. Fluid sampling, in: Kuchuk, F.J., Ramakrishnan, T.S., Onur, M. (Eds.), Wireline Formation Testing: Hardware, Pressure Transient Testing, Interpretation and Sampling. Society of Petroleum EngineersRichardson, Texas, USA, pp. 347–364. URL: https://www.leutert.com/media/oilgas/downloads/sampling/datasheet_downhole-fluid-sampler_en_screen.pdf, doi:10.2118/9781613998434-17.

Lowenstern, J.B., Bergfeld, D., Evans, W.C., Hurwitz, S., 2012. Generation and evolution of hydrothermal fluids at Yellowstone: Insights from the Heart Lake Geyser Basin. Geochemistry, Geophysics, Geosystems. doi:10.1029/2011GC003835.

Lund, J.W., Huttrer, G.W., Toth, A.N., 2022. Characteristics and trends in geothermal development and use, 1995 to 2020. Geothermics 105, 102522. doi:10.1016/j.geothermics.2022.102522.

Regenspurg, S., Wiersberg, T., Brandt, W., Huenges, E., Saadat, A., Schmidt, K., Zimmermann, G., 2010. Geochemical properties of saline geothermal fluids from the in-situ geothermal laboratory Groß Schönebeck (Germany). Geochemistry 70, 3–12. doi:10.1016/j.chemer.2010.05.002.

Ricroch, P., Estublier, A., Guelard, J., Noirez, S., Martin, F., Mougin, P., Karimi, A., . Development of a downhole sampler and an integrated analysis system for in situ deep fluids analysis. URL: https://www.securegeoenergy.eu/sites/default/files/SECURe_D4.8_Final.pdf.

RochesterWireCable., 2012. Signal transmission cable, code: Sc0010162co01.

Schlumberger, 2020. Single-phase reservoir sampler URL: https://www.slb.com/-/media/files/testing-services/product-sheet/single-phase-reservoir-sampler-ps.pdf.

Schubert, B., Flöter, M., Kühne, T., Keusgen, W., 2015. GeoKam Abschlussbericht: Konzeptionierung eines Kabelmodems für ein Kamerainspektionssystem. Fraunhofer Institut für Nachrichtentechnik Heinrich Hertz Institut.

Spatafora, L., Isele, J., Holbein, B., 2016. The GeoKAM - a tool for video inspections in hot deep geothermal boreholes. 41st Workshop on Geothermal Reservoir Engineering, Stanford, CA URL: https://publikationen.bibliothek.kit.edu/1000054080 .

Spatafora, L., Isele, J., Ritzhaupt-Kleissl, H.J., Hagenmeyer, V., Aktaa, J., 2019. Avoiding thermal-stress-induced failures by design optimization when brazing perlucor *Iconel* 718 components. Journal of ceramic science and technology 10, 1. doi:10.4416/JCST2019-00011.

Wheat, C.G., Kitts, C., Webb, C., Stolzman, R., McGuire, A., Fournier, T., Pettigrew, T., Jannasch, H., 2020. A new high-temperature borehole fluid sampler: the multi-temperature fluid sampler. Scientific Drilling 28, 43–48. doi:10.5194/sd-28-43-2020.

Wolff-Boenisch, D., Evans, K., 2014. Review of available fluid sampling tools and sample recovery techniques for groundwater and unconventional geothermal research as well as carbon storage in deep sedimentary aquifers. Journal of Hydrology 513, 68–80. doi:10.1016/j.jhydrol.2014.03.032.