JOINT REPORT ON CHOSEN APPROACHES AND METHODS FOR CALIBRATION

D.T3.5.1

Version 1
08 2017

Content

1. Introduction

1.1. Scope of this deliverable

This report aims at calibration, or better say comparative measures, to make field measurement data comparable, at least within the project GeoPLASMA-CE. This is important, since the measurements are executed by different project partners with different measurement devices. Special attention is given to Thermal Response Test (TRT) measurements, as they play an important role for calibrating thermal conductivity models and furthermore give important hints about the temperature conditions in near surface underground.

This report provides a general strategy and an action plan how and to which extend comparative measurements will take place in GeoPLASMA-CE. It also gives an overview about the principles of TRT measurements as well as possible source of errors and defines quality criteria for performing comparative TRT measurements. Furthermore, it comprises an action plan to perform TRT measurements in the project GeoPLASMA-CE.

1.2. Methodologies and workflows applied

This deliverable founds on literature studies on existing standards and previous workshops and projects dealing with comparative TRT measurements. In addition, a TRT Knowledge Exchange workshop took place in Prague on March 15, 2017. This workshop was visited by partners of the GeoPLASMA-CE consortium and recognized experts on TRT measurements in central Europe. The main focus topic of the workshop consisted in calibration or comparison of TRT devices and measurement workflows. Other topics concerned existing standards on TRT measurements.

In addition to the comparison of TRT measurements, the project partners were asked in a small survey about intended validation measures on other filed parameters and respective devices.

1.3. Aim of the activities within the project GeoPLASMA-CE

The main goal within the project GeoPLASMA-CE is to calibrate the potential maps in the pilot areas to the measured values. To measure the effective thermal conductivity and the undisturbed underground temperature Thermal Response Tests are the first choice at the moment.

But is it possible to combine measurements from different TRT devices to produce one consistent map? During a GeoPLASMA-CE workshop, experts within the field of TRT measurements discussed that it is essential to prove that the results of the different TRT devices of the project partners are comparable. For this it is necessary to perform a ring test with all available devices.

2. Thermal Response Test (TRT) measurements

To design a system of borehole heat exchangers (BHE) correctly it is mandatory to know the thermal ground properties. The most important parameters are the thermal conductivity and the average undisturbed underground temperature. These parameters are site-specific and depend on several factors such as geology, groundwater influence and subsurface temperature (altitude above sea level). Besides this, the thermal borehole resistance, which describes the thermal resistance between borehole wall and fluid, is a needed parameter to check the efficiency of a borehole heat exchanger.

The in-situ Thermal Response Test (TRT) provides a method to evaluate the site-specific thermal ground properties, which are necessary for the design of ground coupled heat pump systems. The technique has become a routine tool in several countries since the first mobile TRT rigs were developed in 1995.

Alternatively, measurements of the thermal conductivity can be done in a laboratory on rock samples or in-situ with needle probes (only possible at soft rocks). The measured value can then be assigned to a specific rock type, but can be different to the effective thermal conductivity in the underground due to the following reasons:

First, the boundary conditions such as saturation and temperature are different in the laboratory. Additionally, the value measured in the laboratory is valid for one specific rock sample, while the result from the TRT is an effective value over all occurring rock types along the borehole. For a heterogeneous geology, it is necessary to take rock samples of each layer, measure the thermal conductivity and calculate the average thermal conductivity as a function of the layer thickness.

Due to the fact, that in most of the pilot areas the geology is heterogeneous we decided within the project GeoPLASMA-CE to use Thermal Response Tests to measure the effective thermal conductivity. The new data can then be used to calibrate the potential maps in the pilot areas.

To ensure that the measurements of the different TRT devices of the project partners are comparable a validation of the devices and the test results has to be done. The reason for this is that every device was built independent of each other and there exists no industrial standard for the complete rig as it is common for all the sensors installed.

2.1. Principles

Thermal Response Tests (TRTs) are a good method to determine the effective thermal properties of the borehole heat exchanger and the rocks. The test evaluation can be done with analytical methods and yields to the effective thermal conductivity and the heat transfer resistance from the fluid to the rocks of the BHE. The effective conductivity includes a conductive, a convective and a advective term. The latter two are caused by water flow and should be comparable small to the conductive term:

$$\lambda_{effective} = \lambda_{conductive} + \lambda_{convective} + \lambda_{advective} \qquad [1]$$

where

$$\lambda_{convective} + \lambda_{advective} \ll \lambda_{conductive}$$

Most of the todays measuring equipment is based on Mogensen’s concept (Morgensen, 1983) who suggested a system with a chilled heat carrier fluid. Nowadays a heated fluid is used. The first mobile test equipment was developed independently at Luleå Technical University, Sweden and at Oklahoma State University, US. Later, similar test equipment have been developed in several countries with small variations from the initial ones, e.g., in the Netherlands a test rig was designed which uses a reversible heat pump instead of a flow heater to alter the fluid temperature. This makes it possible to switch between heat extraction and heat injection. This method should be only used where testing with extracting heat has to be done explicitly, because it has some problems caused by the dynamic behaviour of the heat pump and the need for a heat source/sink. The size of a mobile testing rig varies from the dimension of a trailer to suitcase-sized containers.

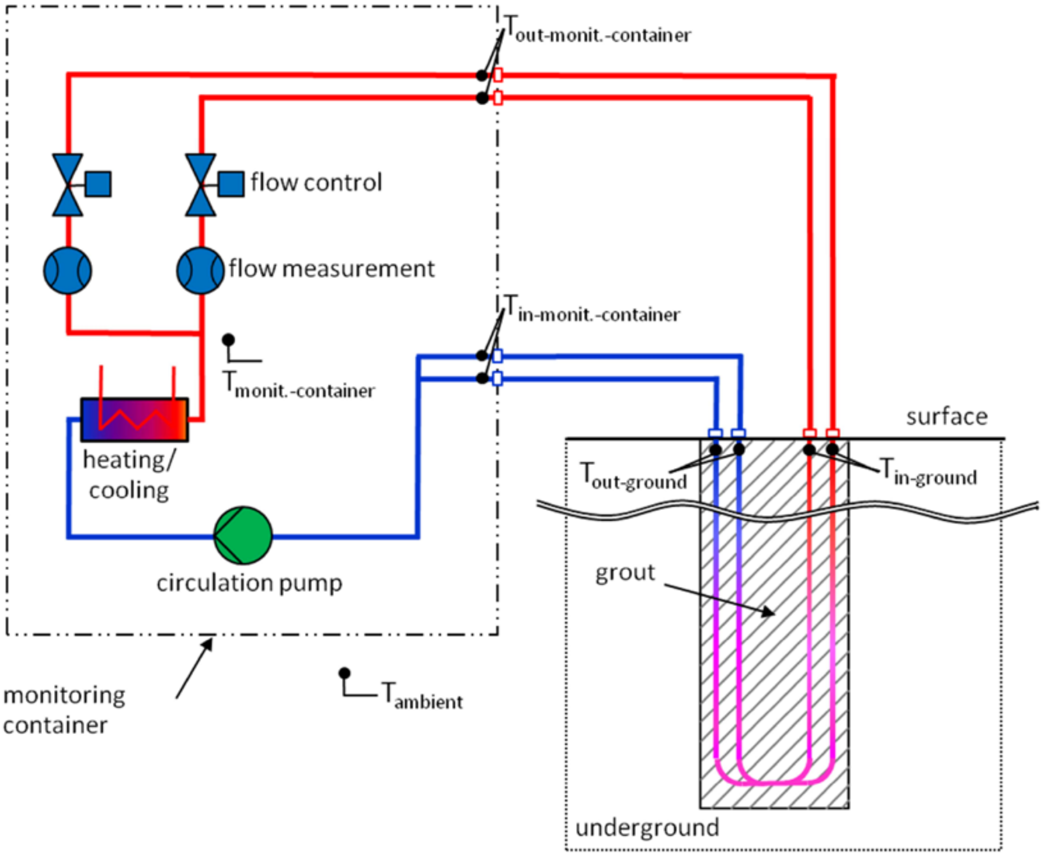

Figure 1: Schematic concept of a Thermal Response Test (VDI 4640 Vol.5 (draft), 2016).

Although, a lot of different devices exist worldwide the principles are the same, see Figure 1. A circulation pump pushes the heat carrier fluid (water) through the heater in the pipes of the borehole heat exchanger (BHE). A borehole heat exchanger is a closed loop system, embedded in grout in a borehole. The test results are dependent on the accuracy of the temperature and flow measurement devices, ambient thermal influences, the (voltage) stabilization of the heater and the pump as well as of the approximations or assumptions of the different data analysis models, which are necessary for data evaluation.

2.1.1. Executing a TRT measurement

After drilling the borehole to the designed depth, the pipes are brought in. Then the borehole is grouted from the bottom to the top and the pipes can be filled with the heat carrier fluid (e.g. water). Then the pressure test of the pipes can be done. Before the TRT measurement can start, a waiting time of 3 days (for rock conductivities > 1.7 W/m/K) to 5 days (for rock conductivities < 1.7 W/m/K) is recommended (Beier, 2008) or (Kavanaugh, 2016). Then the undisturbed ground temperature can be determined, usually made by temperature logging in the borehole or by evaluating the fluid temperature of the circulating fluid with a switched off heating/cooling device and a small sampling interval. The response test facility is placed as close as possible to the BHE and hydraulically connected to the borehole pipes. The test loop (i.e. the collector pipes and the response test device) is filled with water, purged and fully vented. All exposed parts between the borehole and the response test device must be thermally insulated to minimize the influence of the ambient temperature. After that a heat carrier fluid (most suitable is water) circulates through the U-pipe in the borehole.

The average undisturbed ground temperature is determined by circulating the fluid within the system and measuring its temperature at in- and outlet over time. After a while a constant level is reached, which represents the average undisturbed temperature of the system.

Hereafter, a constant fluid flow rate is set and the heating/cooling device is switched on. This is the beginning of the TRT. Mind, that the injected heating/cooling power and the flow rate has to be constant during the whole test. If a double u-pipe is used check, that the load distribution is equal for both pipes. Important is to record the temperature of the fluid directly at the in- and outlet of the BHE and the flow rate of the fluid of each pipe. Additionally, the ambient temperature and the heating power can be of interest for error detection. The sample interval of the logging device is normally set in the range of 30 - 60 seconds. The temperature of the fluid develops in form of a logarithmic function over the time, hence the temperature rise gets smaller. The test proceeds until the conductive heat transport dominates and steady-state conditions are obtained, for at least 48 h. After that, the heating/cooling device can be switched off and the regular TRT measurement is completed. Additionally, the temperature decline can also be measured, hence the circulation pump is left on for another number of hours until the borehole temperature is back near the initial conditions.

