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Status of the Cobold-Project – Cooling of Borehole Objects in Large Depths

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ABSTRACT

The COBOLD (Cooling of Borehole Objects in Large Depths)-Project is part of the ZWERG-project, initiated at the Institute for Applied Computer Science IAI, Karlsruhe Institute of Technology KIT 5 years ago. The basic idea of ZWERG (Ger. Dwarf) is to create a system platform for the fast, affordable and reliable engineering of borehole tools for investigation or interaction purposes. It contains concepts for different probe-prototypes, such as a sample-recovery probe maintaining original pressure and temperature of borehole water samples and the video inspection system for deep and hot boreholes GeoKam, which is realized in a currently running BMWi (Federal Ministry of Economic Affairs and Energy) project. A further development issue is the cooling of standard electronics in hot environments without time-limitation, which is part of the COBOLD-Project.

The central element of COBOLD is a borehole cooling-machine, which realizes the temperature-limitation inside a probe-housing below 70 °C in surroundings with temperatures above 200 °C, by conduction of a reversible thermodynamic process. The principle, on which common refrigerators are based, is therefore adapted to the special borehole conditions by the use of custom-engineered components. For this purpose the main components compressor, evaporator, condenser and throttle are designed, tested and optimized iteratively, based on computer aided simulations and laboratory experiments. COBOLD contains as well high-temperature sensors for redox-potential-, PH-value- and conductivity- measurement inside boreholes, as an exemplary application. For a universal usage, it provides two possibilities for the up-hole connection of the system. It will be usable with a wireline, using an electrical energy supply for the compressor or integrated in the drill-string, where the available high-pressure hydraulics is utilized. This includes also different ways for the data-transmission. The basic version is designed for operations in 0-5000 m deep boreholes with ambient temperatures up to 200 °C and ambient pressures up to 600 Bar, but ways to operate in hotter environments with temperatures over 300°C, through a multistage structure and the use of alternative refrigerants are also part of the investigation efforts.

The objective of the COBOLD-Project is to provide the possibility of widespread borehole-investigation over the entire life cycle, starting with the drilling until the point of renaturation and post-exploration. Besides it shall build the basis for further developments of borehole-tools to push the geothermal research forward. Supported by the modular and standardized engineering within ZWERG the system stays affordable, thus well-operators and scientist will be able to utilize their acquired system individually and durable.

Like this, COBOLD will decisively help remedy the main problems of Geothermal Energy, namely the prospecting-risk, the risk-prediction, the error-tracking and acceptance-problems.

1. INTRODUCTION

Geothermal Energy has a great potential and it is every time and nearly everywhere available. It is therefore the renewable energy source which is predestined to be used as base-load supplier. This predicate is especially meaningful for the "Energiewende" (Ger. energy turnaround) performed in Germany since 2002. But unfortunately Geothermal Energy production remains far below its possibilities. In Germany i.e. this discrepancy is clearly visible. Just the potential of hot aquifers for electricity production, with 2620 Billion kWh, is more than four times higher than the actual demand in Germany (618 Billion kWh in 2012). In case of heat production (7084/476 kWh) this ratio is greater than 14 [AGEB 2013] [ABFT 2003]. This fact is due to the number of problems Geothermal Energy has to cope with. The investment risk, the high costs for exploration and drilling are basic difficulties which occur independently of the location, whereas with different amounts. Other problems are the stagnation of a production caused by incidents or even an actual injury evoked by subsurface-activities linked to the extraction or stimulation in a geothermal field. The geothermal plants in Landau and Staufen in Germany (see table 1) as examples, are illustrating this point.

All scientific and engineering work done within ZWERG is geared to improve this situation by providing tools and methods for widespread investigations and interactions of boreholes. One important step forward would be the facilitation of unlimited operation times and the use of the wide range of standard electronics in high temperature environments. This will be realized by the COBOLD system.

2. USAGE OF COBOLD

2.1 Range of Applications

COBOLD will be usable for different applications. Because of its´ two possibilities of connection the complete time-line of boreholes can be covered. Firstly the so called LWA-(Logging While Drilling) operations are an application-field of the system. Through the cooling-machine integrated in the drill-string, the usage of standard electronics i.e. for sensors at high temperatures during the drilling phase is possible. An example is the option of seismic prediction while drilling with a data-transmission in real-time whereby the aquifer can be located exactly. With this method, prospection risks could be decreased [Brian et al 2009].

