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The GeoKam – A Tool for Video Inspections in Hot Deep Geothermal Boreholes

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ABSTRACT

The video inspection tool GeoKam was developed for providing real insights in deep boreholes in high definition. Its cameras for the front and 360° radial view with adjustable aperture, focus, and lighting allow detailed visual inspection e.g. for the detection of casing leakages. For operations in harsh environments it is designed to withstand 165 °C ambient temperature for a period of around two hours plus two hours travelling time and a pressure of up to 48 MPa. With 95 mm outer diameter it is built in a compact way, regarding the pressure resistant housing and the required heat insulation. Therefore the inspection tool can be used in boreholes with 8 ½ inch (~215 mm) diameter. Thus the temperature, pressure and geometrical parameters cover the operation in most of the geothermal boreholes in Germany. The GeoKam is developed based on the system platform for down-hole tools ZWERG. Most of its components, including housing, heat insulation, temporary cooling system, housing-to-housing connectors, cablehead and electronics including a communication modem are designed in a standardized way and can be reused for the development of further tools in order to reduce costs. This is possible due to a standardization of basic components based on the constraints of the Soultz-sous-Forêts Project in France with 5 km depth, 200 °C ambient temperature and 60 MPa pressure. For the realization of the tool, solutions on several technical challenges had to be developed. One example therefor is the development of a highly loadable metal ceramic composite for the windows in the probe housing. Another is the complicated fabrication of steel and glass Dewar vessels for the heat insulation of tools. In addition to the insulation a cooling module was developed, which allows longer work at deep positions with high temperatures. Furthermore for some components new fabrication methods such as SLM (Selective Laser Melting) are used instead of a conventional cutting fabrication process. This provides further design possibilities and allows advanced useful embodiment designs. In the GeoKam this is the case e.g. at the frame of the camera module or the space-saving lighting system. Besides, the alternative fabrication methods can lead to cost and time reductions. The GeoKam development is almost completed. Currently the complete system is tested under realistic conditions at the Karlsruhe Institute of Technology (KIT) as preparation for planned in situ tests. For this purpose a custom built autoclave has been installed in the geothermal test-hall. In its test space of 2.5 m height and 250 mm diameter a pressure of up to 80 MPa and a temperature of more than 200 °C can be generated with water as media. With the autoclave the conditions of deep boreholes can be closely represented and realistic tests can be conducted. This paper gives an overview over the development process and explains technical details of the complete system and system tests.

1. INTRODUCTION

With the video inspection probe GeoKam, borehole inspections in deep geothermal boreholes can be carried out in the future. Through the development of the probe at the Karlsruhe Institute of Technology – Institute for Applied Computer Science, a major step forwards in the sector of cause study and cause elimination especially for deep geothermal energy has been made. With the realization of video inspections with the GeoKam, inspections for the servicing of boreholes, inspections for the detection of damages or for the exploration of the underground can be made routinely. In order to withstand the harsh requirements in 4 km depth at about 48 MPa and 165°C (max. parameters of 80 % of deep geothermal boreholes in Germany) and thus complying with the inspection task, the probe consists of a robust housing and heat-resistant electronics. Via a wireline, images can be transferred in real-time and important details and defects of the borehole are precisely detected and located. The GeoKam hereby makes an important contribution to the reduction of the well-known risks in the geothermal energy domain [Holbein 2015].

The development of GeoKam extended over a period of three years. Almost all the components of the probe are new developments, built for the first time. This paper gives an overview of the research, the problems and their solutions within the GeoKam project.

2. DESIGN AND FABRICATION

The design of GeoKam is based on the platform ZWERG, which pursues the same strategy as system platforms in the automotive industry. Since approx. six years IAI works on the ZWERG project to develop a system platform for geothermal borehole probes. This platform should provide the expertise of standardized basic components, which are used in many probes, as e.g. a probe housing or thermal insulation for developers and operators of downhole probes [Isele 2015]. The developed components are intended for use in inspection, repairing and logging probes. In addition to the platform complete probes with individual components should be developed as well. A first probe based on ZWERG, is the video inspection probe GeoKam (fig. 1) with which an optical inspection of borehole walls in deep geothermal boreholes can be performed in real-time. [Spatafora 2015-a]

