



Interactive analysis of thermal response tests

USER MANUAL

3.0 VERSION

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www.trtanalysis.com

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Foreword — What to do with an interrupted test?

A thermal response test is the only in-situ measurement that ties the design of a borehole field to the ground it will be drilled into. The ground thermal conductivity and the borehole resistance it yields set the required borehole length, the undisturbed ground temperature it also measures sets the boundary condition that length is sized against, and together they set a large share of the capital cost of a ground-source heat pump installation. Yet the test is a field operation rather than a laboratory one: it runs for several days on a construction site, usually unattended, with a generator, a heater and a pump all expected to hold a steady output from start to finish. The conventional interpretation asks for exactly that constancy, and field conditions do not always provide it. A generator trips, the grid fails, the heat injection stops for a few hours, and the record no longer meets the assumptions the straight-line methods rest on. Such a test is then either repeated at full cost, or interpreted as though nothing had happened, with a bias nobody has quantified.

This software is rooted in my own experience. Before moving to academia, I worked as a consultant in the geothermal industry, where I designed, performed and interpreted dozens of thermal response tests myself, and lost a few of them to an interruption. I know what it costs to tell a client that a TRT will have to be restarted because no recognized method can exploit an interrupted one, and I know the temptation to fit a line through it anyway. TRT Analysis began there: a desktop application for the interpretation of the thermal response tests carried out ahead of any large ground-source heat pump project, and in particular of the records that a field incident occasionally leaves behind.

To read those records as well as the well-behaved ones, I paired two complementary analysis methods. The first-order approximation provides the standards-aligned, slope-and-intercept reading of the heating phase, and of the recovery phase when the test carries one, that practitioners know and trust, while clearly marking the point in time before which the line-source assumption does not yet hold. It keeps the conventional assumptions in exchange: a constant heating power over the window being fitted, and no injection at all once the recovery has started. The short-term g-function goes further. A pre-trained neural network reconstructs the borehole's early-time response, reproducing a detailed transient model, and that response is convolved with the power actually measured, so the interpretation uses the entire test, including the early hours and the recovery, and extends naturally to the pulsed and interrupted tests where the simple model breaks down.

TRT Analysis is developed and distributed by P³ Geothermal, a spin-off company originating from Polytechnique Montréal. Over the years, many graduate students and colleagues have contributed to scientific publications on the models the software rests on: the p-linear averaging of the fluid temperature, fast spectral convolution, and the neural-network approach to transient borehole response. These research contributions have been extensively incorporated into the software (see the [References](#) section). Whenever applicable, a portion of the revenues generated by TRT Analysis is shared with students whose research has contributed to its development. This model reflects my commitment to ensuring that academic contributions are recognized and rewarded beyond the publication of scientific work.

My hope is that TRT Analysis helps the specialists who perform these tests extract everything their data has to offer, and, just as importantly, recognize when a test does not support a confident answer.

Professor Philippe Pasquier, eng., Ph.D.
Lead Programmer, P³ Geothermal



How to cite

If TRT Analysis supported your work, please cite it. Acknowledging this work sustains its continued development and the open sharing of the research behind it.

Citing the software and the manual

Pasquier, P. (2023). *TRT Analysis – Interactive analysis of interrupted and pulsated thermal response tests*. P³ Geothermal inc. <https://doi.org/10.5281/zenodo.15660684>

That DOI is the **concept DOI** — the one Zenodo offers under *Cite all versions*. It always resolves to the latest deposited version, so the citation above never needs revising at a release, and every citation accumulates on a single identifier.

Citing the underlying methods

The interpretation methods implemented in TRT Analysis are documented in peer-reviewed publications. When a specific method is central to your own work (the line-source slope-and-intercept analysis, the recovery-phase interpretation, the p-linear fluid-temperature average, or the neural-network model of the short-term borehole response), please also cite the corresponding paper listed in the [References](#) section at the end of this manual.



Feature overview

TRT Analysis version 3.0 interprets a thermal response test from the raw field record to the undisturbed ground temperature, the ground thermal conductivity and the effective borehole resistance. Every step is interactive and reversible: which data to use, where the heating phase begins and which averaging method applies can all be revised after the fact, and the estimated properties follow each change. Two complementary methods are carried. The first-order approximation fits a line source to the heating phase, and to the recovery phase when the test carries one, and applies to any borehole configuration. The short-term g-function is reconstructed by a pre-trained neural network and convolved with the heat-injection history actually measured, so it also interprets the pulsed and interrupted tests that the line-source assumptions cannot accommodate; it is for now limited to a single U-loop borehole. The table below summarises the principal features available in this release.

 TRT Analysis FEATURE OVERVIEW	
DATA IMPORT & PROCESSING	
CSV import of the TRT time series (Q , V , T_{in} , T_{out})	✓
Paste from a spreadsheet, and copy the loaded table back out	✓
Optional vertical undisturbed-temperature profile	✓
Low-pass filter for measurement noise	✓
Interactive phase selection — circulation, heating, recovery	✓
UNDISTURBED GROUND TEMPERATURE	
Determination methods — manual, circulation phase, vertical profile	3
Mean annual ground temperature T_a from a logged profile	✓
FIRST-ORDER APPROXIMATION (FOA)	
Heating-phase infinite line-source regression	✓
Recovery-phase regression	✓
Ground conductivity λ_s and effective resistance R_b^*	✓
Critical time t_{cr} drawn on the regression charts	✓

p-linear average of the mean fluid temperature	✓
Borehole configurations supported (<i>single & double U-loop, coaxial, standing column</i>)	All 5
SHORT-TERM G-FUNCTION (ANN)	
Pre-trained on 3D transient finite-element data (<i>within 1×10^{-4} °C</i>)	✓
Standard, pulsed and interrupted TRT	✓
Heating and recovery phases interpreted together	✓
Measured heat-injection history by temporal superposition	✓
Interactive calibration with live RMSE feedback	✓
Borehole configurations supported (<i>Single U-Loop only</i>)	1
Maximum test duration (<i>short-term g-function</i>)	21 days
Ground conductivity learned by the network (<i>W/m·K</i>)	0.25 – 8
Grout conductivity learned by the network (<i>W/m·K</i>)	0.25 – 5
Borehole length learned by the network (<i>m</i>)	50 – 250
DIAGNOSTICS	
Reynolds number and flow-regime flag, per phase	✓
Histograms of heating power, flow rate and model residuals	✓
Residual mean, standard deviation and RMSE	✓
Values read off any curve or histogram bar on hover	✓
Scaled borehole cross-section schematic	✓
RESULTS & EXPORT	
Guided analysis-tree workflow	✓
Automatic CSV export — FOA and short-term g-function results	✓
Self-contained project file, shared with the other modules	.ghe
VERIFICATION	
Verification scenarios runnable inside the application	43
Checked against analytical solutions (<i>Ingersoll line source, Horner recovery plot</i>)	✓
Bundled sample test reproduced value for value at every release (<i>non-regression</i>)	✓

ANALYSIS SUITE	
Modules in one application (<i>TRT interpretation, GHE design, GLN hydraulics</i>)	3
Parameters carried from one module to the next (<i>TRT → GHE → GLN, choosing which technique's value travels</i>)	✓
DOCUMENTATION	
Illustrated user manual written for this module (<i>11 figures</i>)	16 000 words
Read inside the application, as a PDF, and online (<i>no registration</i>)	✓
Context help on every panel, opened from the panel itself	✓
Quick-start walkthrough of a complete analysis	✓
Linked reference section — every method traced to its publication	✓
SPECIFICATIONS	
Operating system	Windows 10+, macOS 26+
gheanalysis.com	



Quick start

One application, three modules - TRT Analysis is one of the three modules of the **Analysis Suite**, which are installed together and share a single window. The three buttons at the left of the toolbar switch between them, and the button that is lit tells you which module is active:

-  **TRT** — interpretation of a thermal response test, the subject of this manual.
-  **GHE** — design and simulation of a ground heat exchanger field.
-  **GLN** — design of the hydraulic network that connects it.

Switching module rebuilds the analysis tree, the panels and the console; the window shown in the figure below is the TRT one. Each module is licensed separately, and the licence that applies is that of the active module. The project sheet is shared by the three modules, so a project keeps one identity. Panels shared between modules, such as the heat carrier fluid or the test borehole, change meaning with the module and have their own help page.

The three modules also follow one another: the ground thermal conductivity and the borehole thermal resistance interpreted here are used by GHE to design a field, which GLN then balances hydraulically. Each module can also be used on its own.

Activating a professional licence - TRT Analysis runs in demonstration mode until a valid licence is loaded. In that mode the bundled sample test is loaded at start-up, so a complete interpretation can be followed from end to end, but the data controls are locked: the import, copy and paste buttons, the sampling period, the filter length and the raw-data table are disabled, and projects cannot be saved or opened. Everything downstream stays live, so the phase boundaries, the regression windows and the model sliders can be moved freely on the sample. To activate the professional version, open **License Agreement**  from the main menu and accept the end-user licence agreement. This opens the Licenses panel, a table listing every module of the Analysis Suite with its current status — Licensed, Demo, or Expired — and, once licensed, its expiry date. Click **Open .lic file...** and select the licence file received after purchase: a licence activates the module it was issued for, and a Suite licence activates every module. Licences are available at gheanalysis.com. The licence is validated online each time the software starts; a short offline grace period keeps a previously activated licence working if no connection is available, after which the module falls back to demonstration mode.