In case of unforeseen incidents in a well, which cause i.e. seismic problems or a decreased production rate, it would be helpful to investigate the borehole by gaining various data over the complete depth. This way, a problematic leakage could be detected and closed with appropriate sensors and repair tools. For the broad range of possible operations, tools for various applications are necessary. In the example of the video-inspection tool GeoKam, which is currently developed at the IAI and could be used to detect cracks in the borehole, many hundreds of electronic parts are integrated. Only a small amount of this electronics is realized in a high-temperature version for 200°C, since the number of available high temperature electronics is strongly limited. Moreover the price for these parts is significantly higher compared with standard electronics and there is a temperature limit a little over 200°C, where no more working electronics exist [Bauer 2013]. The maximal operation temperature of the standard electronic components is below 70°C. In case of operations shorter than 8 hours, these components could be heat-protected by using a sufficient insulation and PCM-(Phase Change Material) cooling [Holbein et al 2014], for longer operations or very high operation temperatures an active cooling system is evident (see figure 1).

Table 1: Examples for failure and damage costs in geothermal plants [BINE 2014] [Welt 2014].

Cost for damages caused by production of geothermal plant "Staufen"			
Period 2007 - 2014	Accumulated estimated property damage		50.000.000 €
Costs for unexplained failures in the production of geothermal plant "Landau"			
	Production in kWh	*Deficit in kWh*	*Estimated financial loss in €*
Planned output	26.280.000	-	
Actual output 2010	16.700.000	9.580.000	685.900
Actual output 2011	11.200.000	15.080.000	1.079.700
	Sum	24.660.000 kWh	1.765.600 €

In table 1 two examples of geothermal plants in Germany are shown, where problems with the production or the security occurred. In Staufen, an unintentional water-flow into a stratum close to the wells causes the formation of gypsum, thereby the ground rises, which induces cracks in the buildings of the surrounding town. The electricity production of the plant in Landau lies markedly below the expected production. For the reason there are only unconfirmed theories so far. The figures show that unresolved problems can become very costly for the operator of a geothermal plant, especially when the cause can´t be identified exactly and the failure occurs over a long time period.

Beyond pre-/post-investigations of boreholes, COBOLD can be used in combination with different measurement or interaction devices as well in case of actual failures, for identification and rectification.

2.2 Operation conditions

Figure 1 gives an overview of different operation conditions where the use of COBOLD is reasonable. It is especially intended for long operations in surroundings with high temperatures. The basic single-stage system is usable in ambient temperatures up to 210 °C without time-limitations. Hotter environments would be manageable with a multi-stage design, where a second cycle with another refrigerant is conducted. For the energy supply of the system it´s clear, that the required power increases with higher ambient temperatures. The operation period is not important for this aspect, because the cooling-process is reversible.

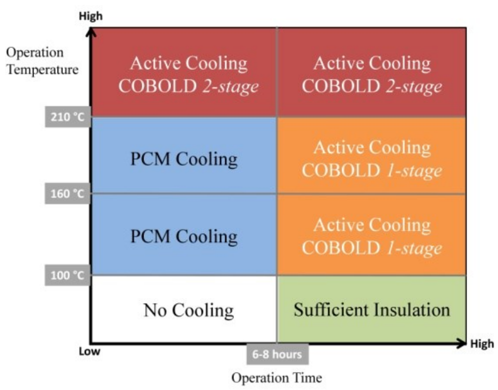

Figure 1: Thermal and time-wise operation range of COBOLD.

3. TECHNICAL CONCEPT OF COBOLD

3.1 Components and connection

As mentioned in the previous sections, COBOLD contains a cooling-machine with two different options of connection, either integrated in a drill-string or at a wire-line. Figure 2 shows the schematic structure of both connection-systems.