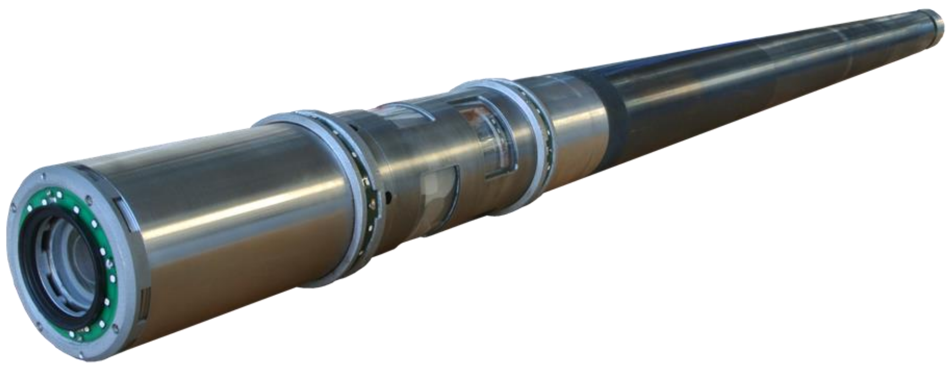

Fig. 1: Video inspection probe GeoKam, function model for 48 MPa and 165 °C

In order to fully utilize the advantages of a system platform, it is necessary that the individual components have a high degree of flexibility. To achieve this, the components of GeoKam are divided into the groups' basic and additional modules. The basic modules are standard components, which can be used universally in every probe. These include e.g. basic electronics, the cablehead or the housing of the probe. The additional modules are the components of the probe, which should realize the desired inspection task, such as the camera module of the GeoKam. A high flexibility is also achieved, if the individual modules can be connected mechanically and electrically to a complete system depending on the application. This way it is possible, who develop special borehole tools based on ZWERG, to produce and operate suitable borehole probes with low costs within short time. (Fig. 2) [Spatafora 2014-b]

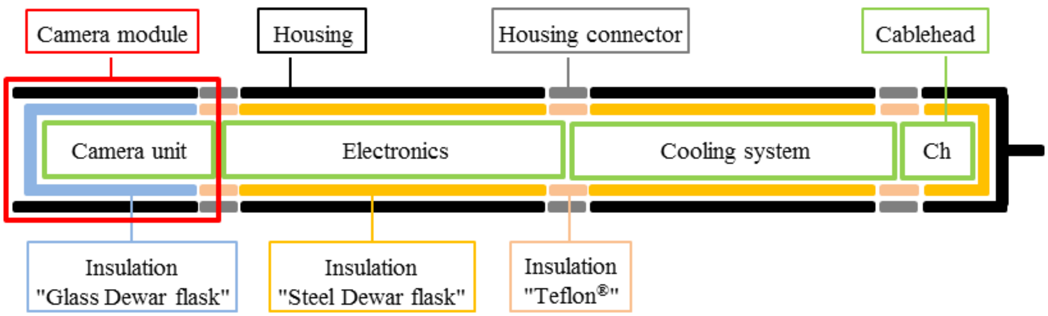

Fig. 2: Schematic design of the GeoKam [Spatafora 2014-a]

The individual modules are designed following the "onion skin principle". Each module based on ZWERG consists of two layers and a core (fig. 3). The first layer, the protection layer, consists of the housing and protects the subjacent levels from the high pressure, corrosive thermal water and shocks during service. The housing also serves as a supporting structure for the other layer and the core. The different housings of the modules e.g. the camera module housing and the electronics module housing can be connected using special joints. The 2nd layer, the insulation layer, is required to protect the heat-sensitive actors and sensors of the core from the high temperatures in the reservoir. This way, more modules can be developed in the future with less effort, because the plurality of components of a module changes only slightly. For example, at the housing of a new module only the housing length will change. [Spatafora 2014-b]