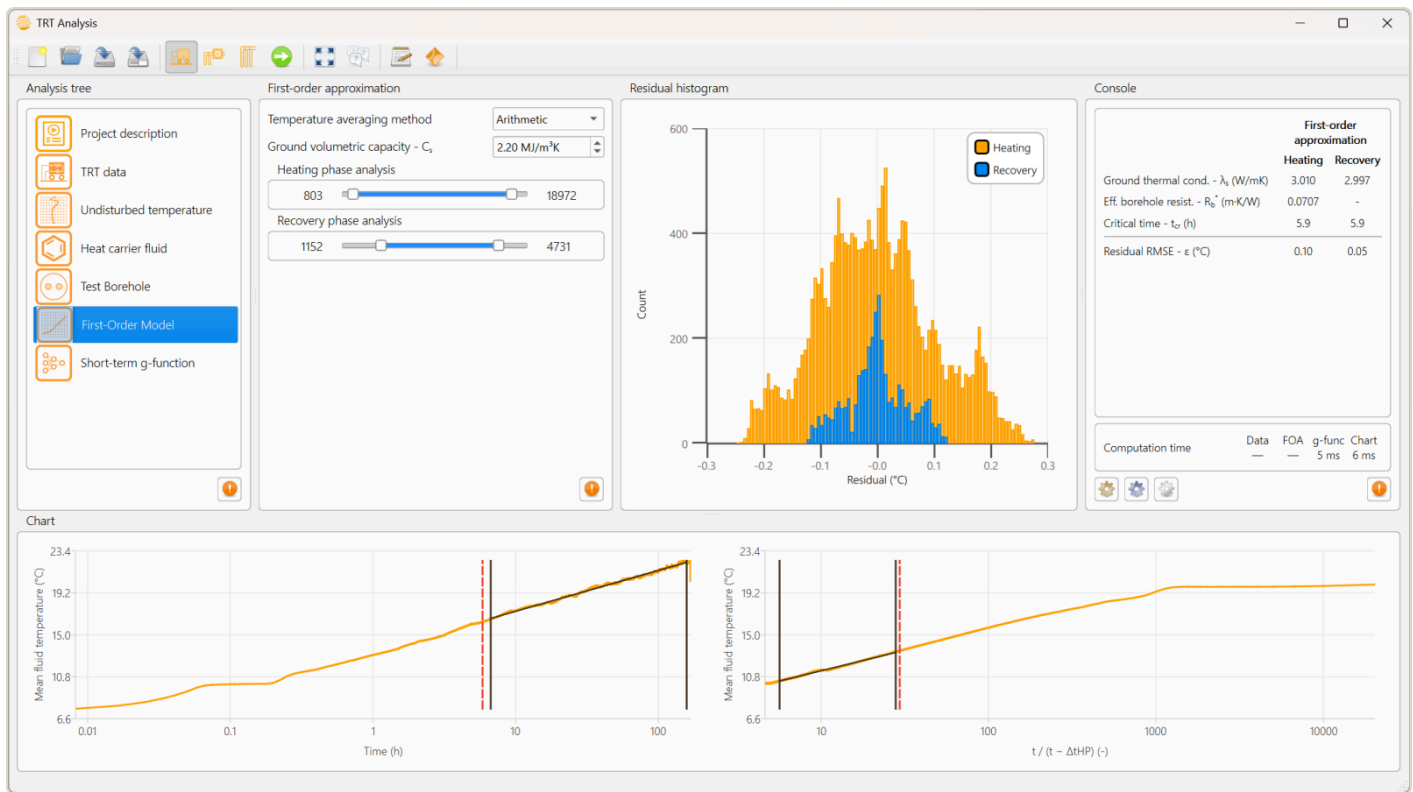


Figure 1 — The Analysis Suite window with the TRT module active — the three module buttons at the left of the toolbar, the analysis tree below them, the active input panel and its chart in the centre, and the results console on the right

A first interpretation - The workflow follows the analysis tree from top to bottom. Each node shows the inputs and charts for that stage; you can move between them in any order, and every change updates the results immediately.

1. **Project description** — enter the client, project and test details.
2. **Thermal response test data** — import the 4-column .csv file, set the sampling period and low-pass filter, then select the test phases with the dual-range slider.
3. **Undisturbed temperature** — determine T_g (manual input, circulation phase or vertical profile). Loading a dataset selects the circulation phase for you, since that method reads T_g from the measurements themselves.
4. **Test borehole** — describe the instrumented borehole (H , borehole and pipe diameters, λ_p , λ_g) and review the resistance breakdown (R_f , R_p , R_g) computed at the operating point of the test.
5. **Heat carrier fluid** — select the fluid and antifreeze concentration used during the test, then read the Reynolds number of each phase to confirm the flow stayed turbulent.
6. **First-order approximation** — fit the heating-phase regression, and the recovery-phase regression when the test carries one, to obtain λ_s and R_b^* .
7. **Short-term g-function** — refine the estimate by adjusting the calibration sliders and minimizing the RMSE.

At any step, the help button  gives guidance on the current panel, and the same content forms the chapters of this manual.

The three pages of the console, on the right, report the phase statistics and the undisturbed temperatures, then the regression results, then the calibrated short-term g-function parameters; selecting a node brings up its page (see

Console). Saving the project also writes the two result files alongside it.

Panel layout and interaction - The module reuses the resizable split layout of the suite. Drag the dividers between panes to give more room to whichever element you are reviewing, typically the charts while a phase boundary is being placed, or the raw-data table while the record is being checked.[–] As elsewhere in the suite, numerical fields respond to the mouse wheel and to the ↑ / ↓ keys as well as to typing.

Three interactions are specific to this module. The dual-range sliders can be moved one sample at a time from the keyboard: click the slider, then press **Q** or **E** to move the start of its window and **A** or **D** to move its end; on the *Thermal response test data* panel, clicking anywhere on the panel is enough. The charts can be zoomed by dragging a selection rectangle with the mouse, or with the mouse wheel about the cursor, to inspect a boundary closely; the **Restore View** button of the main toolbar returns every TRT chart to its full extent at once. Zooming changes the view only, never the data a regression uses. And hovering any curve or histogram bar shows a tooltip with the value under the cursor, named and with its unit; the **Toggle tooltips on or off** button of the main toolbar turns them off.



Saving, loading and exporting

An interpretation is saved with the project rather than on its own. A single `.ghe` file carries the measured data, every phase boundary, every slider position and both sets of results, together with the work of the other modules on the same project. Reopening it restores the analysis exactly as it was left.

Creating a new project - Select  to start a fresh interpretation. All inputs revert to their defaults and any loaded test data is cleared. Because the project is common to the suite, New clears the three modules and not the TRT panels alone. If it has unsaved changes you are asked to save first, and cancelling leaves everything as it was.

Saving a project - Select  to write the project to its current location, or Save As  to choose a new name or folder. The file dialog filters for Analysis Suite project (***.ghe**). Save writes the whole project whichever module is active, so an interpretation is saved from the TRT panels and from those of the other modules alike. If no file has been assigned yet, Save behaves like Save As. The last folder used is remembered across sessions.

Opening a project - Select Open  to browse for a `.ghe` project. Every input, every phase boundary and both sets of results come back as they were saved, and the charts and the console are refreshed with them. Projects written by earlier releases still open, including the `.trt` files of TRT Analysis 1.x; saving one writes it back in the current format. Opening a project activates the **GHE** module, even a project carrying nothing but a test: switch back to TRT with the module button of the toolbar to see the interpretation.

The .ghe project file - The `.ghe` extension is associated with the Analysis Suite application icon  on Windows, so double-clicking a project file in Explorer opens it directly. A `.ghe` file is a compact binary archive (CBOR-encoded JSON) carrying the full project state.

It is also self-contained: the measured data is embedded in it, so the original `.csv` files are not needed to reopen, review or revise the interpretation, and the project can be sent to a colleague or archived on its own. Because the three modules share the file, a project opened and saved from one of them keeps what the others hold.

Exporting - As elsewhere in the Analysis Suite, the results can be taken out as CSV. In this module the export is automatic: two files are written alongside the project every time it is saved, one per interpretation method. Both follow the conventions shared by every CSV of the suite: columns separated by semicolons, a point as decimal separator, SI units, UTF-8 encoding that Excel reads correctly, and a header of lines starting with # giving the project, the software version and the date of the save. Both are overwritten at each save. Nothing is written when no test data is loaded, since there would be no result to report, and the files left by a previous save are then deleted. A save also writes the result files of the other modules, named on the same project, so expect more than these two in the folder.

FILE	CONTENT
<code>{project}_TRT_FOA.csv</code>	First-order approximation results, as displayed on the console's FOA page, reported separately for the heating and the recovery phase.

FILE	CONTENT
<code>{project}_TRT_ShortTerm.csv</code>	Short-term g-function results — the calibrated parameters as left by the sliders, and the quality of the fit they produce. When the short-term model has not been calibrated, these parameters are left empty.

Each file opens with a short header explaining every quantity it carries, then the results themselves, then the **interpretation context**: the settings and the geometry the numbers were produced with. That last block makes a result reproducible: neither λ_s nor R_b^* can be recomputed without the regression window and the inputs used.

First-order approximation results - The file carries one row per quantity and two value columns, one for the heating phase and one for the recovery phase, with the unit in the last column.

QUANTITY	UNIT	DESCRIPTION
RESULTS		
lambda_s	W/m·K	Ground thermal conductivity, from the regression slope
Rb*	m·K/W	Effective borehole resistance, from the heating-phase intercept. The recovery column is empty: that regression carries no borehole-resistance term
q	W/m	Mean heat injection rate per unit borehole length used by the phase
tcr	h	Critical time $5r_b^2/\alpha_s$, before which the line source does not apply
Residual mean	°C	Average of the regression residuals over the fitted window.
Residual sd	°C	Sample standard deviation of the residuals
RMSE	°C	Root mean square of the residuals
INTERPRETATION CONTEXT		
Averaging method	—	Arithmetic mean or p-linear average of the inlet and outlet temperatures
Cs	MJ/m ³ ·K	Ground volumetric heat capacity, which sets t_{cr}
Tg	°C	Undisturbed ground temperature used by the regression
H, rb	m	Active length and radius of the test borehole
Sampling period dt	s	Time between two measurements

QUANTITY	UNIT	DESCRIPTION
Injection duration	h	Length of the heating phase, which the recovery regression relaxes from
Regression windows	sample	First and last sample fitted, for each phase, one row per bound

Short-term g-function results - The file carries one row per quantity and a single value column, holding the position of each slider at the moment of the save.

QUANTITY	UNIT	DESCRIPTION
CALIBRATED PARAMETERS		
lambda_s, Cs	W/m·K, MJ/m ³ ·K	Ground thermal conductivity and volumetric heat capacity
lambda_g, Cg	W/m·K, MJ/m ³ ·K	Grout thermal conductivity and volumetric heat capacity
alpha_s, alpha_g	m ² /s	Thermal diffusivities λ/C the two pairs above imply
s	m	Shank spacing, centre to centre between the two pipes
Tg	°C	Undisturbed ground temperature fed to the short-term g-function
QUALITY OF THE FIT		
Residual mean	°C	Mean of the residuals over the whole test. It is not forced to zero here, so a non-zero value indicates a bias
Residual sd	°C	Sample standard deviation of those residuals
RMSE	°C	Root mean square of those residuals, the figure to minimise while calibrating
INTERPRETATION CONTEXT		
Excitation function	—	How the temperature difference across the borehole was obtained
Cf	MJ/m ³ ·K	Fluid volumetric heat capacity
Mean flow rate	L/min	Averaged over the injection phase, the value handed to the short-term g-function

QUANTITY	UNIT	DESCRIPTION
H, rb, ri, ro	m	Borehole and pipe geometry read by the short-term g-function
kp	W/m·K	Pipe thermal conductivity

An empty cell in place of a value means the corresponding result did not converge, or does not apply. If a file cannot be written — most often because it is still open in a spreadsheet — the console reports it and the `.ghe` project itself is left untouched.



Project description

The Project description panel is the starting point of any TRT Analysis project. It records the administrative context of the test: project identity, site location and client, and provides a general-notes field for the field observations that make an interpretation defensible later. Although none of this information affects the analysis, it travels with the project file, so the numbers you estimate stay attached to the test that produced them.