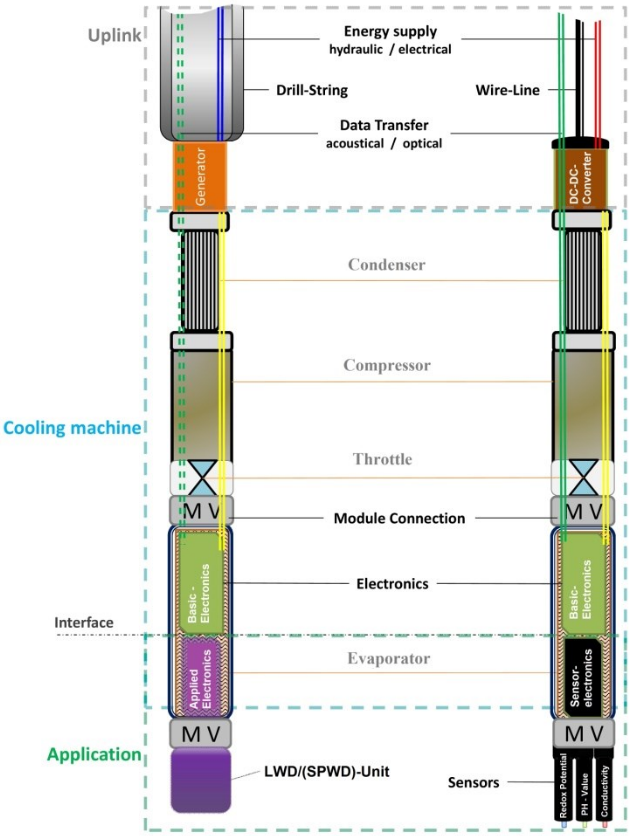

Figure 2: Scheme of the COBOLD-systems with wire-line and drill-string.

The scheme clarifies that most of the components are similar in both applications. The energy supply for the electronics and the cooling-machine compressor in case of the wire-line operation is electrical. The maximal power-input is strictly limited and the focus has to be put on the efficiency of the components. When used in the drill-string a suitable way of energy supply, especially for the greatest consumer like the compressor, is to use the given hydraulic pressure directly or by transforming it into electricity through a generator. In the drill-string usage an important point is the robustness of the system due to the rough operation-conditions. Finally an optimal compromise has to be found, thus COBOLD is supposed to be usable universally.

An important point is the type of data-transmission. One focus of the project will be the evaluation of different ways of data-transmission, depending on the connection of the probe. Possibilities like optical and acoustical transmission are already part of discussions and concepts [Manolakis et al 2011] [Gutierrez-Estevez et al 2013].

To resist the highly corrosive environment and the high pressures in great depths equally, the materials and mechanical design of the components are an important element in the development project. In different preparatory works, also in conjunction with other ZWERG projects, promising materials for the probe-housing, seals and further parts have been identified and are currently tested and compared [Isele et al 2014] [Spatafora et al 2014].

3.2 Cooling processes at different ambient-temperatures.

The discussion about different application possibilities has implied that COBOLD will cover a certain range of environment temperatures. In the initially foreseen version, the cooling-process is conducted with acetone as refrigerant, as illustrated in figure 3. The temperature and pressure levels depend on the actual ambient temperature in the borehole. Table 2 gives the values for a borehole with a temperature of 200 °C [Holbein et al 2013].

Table 2: Sub-processes of the COBOLD cooling-machine process at 200 °C.

1 – 2	*isothermal evaporation*	~ 57 °C (1 bar)
2 – 3	*polytropic compression*	~ 40.6 bar (235 °C)
$3 – 3^*$	*sensitive cooling*	~ 225 °C
$3^* – 4$	*isothermal condensation*	~ 225 °C (40.6 bar)
$4 – 4^*$	*sensitive cooling*	~210 °C
$4^* – 1$	*isenthalpic expansion*	~1 bar (57 °C)