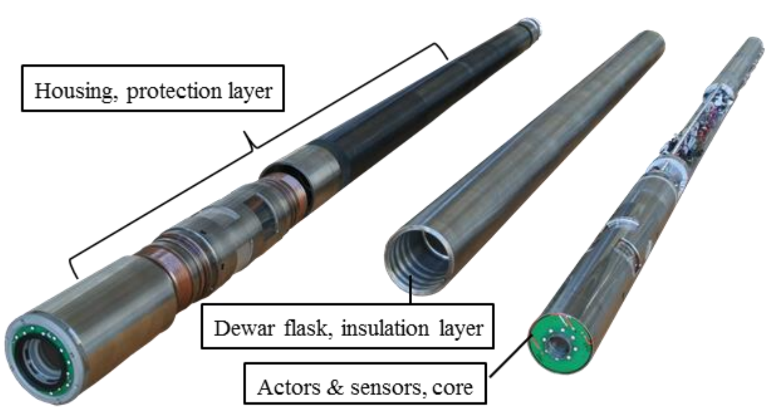

Fig. 3: Video inspection probe GeoKam split into the three different layers

2.1 Housing

The GeoKam with an outer diameter of 95 mm and a total length of 2.4 m is well-suited for the common borehole diameter of 8 ½ inches (~215 mm). Depending of the module the housing is made of Inconel 718 (metal) or of a composite of Inconel 718 and magnesium spinel (transparent ceramics). The specific characteristics of the used materials bring many advantages to the housing design. The high thermo-mechanical strength of the corrosion resistant materials allows a relatively thin-walled housing, which offers more space for other components inside the probe. With a wall thickness of 8 mm for the Inconel 718 and 12 mm for the magnesium spinel the housing of GeoKam is theoretically usable for a pressure up to 60 MPa and a temperature up to 200 °C. Besides the advantages of these special materials there are also disadvantages, which mainly occur during manufacturing of the components. Thus, the components of Inconel 718 are manufactured preferably by machining in the solution-annealed state due to their high final strength, to hold the tool wear during the machining as low as possible. Following the mechanical production of the components, the final strength of the material is achieved by heat treatment (age hardening). Important dimensions such as a fit should be manufactured with an oversize in the solution-annealed state and calibrated to the specific size after the heat treatment, because the heat treatment of Inconel 718 causes a volume change of the component. But also in the solution-annealed state of Inconel 718 the chip removing process is difficult and may cause problems. Because the casing material (Inconel 718) is not available as pipe in the required dimensions, it is manufactured from a massive rod. Therefore, the housing must be drilled out to the nominal size with a deep-hole drill. For drilling, machines with high driving performance and robust guidance of the drill (robust steady rest bushing) are required. Because of the high material strength, also in the solution-annealed state, a drift of the drill, due to a unfortunate ratio between drilling-diameter and housing-length is unavoidable (fig. 4). By subsequent reworking of the housing outer diameter this offset can be corrected again.

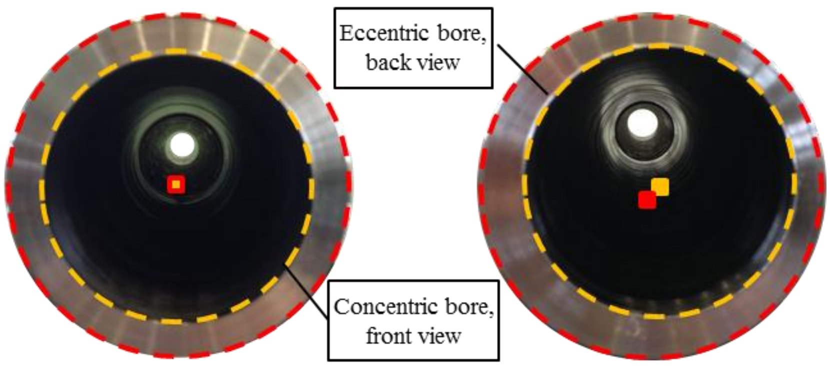

Fig. 4: Result after the deep-hole drilling of Inconel 718 housing with a drilling depth of 2 m, offset of the bore

Similar to the Inconel 718 manufacturing is the production effort for the magnesium spinel windows of the housing. The used magnesium spinel sourced from CeramTec-ETEC GmbH (located in Germany) with the product name Perlucor, is a polycrystalline transparent ceramic, which is produced by sintering a pressed powder in the desired geometry. For Materials with a high hardness, as ceramics, a near-net-shape fabrication in a partly-sintered softer state is preferred. After the machining the ceramic is brought to the final strength in a further sintering process. Unfortunately, this procedure cannot be applied for Perlucor, thus the mechanical machining of the components must be made with the final material strength.

In order to connect several modules together, each housing part has threads at its housing ends. A special coupling allows the connection of two or more modules (fig. 5, left). If the housing coupling has a right- and a left-hand thread, two housing parts can be screwed against each other without twisting cables in the probes core. Thereby the thread pitch should be selected as large as possible, because otherwise the jointed parts might clamp or partly fretting. The seal between two housing parts is ensured with O-rings, which can be easily replaced after abrasion. Consequently the GeoKam has no drive, which allows a 360 ° rotation of the housing with the camera module. The panoramic view is realized by turning the camera unit inside the housing. The screwed housing is therefore a robust pressure vessel without moving parts, which also brings advantages regarding the explosion protection directives (ATEX).