After the TRT measurement the following information are needed additionally for test evaluation:

- length and radius of the bore hole (see drilling documentation)
- type and layout of the BHE, amount, diameter and thickness of the pipes (see drilling documentation)
- heat capacity and density of the heat carrier fluid (temperature dependent), especially if antifreeze fluid is involved

2.1.2. Processing of TRT measurements

The test evaluation can be done by analytical methods (line or cylinder source approximation) or with numerical methods (e.g. finite elements or finite difference) by simulation. The most common method to process and evaluate a TRT measurement is represented by the analytical line source method (VDI 4640 Vol.5 (draft), 2016). This simple method can be applied as long as the heat transfer in the BHE is dominated by thermal conduction (see also equation [1[1]). At more complicated situation or if a detailed thermal conductivity profile of the drilled section is needed, methods based on numerical modelling or inverse approximation of subsurface models can be applied.

The analytical line source method leads to the following output parameters:

- Effective thermal conductivity, averaged for the investigated section of the BHE tubing.
- Thermal resistance of the borehole based on an estimation of the volumetric heat capacity of the thermally activated subsurface volume around the BHE.

The VDI guideline (VDI 4640 Vol.5 (draft), 2016) presents the following methods based on the line source approach:

Straightforward estimation of the average effective thermal conductivity and the thermal resistance of the borehole

The effective thermal conductivity is corresponding to the slope (k) of the linear approximation of the measured fluid temperature T_f (average of T_{inlet} and T_{outlet} at the time t) against the logarithm of time during the test (ln(t)):

$$\lambda = \frac{\dot{q}}{4\pi k} \qquad [2]$$

Where: $\dot{q}$… average specific heat transfer rate in the BHE (W/m), realized during the test and λ… effective thermal conductivity (W/m/K).

One can estimate the thermal resistance of the BHE from the following equation:

$$R_b = \frac{1}{\dot{q}}\left[T_f(t) - T_b - \frac{1}{4\pi\lambda}\left(ln\left(\frac{4\alpha}{r_b^2}\right) - \gamma\right)\right] \qquad [3]$$

Where: R_b… thermal borehole resistance (K/W/m); $T_f(t)$… fluid temperature (average inlet, outlet of BHE) at time t; T_b… undisturbed fluid temperature at t=0[1]; α… thermal diffusivity ($\alpha = \frac{\lambda}{cv}$); r_b… radius of the BHE (m) and γ… Euler-Mascheroni constant (~ 0,5722…).

To apply the straightforward method, the TRT period as well as the observation period has to be sufficiently long ($t>t_{min}$). For more information on the minimum duration and observation period of a TRT please see chapter 2.3.

Stepwise processing and quality control

The quality of the measurement and the data processing (selection of observation period of the measured heat respond of the subsurface) can be evaluated in terms of a stepwise assessment of the effective thermal conductivity. This can be done based on:

- A prograde evaluation of the effective thermal conductivity (TC) at varying observation periods t.
- A retrograde evaluation of the effective TC.

Both methods rely on equation [2] bur are accounting for different methods for defining the observation period t. In case of a good approximation of the line source model to the measured thermal response of the underground $T_f(t)$, the stepwise determined TC values λ(t) converge to a constant value, which means: $\Delta\lambda(t_i, t_{i+1}) \rightarrow 0$.

The stepwise evaluation can be stopped when reaching a certain convergence criterion (e.g. Δλ > 0,1W/m/K). The general processing scheme is shown in Figure 2.

Prograde evaluation:

The prograde evaluation starts at a starting point of time considering the before estimated minimum duration period of the TRT measurement ($t_s > t_{min}$, see also equation [4]) and stepwise extends the total observation period for the time increment Δt. After n runs, the total TRT observation period (t_0) is given by $t_0 = t_s \cdot n \cdot \Delta t$. More information on this evaluation method can be found in the VDI guideline (VDI 4640 Vol.5 (draft), 2016, pp. 14-15).

Retrograde evaluation

The stepwise retrograde evaluation method follows the same principles, but starts at the observation time at the end of the TRT measurement. Also selecting an appropriate time increment (Δt), one stepwise extends the observation period by multiples of Δt until the whole TRT measurement period or $t_0 - t_{min}$ is reached. This method has the advantage in revealing the critical minimum observation period ($t \geq t_{min}$) to achieve convergent solutions of the stepwise application of equation [2].

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[1] Approximated by the subsurface temperature at the midpoint depth of the BHE, derived from baseline measurements.

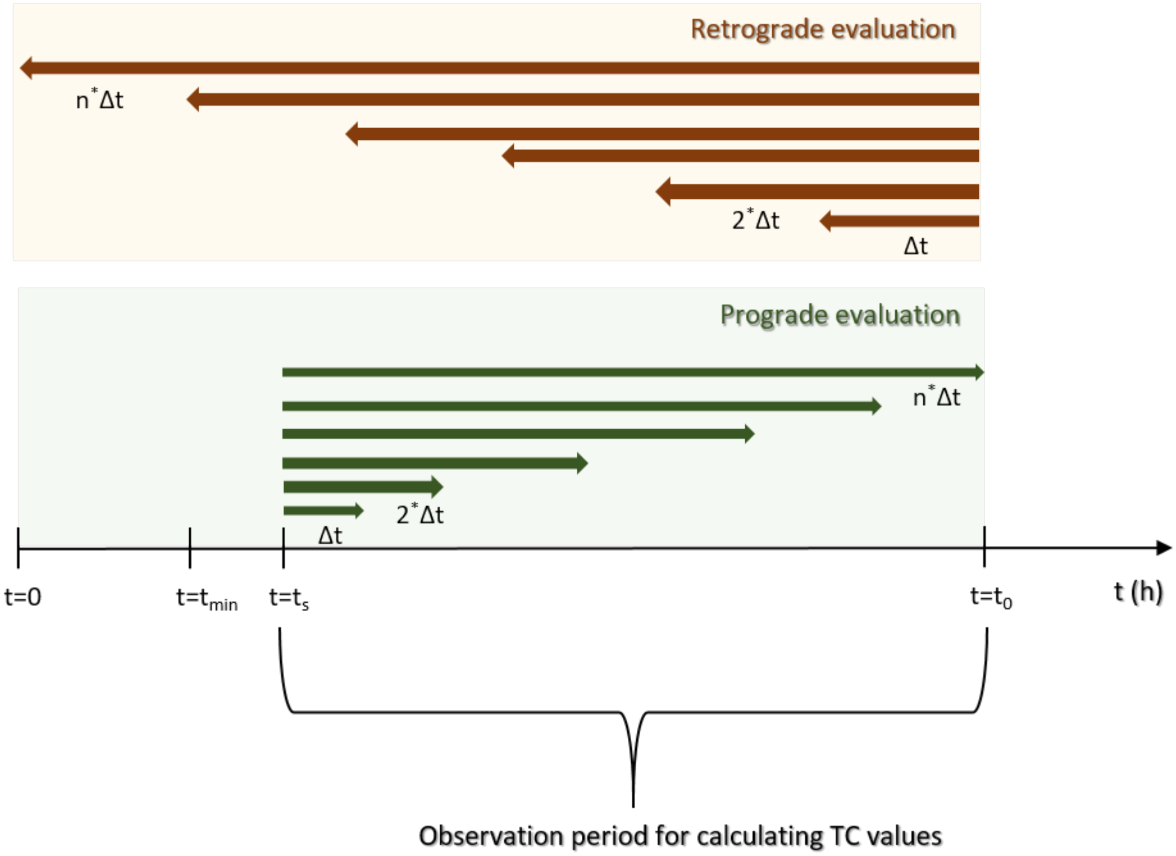

Figure 2: Workflow scheme for applying the stepwise evaluation methods for estimating TC values.

2.2. Problems and challenges

As mentioned in chapter 2.1 the conductive part of the heat transfer has to be dominating. At test sites with a strong groundwater flow (advection) the thermal conductivity becomes masked and the analytical evaluation approximations may get invalid. To check for excessive groundwater use, the step-wise evaluation of the thermal conductivity flow at data evaluation, see (VDI 4640 Vol.5 (draft), 2016). If the step-wise evaluated curve is not converging to a steady value (e.g. continues to rise) the evaluation with the analytical approximations is not valid. A more complex evaluation with numerical methods with good knowledge of the groundwater properties can lead to a proper evaluation. In open boreholes (e.g. in Sweden) or poorly grouted BHEs the conductive part of the heat propagation dominates; hence groundwater can flow up- and downwards in the borehole. This leads to tests which cannot be evaluated at all.

2.3. Sources of errors

Several possible sources of errors can occur during the performance and evaluation of a thermal response test. In the following, the most common are named.

Drilling and hydratation effects: During the drilling and grouting process heat or cold, depending on the season, is injected in the underground. Additionally, when the cement of the grout reacts with the water hydratation heat is released until hardening, which influence the undisturbed underground temperature. With a raff calculation of the released het, the hydratation yields to 200-500 Wh per bore meter within the first 7 days. This value is equivalent to a mean power of 1-3 W per bore meter for 7 days.[2] This process needs about 28 days with an exponential decrease of heat production. When a TRT begins directly after the grouting of the BHE, the required undisturbed underground temperature is disturbed, which leads to an error. It is essential to wait with the test begin at least 3 - 5 days after grouting.

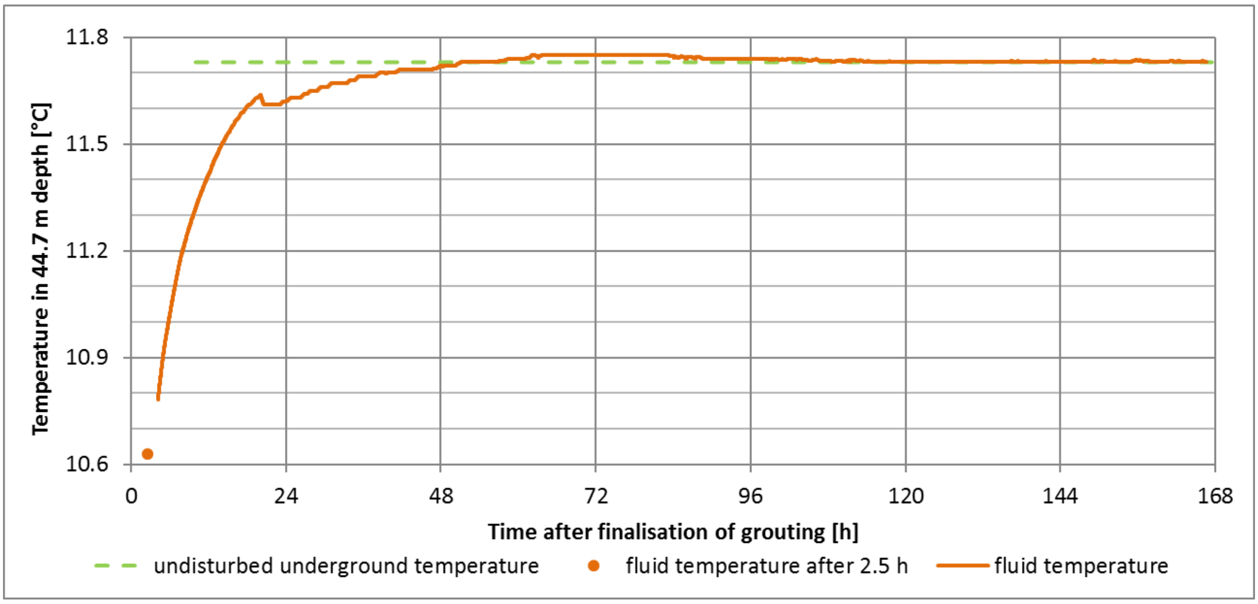

Figure 3: Temperature profile in a depth of 44.7 m in dependency of time after finalisation of grouting for a BHE in Germany, Dresden (Nitschke, 2016).