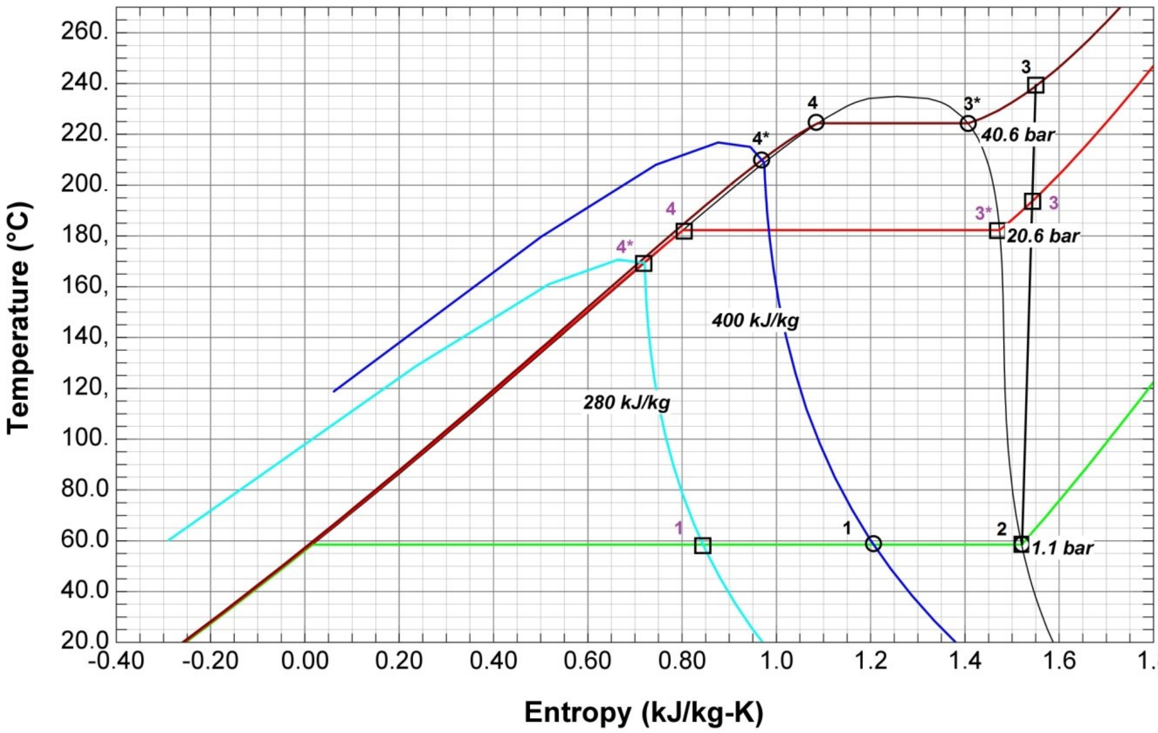

Figure 3: Cooling process with acetone at different borehole temperatures in a Temperature-Entropy diagram. (Pink numbers for the cycle in a ~160 °C condenser environment and black numbers in a ~200 °C condenser environment)

The process parameters can be estimated using the entropy *s* and temperature *T* differences and a defined mass-flow *dm/dt* as follows:

$$cooling\ \ capacity = dm/dt * (s_2 - s_1) * T_1 \quad (1)$$

$$condenser\ heat\ output \approx dm/dt * (s_4 - s_{3*}) * T_4 \quad (2)$$

$$compressor\ input \approx dm/dt * (s_3 - s_4) * (T_4 - T_1) \quad (3)$$

The values (table 3) show that the performance of the cooling-process sinks with higher operation temperatures in the borehole. This means, that it is necessary to adjust the mass-flow to provide a similar cooling capacity. The same is true for the required condensation pressure, which has to be reached by the compressor. For higher mass-flows and pressure ratios, the needed input powers increase.

Table 3: Comparison of process parameters at different borehole temperatures.

with refrigerant: acetone – in 1st Stage				
Borehole temperature (°C)	mass-flow (kg/h)	cooling capacity (W)	condenser heat-output (W)	compressor input (W)
202	3.5	105.8	-154.9	76.7
163	2	122.8	-169.7	52.5
with refrigerant: H2O – in 2nd stage				
352	0.65	200	-155.7	199.3

As the values show, the system can be adjusted to different conditions. In case of much higher borehole temperatures i.e. 350 °C, the table shows the process parameters for a 2nd stage using a 2nd refrigerant (water) as well. In Figure 4 the corresponding process diagram can be seen. With this 2-stage variant the manageable ambient temperatures are already really high. However it is conceivable to use more stages, until the temperature-limit is given by the used housing materials. So far it is scheduled to realize the single-stage system, thus most of the boreholes in Germany don´t exceed temperatures of 200 °C. Another practical aspect is that with a multi-stage system a greater total-length must be calculated on.