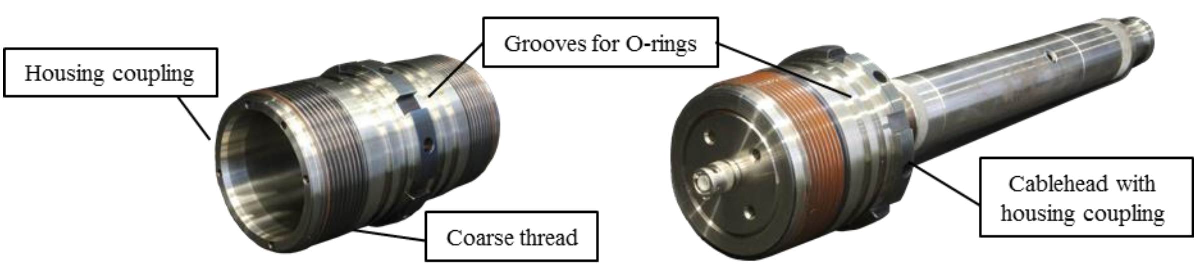

Fig. 5: Housing components for connecting the different modules of the GeoKam

In the field of the camera, the housing is composed of a composite of Inconel 718 and Perlucor to obtain a clear view to the borehole wall (fig. 6). The required composite is one of the major challenges of the GeoKam project, because the originally planned composition by shrinking cannot be realized within the given project duration. Alternatively, a special one-component epoxy adhesive (company: CeramTec-ETEC GmbH) with the required properties is used. Momentarily it cannot be said precisely how long the adhesive and thus the composite withstands the harsh environment conditions during operation, because there are no specific long-term studies for the use in geothermal applications. Tests in an autoclave will provide some information in this direction. This described problem clarifies that for the manufacturing of a high-strength composite between Inconel 718 and Perlucor further R&D effort is needed, which goes beyond the GeoKam project. [Spatafora 2015-a]

Fig. 6: Housing of the camera module; several windows allow a detailed axial and radial view to the borehole [Spatafora 2015-a]

2.2 Thermal insulation

The high operation temperature of about 165 °C requires the use of insulations, so that the actors and sensors do not overheat and the probe operates reliably. Due of the limited space inside the probe, insulations with a high insulation effect and a guaranteed assembling is essential. In view of the robust design and good insulation properties, stainless steel Dewar flasks are used. These cause a minimum heat input through the housing wall and can be manufactured cylindrical to realize a space without annoying edges. The design of the steel Dewar flask demands a relatively thin inner pipe, in order to reduce the heat input from the outer pipe through the connecting rings to the inner pipe to a minimum (fig. 7). The deepening of beads at the inner pipe of the Dewar shall compensate a difference in length, which is caused by the temperature difference during operation between the thermal water and the interior of the probe. For the production of the Dewar a vacuum is first created and then locked through bores on the front side. However, the production of a useful and durable vacuum is not trivial. Apart from a special vacuum furnace with a furnace length of 2 m (needed for GeoKam), several manufacturing steps for producing a steel Dewar flask are required. The steel Dewar flask of GeoKam is currently still in development, a prototype with 0.5 m length was already manufactured. Unfortunately, the results are not as expected and further research effort is required. In addition to the cylindrical steel Dewar flasks, Teflon® stoppers are used to reduce the heat input in axial direction (fig. 7). [Spatafora 2015-b]

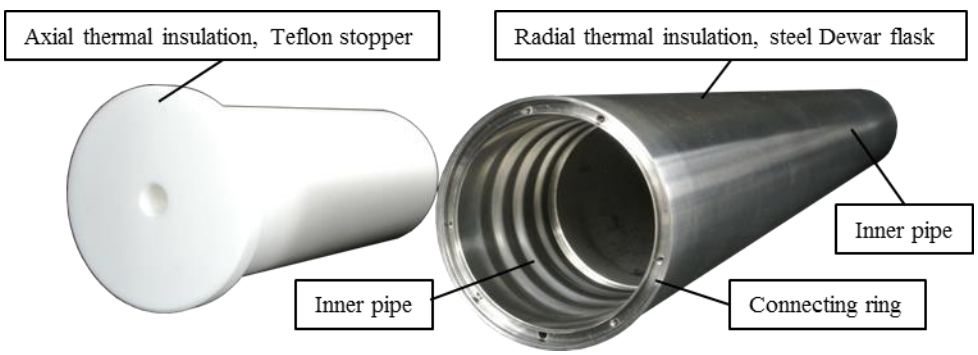

Fig. 7: Steel Dewar flask and Teflon stopper for the axial and radial thermal insulation of the GeoKam [Spatafora 2015-a]

By using MLI (Multi-Layer Insulation), the heat input can be further reduced significantly. The used MLI consists of a very thin aluminum foil with a fiberglass fleece as separating layer, which is wrapped several times around the inner pipe of the steel Dewar flask (fig. 8).