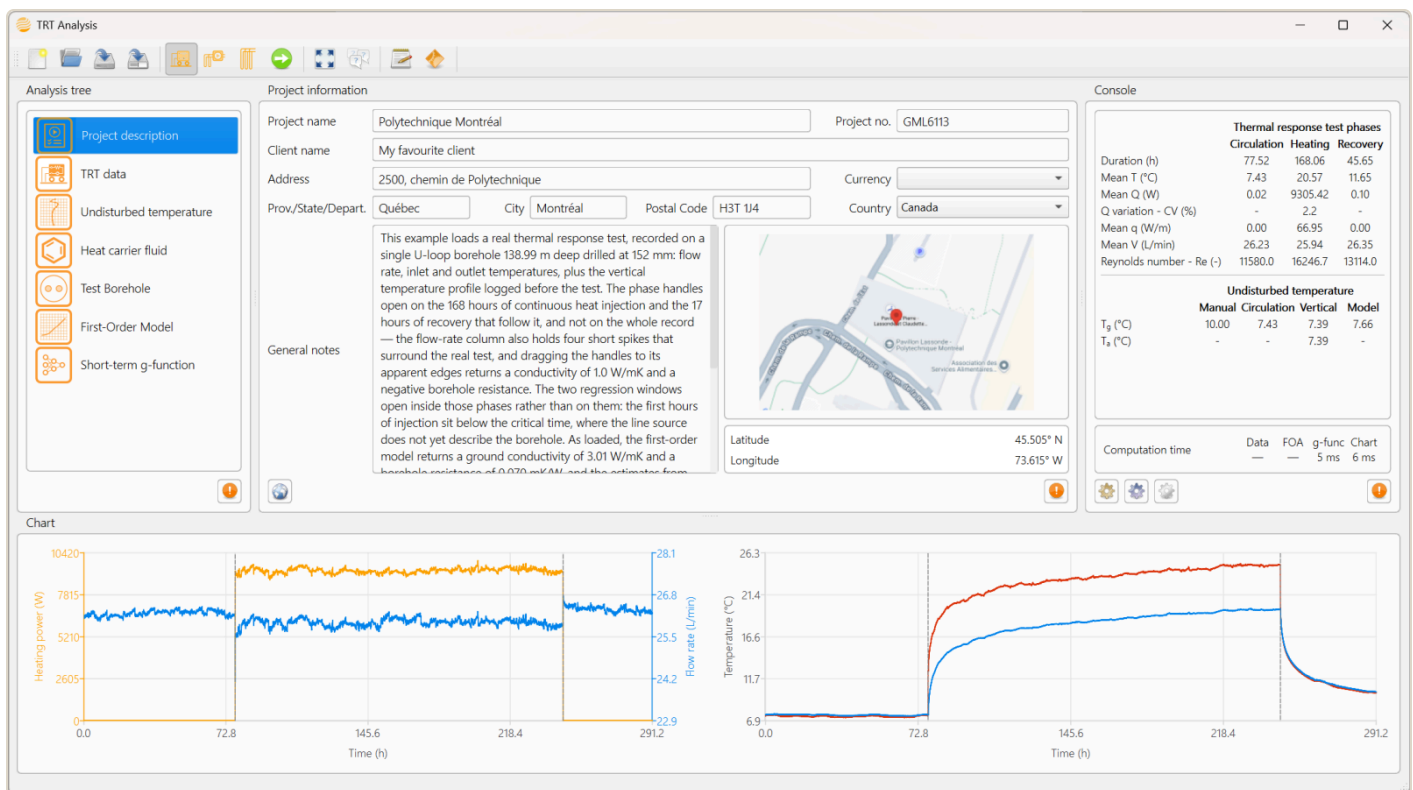


Figure 2 — Project description panel — project number, name and client, project type, site address with the location map, currency, and the general-notes field

Project information - Enter the project number, project name and client name for your records.

This panel is the same in every module of the Analysis Suite, since a project keeps one identity whichever module is working on it. One of its fields, the **currency**, is used only by the  design module for its cost reporting and has no effect on a TRT result.

Site location and map - Provide the site address, city, postal code, province/state and country, then press the Validate address button . It sends the address to an online mapping service, which returns the site latitude and longitude and displays a location map. An active internet connection is required. If the address cannot be resolved, refine it and validate again; a complete street address gives the best result. The coordinates are stored with the project for documentation.

General notes - Use the General notes field for anything that may influence the interpretation of the test. The thermal conductivity and borehole resistance you are about to estimate will be used long after the test rig has left the site, often by a different engineer sizing the borehole field, and the notes recorded here are what make the result defensible later. This text travels with the project and is the place to record the reasoning behind your interpretation choices.[–]



TRT in practice: documenting the conditions a result depends on

What to record. Document the drilling method, the borehole completion (grout type, pipe configuration, shank spacing), the test equipment and its nominal heating power, the ambient conditions during the test, the lithological log, and the date the borehole was completed. These are the observations a later reviewer will look for when deciding how far to trust the reported λ_s and R_b^* .

Thermal contamination from drilling. Heat is released by the rig (compressor, friction) and by the installation itself (grout placement, heat of hydration), thermally contaminating the borehole and the ground around it. A period of at least one week should elapse between completion of the GHE installation and the start of the TRT; record the completion date so the interval can be checked.

Groundwater. Note any evidence of groundwater flow, a productive aquifer, a fractured zone or artesian conditions, because advective heat transport violates the conduction-only assumption shared by both models (see *Analysis with first-order approximations* and *Analysis with the short-term g-function*) and tends to inflate the apparent conductivity. A test that looks unusually conductive over a flowing zone should be interpreted with caution.



Thermal response test data

This step loads the measured thermal response test data and lets you isolate the phases of the test (circulation, heating and recovery) used by the analysis models.

To load a TRT data file, use the import button . The file must be a comma-separated values (.csv) file with **4 columns** and with a full point as the decimal separator. The measurements can also be pasted straight from a spreadsheet with the paste button  or Ctrl+V, in the same 4-column layout, and the loaded table can be copied back out with the copy button  or Ctrl+C. A malformed file, with a short row or a non-numeric cell, is refused; the message names the first offending line so it can be corrected at the source.

Heating power — Q (W) - The first column of the file must be the heating power Q in watts.

Circulation flow rate — V (L/min) - The second column must be the flow rate V in liters per minute. The flow rate is only required for the Reynolds number calculation or for the short-term g-function. If the flow rate has not been measured and that model is not required, a dummy value can be used to populate the .csv file.

Fluid temperature — T (°C) - The last two columns are the temperatures, in degrees Celsius, measured in the fluid at the borehole inlet $T(z=0 - \downarrow)$ and outlet $T(z=0 - \uparrow)$, or at locations deemed appropriate to represent these measurement points. The notation names the point of measurement: **z = 0** is the ground surface, where both probes sit, and the arrow gives the direction of flow in the pipe, $\downarrow$ for the fluid running down into the borehole and $\uparrow$ for the fluid coming back up. $T(z=0 - \downarrow)$ is therefore the temperature entering the borehole and $T(z=0 - \uparrow)$ the temperature returning from it.

Sampling period — dt (s) - Provide the time interval between two measurements, in seconds. It is assumed that the TRT data was recorded at a regular interval and at the end of the sampling period; thus, no data point is drawn at $t = 0$. Field records are usually sampled every 15 to 300 s. dt can be corrected after an import: the time vector, the phase durations, the chart axes and the time base of both models are rebuilt over the same measurements, and the phase boundaries already set are kept.

Low-pass filter length — n (-) - To remove white noise, a low-pass filter of length n can be used to smooth the data. A length $n = 1$ corresponds to no smoothing. For $n > 1$, a moving average centered at $(n-1)/2+1$ is applied over a window of length n. The same filter is applied to each column of the TRT data file. Four lengths are offered: 1, 3, 7 and 15.

Phase selection - Once the data is loaded, use the dual-range slider to select the heating phase and, if applicable, distinguish between the circulation and recovery phases. To refine the selection to the exact sample, press **Q** ($\leftarrow$) or **E** ($\rightarrow$) to move the start of the heating phase and **A** ($\leftarrow$) or **D** ($\rightarrow$) to move its end. The keys work once this panel has the keyboard focus (click the slider, the table or anywhere on the panel), but not from the chart panel. Zooming the charts to inspect a boundary changes the view only, never the selection.

Everything before the lower handle is the circulation phase, everything between the handles the heating phase, and everything after the upper handle the recovery phase. A test with no circulation, or no recording after shut-off, leaves that phase empty, and the figures that depend on it are reported as a dash.

Heating power and flow rate - The heating power Q is plotted against the left axis and the circulation flow rate V against the right axis, each in the colour of its own axis title, over the whole duration of the record. This is the chart on which the quality of the test is judged: the heating power should form a flat plateau over the heating phase, and the flow rate should be steady. A drifting or stepped power trace means the constant-power assumption of the first-order approximation is not met, and the short-term g -function should be preferred. Vertical markers show the phase boundaries selected with the dual-range slider.

Inlet and outlet fluid temperature - Shown alongside the previous chart. The temperatures measured at the borehole inlet $T(z=0 - \downarrow)$ and outlet $T(z=0 - \uparrow)$ are drawn against time, with the same phase-boundary markers. The separation between the two curves is the temperature rise across the loop; a large separation, together with a low flow rate, is the visual signature of the near-laminar conditions that bias R_b^* high and λ_s low.

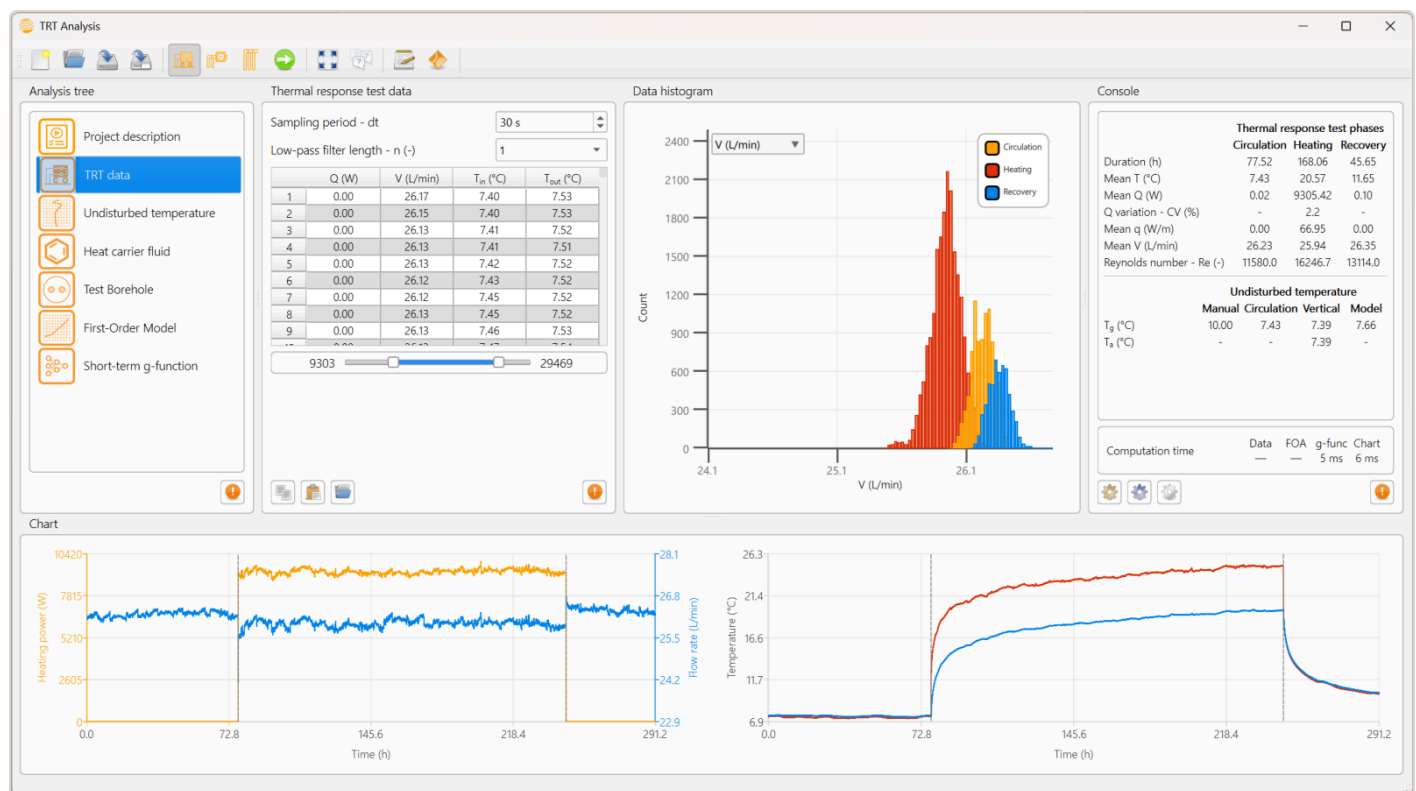


Figure 3 — Thermal response test data panel — the imported time series with the dual-range slider selecting the heating phase, the heating power and flow rate chart (left) and the inlet and outlet fluid temperature chart (right), each with the phase-boundary markers

[–]



Summary & charts: the histograms and the statistics reported in the console

Data histogram - The panel to the right of the table shows the distribution of the heating power Q , or of the flow rate V , over each of the three phases, chosen with the drop-down above it. Its vertical axis is a count of samples, and hovering a bar names the class and its count. The distribution shows whether the heat injection and the circulation held steady: a narrow, single-peaked heating-phase distribution supports the constant-power assumption on which the first-

order approximation rests, while a broad or multi-peaked one says the power drifted and the short-term g-function should be preferred.