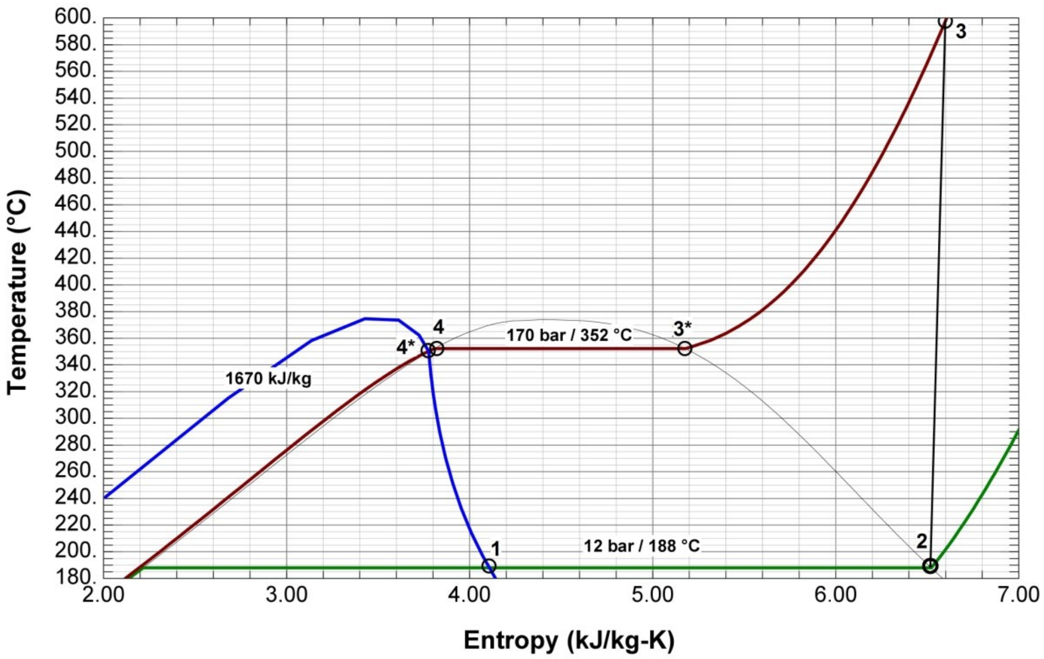

Figure 4: Cooling process with water as 2nd stage in a Temperature-Entropy diagram.

4. SIMULATIONS AND EXPERIMENTAL WORK

For the embodiment-design of the components and the designing of the complete system, simulations and experiments are of high importance. Although the cooling-machine principle is state of the art and realized in most of the refrigerators or air conditioning systems in everyday life, the extreme operation conditions in deep boreholes, an iterative approach is necessary. One important element of the cooling-machine, that shall be picked for illustration are the heat-transfers. The first transfer, which is performed by the evaporator, takes place inside the housing between the refrigerant and the loads in the cooled area. The second one is realized by the condenser, between refrigerant and borehole fluid. For the heat-exchangers an optimum between the size, the robustness for a long lifetime and the functionality, which means the transferable heat-flow has to be found. Additionally there´re factors like the machinability and price of the used materials which have to be taken into account. Figure 5 shows a simulation result for the inner heat-transfer. A special focus lays on the warm-up phase, before the refrigerant starts evaporating. In this phase the heat-transfer is poor, because the flow velocity inside the evaporator and the heat-transfer coefficients are very low.