Fig. 8: Thermal insulation of the GeoKam inner pipe of the steel Dewar flask with wrapped MLI

In order to keep the heat input in the area of the camera unit low, a glass Dewar flask is used. Due of its fragility, the glass Dewar flask is embedded in a steel frame, so that shocks or vibrations on the housing are damped and the Dewar does not break. The steel frame is also used for the installation of the Dewar in the camera module, because brackets and fixtures can be easily attached on it (fig. 9) [Spatafora 2014-a]. As with the steel Dewar flasks, MLI is wrapped on the inner pipe of the glass Dewar flask. The foil is fixed with a glass adhesive and clips (fig. 10). To generate a long-term stable vacuum a getter is used, which absorbs the released gases over time.

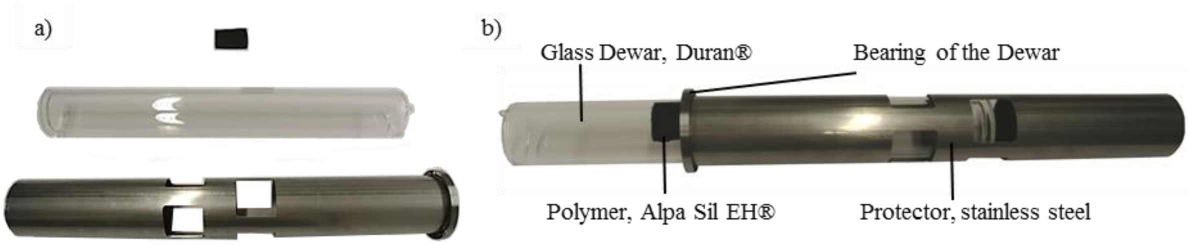

Fig. 9: Components a) and assembly b) of the glass Dewar flask [Spatafora 2014-a]

Fig. 10: Inner pipe of the glass Dewar flask with wrapped MLI

2.3 Cooling module

The camera unit and the probe electronics work without problems at temperatures below 105 °C. However, the maximum set operation temperature of 165 °C exceeds this value, thus in addition to the insulation a cooling system is required. With the cooling system it is possible to perform a video inspection during longer periods and thereby obtain more detailed recordings. The cooling of GeoKam is realized by a PCM (Phase Change Material) and heat pipes, which absorb the heat from the heat-sensitive regions and transfer it to the reservoir with PCM. This type of cooling has the advantage that the design is very compact and the heat is not directly stored nearby the heat source (fig. 11). In order to facilitate the handling with the PCM, it is charged into cartridges, so the "consumed" PCM can be exchanged easily after an inspection. By opening the probe at the cablehead, the "consumed" PCM cartridge can be removed and another cartridge can be inserted. In this way an operator can perform several inspections successively without large pauses. [Spatafora 2015-a]

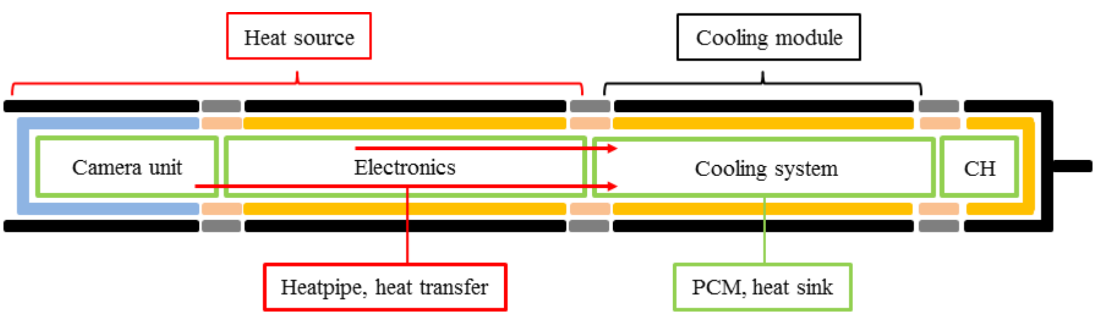

Fig. 11: Schematic design of the cooling system of GeoKam [Spatafora 2015-a]

Due the compact design of the cooling system inside the GeoKam remains enough space for the electronics. The electronics are fixed on a mounting plate, made of aluminum in which heat pipes are integrated. The heat pipes pass through the PCM reservoir and also the complete mounting plate and realize the heat transfer between the two areas. (Fig. 12)