Phase statistics - The numerical characterisation of each phase, duration, mean fluid temperature, mean heating power, the coefficient of variation of that power in percent, mean unit power, mean flow rate and Reynolds number, is reported on the first page of the console, which selecting this node brings up; the figures follow the handles as they move.



TRT in practice: what makes a dataset worth interpreting

A sound test, from the field. Everything the two models produce is conditioned by the record loaded here. A sound dataset comes from a test of sufficient duration, commonly 48 hours or more of heating, run at a stable, accurately metered power, with the flow held high enough to stay turbulent and the above-ground pipework insulated against day-to-night ambient swings. The fluid temperatures and the heat injection rate should be logged together, on the same clock, throughout circulation, heating and recovery. The conduct of the test itself is not covered by this manual; consult the IEA ECES Annex 21 final report for equipment, procedure and reporting practice.

The heating power itself. Check the heating power as carefully as the temperatures. The unit power $q = Q/H$ enters the regression slope in direct proportion, so a wattmeter reading three percent high gives a conductivity three percent off, and the residuals do not show it. The calibration of the test unit is therefore a subject of its own: Eslami Nejad et al. (2018) and Karrer et al. (2024) both describe rigs built to check a TRT unit against a known response before it goes to site. Where the test hole can be instrumented over its depth rather than at its head, a distributed measurement returns conductivity as a function of depth instead of a single average, whether by heat extraction (Rolando et al., 2017) or by optical fibre (Galgaro et al., 2018). Dalla Santa et al. (2022) carry the fibre approach further, recovering a high-resolution conductivity profile from repeated tests in a stratified ground where a single test average would have flattened fifteen distinct units into one figure. This module does not interpret either kind of measurement, but both are useful when a single figure for a layered ground looks too uniform.

The filter does not fix an unstable test. The low-pass filter removes measurement noise. Real swings in the heating power or the flow rate are part of the signal, and smoothing them only hides a problem the first-order approximation cannot handle. Keep the filter length n as small as the noise allows; if the power drifted substantially, do not filter it flat: turn instead to the short-term g-function, which is built to accept a varying heat-injection rate.

Phase boundaries. The first-order approximation requires an accurate identification of the beginning and end of the heating phase, since its regression is fitted over that window. Place those limits carefully, using the keys to move them one sample at a time: a boundary off by a few points shifts the slope and intercept from which λ_s and R_b^* are read. Beware in particular of short parasitic spikes in the Q column, before the test proper or after it: dragging a handle out to the apparent edge of the column can enclose them and drive the interpretation to an absurd conductivity and even a negative R_b^* .



Undisturbed temperature

Using the drop-down menu, three methods are provided to identify the undisturbed ground temperature T_g , and one of them also evaluates the mean annual ground temperature T_a (see *Vertical profile*). Whichever method is selected, the T_g it produces is the one handed to the first-order approximation and used as the starting position of the T_g slider of the short-term g-function.

T_g and T_a are two different temperatures - The panel reports both, and they are easily confused.

- **T_g , the undisturbed ground temperature**, is the temperature of the ground as it stands **immediately before the heat injection starts**, averaged **over the whole height of the borehole**. It is read at one moment, not over a year, and it describes the entire column the borehole exchanges heat with, not one depth. It is the initial condition both interpretation models assume, and everything the test measures afterwards is a departure from it.
- **T_a , the mean annual ground temperature**, is what the ground averages over a full year. It is obtained by keeping **only the part of the ground that seasonal variations no longer reach**, that is, by discarding the near-surface zone whose temperature swings with the calendar. It is T_a , not T_g , that should be carried into the sizing of a system: a borehole field is sized over years of operation, so the temperature it works against is the annual average of the ground, not the value the ground happened to hold on the day of the test.

In practice T_a comes from a vertical profile, and the work consists in identifying the section of that profile which the seasonal signal no longer disturbs. This is why T_a appears only when a profile has been read, and why the two methods that work from the test data alone cannot produce it.

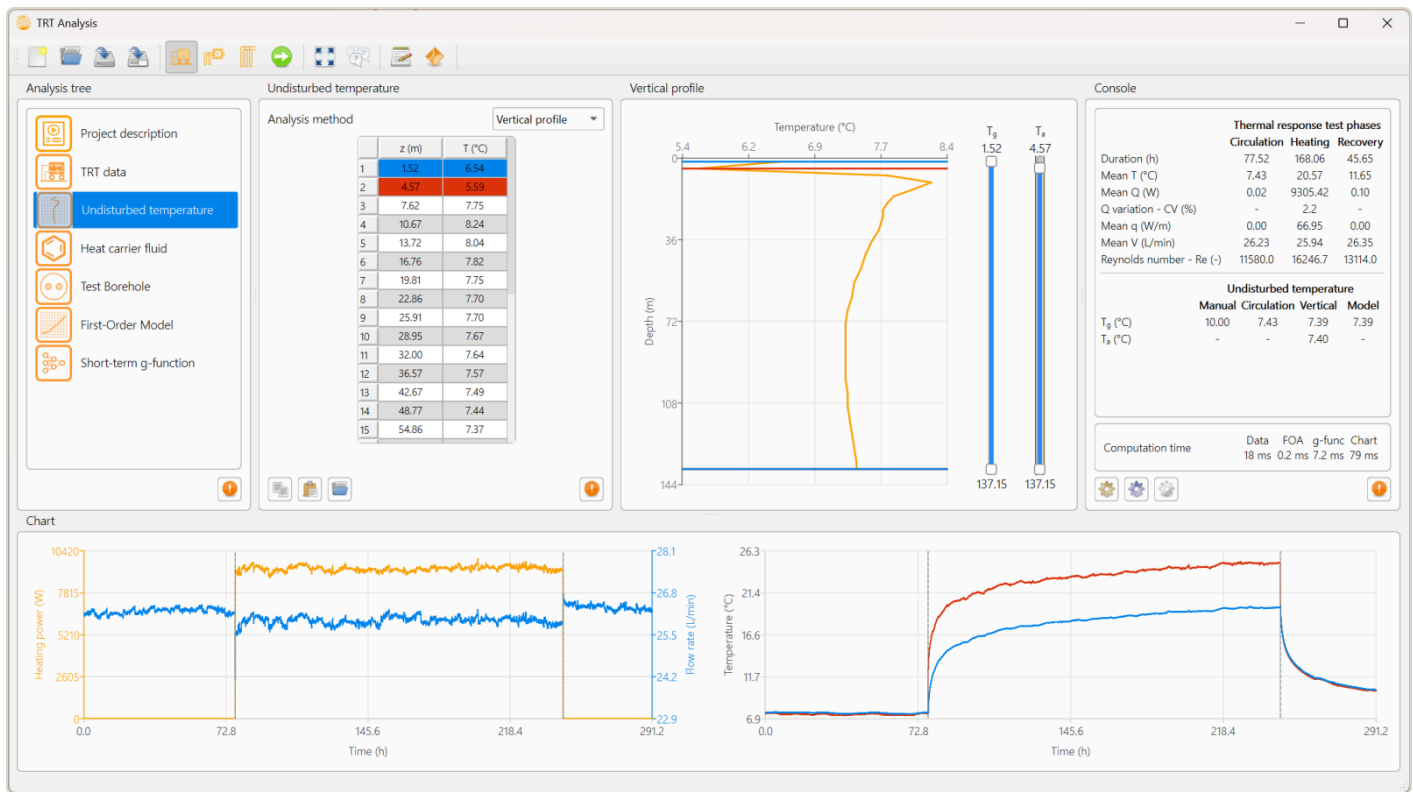


Figure 4 — Undisturbed temperature panel — method selector on the left, and on the right the chart of the selected method: the vertical temperature profile plotted against depth with the dual-range sliders selecting the T_g and T_a intervals, or the circulation phase with its window and mean

The three options read the ground in three different ways. A depth-resolved temperature log read down a borehole (**Vertical profile**) gives temperature against depth, and the mean annual temperature T_a with it. **Circulation phase** reads the temperature of the fluid circulated through the loop without heating. **Manual input** takes a value established outside the test, from a nearby log or a regional dataset. Their reliability is discussed under *TRT in practice*, below. Loading a dataset selects **Circulation phase** automatically, since that method reads T_g from the measurements themselves.

Manual input - This method allows the user to directly provide a value for T_g , from -10 to 40 °C.

Circulation phase - This method gives the average over the whole height by construction: the fluid has just travelled down and up the entire loop, so the temperature it comes back at is already the mixture of everything it met on the way. If a circulation phase was identified in the previous step, the dual-range slider allows selection of the data deemed representative of T_g . The **Q/E** and **A/D** keys move the start and the end of the window one sample at a time. If the test carries no circulation phase, this method has nothing to read and the value is reported as a dash.

Selecting this method draws the circulation phase alone in the panel, inlet and outlet temperatures against time, with the two window boundaries marked and the resulting mean drawn as a horizontal orange segment between them. That segment is the T_g the console reports for this method.

Vertical profile - By selecting this option from the drop-down menu, you can load a vertical temperature profile using the import button . The file must be a comma-separated values (.csv) file with **2 columns** and with a full point as the decimal separator. The first column is the depth in meters (m) and the second column is the temperature in degrees

Celsius (°C). A profile must hold at least two measurements, carry no negative depth, and its depths must **increase strictly from one line to the next**, since each reading is weighted by the thickness of its own slice. A file that breaks one of these rules is refused and the offending line is named. The table can also be edited in place, and the same rules apply cell by cell: a value that would break one of them is rejected and the previous one restored. The profile is then drawn in the panel, temperature on the horizontal axis placed at the top and depth increasing downward, so the chart reads like the borehole itself. The two dual-range sliders beside it select the depths used for each temperature, and the two windows are chosen differently. The blue one, for T_g , should span the **whole height of the borehole**, from the surface down to its base, since that is the average both models expect; unlike the circulation phase, the profile only gives that average if the window covers the full column. The red one, for T_a , must be confined to the section the seasonal signal no longer reaches: near the surface the readings follow the season, and below a certain depth they settle. Place the red window in that settled section. The **Q/E** and **A/D** keys refine each interval. The four labels beside the sliders give the **depth in metres** of each boundary, and the same four rows are tinted in the table, blue for T_g and red for T_a . A profile can equally be pasted from a spreadsheet with the paste button  or Ctrl+V, in the same two columns, and the loaded profile copied back out with the copy button  or Ctrl+C.