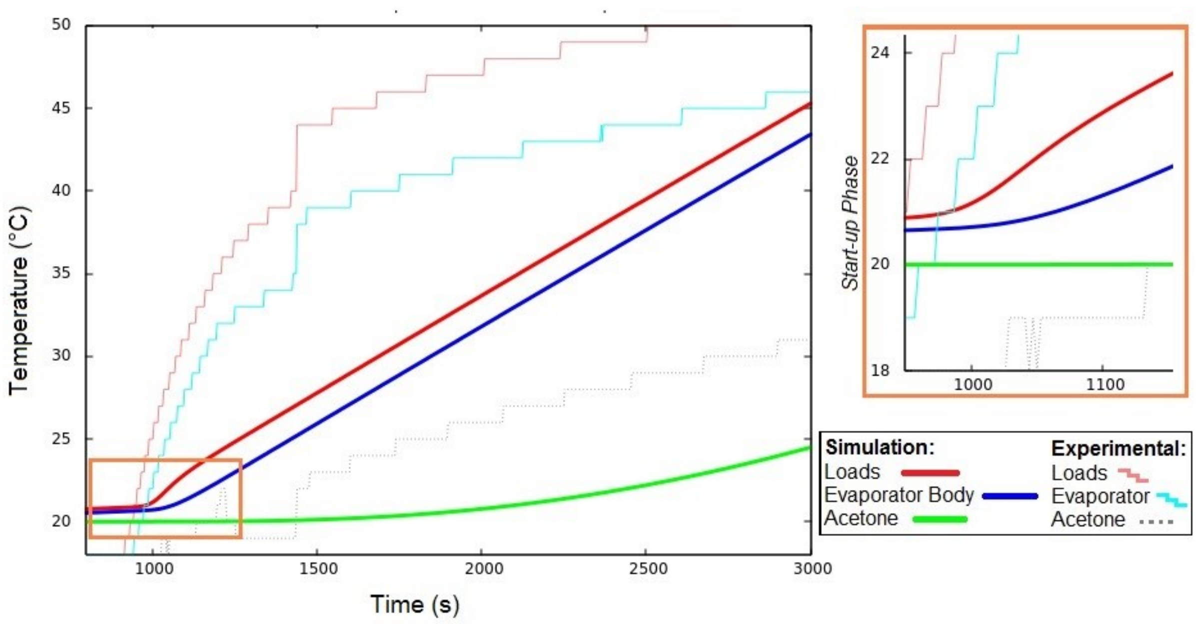

Figure 5: Simulated and experimental temperature-time profile of the evaporator heat-transfer.

This consideration is important as the temperature-limit of the electronic components shall not be exceeded at any time of the operation. Especially in the starting phase, components with a high heat loss are heating up fast. To prevent overheating the refrigerant has to react fast enough, which means the heat-transfer of the evaporator must be sufficiently good. The diagram shows the comparison of the simulated temperature profiles of the electrical loads and the refrigerant acetone. In this example the maximal load temperature grows fast in the beginning, than the slope sinks to almost zero when the convection flow of the refrigerant starts working. The simulated profiles seem not to fit well, but the tendency is reproduced in the right way. When reaching the evaporation phase the simulated and experimental values of the maximal load-temperatures should be similar. From this point the complete heat inside the cooled area is consumed by the evaporation of the refrigerant, thus the temperatures are hold constant (or even sink, if the cooling capacity is higher than the total heat-input). This stationary phase has to be reached for an optimal performance of the system. For the outer heat-transfer equivalent simulation are conducted and compared with experimental data. The results are an important indication for the validation and adaption of the heat-exchanger design.

To test the single components and the complete cooling-process, a test-stand has been constructed. It allows simulating different ambient temperatures corresponding to different conducts of process. By using heat-bands and controller it is possible to simulate various temperature-profiles, i.e. a slow increase up to a constant maximal temperature, like in the immersion-phase, when the probe is brought into a borehole. Figure 6 is a photo of the test-stand. The two levels separate the high-pressure-temperature from the low-pressure-temperature side. The big cylinder at the top is a deep fry, huge enough to receive the condenser, for the simulation of a liquid environment with high temperature. At the bottom the housing of the cooled area is placed. It is packed into a heating-jacket and contains the evaporator on which electrical loads are mounted. At the right, the compressor, which is driven pneumatically, is installed. It can be adjusted by different mass-flows and output-pressures by changing the stroke and the lifting-frequency. Between the condenser outlet and the evaporator entry, a throttle line is integrated. Different throttle elements such as capillaries and expansion valves are tested, for identifying the best solution for the special operation conditions [9]. The test-stand contains thermocouples, pressure sensors and manometers at all important positions in the system as well as computational data acquisition and handling devices. This way, the experimental data can be easily compared with prognoses provided by simulation-programs and further be used in CAD/CAE software for the design of newer component-prototypes.