Power supply / re-testing of a BHE: Variations and interruptions in the power supply can lead to significant errors. If the power supply varies a lot the flow rate and the heat injection rate in the underground is not constant. Variation in the power supply for flow rates can be regulated with a frequency controlled circulation pump. If an interruption of the power supply occurs during the test, it is recommended to wait, until undisturbed temperature conditions are arrived, and repeat the test. For re-testing a bore, a typically delay time of 10 to 12 days in mid to high conductive formations and 14 days in low conductive formations is recommended, so that the loop temperature is within 0.3 °C of the pretested initial ground temperature (Kavanaugh, 2016). If this waiting time is to long there is the possibility to resume the test after the interruption immediately and use the “equivalent time method” for the test evaluation (Beier, 2008).

Evaluation method: Another possibility to generate errors is the incorrect evaluation of the gained data. Very important for the correct evaluation is the selection of an appropriate evaluation period. The minimum starting time, where the error of the line source approximation is small enough, can be calculated by the minimum time criterion (formula [2], (VDI 4640 Vol.5 (draft), 2016)).

$$t_{min} \geq \frac{p \cdot r_b^2}{\alpha} \qquad [4]$$

Hereby is α the thermal diffusivity ($\alpha = \lambda / c_v$ in m/s^2), t_{min} the starting time of the evaluation, r_b the borehole radius and p a factor, which is related to the percentage error of the analytic approximation. Depending on the tenable approximation the factor p has to be chosen, see Table 1 and Figure 4.

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[2] Calculated with a grout density of 1.5 g/m³, a cement proportion of 10-30 % and a hydratation heat rate of 200 J/g, see (Niederbrucker & Steinbacher, 2007) and (Bosold & Pickhardt, 2014). Assumption of borehole diameter = 140 mm.

Table 1: Factor p and related line source approximation error.

parameter p	5	10	20	40	50	100
related approximation error in %	10,5	5,3	2,5	1,5	1,0	0,5

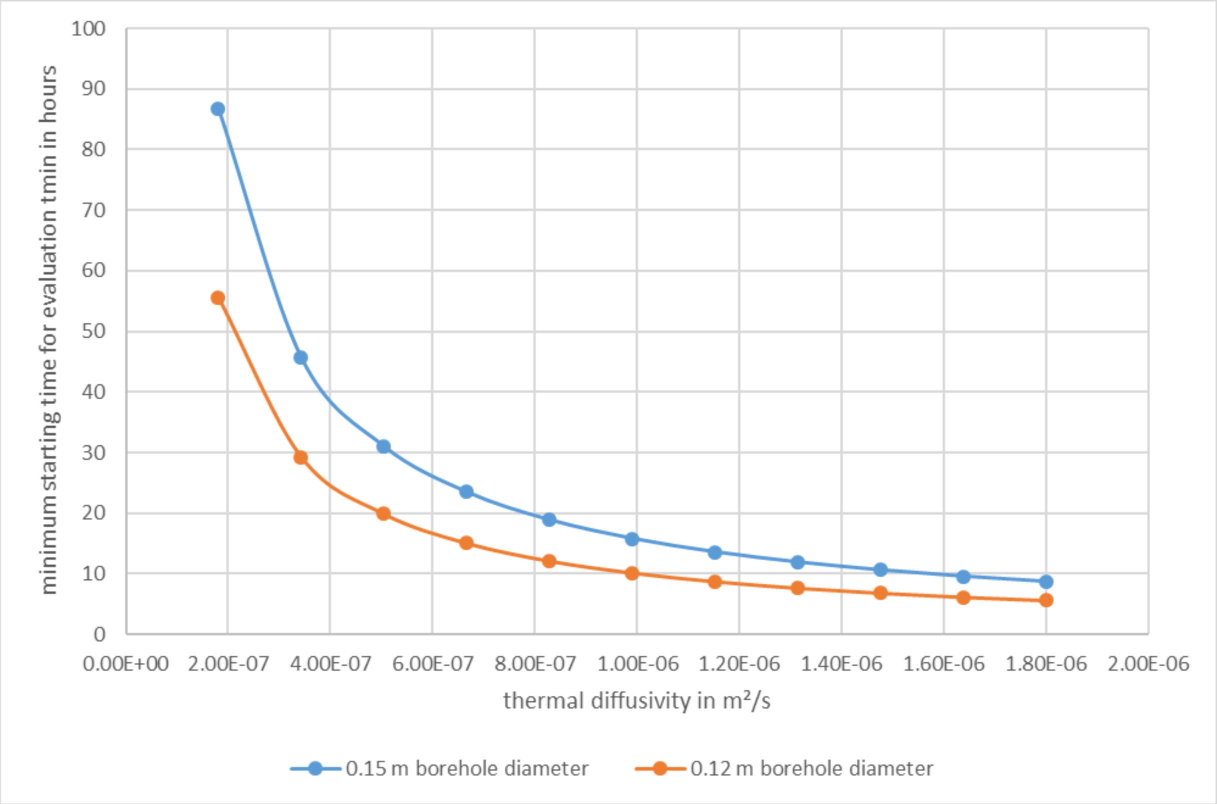

Figure 4: Minimum starting time in dependence of the thermal diffusivity and the borehole diameter, to ensure a line source approximation error < 5.3 % (factor p=10).

Ambient heat losses: Uncontrolled heat losses or gains to or from the environment due to insufficient thermal insulation can have a significant adverse influence when the results are analysed with the line source method. The problem may be overcome by good insulation of the device and pipes. Moving the temperature sensors into the piping in the ground (Witte, van Gelder, & Spitler, 2002) may also help.

Error Estimation: In (Zervantonakis & Reuss, 2006) the total error of the ground thermal conductivity and borehole resistance consists of three basic components: (a) the error of the measurement device, (b) the error of the evaluation method and (c) the uncertainties of the borehole parameters (e.g. borehole length). Table 2 gives an overview of the error component as an example.

Table 2: Total error of measurement of two TRT devices (apparatus) with and without power control in comparison as an example of error estimation (Zervantonakis & Reuss, 2006).

Total error component	**Value**	
	Apparatus with power-control	***Apparatus without power-control***
Temperature	± 0.06 K	± 0.17 K
Volumetric flow-rate	± 1 %	± 1 %
Heating power	± 2.3 %	± 5 %
Systematic error of the line-source theory for a test-duration of 4 days	± 2.5 %	± 2.5 %
Undisturbed ground temperature	± 0.2 - 1 K	± 0.2 - 1 K
Ground thermal conductivity	ca. ± 6 %	ca. ± 9 %
Borehole resistance	ca. ± 10 %	ca. ± 14 %

As another example of error estimation of the gained data from a specific 96h-TRT in Austria Table 3 and Table 4 shows values of a parameter variation study. It can be followed, that it is important that the accuracy of the measured values during the TRT are at least within 0.1 Kelvin (temperature difference), within 1 meter for the BHE length and the flow rate within 50 l/h. For the calculation of the borehole resistance R_B the drilling diameter is the most sensitive parameter, followed by the mean undisturbed soil temperature and the estimation of the heat capacity of the soil.

Table 3: Parameter Variation for error estimation of the effective conductivity for a specific thermal response test in Austria, Illmitz.

Variation of parameter	**Sensitivity of determined effective heat conductivity λ in W/m/K**	**Sensitivity of determined effective heat conductivity λ in %**
measured temperature difference between in- and outlet ± 0.1 K	± 0.11	± 5.0
BHE length ± 1 m	± 0.03	± 1.4
Measured flow rate ± 50 l/h	± 0.05	± 2.3
Selection of minimum time criterion t_{MIN} from 6 to 48 h	± 0.08	± 3.7

Table 4: Parameter Variation for error estimation of the borehole resistance for a specific thermal response test in Austria, Illmitz.

Variation of parameter	Sensitivity of determined borehole resistance R_B in K.m/W	Sensitivity of determined borehole resistance R_B in %
Mean undisturbed soil temperature ± 0.2 K	± 0.004	± 5.7
Drilling diameter - 10 mm	- 0.01	- 14.3
Drilling diameter + 20 mm	+ 0.01	+ 14.3
Heat capacity of the soil ± 0.2 MJ/m³/K	± 0.004	± 5.7
Heat conductivity of the soil ± 0.15 W/m/K	± 0.002	± 2.9
measured temperature difference between in- and outlet ±0.1 K	± 0.004	± 5.7
BHE length ± 1 m	± 0.001	± 1.4

3. Existing standards and guidelines of TRT measurements

3.1. Previous activities for defining harmonized standards

In the past 20 years, some comparison measurements have been performed at various places in Europe. Several projects have been presented during the first workshop on geothermal response tests on 25th and 26th October 2001 in Lausanne. The workshop has allowed to determine the state of the art of thermal response testing in Europe. Both advantages and limitations of TRTs has been presented and discussed in detail. It was shown that TRT measurements offer a significant potential for tuning the performance of large scale shallow geothermal applications. Even then, it became apparent, that the TRTs themselves require quality control.

Around the year 2000, three tests have been carried out in Langen, Germany, in one well field. Two tests at a 70-m drill hole leaded to very similar results, while the result of the third test is higher. The reason for this is that the third test was performed at a 99 m BHE with poor grouting material (Mands, Sanner, & Grundmann, 2001).

In Mol (Belgium, 2000) one Dutch and two German TRT devices were tested at three BHEs, where different grouting material was used (Sauer, Mands, Grundmann, & Sanner, 2016). The results for the thermal ground conductivity are with a variation between 2.4 and 2.5 W/(m,K) fairly the same, while the borehole thermal resistance was different dependant on the used grout (Sanner, 2001)

An additional remark of the workshop has been made concerning the flow conditions. It was mentioned, that if the test has executed based on turbulent fluid flow, but the system is later set for laminar flow, a correction has to be made (Eugster & Laloui, 2001).