Summary & charts: the chart of the selected method and the temperatures in the console

Comparing the methods - The first page of the console, in the block below the phase statistics, reports T_g for all three determination methods side by side, manual entry, circulation phase and vertical profile, whichever one is currently selected here, plus T_a where a profile has been read. A fourth column shows the T_g the short-term g-function currently carries on its own slider, which it calibrates rather than determines. Comparing the columns is only meaningful when the profile window spans the full height of the borehole; otherwise the circulation phase and the profile do not measure the same average, and a gap between them reflects the window rather than the ground.



TRT in practice: why measuring the undisturbed ground temperature accurately matters

Why it matters. T_g is the baseline every other number is read against. It is the reference of the first-order regression, the starting position of the short-term g-function's T_g slider and, once the interpretation is complete, the boundary condition the borehole field is sized against. An error on T_g therefore moves λ_s , R_b^* and the sizing that follows. Its cost follows from the sizing equation: in a design driven by the heating peak, the borehole length is inversely proportional to the difference between T_g and the minimum entering fluid temperature the design allows, so an error on T_g is an error of the same absolute size on that difference. A 1 °C error is therefore worth about 10% of the total GHE length where the design works against a 10 °C approach — T_g at 10 °C and a minimum EFT near 0 °C — and about 7% where an antifreeze mixture allows the loop down to -4 °C.

Which of the three methods to trust. They are not equally reliable, and the trade-offs between them are examined in detail by Gehlin and Nordell (2003). A logged vertical profile is the most informative, because it shows how the temperature varies with depth and yields T_a as well. The circulation phase is the most common field practice, but it asks for a circulation long enough that the fluid and the rig have come into equilibrium with the ground, and it remains

exposed to the heat the circulation pump adds to the loop. Manual input is best reserved for a value obtained independently, from a nearby log or a regional dataset.

Reading the circulation phase. The circulation must run long enough. A test unit arrives empty and is filled on site with water that is not at T_g , warmer in summer and colder in winter, and its above-ground pipework starts at the ambient temperature as well. What the first minutes of circulation measure is therefore the water that was put in and the rig that holds it, not the ground. Stability can take several hours. Place the window on the plateau the record settles onto: late enough for the heat or cold introduced on site to have dissipated, and short of the point where the accumulated pump work has begun to lift the curve. Gehlin and Nordell (2003) approach the same problem from the other end, logging the flow temperature at a short sampling interval so that the first pass of fluid through the loop can be read before the pump has had time to add anything to it. The record itself shows which end of the phase is cleaner: take the plateau when the fill water dominates the first hours, and the first pass when the pump drift never lets a plateau form. The shape of the phase tells the two apart. A drift over the first hours is the fill water and the pipework coming to the temperature of the ground, downward in summer and upward in winter; a slow rise that continues once that has settled is the pump adding heat to the loop.

Log a profile when you can. A profile is informative well beyond T_g and T_a , as shown from field practice by Holmberg et al. (2018). Two instruments can produce it: a fibre-optic system logged along the borehole, or a submersible temperature sensor fitted with a clock or a pressure sensor, the pressure reading converted into depth. With a submersible sensor, hold each depth long enough for the reading to stabilise before moving to the next; a value taken before the sensor has equilibrated with its surroundings is not representative of that depth. Two ways are open for the measurement itself. The probe can be lowered straight into the borehole while it still stands full of water, **before the grout is placed**, which reads the ground before the installation has disturbed it at all. Or it can be lowered down the pipes of the completed loop, filled with water or with the antifreeze mix, provided **at least a week has passed since the installation** so that the heat released by the drilling and by the setting grout has dissipated. Where a layered ground is suspected, log the profile even if T_g is to be read from the circulation phase, and keep the log with the test record.

Timing matters too. In some regions T_g and the mean annual temperature T_a differ substantially, and a test run at the end of summer or the end of winter can return a near-surface temperature that is not representative of the ground the borehole field will actually see over the year. Where the two diverge, record both and note which one the downstream sizing and design should use.



Heat carrier fluid

The heat carrier fluid circulated during the test sets the flow regime in the pipes and the heat it carries along the loop. In the TRT module the fluid properties serve three purposes:

- **Confirming the flow regime.** The fluid's viscosity and density fix the Reynolds number for the measured flow rate and pipe inner diameter, which is how the loop is confirmed to run turbulent, the regime a thermal response test should be conducted under. A fluid that is too concentrated, or a flow rate too low, pushes the loop toward laminar flow, which inflates the convective resistance R_f and, with it, the apparent borehole resistance R_b^* .
- **Computing the theoretical R_b^* .** That same Reynolds number sets the convective resistance R_f , one of the three resistances of the theoretical R_b^* reported on the *Test borehole* panel.
- **Feeding the short-term g-function.** The fluid volumetric capacity $C_f = \rho_f \cdot c_p$ sets how much heat the moving fluid carries along the loop, an input the short-term g-function needs to reconstruct the early-time response. It plays no role in the first-order approximation.

Here you describe the fluid that was **actually used during the TRT**: the goal is to reproduce the physics of the test as it was performed. From the fluid type and its concentration, the thermal conductivity (k_f), dynamic viscosity (μ_f), density (ρ_f) and specific heat (c_p) are computed from the correlations of Melinder (2007).

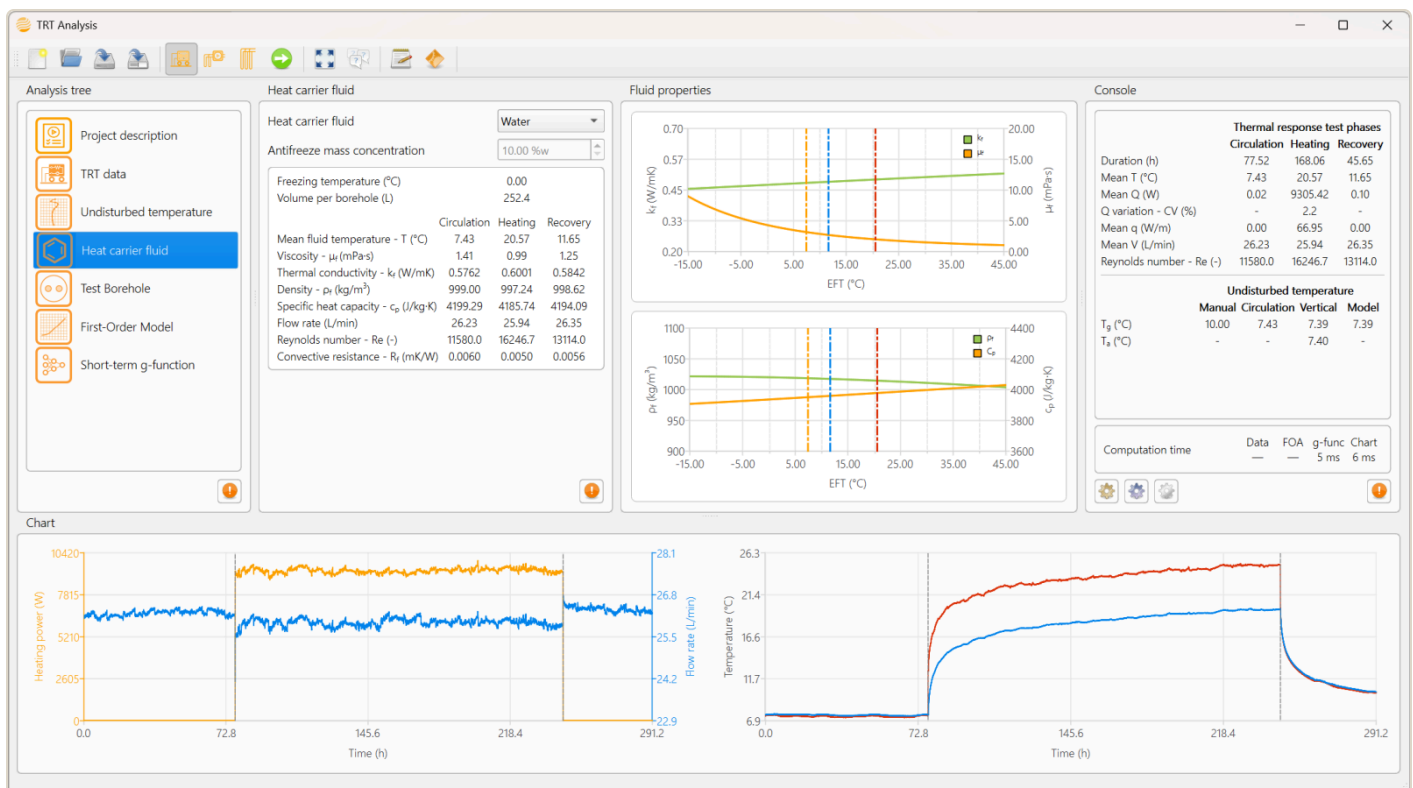


Figure 5 — Heat carrier fluid panel — fluid selector and antifreeze-concentration input, the three phase columns (circulation, heating, recovery) of properties evaluated at each phase mean temperature, and the property charts (k_f , μ_f , ρ_f , c_p) against temperature

Heat carrier fluid - Five fluids are available: pure water, ethylene glycol, propylene glycol, methyl alcohol and ethyl alcohol. Their thermo-physical properties are computed from the Melinder correlations over the full temperature range. Select the fluid that was circulated during the test.

Water is the default because most test boreholes are filled with it: a TRT is usually run on a purpose-drilled test hole rather than on a completed borehole of the final system, and for that hole water is simpler and cheaper to source, handle and dispose of than a glycol mix. When the loop held an antifreeze mix, select that fluid instead; the usual cases are given under *TRT in practice*, below.

Antifreeze mass concentration - Specify the mass concentration of antifreeze, assuming the solvent is pure water. The units are kilograms of antifreeze per kilogram of solution, reported as a percentage. Enter the concentration of the fluid as it was mixed for the test.

Summary & charts: fluid properties per phase and the resulting flow regime

The three phase columns - In the TRT module the summary table carries **one column per phase of the test: Circulation, Heating and Recovery**, in place of the cooling and heating design columns of the  design module. Each column is headed by the **mean fluid temperature measured during that phase**, the average of the inlet and outlet readings over its samples, and every value below it is evaluated at that temperature: viscosity, conductivity, density, specific heat, the mean measured flow rate, the resulting Reynolds number and the convective resistance R_f .

Because the columns are keyed to the phases, they follow the phase boundaries. Moving a slider handle on the *Thermal response test data* panel changes the mean temperatures here, and with them the properties, the Reynolds numbers and the resistance breakdown of the test borehole.

Freezing point, fluid volume and the property charts - The table also reports the freezing temperature of the mixture and the volume of fluid contained in the pipes, and the charts beside it plot each property as a function of temperature. A low R_f is the signature of good, turbulent heat transfer between the fluid and the pipe wall; a high R_f over the range of temperatures reached during the test is a warning that the flow regime may have compromised the measurement.