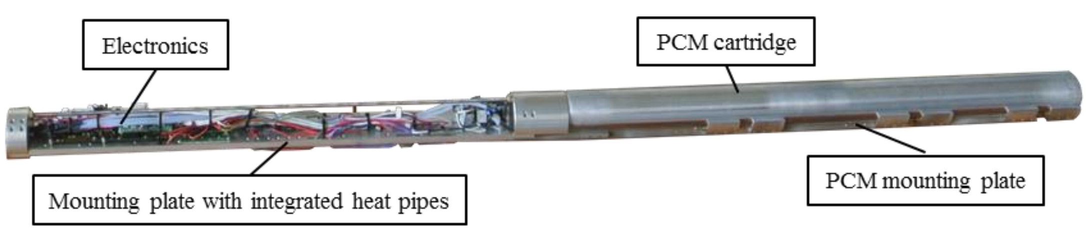

Fig 12: Cooling system of the GeoKam; left) mounting plate for the electronics with integrated heat pipes; right) mounting plate for the PCM reservoir with integrated heat pipes

2.4 Camera modul

The camera unit of GeoKam is well protected from the housing and the glass Dewar flask inside the camera module (see fig. 2). The remaining space is very small; therefore, a compact design is required. In total three cameras with lenses and camera sensors are installed. Due to the small available space, each camera is positioned axially with the probe axis. In the range of the side windows mirrors permit the view to the borehole wall. The camera unit can be rotated around its own axis in order to obtain a 360 ° view of the borehole wall. Furthermore, each camera lens is equipped with an aperture and a focus that can be adjusted precisely using small drives, to obtain a high quality image. (Fig. 13)

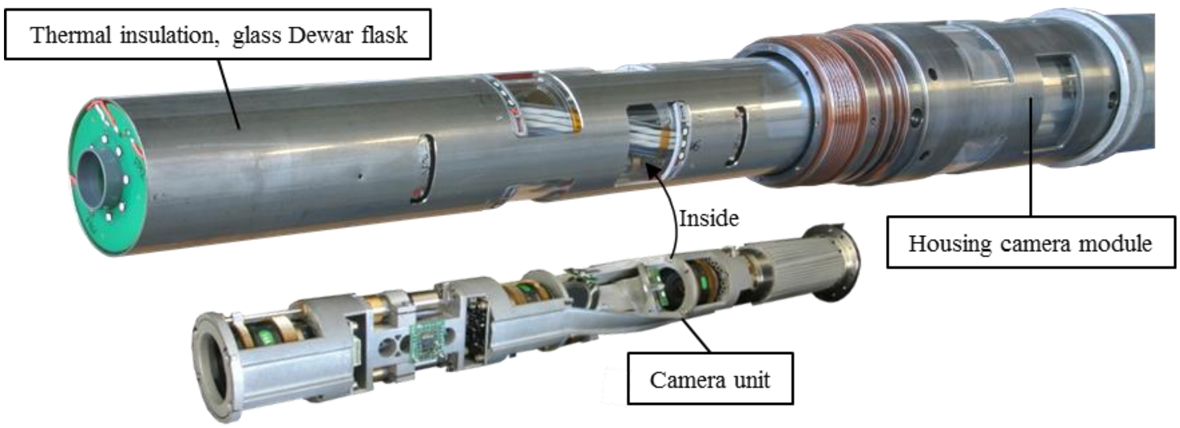

Fig. 13: Components from the camera module of the GeoKam

To inspect the borehole wall in a best possible way, a large field of view from the camera module is needed. Moreover, two side cameras for the radial view to the borehole wall are required due to the design of the housing, which increases the complexity of the camera unit. The side windows on the housing are located on two levels not perpendicular to each other, but rotated by 60° (see. fig. 13). For example: Does the inspector prefer to examine a long crack along the borehole wall and the field of view of one side camera is not enough, it is possible to switch to the second side camera easily. However, this requires that both side cameras are positioned and rotated to each other by 60°, such as the side windows of the housing. In the first function model of GeoKam (Albertha), this could not be realized. The components have been manufactured by machining, hence production-related the side cameras are rotated to each other by 180°. (Fig. 14) [Spatafora 2015-a]