The results of a test series in Mainz (2003), Germany, where two tests were done in virtually the same underground conditions, are the same if rounded to one decimal place (Sanner, Hellström, Spitler, & Gehlin, 2005).

A long-term test from 2009 to 2011 at a test site in Darmstadt, Germany, has been performed. Unfortunately, the results are not available for the public at the moment.

In 2016, another benchmark test has been organized by the Technical university of Darmstadt in the frame of an academic thesis. The project partner Geological Survey of Austria participated at this experiment. Unfortunately, there are no results yet we can present in this report.

In the frame of GeoPLASMA-CE, we have organized an international expert workshop on TRT measurements and the need for calibration / comparison of different test devices. 22 participants from research institutes, companies and associations presented their experience with TRT measurements and discussed afterwards the relevance of the validation of TRT devices and possible realizations.

3.2. Description of existing standards

The preliminary work and first attempt to give some definition and rules for TRT measurements was made in the IEA ECES Annexes 8 and 13. Between 2007 and 2011, an expert group developed basic standards and initiated a worldwide TRT standard procedure published in (IEA ECES Annex 21, 2013). This report also included a summary of the state-of-the-art, new developments in both devices and evaluation methods and dissemination activities.

A minimal concept of TRT measurements is described in (DIN EN ISO 17628, 2015). However, the description is poor, no theoretical background is explained and no limitations regarding the application of the evaluation model are given.

The initial guideline based on the results of Annex 21 and further experts is the (VDI 4640 Vol.5 (draft), 2016) with the title “Thermal Use of the Underground – Thermal Response Test”. The guideline is currently available only as draft version. The final version is planned to be available in the end of 2017. It gives detailed information and requirements on TRTs, the theory and limitations of the models are explained and the experimental set-up und monitoring equipment is described. Furthermore, the performance of a TRT and the evaluation of the results is described there. A short summary of the three mentioned guidelines is given in the table below.

Table 5: Summary and comparison of the existing standards for thermal response tests.

	IEA ECES Annex 21	EN ISO 17628	VDI 4640 Blatt 5
boundary and site conditions		• vertical or slanting BHE • max. 400 m length • max. 200 mm borehole diameter	• max. 45° from vertical • min. 25 m length • dominant conductive heat flow • undisturbed temperature field • steady electric energy supply and water (if necessary)
device configuration	• heating or cooling device • data acquisition unit • electric power	• heating or cooling device • circulating pump	• heating or cooling device with constant power

	• temperature sensors for in- and outlet and air temperature • sensor for power consumption	• data logging device for energy supply, temperature for flow and return, ambient temperature and flow rate • temperature and flow rate sensors • thermal insulation	• circulating pump (variable, with evenly distributed flow rate) • temperature sensor in every circle (in the tube at the probe heat) • expansion tank, venting valve and safety installation against overheating and flow rate problems • heat transfer fluid with known specific heat capacity and density (water recommended) • measurement of fluid flow in every circle
performance	• place device as close as possible to the test hole and connect • test loop is filled with brine and purged • Measurement of the undisturbed underground temperature • insulate all exposed parts • temperature development is recorded at a set time interval (some seconds) • Test proceeds until steady-state conditions are obtained (duration can vary from 12 to 250 h)	• 5 days after backfilling of the annular space • Measurement of the undisturbed underground temperature • heated must be pumped with a constant velocity • measurement of the fluid temperature at in and outlet of the probe with start of the circulation • Temperature measurements with a resolution of several seconds • turbulent fluid flow • constant heat supply • min. measurement time calculated with minimum time criterion • measurement of the ambient temperature	• min. 3, better 5 to 7 days after backfilling of the annular space • place TRT device directly next to BHE • measurement of the undisturbed underground temperature • connection with BHE, venting of the system and adjustment of the fluid low • constant heat load • measurement of the inlet and outlet temperatures as well as the fluid flow during the whole measurement time • registration interval less than 60 seconds • measurement lasts several days (minimum time criterion)
evaluation	• analytical methods (like line source approximation) • numerical methods	• Line source model	• Line source model • Sequential forward evaluation

			• Sequential backward evaluation
additional	• Enhanced geothermal response test • TRT while drilling • Step pulse • Non-wired immersible measuring object for temperature (NIMO-T)	•	• Description of an in-depth dissolved TRT • Multiple pulse test • Repetition of a test

The comparison of the existing standards in Table 5 shows, that the elaborated TRT standards in (VDI 4640 Vol.5 (draft), 2016) are the most detailed. Although there is actually only a draft version available, it will be considered for the joint workflows applied in GeoPLASMA-CE.

4. Comparison of the TRT devices of the GeoPLASMA-CE partners

In GeoPLASMA-CE, several different TRT devices will be used for assessing in-situ values of the effective thermal conductivity. In this chapter, we would like to shortly present and compare these devices.

The TRT device of GBA (Figure 5) was built 2009 by UIT Dresden, Germany, and is a 1.5 x 0.5 x 1.5 m piece of equipment fixed on a trailer. It can be attached to single- and double-U probes as well as to concentric BHEs. The device works regularly with heat injection but is also prepared to connect it to a heat pump. The 10-kW heater can be regulated with an electronic contractor (pulsed in part load). The integrated 500-kW centrifugal circulation pump has a maximum flow rate of 5 m^3/h and can be controlled over frequency. The device has 7 temperature sensors which are located directly at the BHE and at the in- and outlet before and after the heater. The flow is measured with a magnetic flow meter and can be regulated with mechanical flow meters. The entire system can be controlled by a central control unit from Siemens.

Our project partner geoENERGIE Konzept owns a TRT device (Figure 6) built in 2008 by master electrician F. Reimelt, Germany. The mobile box with the device fixed inside has a size of 0.85 x 0.75 x 0.65 m. It can be attached to single- and double-U probes as well as to concentric BHEs. The device operates with heat injection only and its 12-kW heater can be regulated stepwise within 3 steps whereas the first step is variable. The glandless circulation pump can be regulated within 3 steps as well whereby the power is 90, 125 or 195 W. The two temperature sensors which are located at the in- and outlet before and after the heater as well as the temperature sensor for the ambient temperature have separate data logger which record the data with a minimum interval of 2 s. The fluid flow is measured by a turbine flow sensor with hall-effect detection and can be regulated with mechanical valves. The device has no central control unit but the monitoring unit which checks the fluid flow and power supply sends a SMS if any interruptions which can cause damage occur.

The third TRT device (Figure 7) in the project belongs to the Polish Geological Institute and was built by UBeG GmbH & Co. KG, Germany, in 2015. The 1.0 x 0.8 x 0.6 m portable box is mounted on a caterpillar and can be connected to single- and double-U probes as well as to concentric BHEs. The device is able to work with heat injection only and its 9-kW heater is adjustable stepless with a programmable logic controller (PLC). The power of the integrated circulation pump can be set between 9 and 125 W. The device has two temperature sensors, one before and one after the heater. The fluid flow is measured with an ultrasound sensor and regulated with mechanical valves. The entire system can be controlled by a central control unit from Schneider Electric.

All three devices need 3-phase, 16-A power which is commonly consumed on construction sites. In some cases where no site power supply is available a power generator can be used.

Figure 5, Figure 6 and Figure 7 gives impressions of the different TRT measurement devices of the project partners in the field. In Appendix A are the detailed technical specifications of the three devices in a table.

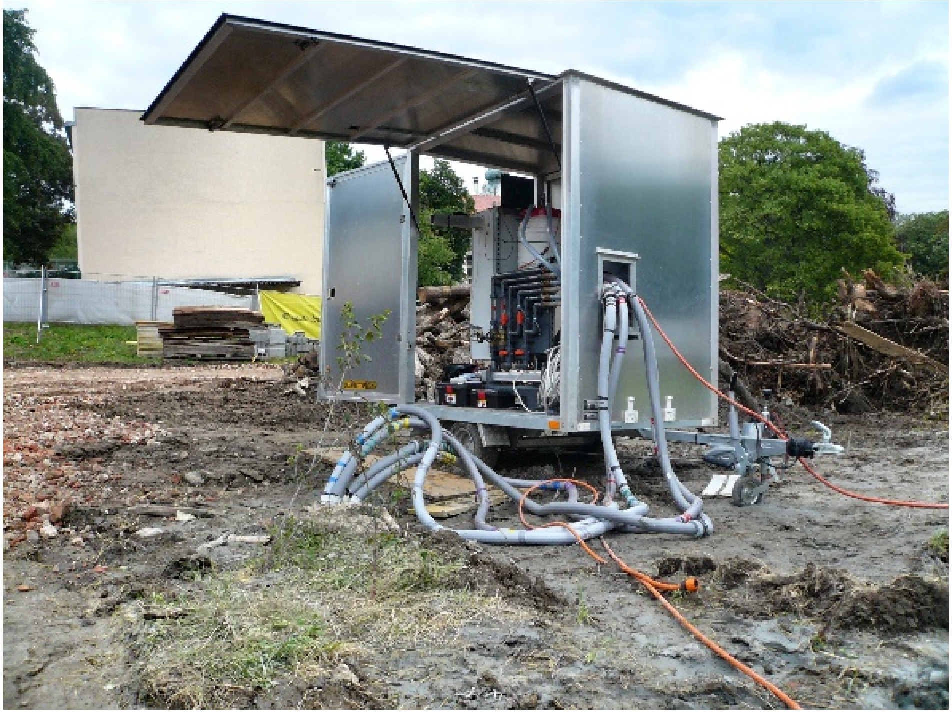

Figure 5: TRT Device #1 (LP – Geologische Bundesanstalt).

Figure 6: TRT Device #2 (PP03 – geoENERGIE Konzept GmbH).

Figure 7: TRT Device #3 (PP08 – Polish Geological Institute – National Research Institute).

Main difference of the three TRT devices:

- The devices were built between 2008 and 2015. Some components might be younger due to replacement.
- The size varies from a box which can be carried by two people to a trailer.
- The device from GBA is prepared to connect it to a heat pump.
- Maximum power of the heater varies from 9 to 12 kW.
- The heater from device #1 can be regulated stepless with an electronic contactor. The heater of device #3 can be controlled stepless as well with PLC. In contrast device #2 is adjusted by 3 heat steps whereby the first step is variable.
- Device #1 has a 500-W centrifugal pump whereas device #2 and #3 have an adjustable glandless circulation pump up to 125 W.
- The centrifugal pump of device #1 can be regulated frequency controlled, whereas device #2 has 3 speed-stages and device #3 can be controlled stepless by an additional software stick.
- The number of temperature sensors vary from 2 to 7.
- Device #1 has a magnetic flow meter, device #2 a turbine flow sensor with Hall-effect detection and device #3 an ultrasound sensor.
- Device #2 has no central control unit and decentral data loggers whereas the other two devices have one common data logger for all sensors and a central control unit.