TRT in practice: enter the fluid that was actually circulated

Match the fluid actually circulated. The fluid entered on this panel must match the one used during the test, at the concentration it was actually mixed to. Substituting water for a glycol mix, or rounding the concentration, changes the computed viscosity and density and biases the Reynolds number. Antifreeze shows up in two narrower situations: a test run on a production borehole already filled with the fluid planned for the final system, or a winter test where the borehole was charged with antifreeze beforehand to protect it from freezing before the test could start; in both cases enter that fluid rather than the water default. If the fluid or its concentration was not recorded, enter the best available estimate and state it in the report, so a later reviewer knows that the Reynolds number, and the resistance that depends on it, rest on an assumption.



Test borehole

This panel describes the **instrumented borehole of the test, as it was designed and built**: its dimensions, its pipes and its grout. The geometry is taken from the drill record, the pipe product sheet and the completion report, and the two interpretation models read it directly.

The panel uses that geometry to compute a **theoretical** effective borehole resistance R_b^* , together with its breakdown into R_f , R_p and R_g , exactly as the  design module would for the same borehole. This theoretical value exists to be compared against the **experimental** R_b^* that an interpretation method deduces from the measured record, when that method delivers one: the first-order approximation always does, and the short-term g-function does as well, implicitly, through its calibrated parameters. Comparing the geometry-based value with the test-based one is the purpose of this panel.

Not every value entered here was measured on this test. The grout conductivity λ_g is the clearest example: it is the value the product was specified at, not something a thermal response test can see directly, and every resistance computed from it, R_g and R_b as much as R_b^* , inherits that status.

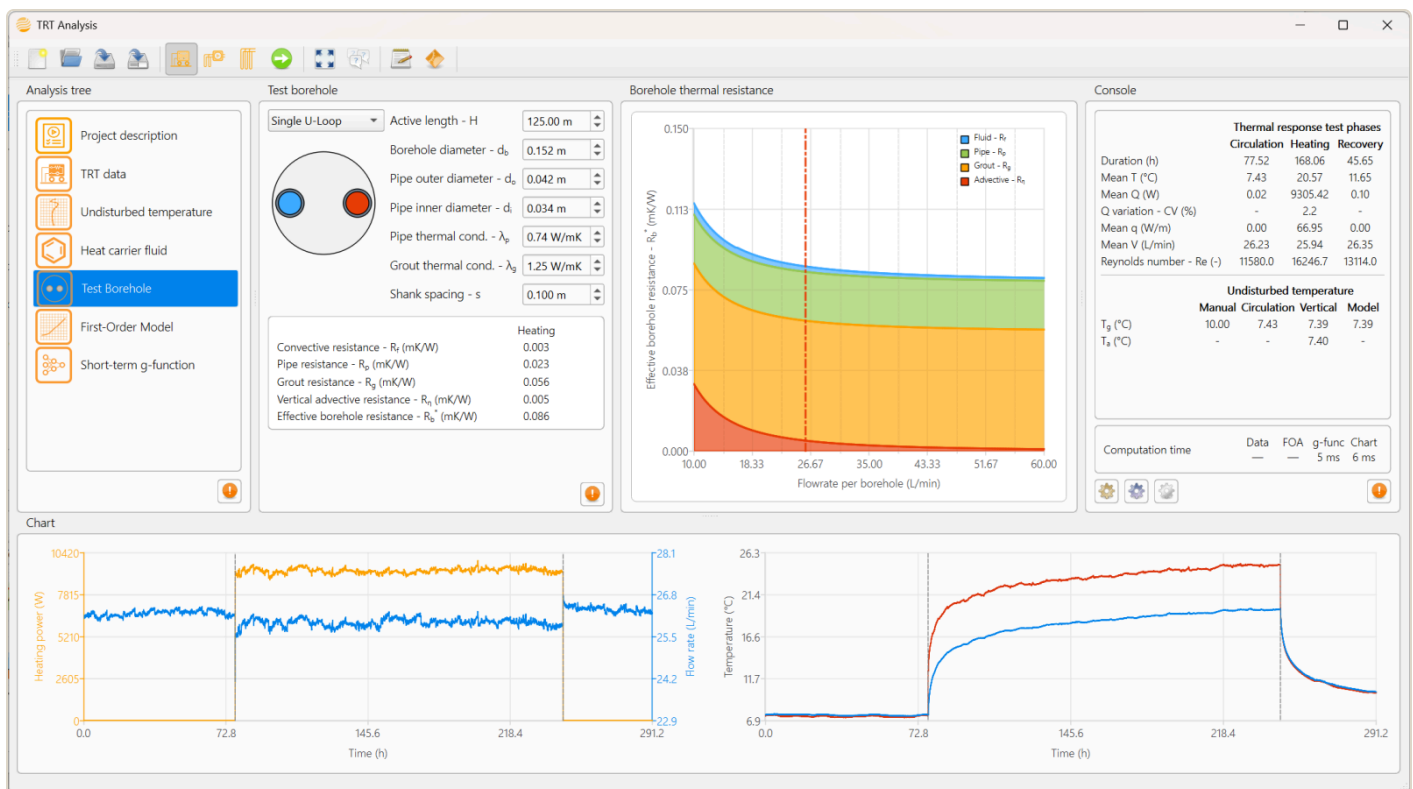


Figure 6 — Test borehole panel — the geometry of the instrumented borehole with its scaled cross-section, the resistance breakdown (R_f , R_p , R_g , R_b , R_b^*) computed at the mean flow rate and mean fluid temperature of the heating phase, and the effective-resistance-versus-flow-rate chart

Borehole configuration - All five configurations are available: single U-tube, the two double U-tube arrangements, coaxial and standing column. A thermal response test is run on whatever borehole was drilled, and the resistance breakdown below is computed for the configuration you select, exactly as it is in the design module.

Active length — H (m) - The length of borehole that actually exchanges heat with the ground. Above-ground piping, and any piping not embedded in grout, is excluded from H . H converts the measured heating power into the unit power $q = Q/H$ that both regressions fit, and it is an input of the short-term g-function. It is the most consequential figure on this panel (see *TRT in practice*, below).

Borehole diameter — d_b (m) - At least the diameter of the drill bit. In soft or incompetent rock it can be increased to account for lateral abrasion. It sets the grout resistance R_g and, through $r_b = d_b/2$, the critical time $t_{cr} = 5 r_b^2/\alpha_s$ before which the line-source approximation does not apply.

Pipe inner and outer diameters — d_i, d_o (m) - The inner diameter fixes the flow velocity, and with it the Reynolds number, the exchange surface and the residence time of the fluid in the loop. The two together give the pipe wall thickness and hence the pipe resistance R_p . Both are entered as **diameters**.

Shank spacing — s (m) - The distance between the two legs of the U-tube, used for the resistance breakdown shown below. The short-term g-function does not read this field: it calibrates its own spacing s against the measured temperatures, over a range it derives from d_b and d_o (see *Analysis with the short-term g-function*).

Pipe thermal conductivity — λ_p (W/m-K) - Used to compute the pipe resistance R_p , and an input of the short-term g-function. Since the range of values of the pipe volumetric heat capacity is narrow, a fixed $C_p = 1.9 \times 10^6$ J/m³/K is assumed.

Grout thermal conductivity — λ_g (W/m-K) - Used for the resistance breakdown shown below. Like the shank spacing, it is *not* an input the interpretation depends on: the short-term g-function calibrates its own λ_g and C_g against the data, precisely because the conductivity achieved in the field is rarely the one printed on the bag.

As these values are entered, a scaled cross-section of the borehole (the grout annulus, the two pipes of the U-tube and their spacing) is drawn alongside the inputs. A unit error or a swapped diameter shows up in the drawing.

One quantity the breakdown needs is not entered anywhere on this panel: the ground thermal conductivity λ_s . It is taken from the **first-order model** as soon as it has a result, falling back to the design module's default of 2.5 W/m-K when the test has not yet been fitted. Refine the regression window in the first-order model and every resistance below follows; the λ_s in play at any moment is the one reported on the FOA page of the console.

Which model reads which configuration - The first-order approximation fits a line source without reference to the pipe arrangement, so it applies to any of the five configurations above (see *Analysis with first-order approximations*). The short-term g-function does not: its network was trained on single U-loop boreholes only, so its own panel carries a configuration selector frozen on *Single U-Loop*, and everything it reports, including its own R_b^* , is computed for a single U-tube regardless of what this panel shows (see *Analysis with the short-term g-function*). Read its results with that in mind whenever the test borehole is not one.

Which input feeds which model - The fields do not all carry the same weight:

- **H** — read by both models, and the most consequential geometric input of the two interpretations.

- d_b — read by both: it sets t_{cr} for the first-order approximation and the borehole diameter for the short-term g-function model.
- d_i , d_o , λ_p — read by the short-term g-function, and by the Reynolds number of the phase statistics; the first-order approximation does not use them.
- s , λ_g — used for the breakdown on this panel only. The short-term g-function calibrates its own spacing and grout properties against the data.



Summary & charts: the resistance breakdown of the test borehole

The resistance breakdown, at the operating point of the test - The design module evaluates the borehole resistance at its design temperature limits and its design flow rate per borehole. A thermal response test has neither: the breakdown reported here is recomputed instead at the **measured** operating point, the mean flow rate and the mean fluid temperature of the heating phase reported on the console's phase-statistics page. It follows the phase boundaries. The table has a single column, headed *Heating*, since a TRT is a heat injection.

Three resistances in series between the fluid and the borehole wall combine into the **local borehole resistance** R_b , a cross-sectional quantity that treats each leg of the U-tube as if it exchanged heat with the ground on its own, independently of the other:

- **Convective resistance R_f** — between the fluid and the pipe inner wall, set by the flow regime (Reynolds number) and therefore by the fluid, the flow rate and the pipe inner diameter.
- **Pipe resistance R_p** — the conduction across the pipe wall, set by the pipe diameters and the pipe conductivity λ_p .
- **Grout resistance R_g** — from the pipe outer wall to the borehole wall, set by the grout conductivity λ_g and the position of the pipes.

The three come from the explicit multipole formulas: the single U-tube form of Claesson and Javed (2018), and the double U-tube form of Claesson and Javed (2019) for the configurations that carry four pipes. These closed-form expressions update the breakdown at every change of an input; Javed and Claesson (2017) present the same second-order theory in a form compact enough to check by hand.

R_b leaves out one real effect: the warm fluid on its way down heats the cooler fluid on its way back up, through the grout, over the full depth of the borehole, a thermal short-circuit between the two legs that a cross-sectional resistance cannot see. The panel accounts for it and reports the **effective resistance** R_b^* , which is always at least as large as R_b and grows further above it with a longer borehole, a higher flow rate, or pipes placed closer together, exactly as it does in the  design module. Alongside it, the panel also reports two more figures that state that same gap in different terms: the **vertical advective resistance** $R_\eta = R_b^* - R_b$, the resistance the short-circuit itself is worth, and the **borehole efficiency** χ , the same gap as a dimensionless figure. Neither R_b nor R_b^* accounts for the thermal capacity of the pipes, grout and fluid, which is why the first-order approximation requires the borehole to have reached a thermal steady state before its heating-phase intercept can be read as R_b^* .

The effective-resistance-versus-flow-rate chart - Beside the table, a chart titled *Borehole thermal resistance* plots R_b^* against flow rate for the borehole configuration and ground conductivity currently on this panel, with a vertical marker at the same mean flow rate of the heating phase used for the table. It draws four **stacked, cumulative** bands rather

than four independent curves, in the order the legend lists them bottom to top: the advective short-circuit term alone, then that term plus R_g , then plus R_p , and the topmost boundary closes the stack at the total R_b^* .