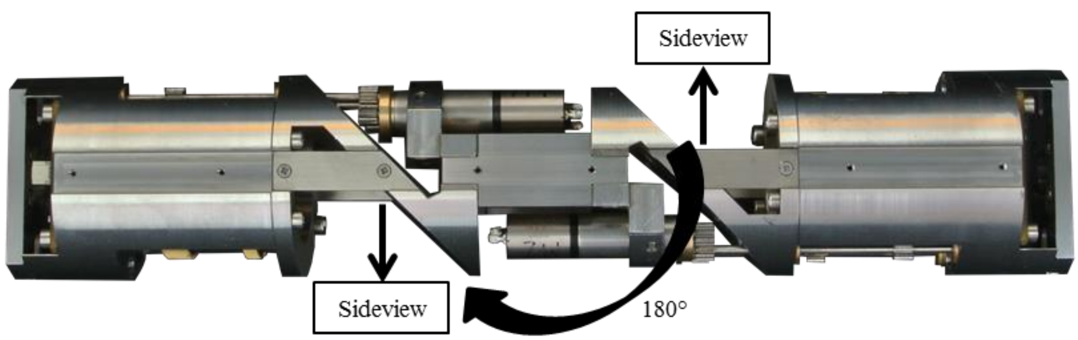

Fig. 14: Camera unit of the GeoKam in the area of the side windows and view direction of both cameras with 180° offset of the first function model "Albertha"

In the second function model (Bilbo) the machining process has been changed to the SLM process (Selective Laser Melting), whereby new design options arise. With this manufacturing method it is possible to realize the rotation by 60° between both side cameras of the camera unit (fig. 15). In addition, the weight of the individual SLM components is significantly lower with this technology in comparison to the conventionally manufactured components. Nevertheless, for the SLM process a certain expertise in the component design is needed. The components are designed as shell models and e.g. may not have overhangs or large changes in the wall thickness. If the design rules in the design and construction of the components are considered, a tolerance range of 50 µm can be produced, which is sufficient for the camera unit of GeoKam. [Spatafora 2015-a]

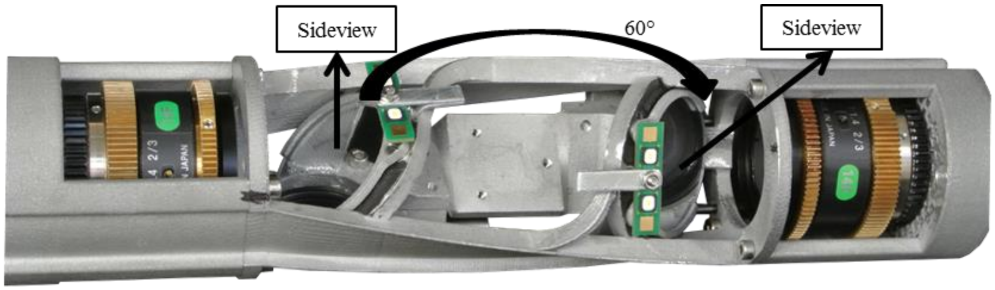

Fig. 15: Camera unit of the GeoKam in the area of the side windows and view direction of both cameras with 60 ° offset of the second function model "Bilbo"

The advantages of the SLM process are also successfully used in other parts of the GeoKam. For example, it allowed to manufacturing the lighting system of GeoKam in a space-saving way.

3. STRESS TEST

For the test of GeoKam under real conditions, an autoclave has been acquired, in which the probe can be tested with a load up to 80 MPa and 200 °C. The pressure chamber of the autoclave allows testing probes with a maximum length of 2.5 m and 0.25 m diameter. The chamber can be filled with water and securely closed with a massive cap. If the probe is in the sealed pressure chamber and the chamber is flooded with water, a pump produces the necessary pressure. The temperature of the water is realized via a heating jacket around the pressure chamber housing. Hereby the same hydrostatic pressure and temperature act on the probe as in a geothermal borehole.

The autoclave offers the possibility to examine different parts of the probe relatively quick and inexpensively. Furthermore, additional measuring devices, which would not be usable in a geothermal borehole, can be installed and the data can be recorded and analyzed in real-time. Thus, problems in the function of the probe or errors in the design can be detected and eliminated faster. One of the first components of the GeoKam, which has been tested in the autoclave, is the housing of the camera module. In a first test the housing, consisting of a composite of Inconel 718 and Perlucor (see chap. 2.1), has been examined only with pressure. Besides the housing also the high pressure feedthroughs have been checked for tightness in this test. The autoclave test was performed with a pressure of about 50 MPa.

The results of the study are promising. The electric high pressure feedthroughs are suitable for pressures of 50 MPa and have no leaks. Only in the first test run one of the electric pressure feedthroughs has not been tightened with the correct torque, so that this was minimal leaky (a few drops entered the housing). The composite between Inconel 718 and Perlucor is tight as well, although one of the two side windows has defects after the first test (fig. 16). The exact cause why this occurs is currently being investigated by the Perlucor supplier. An optimized window is already in progress, so further tests can be continued in the near future. Anyway the result shows that Perlucor is a suitable material for this application, because a total failure with water inlet is not expected despite defects of the window.