Since all three devices consist of different components it is mandatory to compare the results of all three devices gained at one or several comparative borehole heat exchangers.

5. Requirements on comparative TRT measurements and joint standards for GeoPLASMA-CE

This chapter deals with so-called benchmark TRT measurements, which intend to make the achieved results, especially the determined effective thermal conductivity, comparable between similar lithological units investigated in different pilot areas based on different TRT devices.

5.1. GeoPLASMA-CE knowledge exchange workshop and decisions at teleconferences

The most important outcomes of the GeoPLASMA-CE Knowledge Exchange Workshop on TRT measurements in Prague on March 15th, 2017 for comparative TRT measurements can be summarized as followed:

Decisions:

- The term “calibration” is more a trimming tool to get reproductive readings of a sensor. The term “validation” means, that a method correctly determines values, obtained by another proven method. **Therefore, the term “validation” should be used for the comparative measurements in GeoPLASMA-CE**.
- Due to the fact, that the calculated value for the thermal conductivity contains an error it is sufficient to indicate the achieved value for one digit after the comma[3].

Ideas:

- Compare devices used in GeoPLASMA-CE on borehole heat exchangers (BHEs) with known settings and reference values. This can be achieved by a combination of benchmark tests combined with laboratory or in-situ measurements of the rock units drilled.
- Compare the evaluation method used by the involved project partners based on a common benchmark data set.
- Validate the devices used in GeoPLASMA-CE under laboratory conditions, for example, at the ZAE in Garching near Munich, Bavaria. At least, temperature sensors used in TRT devices should be calibrated or validated to know the current accuracy.

Open Questions:

- How often do sensors of a TRT devices have to be calibrated?
- Which minimum standards need to be defined for comparative / validation measurements?
- Which minimum standards need to be defined for benchmark BHEs?

We have considered the outcomes of the GeoPLASMA-CE Knowledge Exchange Workshop on March 15, 2017 in order to elaborate a concept of validation tests, which will be presented in the subsequent chapters. As mentioned in chapter 3, the project partners decided to follow the already elaborated standards for TRT measurements in (VDI 4640 Vol.5 (draft), 2016) for the comparative measurements on BHE within GeoPLASMA-CE. Where necessary, we have added or adapted strategies and workflows tailored for the needs of GeoPLASMA-CE.

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[3] In GeoPLASMA-CE we want to achieve a maximum relative error of the determined effective thermal conductivity of around 5% or ±0,1 W/m/K.

5.2. Requirements of benchmark BHE sites

Benchmark TRT measurements can either be performed at existing borehole heat exchangers (BHEs) or at real benchmark BHE sites, constructed for this purpose. In GeoPLASMA-CE, we plan to execute benchmark TRT measurements in both, existing BHEs and recently constructed BHE benchmark sites. In addition, we also intend to perform laboratory validation tests on the TRT devices applied in GeoPLASMA-CE

In the following chapters, we present the minimum requirements for benchmark sites.

5.2.1. Requirements for benchmark tests in existing BHEs

- Already existing borehole, developed as borehole heat exchanger (BHE) with concentric-, single or double U-pipes, grouted.
- Permission of the land owner for research measurements
- BHE has not been used for heating / cooling purposes so far
- BHE is not in use for a period of (at least) 9 weeks to allow three TRT benchmark measurements
- BHE is accessible with off-road vehicle
- Length of the BHE > 25 m with inclination < 45°
- A geological cross section and information about significant ground water bodies are available
- Knowledge of geometry of the BHE (diameter of borehole, drilling depth, diameter and thickness of the pipes, placement of the pipes, used spacers)
- Knowledge of the used grouting material of the BHE (API class and its freeze-thaw resistance)
- Three phase power connection nearby or electrical power generator

5.2.2. Requirements for benchmark test sites

As discussed on the knowledge exchange workshop in Prague, it would be of special interest to implement borehole heat exchangers with sophisticated measurement equipment at specific geological sites with constant and well-known (hydro-) geological conditions. These benchmark test sites will only be used to validate TRT devices and associated processing procedures.

General Requirements for the test sites:

- Test site preferably owned by public institutions to grant free access to participants of the benchmark test
- Good accessibility of the site to cars and trailers
- Preferably homogenous geologic build-up
- Low thermal influence of groundwater flow to ensure a dominating conductive heat transport regime between the BHE and the surrounding rock. Depending on the overall thermal conductivity of the investigated subsurface section, the product of aquifer thickness and Darcy velocity should not exceed certain criteria, determined by the so-called Peclet number (see also Figure 8).
- No thermal disturbance in the surrounding due to installations (e.g. pipelines, canals or existing shallow geothermal uses)

- Stable power-supply and water connection available

Figure 8: Dependency on the Darcy velocity on the net aquifer thickness (Peclet number) for application of TRT benchmark tests at a 100-meter BHE for two different average thermal conductivity (TC) values of the BHE section not accounted for advective thermal heat transport. This graph bases on the assumption that the total effective TC including heat advection does not exceed 4 W/m/K.

The estimation of the maximum allowed advective influence of moving groundwater at a TRT benchmark test site is depending on the so-called non-dimensional Peclet number (*PE*), which describes the ratio of convective to conductive heat transport. We approximated the effective TC also considering advective heat transport by:

$$\lambda_{eff} = \langle\lambda\rangle \cdot (1 + PE) \qquad [5]$$

λ_{eff}… effective Thermal conductivity, <λ>… bulk thermal conductivity of the aquifer.

Considering a 100-meter-long BHE and average bulk conductivities of 2,0 W/m/K (sedimentary basin) or 3,0 W/m/K (hard rock area), the critical Peclet numbers varies between 54 and 110 for a maximum effective overall TC allowed of 4,0 is (range of validity of SIA 384/6 guideline on correlating overall TC values to heat transfer rates).

Requirements for the drilling and implementation of the heat exchanger:

- Detailed geological documentation of the drilling process, if possible assessment of drilling cores along the entire drilling section for in-situ and laboratory TC measurements on rock samples
- In-situ or laboratory TC measurements of the fresh probe of every stratigraphic unit

- Analysis of rock/sediment samples in laboratory of every stratigraphic unit
- Borehole equipped with a heat exchanger (single, double or concentric pipes) and spacers for centric installation of the pipes – take care of temperature resistance for higher temperatures (up to 60 °C) of the pipe material
- Borehole equipped with fibre optical cable for measuring the temperature profile with a DTS (distributed temperature sensing) system. The cable is usually installed together with the pipes.
- Grouting of the BHE with a proper material: high thermal conductivity at homogenous zones, thermal isolating grout (low thermal conductivity) in seasonal zone (at least upper 10 m), groundwater influenced zones and fractured zones, depending on geological drilling profile
- Measurement station for DTS measurement device

5.2.3. Laboratory validation and calibration of TRT devices and its components

Currently, the ZAE Bayern (Bavarian centre for applied energy research) is developing a laboratory test bed for the evaluation and calibration of TRT devices. The concept was presented by M. Reuss from ZAE Bayern at the GeoPLASMA-CE Knowledge Exchange Workshop in Prague on March 15, 2017. This test bed aims to simulate the subsurface and allows a precise check of the TRT equipment itself. This covers the temperature and volume / mass flow sensors, the heating source, thermal insulations of the device related pipe systems as well as the control system of the TRT device. The GeoPLASMA-CE project team also intends to validate the TRT devices involved in the project at the ZAE Bayern testbed. Based on a feedback from M. Reuss, the testbed will be ready to use from spring 2018. This activity will also include a validation of the temperature sensors used in the TRT devices in a separate validation turn at ZAE Bayern.

5.3. Joint GeoPLAMSA-CE standard for executing and processing TRT measurements

In addition to minimum criteria for benchmark BHE sites, we also define joint standards for executing and processing TRT measurements. Moreover, we will also apply these standards on ordinary TRT measurements performed in the frame of GeoPLASMA-CE. In that context, we define the following requirements:

Preparing the BHE for TRT measurement

- Waiting time after drilling at least 7 days, waiting time between TRT tests at same site at least 14 days.
- BHE pipes should be filled (preferably with water) at least 24 h before starting the TRT. If the BHE is not filled with water, the chemical composition heat carrier fluid should be known and documented.

Baseline temperature measurements

- Measurement of the pre-test temperature profile at the BHE T-Profile right in advance of the TRT measurement based on a logging device (temperature logger or fibre optical cable). The accuracy of the temperature measurement devices has to be validated by means of comparative measurements. Ensure a data logger sampling interval of less than 5 seconds.

The estimation of the undisturbed average BHE fluid temperature via non-heating circulation tests of the TRT device does not fulfil the standards at GeoPLASMA-CE to reach a maximum error of 5%. This method should not be applied in the project.

Performing the TRT measurement

- Planning the maximum duration of the test: Calculation of t_{MIN} with factor p = 10 (approximation < 5.3 %) and estimated thermal diffusivity or the underground (see also Table 1).
- TRT based on a constant power load (more than 30 W/m and turbulent flow conditions (Re > 3000)[4]
- Data logging of fluid temperature at in- and outlet of each pipe as well as the flow rate at a sampling interval less than 60 seconds.
- Temperature log of the ambient atmosphere temperature during the test (sampling interval less than 6 h)
- Evaluation of the validity of the line source approach and update t_{MIN} based on rough determination of preliminary estimated thermal conductivities (see also chapter 2.3 and equation [2]). Verification of the line source approximation requirements by applying the „forward step evaluation method".

- Duration of the TRT: Do not stop the heating and circulation before minimum duration criteria $t_{TRT} = t_{MIN} + 48$ h is reached without any interruption of the power supply. As indicated in chapter 2.3, we recommend re-starting a TRT measurement in case of a significant interruption of the power supply (more than 20 mins). If this is not possible, a processing of the TRT measurement based on the approach of the "equivalent time method" (Beier, 2008) can be executed. However, this case has to be documented on the joint TRT data assessment sheet.
- Documentation of the TRT measurement based on a harmonized TRT data assessment sheet (see Annex B).

Post-TRT measurements and data processing

- Measurement of two additional temperature profiles in the BHE tubing at the following points in time: 1 hour and between 12 and 24 hours after the accomplishment of the test. Documentation of the shut down time at the TRT data assessment sheet
- Data processing based on a harmonized line source evaluation workflow (see also chapter 2.1.22.1.2) as proposed in the VDI guideline (VDI 4640 Vol.5 (draft), 2016).

For training and comparison purposes, we also intend to perform a benchmark test on the processing of TRT measurements based on a dataset from the IEA ECES Annex 21. ZAE Bayern will provide this dataset.