Through the modular structure of the test-stand, the components can be separated and tested alone as well. Besides, extensions of the test-stand can be simply implemented. First experiments approached the question of an adequate expansion, respectively an adequate throttle design. The results so far showed that capillaries with a fitting ratio between inner diameter and length are a practical and simple option for the throttle element. The disadvantage of this way to expand the condensate is the inflexibility as price for a reliable and robust design. This example is representative for the conflict of objectives which is typical for the entire development of the borehole cooling-tool and other borehole systems [Holbein 2014].

A next step for the tests is the simulation of the ambient pressures in high depth of several hundred bars, which is technically challenging. This will allow stress-tests with the housing materials at one hand and on the other hand provide a possibility to investigate the influence of the actual borehole-fluid composition on the outer heat-transfer and other functionalities of the refrigeration-system.

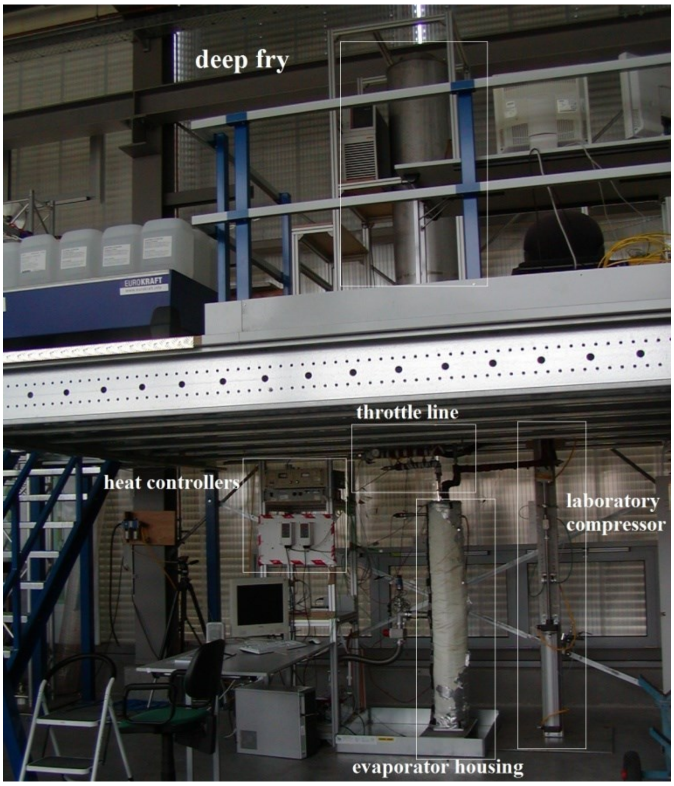

Figure 6: Photo of the borehole-tool test-stand in the laboratory of the IAI.

5. PROJECT STATUS

COBOLD was supposed to be funded by the BMWi. Corresponding to the wide range of tasks in the COBOLD-Project, a wide field of project-partners, containing experts in many of the various needed technical disciplines, was supposed to congregate. Unfortunately the project outline was surprisingly rejected in July 2014 because of the "high technical risk". Therefore a reduced proposal (see Figure 7) was created and submitted. The project named GARM – Geothermal Adjusted Refrigerator Module, focuses on the technical core, the active cooling system module and its critical components. It is supposed to serve as feasibility analysis, with the aim to prepare the further project with a significantly reduced technical risk.

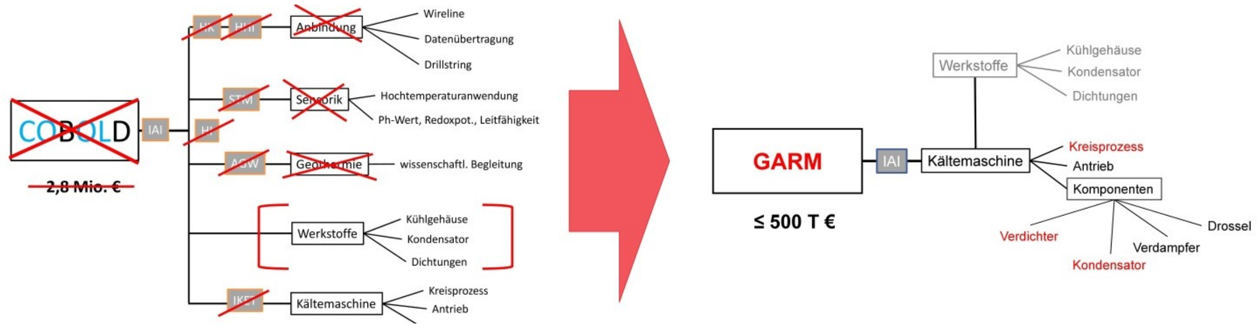

Figure 7: Reduction of the COBOLD extent for GARM.