Because the bands are cumulative, an individual resistance reads as the **thickness** of its band, not the height of any single curve above the axis: R_p , for instance, is the vertical gap between the third boundary and the one below it, not the height of either curve on its own. Hovering a boundary reports the flow rate and the cumulative resistance up to that boundary.



TRT in practice: the conditions that decide whether R_b^* is trustworthy

The active length first of all. A 10 % error on H induces a 10 % error on the ground thermal conductivity λ_s , and it carries into R_b^* as well. The relation is one to one, because H sets the unit power $q = Q/H$ that enters the regression slope in direct proportion, and nothing downstream can compensate for it. Establish H from the completion record rather than from the drilled depth, and exclude every metre of pipe that is not embedded in grout.

Flow regime next. A flow rate high enough to keep the loop turbulent is the precondition for a meaningful R_b^* . The high convective resistance of laminar or transitional flow inflates the measured R_b^* and depresses λ_s , and no interpretation can undo it after the fact. The regime follows from the pipe inner diameter and the measured flow rate, so confirm the Reynolds number of the heating phase in the console phase statistics before trusting the resistance.

Pipe placement and spacers. The resistance depends strongly on where the pipes sit in the borehole. The models assume pipes held apart at their spacing; in reality they tend to cluster together during grouting unless spacers are installed along the full depth. A set of pipes resting against one another can easily double the effective resistance, so a value higher than the completion suggests may point to the installation, not to the ground.

Grout quality. The grout conductivity depends on the water-to-solids ratio and on thorough mixing. A poorly mixed or over-diluted grout delivers a conductivity below its specification, permanently raising R_b^* . When the short-term g-function calibrates λ_g to a value well below the product figure, poor grout placement is a likely explanation.

Using the measured R_b^* . The **first-order approximation** obtains its R_b^* from the intercept of the heating-phase line, once the slope has fixed λ_s . [–] The **short-term g-function** obtains its own R_b^* implicitly, as the resistance produced by the calibrated grout, spacing and geometry across the full transient, a third figure alongside the one on this panel and the one from the first-order approximation, all three computed by the same multipole method but from different inputs: entered here, fitted by the first-order approximation, calibrated by the short-term g-function. Agreement between them is a good sign; a marked discrepancy usually points to a non-turbulent flow, an unstable heating power, or a completion unlike the one assumed. What a test returns is the *effective* resistance, not the internal resistance between the two legs (Lamarche et al., 2017). Marcotte and Pasquier (2008) show how much the figure moves with the way the mean fluid temperature is formed. The R_b^* returned by a test is valid for the conditions of that test, its flow rate, its fluid and the geometry of the test borehole, and should not be transferred unchanged to a design that differs in any of them. Its proper use is as the field-validated anchor a designer reproduces before exploring alternatives (a higher design flow rate, a more conductive grout) in the design module. Once the system runs, the same quantity can be re-estimated from operating records rather than from a dedicated test, which is a useful way to see whether the installed field behaves as the tested borehole did (Mikhaylova et al., 2017).

A standing column well is not a closed loop. The configuration selector accepts one, and the breakdown above is computed for it, but neither interpretation model accounts for what sets a standing column well apart: it exchanges water directly with the aquifer, and that exchange continues even without a bleed. Where the formation is tight enough that conduction dominates, the well behaves close enough to a closed loop that the first-order approximation still returns a plausible conductivity. Where a sufficiently permeable layer is present, the continuous recirculation between the supply and the return sets up a radial flow within that layer, and the resulting advective heat transport inflates the apparent conductivity well beyond anything conduction alone would produce, even with no short-circuiting to the surface during the test. Robert et al. (2022) document this on a standing column well tested through a layered aquifer, where the first-order approximation returned a thermal conductivity too high to be physical once the permeable layer was reached.



Analysis with first-order approximations (FOA)

The first-order approximation (FOA) models interpret the heating phase of the TRT through a simple linear regression, yielding the ground thermal conductivity λ_s and an **experimental** effective borehole resistance R_b^* , the value to be read against the theoretical one on the *Test borehole* panel. A recovery phase is not required for this: when the test includes one, its own regression can be run as an independent check on λ_s , not as a second measurement the interpretation depends on.

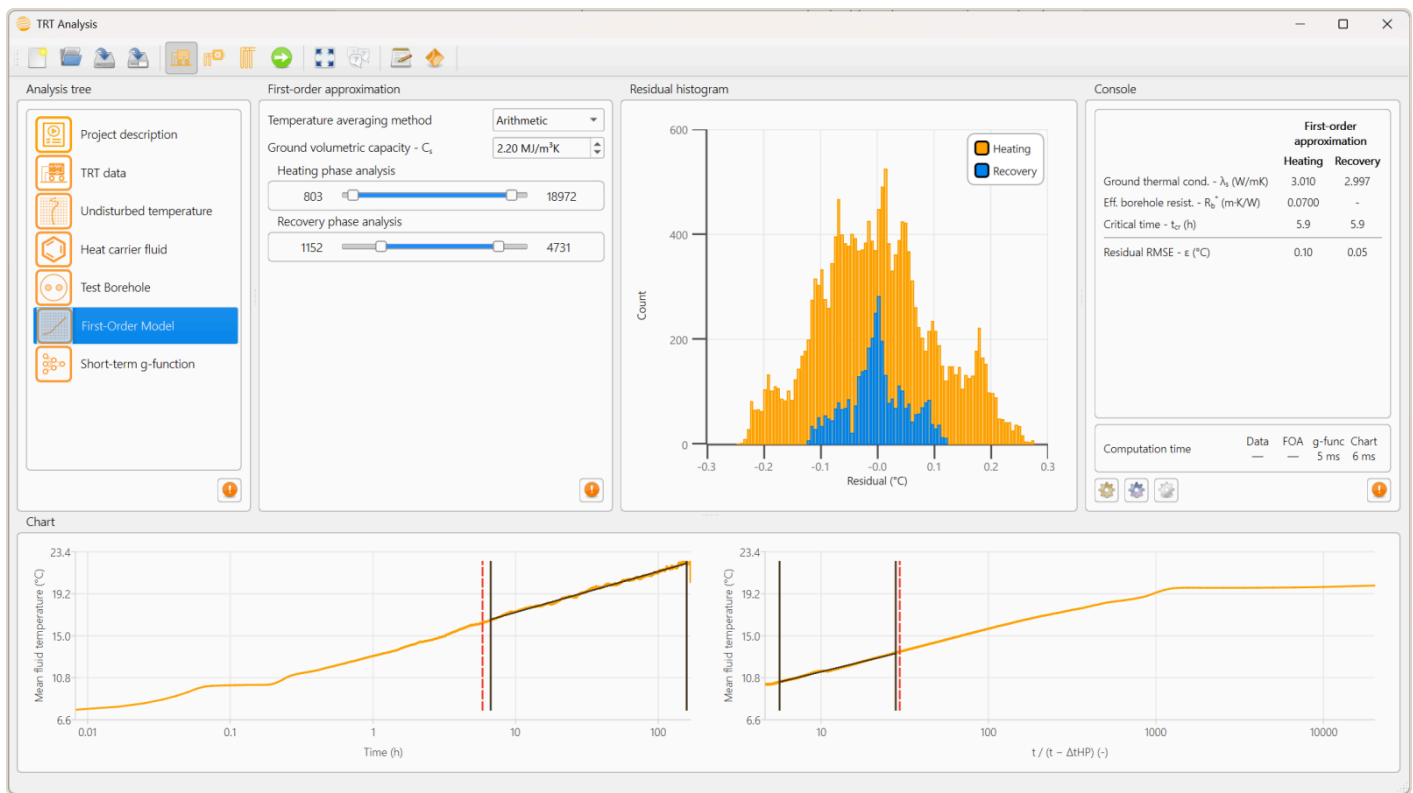


Figure 7 — First-order approximation panel — the heating-phase regression of mean fluid temperature against $\ln(t)$ and the recovery-phase regression, with the critical-time t_{cr} line marking the data that must be excluded from each fit

Heating phase analysis - The thermal response of a GHE during the heating phase can be modeled with reasonable accuracy by:

$$T(t) = T_g + q R_b^* + (q / 4\pi\lambda_s) E_1(r_b^2 / 4\alpha_s t)$$

where $T(t)$ is the mean fluid temperature, T_g is the undisturbed ground temperature, q is the constant unit heating power, R_b^* is the steady-state borehole effective resistance, λ_s is the ground thermal conductivity, r_b is the borehole radius, α_s is the ground thermal diffusivity and E_1 is the exponential integral function.

This is the infinite line-source model, whose analytical solution goes back to Carslaw and Jaeger (1959) and which has been the basis for TRT interpretation since Mogensen (1983): the borehole is idealized as a constant-strength line of heat in an infinite, homogeneous, conduction-only medium.

Using the first-order approximation of E_1 allows expressing the mean fluid temperature by a regression model of the form $T(t) = m \ln(t) + b$, with $m = q/(4\pi\lambda_s)$. This equation has an approximation error of less than 10% for $t \geq t_{cr} = 5 r_b^2 / \alpha_s$.

The slope of the late-time fluid temperature against $\ln(t)$ gives the conductivity and the intercept gives the borehole resistance, so the active length H and the late-time portion of the test must both be right. The slope method itself, and its assumptions, are reviewed in detail by Gehlin (2002) and Spitler and Gehlin (2015).

A dual-range slider is used to interactively select data and compute the regression coefficient m associated with these points. The **Q/E** and **A/D** keys move the start and the end of the window one sample at a time. The critical time t_{cr} is drawn with a vertical red line and corresponds to the moment after which the approximation error is smaller than 10%; data located **before** the red line should not be used for the analysis. The t_{cr} reported by the console is the position of that red line. On the chart, the mean fluid temperature is plotted against $\ln(t)$, on which the line-source model predicts a straight line, and the fitted regression is overlaid on the selected points. A late-time portion that curves away from that line is one of the few visual signs of groundwater advection or of a heating power that did not hold constant.

Recovery phase analysis - At the beginning of the recovery phase, heating is stopped and the fluid returns towards the undisturbed temperature. Using the FOA of E_1 and the principle of temporal superposition, the recovery response can be modeled by:

$$T(t) = T_g + (q / 4\pi\lambda_s) \ln(t / (t - t_h))$$

where t is the time since the beginning of the heating phase and t_h is the heating phase duration. The FOA gives a regression model of the form $T(t) = m \ln(t/(t - t_h)) + b$, with $m = q/(4\pi\lambda_s)$. Further first-order forms of the recovery, built on the time derivative of the temperature rather than on the temperature itself, are developed by Pasquier (2018).

Again, a dual-range slider selects the data and computes m , plotted this time against the ratio $t/(t - t_h)$. The critical time t_{cr} is drawn with a vertical red line; because time runs backwards on this axis, the exclusion rule reverses, and data located **after** the red line should not be used for the analysis.