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[4] A Reynolds number Re > 3000 corresponds to a flow rate of 240 l/h (32 mm pipe) or 307 l/h (40 mm tubes) per pipe, calculated for a water temperature of 20 °C. For a BHE with a double U-pipe (32 mm) the minimum flow rate for the test should be 480 l/h. The faster the fluid, the more turbulent the water and the better the heat transfer.

6. Work plan of TRT measurements applied in GeoPLASMA-CE

In GeoPLASMA-CE, TRT measurements aim at determining interval in-situ values of the effective thermal conductivity, which also accounts for the possible influence of thermal advection due to groundwater flow. The TRT data-sets will be later used to validate mathematic prediction models of the effective thermal conductivity (TC). Validated TC models will in turn be used to prepare the potential maps for closed loop systems and to derive the joint parameter lists of TC values associated to generalized rock types (for more information see also deliverable D.T2.3.2).

The elaborated work plan consists the man work steps:

- Benchmark and validation test of the TRT devices and its relevant data sensors
- Benchmark and validation tests on processing routines
- TRT measurements in recently constructed borehole heat exchanges (BHEs).

In GeoPLASMA-CE, we aim at reaching a maximum error associated to TRT measurements of 5% of the measured value or ±0,1 W/m/K. For that reason, the maximum resolution of the produced TC key values will be limited to 0,1 W/m/K.

6.1. Validation and benchmark tests

To determine any differences between the TRT devices used in GeoPLASMA-CE, it is planned to select BHE benchmark sites to allow comparative measurements. BHE selected must fulfil the requirements presented in chapter 5.2. In GeoPLASMA-CE, we selected the **device of PP03 (geoENERGIE Konzept) to act as a standard** for benchmark tests between the other devices used in the project, as PP03 has allocated the highest budget for TRT measurements.

By now, only one TRT benchmark site is already identified to be available at the premises of the lead partner from spring 2018 on. It will be used for comparative measurements between the TRT devices of the lead partner and project partner PP03. Further benchmark sites will be identified for comparative measurements between PP03 and PP08 will be identified during the upcoming weeks and months.

In addition of the comparative TRT benchmark tests under real life conditions at existing BHEs, we intend to perform validation tests of the entire device and the temperature sensors installed in the devices under laboratory conditions at ZAE Bayern in spring 2018.

6.2. Benchmark test on processig routines

To test, if there are differences in the processing methods of the involved partners, we intend to perform a benchmark test performed on a reference data-set used for the IEA ECES Annex 21. This data-set will be provided by ZAE Bayern in summer 2017, so that the benchmark test will be accomplished until autumn 2017. Based on the outcome of this test, we will select a harmonized processing workflow of TRT measurements to be applied in the project.

6.3. TRT measurements for assessment of filed data

In GeoPLASMA-CE we intend to perform TRT measurements in recently constructed BHE. In order to not interfere to the existing market on TRT measurements, we will limit the project related survey on small scale BHEs used in single-family houses[5]. For that purpose, we will inform stakeholders in the pilot areas, like authorities, sectorial agencies and experts, on the planned surveys in order to get access to recently constructed small scale BHEs. The measurements performed in GeoPLASMA-CE will be carried form the project budget. The joint fact sheet of the TRT surveys planned in the 6 pilot areas is presented in Annex C

The subsequent Table 6 summarizes the number of TRT measurements currently planned in the GeoPLASMA-CE pilot areas. This schedule will be updated on demand.

Table 6: Work plan on performing TRT measurements, in-situ TC surveys and TRT benchmark tests.

Pilot area	*Maximum number of TRT measurements scheduled*	*Benchmark BHE test planned*	***Responsible** and involved project partners*
Vogtland/W-Bohemia	**DE**: 18 **CZ** TC measurements on rock samples	no	**PP03**
Walbrzych/ Broumov	**PL**: 2 **CZ, PL**: TC measurements on rock samples	Yes (site not known yet)	**PP08**, PP05, PP03
Krakow	3	no	**PP08**
Vienna	10 (additional TC measurements on soft-rock drilling cores)	Yes (benchmark BHE at premise of LP-GBA	**LP-GBA**, PP03
Bratislava / Hainburg	**SK**: up to 3 measurements if BHE sites are available **AT**: 5 (additional TC measurements on rock samples)	no	LP-GBA (AT), PP03 (SK)
Ljubljana	On demand only	no	**PP03**

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[5] Normally, TRT measurements are only performed in large scale shallow geothermal applications due to the significant costs of the survey (around EUR 3.000).

7. Other validation and comparison aspects relevant for GeoPLASMA-CE

In GeoPLASMA-CE, we consider validation and benchmark tests to ensure a comparability of the field data achieved and to reduce data assessment errors. To avoid excess work load we elaborated a strategy, which differs between (a) **compulsory** and (b) **voluntary** validation measures.

Compulsory validation measures are affection of field data surveys, which are used to derive joint datasets (e.g. parameter list of thermal conductivities associated to litho-stratigraphic units) or require a low range of error (e.g. TRT measurements). Voluntary validation measures cover all other field surveys and do not necessarily have to be performed.

The subsequent Table 7 lists all currently scheduled methods of assessing field data also including the applied devices and probes:

Table 7: List of all currently scheduled methods

Project Partner	**Field survey planned**	**Method applied**	**Device(s) used**	**Validation measures**		
				Compulsory	*voluntary*	*Explanation*
LP-GBA	Effective thermal conductiviy	TRT measurements	Prototype developed by UIT Dresden	yes		BHE benchmark test (AT), laboratory benchmark test, calibration of temperature probes
LP-GBA	Bulk thermal conductivity (TC of dried and saturated rock sample)	Soft rock drilling cores	Line probe sensor: Applied Precision Ltd; ISOMET Model 2104	No	Yes	Comparison with results of BHE benchmark test
		Hard rock samples	Laboratory not selected yet	Yes		Delivery of rock sample to reference laboratory (not defined yet)
LP-GBA	Volumetric heat capacity	see bulk thermal conductivity	Laboratory not selected yet	No	Yes	see bulk thermal conductivity
LP-GBA	Groundwater temperature	multi probe monitoring	pt-100 thermistor probes	No	Yes	Internal calibration at GBA;
PP03 - geoENERGIE	Effective thermal conductivity	TRT measurements	TRT device 2.1 developed by Frank Reimelt	yes		Reference TRT device for BHE benchmark tests; laboratory benchmark test, calibration of temperature probes

PP05 - CGS	Bulk thermal conductivity (of dried rock sample)	Hard rock samples	TCS device: Institute of Geophysics of the Academy of Science of Czech Republic (Mr. Dědeček, certification: No, measurement device: Thermal Conductivity Scanner by Prof. Yuri Popov, http://www.tcscan.de/)	Yes		Delivery of rock sample to laboratory
PP05 - CGS	Volumetric heat capacity (of dried rock sample)	Hard rock samples	TCS device: Institute of Geophysics of the Academy of Science of Czech Republic (Mr. Dědeček, certification: No, measurement device: Thermal Conductivity Scanner by Prof. Yuri Popov, http://www.tcscan.de/)	No	Yes	Delivery of rock sample to laboratory
PP05 - CGS	Groundwater temperature	multi probe monitoring	pt-100 thermistor probes	No	Yes	Internal calibration at CGS
PP05 - CGS	Groundwater pH	multi probe monitoring	pH probe	No	Yes	Internal calibration at CGS
PP05 - CGS	Groundwater conductivity	multi probe monitoring	conductivity probe	No	Yes	Internal calibration at CGS
PP06 - SGIDS	Groundwater temperature	multi probe monitoring	pt-100 thermistor probes	No	Yes	Validation measurements at GBA
PP06 - SGIDS	Groundwater temperature and groundwater regime	regime of the temperatures and groundwater level	multisensor - barologer, conductivity, temperature	No	Yes	Internal calibration at SGIDS
PP07 - GeoZS	Volumetric heat capacity	Soft rock samples	KD2 Pro	No	yes	Internal calibration at GeoZS
PP07 - GeoZS	Bulk thermal conductivity (TC of dried and saturated rock sample)	Hard rock samples	TCS meter (TC and TD scanner)	yes		Delivery of rock sample to reference laboratory (not defined yet)
PP07 - GeoZS	Groundwater temperature	multi probe monitoring	HOBO Water Temperature Pro v2 Data Logger and ELTRATEC GSR 130 NTG Logger	No	yes	Internal validation at GeoZS
PP07 - GeoZS	Groundwater chemistry	Groundwater sampling	Laboratory not selected yet	No	Yes	Delivery of groundwater sample to reference laboratory (not defined yet)
PP07 - GeoZS	Electric conductivity of groundwater	multi probe monitoring	ELTRATEC GSR 130 NTG logger	No	yes	Internal validation at GeoZS

PP08 - PGI NRI	Effective thermal conductiviy	TRT measurements	Model GERT (produced by UBEG)	Yes		BHE benchmark test (PL), laboratory benchmark test, calibration of temperature probes
PP08 - PGI NRI	Thermal conductivity of dried rock sample	Hard rock samples	TCS Thermal Conductivity Scanner (Lippmann and Rauen GbR (Germany)	Yes		Delivery of rock sample to reference laboratory (not defined yet)
PP08 - PGI NRI	Bulk thermal conductivity (TC of dried and saturated rock sample)	Soft rock samples	KD2PRO- Thermal Needle (Decagon Devices)		No	
PP09 AGH UST	Groundwater temperature	multi probe monitoring	Model 107 TLC Meter (Solins)	No	Yes	Internal calibration at AGH UST, standard sample are provided by the manufacturer
PP09 AGH UST	Electric conductivity of groundwater					

7.1. Compulsory validation measures

Currently, compulsory validation measures only include:

- TRT devices and related temperature probes to achieve a maximum error of 5%
- Determination of the bulk thermal conductivity on hard rock samples (combined from TC measurements on dried and saturated samples) for the elaboration of the joint parameter list

7.1.1. TRT validation tests

The minimum requirements on TRT validation tests and the planned work plan are described in chapter 5.2 and 6. We decided to use the TRT device of PP03 as a reference device for the planned benchmark tests. In addition, temperature and volume / mass flow probes included in the TRT devices used in GeoPLASMA-CE will be validated in the laboratory of ZAE Bayern.

7.1.2. Bulk thermal conductivity of hard rock samples

The benchmark test on bulk thermal conductivity measurements will be performed by comparative measurements at reference laboratory. The reference laboratory can either represent a certified laboratory or be selected by the project partners.

The compulsory validation measurements have to be performed on at least three rock samples from different rock units. The exchange of samples will be performed either via postal service or during meetings and workshops of the project partners.