Due to the actual funding situation, the project extent had to be reduced strongly. It would have been a great advantage to bring all the experience and expertise collected by the partners´ work in previous projects together and to form an expert-group for pioneering engineering developments for geothermal research. This widespread concept must be postponed. Hence, parallel to the current work on GARM, attempts to receive funding from other institutions are running.

The original project concept also offers the opportunity of interdisciplinary work between different approaches. This is why different work-groups with experiences in the field of geothermal energy research, namely the "AGW" (State research Centre for Geothermal Energy, Baden-Württemberg Germany), driller-companies with a practical point of view like "Herrenknecht", professionals in data-acquisition of borehole fluids from "Hydroisotop" [Eichinger et al 2005] and engineering institutes with different specialties namely thermodynamics (IKET-KIT), sensor-technic and development (Kurt Schwabe Institute, Sensortechnik Meinsberg), data-transmission (Fraunhofer Heinrich Hertz Institute) and mechanical and electronic engineering of tools (IAI-KIT), recognized the connecting factors and agreed to the COBOLD proposal.

In other projects like "GeoKam" in which partially the same disciplines are required and dealt with by some of the aforementioned parties, this type of constellation proves itself as expedient.

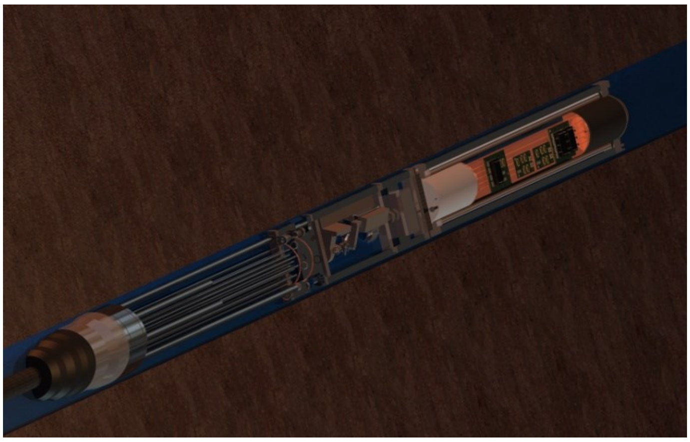

Figure 8: Picture of an early model of the COBOLD-probe, sliced for an inboard-view.

6. CONCLUSION

According to the growing demand for a renewable base-load supplier the role of geothermal energy has to be enforced. This can only be done if the possibilities for widespread borehole investigations are enlarged and advanced tools are accessible for the scientific generality. Many examples show that most of the problems of geothermal energy are linked to the lack of borehole data of especially the interesting areas where the surrounding conditions are rough. Advanced possibilities of borehole investigation, build the basis to develop tools for downhole interaction i.e. for casing repair. Altogether this is important for a quality management in the geothermal energy systems.

The preliminary work for the borehole cooling-machine is well advanced and builds a stable basis for an efficient project-progression. Experiments with the constructed test-stand are actually running and deliver helpful data for the design and the assembly of the components. Through the tests on the special thermodynamic process, important substance parameters are ascertained and instructive experiences are made.

The unifying concept of COBOLD would mark a great step for the investigation of boreholes with high temperatures, since it contains a solution for longtime cooling in combination with solutions for energy supply, data transfer and water sensors. Hopefully this project can be realized early. Nevertheless, the essential part of it is the cooling-machine for boreholes. Since the problematic with the high requirement of electronics at one hand and high temperatures at the other hand, especially in case of long operation periods is still unsolved. Regarding the limitations of current tools and the number of boreholes worldwide where temperatures above 300 °C occur, which are most interesting for geothermal energy production, an active cooling system would be a milestone for further investigation- and interaction-tool developments.

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