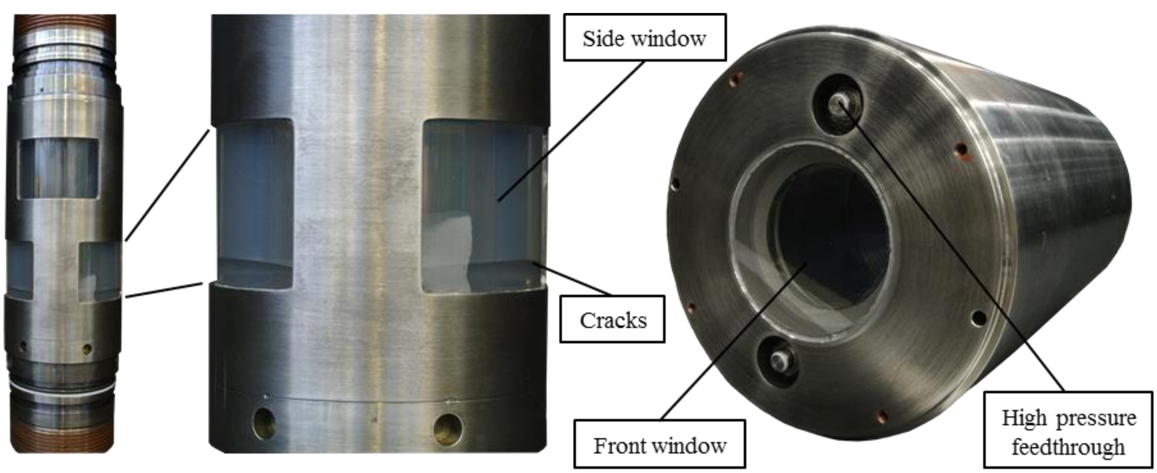

Fig. 16: Results after the test of the camera module housing in an autoclave under 50 MPa pressure, left) cracks in the side windows, right) front window without defects

4. CONCLUSION AND OUTLOOK

The ZWERG - GeoKam project shows that downhole probes can be developed in a relatively short time based on a system platform and it demonstrated how time consuming it can be to buy components with special demands (e.g. pipes) for the first time. The GeoKam provides many important components, which can be used universally for further probes in the future. The applied technologies, such as the SLM process, allow a cost effective and rapid integration of additional modules in the platform. With a cooling system and a thermal insulation, it offers additional capabilities. Through the cooled probe interior, it is now possible to use sensors and actors from other industries with lower operating temperatures and thereby expand operation possibilities. With the acquisition of the autoclave an important basis for further R&D has been created so that it is economically practicable to develop a new probe in a shorter time.

The GeoKam project is in the final stages. Almost all the components have been successfully developed. Only optimizations at the side windows, the steel Dewar flasks and the data transfer are still carried out. Once this development is complete, the GeoKam will be ready for in situ usage in boreholes.

REFERENCES

Spatafora, L., Isele, J., and Holbein, B.: Forschungsergebnis: GeoKam-Mechanik, Elektronik und Design des Videoinspektionssystems, Beitrag, Der Geothermiekongress DGK 2015, Essen (2015-a).

Spatafora, L., Armbruster, P., Basuki, W. W., Bauer, C., Dietze, S., Heuser, P., Holbein, B., Isele, J., and Rizvanovic, A.: Video Inspection Probe for Deep Geothermal Boreholes – GeoKam, Proceedings, World Geothermal Congress, Melbourne, Australia, (2015-b).

Isele, J., Bauer, C., Dietze, S., Holbein, B., and Spatafora, L.: The ZWERG project: a platform for innovative logging tools, Proceedings, World Geothermal Congress, Melbourne, Australia, (2015).

Holbein, B., Isele, J., Spatafora, L., and Hagenmeyer, V.: Quality management and improvement for geothermal energy projects using the platform based tool development technology – ZWERG, Beitrag, EST 2015 - Energy, Science and Technology, Karlsruhe (2015).

Spatafora, L., Isele, J., Holbein, B., Heuser, P., Basuki, W. W., Bauer, and Dahm, R..: Video Inspection Probe for Deep Geothermal Boreholes – GeoKam, Proceedings, 39th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2014-a).

Spatafora, L.: Inspektion tiefer Bohrlöcher mit GeoKam, Beitrag, Der Geothermiekongress DGK 2014, Essen (2014-b)