7.2. Voluntary validation measures

Although we recommend to apply validation measures on all devices used in type of field campaigns applied by more than one project partner, we decided to keep it at a voluntary level to avoid massive work load.

Referring to deliverable D.T3.1.1, the following field campaigns are planned:

- Measurement of the bulk thermal conductivity at soft rocks based on a line source probe: this measurement will only be performed by LP-GBA, who intends to perform a validation test at the benchmark BHE site.
- Groundwater temperature surveys: We recommend performing validation tests for temperature probes. The validation can be performed by the use of a calibration bath (temperature controlled basin) and a reference thermometer. LP-GBA offers to validate sensors at his laboratory.
- Determination of the volumetric heat capacity on rock samples: The validation can also be achieved by benchmark measurements at a reference laboratory. However, the potential of closed loop systems in terms of the heat transfer rate is only indirectly depending on the heat capacity, which determines the heat storage available in the surrounding of a borehole heat exchanger for shallow geothermal use.
- Groundwater chemistry: As the groundwater chemistry does not control the potential of use, we assume that no validation measures are necessary. In addition, only PP07 is currently planning laboratory measurements.
- Electric conductivity of groundwater samples: This parameter also does not influence the potential of shallow thermal use.

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List of Annexes

Annex A	Technical specification of the TRT devices of the project partners in comparison
Annex B	Joint TRT data assessment sheet (to be used in GeoPLASMA-CE)
Annex C	Fact sheet on TRT measurement in external borehole heat exchangers in GeoPLASMA-CE

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D.T3.5.1 JOINT REPORT ON CHOSEN APPROACHES AND METHODS FOR CALIBRATION

Annex A: Technical specification of the TRT devices of the project partners in comparison

Version 1
08 2017

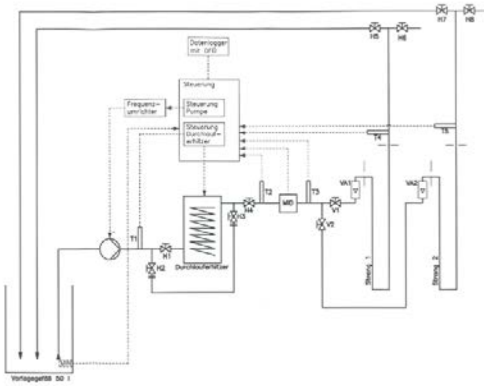
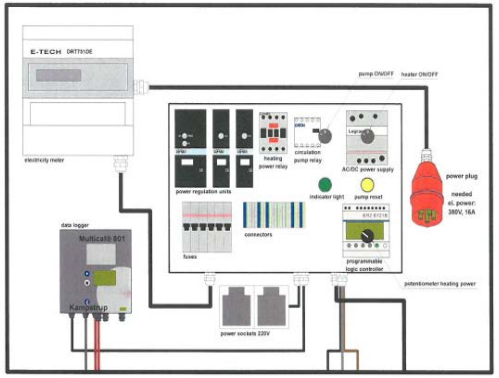
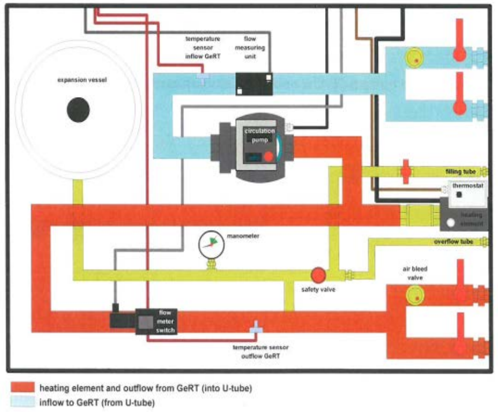
Geologische Bundesanstalt
LANDESAMT FÜR UMWELT, LANDWIRTSCHAFT UND GEOLOGIE
Freistaat SACHSEN
CZECH GEOLOGICAL SURVEY
GeoZS Geološki zavod Slovenije
AGH University of Science and Technology
geoENERGIE Konzept
GiGa infosystems
Bundesverband Geothermie
City of Ljubljana

GENERAL INFORMATION			
operator	**Geologische Bundesanstalt**	**geoENERGIE Konzept GmbH**	**PGI-NRI**
country	**Austria**	**Germany**	**Poland**
manufacturer	UIT Dresden	Wärmepumpen & Elektrotechnik Frank Reimelt	UBeG GmbH & Co. KG
year of manufacture	2009	2008	2015
mobility of the device	Built on pallet, fixed on trailer, detachable	mobile box	transportable box (mounted on caterpillar)
size of the device	1.5 m x 0.5 m x 1.5 m	0.85 m x 0.75 m x 0.65 m	1.0 m x 0.8 m x 0.6 m
size of casing (L x W x H)	2 m x 1.5 m x 2.5 m	dto.	dto.
device lockable	yes	yes	yes
possible BHE types	1xU, 2xU, Concentric	1xU, 2xU, Concentric	1xU, 2xU, Concentric

TECHNICAL INFORMATION			
specifications heater / cooler			
heat injection	yes	yes	yes
heat extraction	no (prepared to connect a heat pump)	no	no
type of heater / cooler	Schniewindt, CSN flow heater 97-AS	?	Conti-Electron, screw-in heater CEL 631-636
power connection	3-phase, 400 V, 50 Hz	3-phase, 400 V, 50 Hz	
maximum power	10 kW	12 kW	9 kW
regulation of heater	currently with electronic contactor, infinity variable but pulsed in part load (modification planned to fixed heat steps)	3 heat steps; first step variable	step less with PLC
specifications circulation pump			
type of circulating pump	centrifugal pump Stübbe Typ SHB 20-100	glandless circulation pump Wilo TOP-S 25/7,5	Wilo Stratos 25/1-8
power	550 W	90 / 125 / 195 W	9 - 125 W
total dynamic head	15 m	7.5 m	8 m
maximum flow rate	5 m^3/h	8 m^3/h	~ 8m^3/h (theoretic) / ~ 2m^3/h (reality)

regulation of pump	frequency controlled, feedback loop with flow sensor	Speed-stage switching (3 steps)	yes
specifications temperature sensor			
type temperature sensor	E&H Easytemp TMR-31, PT 100, class A	PT1000, class B	Pt500 – EN 60 751
signal transmission	4-20 mA	2 conductors	4-20 mA
number of sensors	7	3	2
response time	< 1 s	2 s	2 s
total deviation of electronics and sensor (from datasheet)	0.25 K + 0.002 x |T|	± 0.5 K	$E_c \pm (0.5 + \Delta\,\theta_{\min}/\Delta\,\theta)\%$
paired temperature sensors	yes	-	yes
last calibration date of sensors / maximum relative deviation between sensors	06.08.2013 / 0.02 K		23.01.2015 / 0.021 K
temperature range		-50 … 150 °C	0 … 180 °C
position of sensors	directly at BHE, in- and outlet before and after heater	in- and outlet before and after heater	before and after heater
specifications flow meter			
type of flowmeter	Siemens Sitrans F M MAG 5000 + MAGFLOW 5100 W	Sika, VTH 25 MS -180	Kamstrup Ultraflow 54
type of sensor	magnetic flow meter (MAG)	turbine flow sensor with Hall-effect detection	ultrasound sensor
signal transmission	4-20 mA & digital output	pulse output	
accuracy (from data sheet)	0.4 % ±1 mm/s	± 5 %	
last calibration date / maximum deviation to reference	24.09.2010 / 0.13 %		
flow regulation of double u-tubes	mechanical flow meters	mechanical valves	mechanical valves

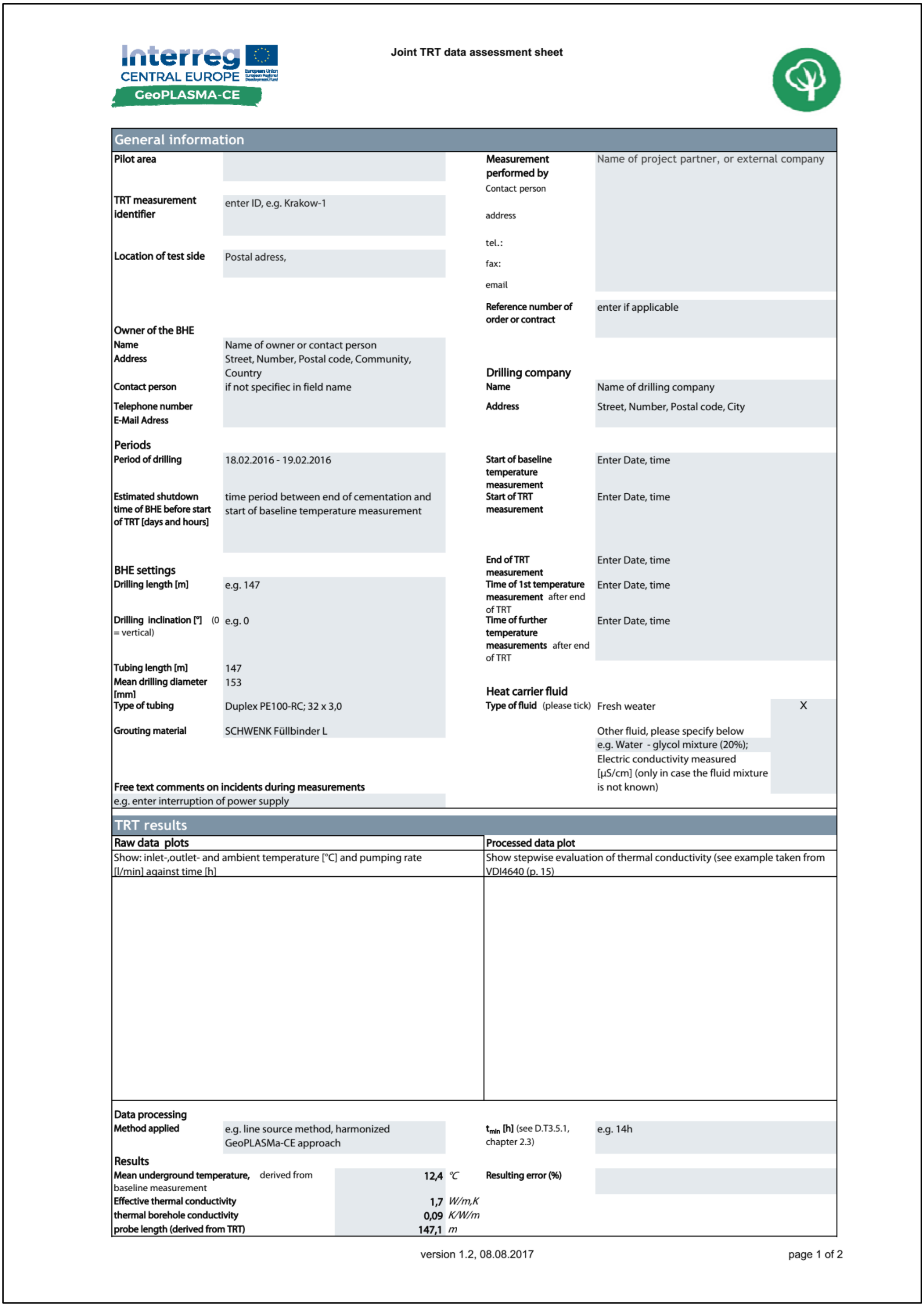
specifications control system			
type of control system	Siemens SPS - Simatic S7	no central control unit	Schneider SR2B121B
uninterupted power supply - UPS	only for control circuit	no UPS	no
datalogger			
type of datalogger	UIT LogTrans16-GPRS	Greisinger EASYlog 40 KH Greisinger EASYlog 40IMP-T	Kamstrup Multical 801
central / decentral datalogger	1 common datalogger for all sensors	3 datalogger for temperature 1 datalogger for flow meter	1 datalogger for all sensors
resolution	16 bit	-	-
minimum sampling interval	10 s	2 s	
max. value storage	2048 MB / 2,000,000 records	48'000 records	
additional information			
general power connection	electricity, 3-phase, 16 A	electricity, 3-phase, 16 A	electricity, 3-phase, 16 A
hydraulic extension tank	50 liter	-	yes
remote data transmission	GPRS to HTTP/FTP server	no, but alert via SMS	
remote control	no	no	no
measurement devices for temperature profile	Geowatt NIMO-T HT temperature cable lot (max. 200 m)	vanESSEN Mirco Diver	

principle layout		Not available	 Schema of the switch unit  🟥 heating element and outflow from GeRT (into U-tube) 🟦 inflow to GeRT (from U-tube) Schema of the hydraulic part of the GeRT-device

D.T3.5.1 JOINT REPORT ON CHOSEN APPROACHES AND METHODS FOR CALIBRATION

Annex B: Joint TRT data assessment sheet

Version 1
08 2017



Joint TRT data assessment sheet

General information

Pilot area	
TRT measurement identifier	enter ID, e.g. Krakow-1
Location of test side	Postal adress,

Owner of the BHE

Name	Name of owner or contact person
Address	Street, Number, Postal code, Community, Country
Contact person	if not specifiec in field name
Telephone number	
E-Mail Adress	

Measurement performed by	Name of project partner, or external company
Contact person	
address	
tel.:	
fax:	
email	
Reference number of order or contract	enter if applicable

Drilling company

Name	Name of drilling company
Address	Street, Number, Postal code, City

Periods

Period of drilling	18.02.2016 - 19.02.2016
Estimated shutdown time of BHE before start of TRT [days and hours]	time period between end of cementation and start of baseline temperature measurement
Start of baseline temperature measurement	Enter Date, time
Start of TRT measurement	Enter Date, time
End of TRT measurement	Enter Date, time
Time of 1st temperature measurement after end of TRT	Enter Date, time
Time of further temperature measurements after end of TRT	Enter Date, time

BHE settings

Drilling length [m]	e.g. 147
Drilling inclination [°] (0 = vertical)	e.g. 0
Tubing length [m]	147
Mean drilling diameter [mm]	153
Type of tubing	Duplex PE100-RC; 32 x 3,0
Grouting material	SCHWENK Füllbinder L

Heat carrier fluid

Type of fluid (please tick)	Fresh weater	X
	Other fluid, please specify below e.g. Water - glycol mixture (20%); Electric conductivity measured [µS/cm] (only in case the fluid mixture is not known)	

Free text comments on incidents during measurements

e.g. enter interruption of power supply

TRT results

Raw data plots	**Processed data plot**
Show: inlet-,outlet- and ambient temperature [°C] and pumping rate [l/min] against time [h]	Show stepwise evaluation of thermal conductivity (see example taken from VDI4640 (p. 15)

Data processing

Method applied	e.g. line source method, harmonized GeoPLASMa-CE approach
t_{min} [h] (see D.T3.5.1, chapter 2.3)	e.g. 14h

Results

Mean underground temperature, derived from baseline measurement	12,4	*°C*
Effective thermal conductivity	1,7	*W/m,K*
thermal borehole conductivity	0,09	*K/W/m*
probe length (derived from TRT)	147,1	*m*
Resulting error (%)		

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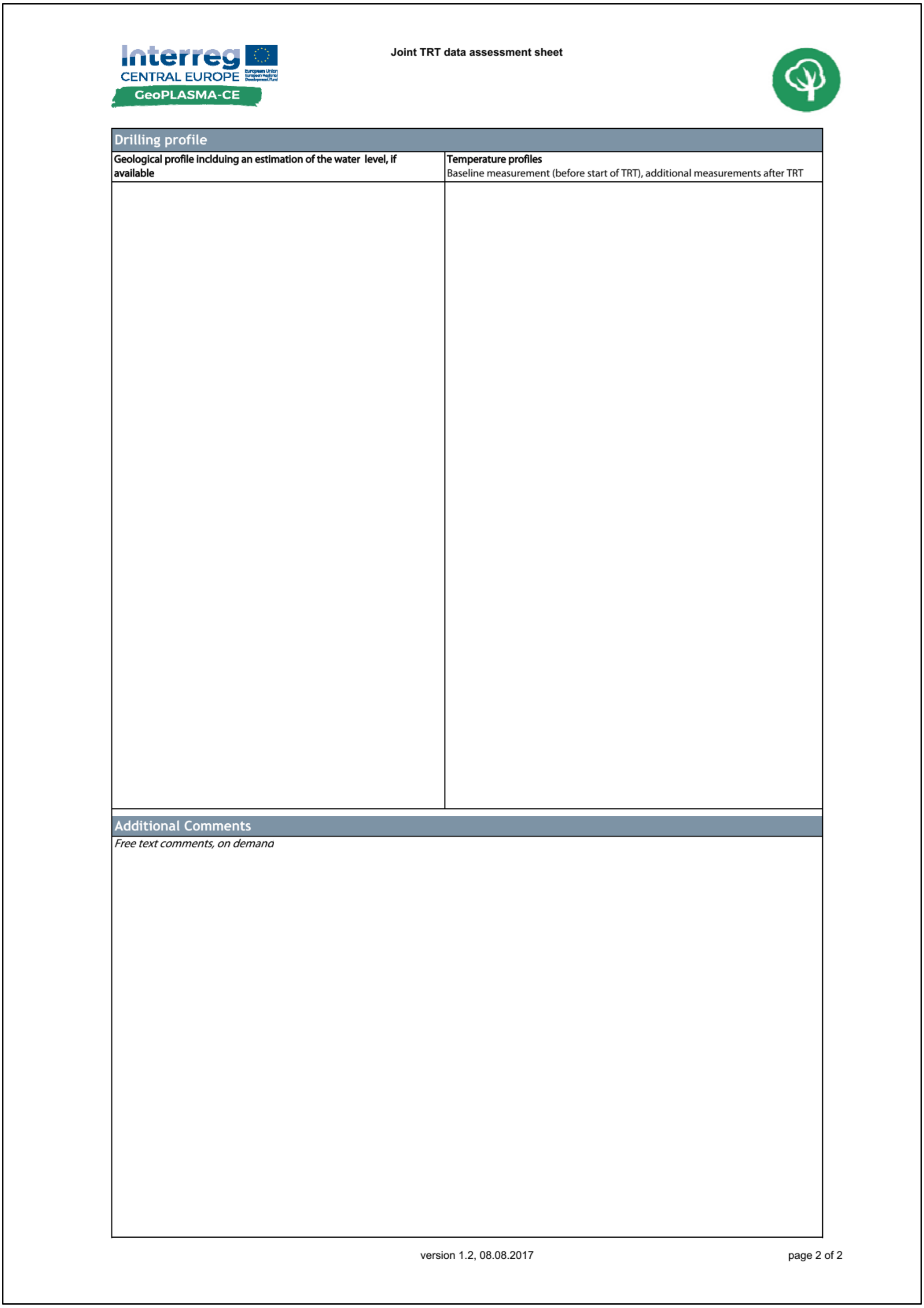

Joint TRT data assessment sheet

Drilling profile

Geological profile inclduing an estimation of the water level, if available	**Temperature profiles** Baseline measurement (before start of TRT), additional measurements after TRT

Additional Comments

Free text comments, on demand

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Interreg
CENTRAL EUROPE
GeoPLASMA-CE
European Union
European Regional
Development Fund

D.T3.5.1 JOINT REPORT ON CHOSEN APPROACHES AND METHODS FOR CALIBRATION

Annex C: Fact sheet on TRT measurement in external borehole heat exchangers in GeoPLASMA-CE

Version 1
08 2017

About TRT measurements in GeoPLASMA-CE

The EU Interreg project GeoPLASMA-CE addresses the use of shallow geothermal energy in the Central Europe countries Germany, Poland, Czech Republic, Slovakia, Austria and Slovenia. We aim at fostering the use of shallow geothermal methods by providing guidelines and potential maps to stakeholders in six selected pilot areas.

Thermal Response Test (TRT) measurements deliver values of the effective thermal conductivity averaged for the drilled section of a borehole heat exchanger (BHE). The "effective thermal conductivity" also accounts for the possible influence of heat transport by groundwater flow and therefore reflects the real life potential of a BHE based shallow geothermal use (also called: closed loop systems).

The results of TRT measurements are crucial to validate potential maps for shallow geothermal use based on borehole heat exchangers. For that reason, we are planning to perform TRT measurements in most of our six pilot areas!

We offer a limited number of free of cost TRT measurements in small-scale BHE utilizations to get access to in-situ measurements of the effective thermal conductivity.

In turn, you may benefit from knowing the performance and quality (borehole resistance) of the BHE constructed for your heating and cooling purpose. The TRT measurement itself will only last between 3 and 5 days – of course, you will get access to all results we achieved at your site.

In order to avoid a negative influencing on the existing market, we define certain requirements for performing free TRT measurements as listed below.

Requirements for performing free TRT measurements

- Small scale private use of the BHE, maximum capacity < 10kW (sum of all boreholes) and non-commercial use
- The BHE has not been in use yet
- Car / trailer access to the BHE
- Electricity and water supply available (costs for electricity have to be carried by the owner of the BHE).
- Acceptance to use the results of the TRT measurements for the purpose of the project GeoPLASMA-CE.
- The project team reserves all rights to perform TRT measurement. No rights or obligations can be derived from this offer
- The BHE site must be within one of our six pilot areas

How to apply for a free TRT measurement

If you are interested please contact info@geoplasma-ce.eu or visit our website www.geoplasma-ce.eu for further information on the project partner responsible for the pilot area your BHE is located in.