The unit power q follows your selection - The slope alone does not give λ_s : the model reads it from $m = q/(4\pi\lambda_s)$, so the unit power q enters the result just as directly. The two phases do not use q in the same way:

- **Heating phase** — q is the mean heating power measured from the **beginning of the heating phase to the last point selected**, divided by the active length H . Moving the upper handle of the regression window therefore changes q as well as the slope, and both change λ_s ; the power stays consistent with the stretch of test being fitted. A window that stops just after a power interruption includes that interruption in its average.
- **Recovery phase** — q is the power measured over the **whole heating phase**, not over the recovery window, since it is the injection that created the thermal disturbance the recovery relaxes from. Moving the recovery window changes the slope but not q .

Both values are reported, in W/m, in the result files written alongside the project.

Averaging method for the fluid temperature - Two options are offered to estimate the mean fluid temperature during the heating phase. The first is the arithmetic mean of the borehole inlet and outlet fluid temperature (the only option for the recovery phase). The second is the so-called p-linear average, deemed to better represent the mean fluid temperature in the GHE.

The arithmetic mean is known to overestimate the mean fluid temperature, and therefore the borehole resistance, when the inlet-to-outlet temperature difference is large; the p-linear average was introduced by Marcotte and Pasquier (2008) to reduce this bias.

Ground volumetric capacity - The ground volumetric heat capacity C_s (in millions of J/m³/K, from 1.6 to 2.8) is used only to compute the critical time t_{cr} . This value must be provided because the FOA method cannot estimate it.

Assumptions and limitations - The FOA models assume a constant heating power during the heating phase, a thermal steady-state in the GHE, a constant circulation flow rate, the absence of groundwater flow around the GHE, the lack of axial effects and no heating during the recovery phase. If one or more of these assumptions are not met, the FOA model should not be used.

The pipe arrangement is not among them. The line is fitted to the measured mean fluid temperature and to the unit power $q = Q/H$, and neither depends on how many pipes the hole carries, so the method applies to any configuration of the test borehole: *Single U-Loop*, either *Double U-Loop*, *Coaxial* or *Standing Column*. The effective resistance R_b^* read from the intercept is simply the one that configuration produces, whatever it is.

The constant-power assumption is frequently broken in the field. Where the injected power drifted or stopped, the choice is between accepting the bias and fitting the measured history itself, either by superposing line sources in time and estimating the parameters numerically (Mazzotti et al., 2018) or by the short-term g-function of the next node.

The no-groundwater assumption is the hardest to detect from the temperature record alone. Where advection is known to be significant, the conduction-only line source is the wrong model outright, and a moving line-source formulation such as that of Pasquier and Lamarche (2022) is required to recover the ground properties. It need not affect the whole borehole to matter: Voirand and Maragna (2025) report tests where a distributed measurement traced the enhanced heat transfer to one depth interval rather than to the whole borehole, something the inlet and outlet temperatures that feed the regression cannot localise.

Summary & charts: the regression residuals and the results in the console

Residual histogram - The panel to the right of the inputs shows the distribution of the regression residuals, the difference between each measured mean fluid temperature and the fitted line, over the window currently selected. The residuals of a least-squares fit always average zero, so their *shape* is what matters: a narrow, symmetric bell says the line describes the data; a skewed or double-peaked distribution says it does not, usually because the window still contains data from before t_{cr} or spans a change in the heat injection. The histogram axis is bounded on percentiles of the residuals, so a few outliers do not compress it.

Where the regression results are reported - The numbers themselves, λ_s , R_b^* , t_{cr} , and the mean, standard deviation and RMSE of the residuals, are reported on the second page of the console, in two columns, one for the heating phase and one for the recovery phase. Selecting this node brings that page up, and the figures update as the regression windows move.



TRT in practice: cross-checking the two regressions

When a recovery phase was recorded, treat the heating-phase and recovery-phase conductivities as an independent cross-check: they are derived from different data through different regressions, so close agreement is reassuring, whereas a marked discrepancy is a warning sign. The usual causes are an unstable heat injection rate, a test cut short before t_{cr} , or groundwater advection, the conditions under which the line-source assumptions fail. In those cases, turn to the short-term g-function, which uses the full transient and tolerates a varying power. Note also that the recovery phase returns only λ_s , not R_b^* , since the borehole resistance is carried in the heating-phase intercept.

The window the line is fitted over moves λ_s the most — more than measurement noise, and more than any of the properties entered on the other panels. Oh et al. (2022) rank the experimental factors that govern an analytical interpretation and find the start of the fit ahead of the test duration. Report the regression window alongside the conductivity, and place its start on t_{cr} , not where the line looks straightest.

The ground volumetric capacity C_s is the one input here that need not be known precisely. It does not affect the conductivity λ_s directly: it only sets the critical time t_{cr} , the boundary before which the approximation is invalid. A rough value is therefore adequate: if it places t_{cr} slightly off, discard the data points near the line.



Analysis with the short-term g-function

This model works from the **short-term g-function** of the test borehole: the temperature response the borehole produces for a unit step of heat, resolved from the very first minutes rather than only at late times. It accounts for the pipe and borehole geometry, the thermal properties (λ and α) of the fluid, pipes, grout and geological materials, and the fluid vertical velocity in the pipe loop. For a given set of input parameters it simulates the fluid temperature at the borehole inlet $T(z=0 - \downarrow)$ and outlet $T(z=0 - \uparrow)$. It is for now limited to a **single U-loop** borehole, whatever configuration the *Test borehole* panel carries.

That response is evaluated by a **pre-trained artificial neural network** that reproduces the output of a transient 3D finite-element model to within $1 \times 10^{-4} \text{ }^{\circ}\text{C}$ (Pasquier and Marcotte, 2020), fast enough to follow the sliders. The network stands in for a detailed physical computation and is not fitted to your data: for the same inputs it returns the same response.

Coupled with an efficient temporal superposition scheme (Marcotte and Pasquier, 2008; Pasquier et al., 2013), the model captures the temperature changes due to variations in heating power for a TRT shorter than 21 days. This allows the simultaneous analysis of heating and recovery phases, pulsed TRTs and interrupted TRTs.

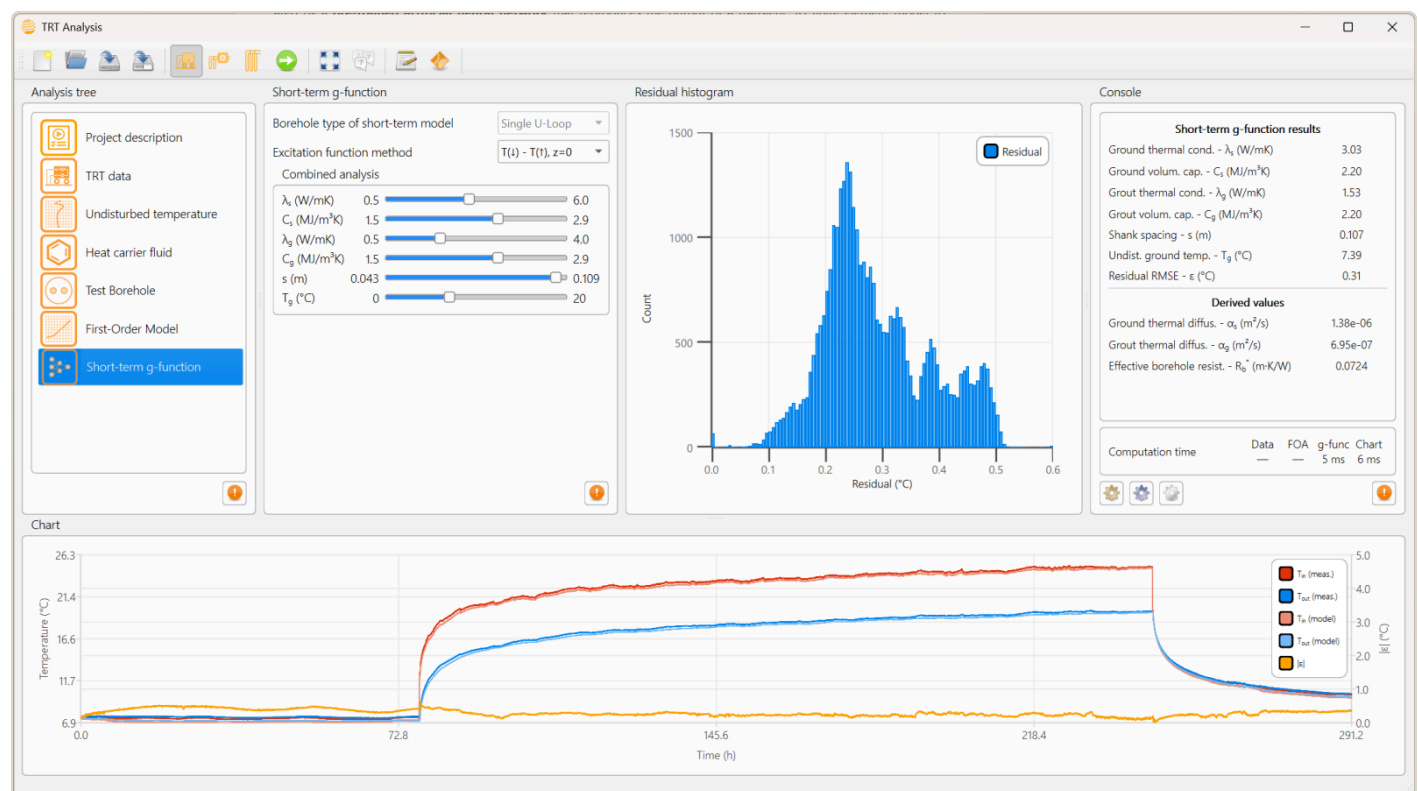


Figure 8 — Short-term g-function panel — the excitation-function selector and the six calibration sliders (λ_s , C_s , λ_g , C_g , s , T_g) on the left, the residual histogram on the right, and the console page reporting the calibrated parameters and the fit statistics

For the geometry and properties you supply, the model reconstructs the borehole's unit response, its g-function, and convolves it with the measured heat-injection history. Because the measured power drives the convolution, the model follows every ramp, pause and shut-off in the test, which is why it can interpret the early hours, the recovery, and pulsed or interrupted tests where the line-source model cannot. Pasquier (2018) showed that the first hours of a test carry usable information about the ground, recovering a thermal conductivity within 10% of a reference value from the first three hours alone. Tests deliberately made of successive pulses fall within the same framework (Fossa et al., 2018).

Excitation function method - The drop-down at the top of the panel selects how the temperature difference across the borehole, from which the excitation of the convolution is built, is obtained from the record:

- **$T(\downarrow) - T(\uparrow), z=0$** — directly from the two measured temperatures. This is the default, and the right choice whenever both probes are trustworthy.
- **$Q/(V \cdot C_f)$** — from an energy balance on the measured heating power and flow rate. Both describe the same physical signal, so a marked disagreement between the fits they produce means the power, the flow rate and the temperature difference are not consistent, usually because of a mis-scaled flow meter or a fluid other than the one declared.

The flow rate passed to the model is the mean over the **heating phase** alone, so a pump stopped during the recovery does not lower it.

Interactive calibration - Six single-handle sliders are used to interactively select λ_s , C_s , λ_g , C_g , s and T_g . After clicking a slider, the **A/D** (or **Q/E**) keys move it one step. Each move re-runs the simulation and updates the fit statistics and the chart.

The measured inlet and outlet temperatures are drawn as thick red and blue curves, and the simulated temperatures as thinner, lighter curves in the same two colours. Calibration consists in moving the sliders until the thin curves lie on the thick ones. Judge the fit over the entire record: parameters that reproduce the heating phase but miss the recovery have not identified the ground.

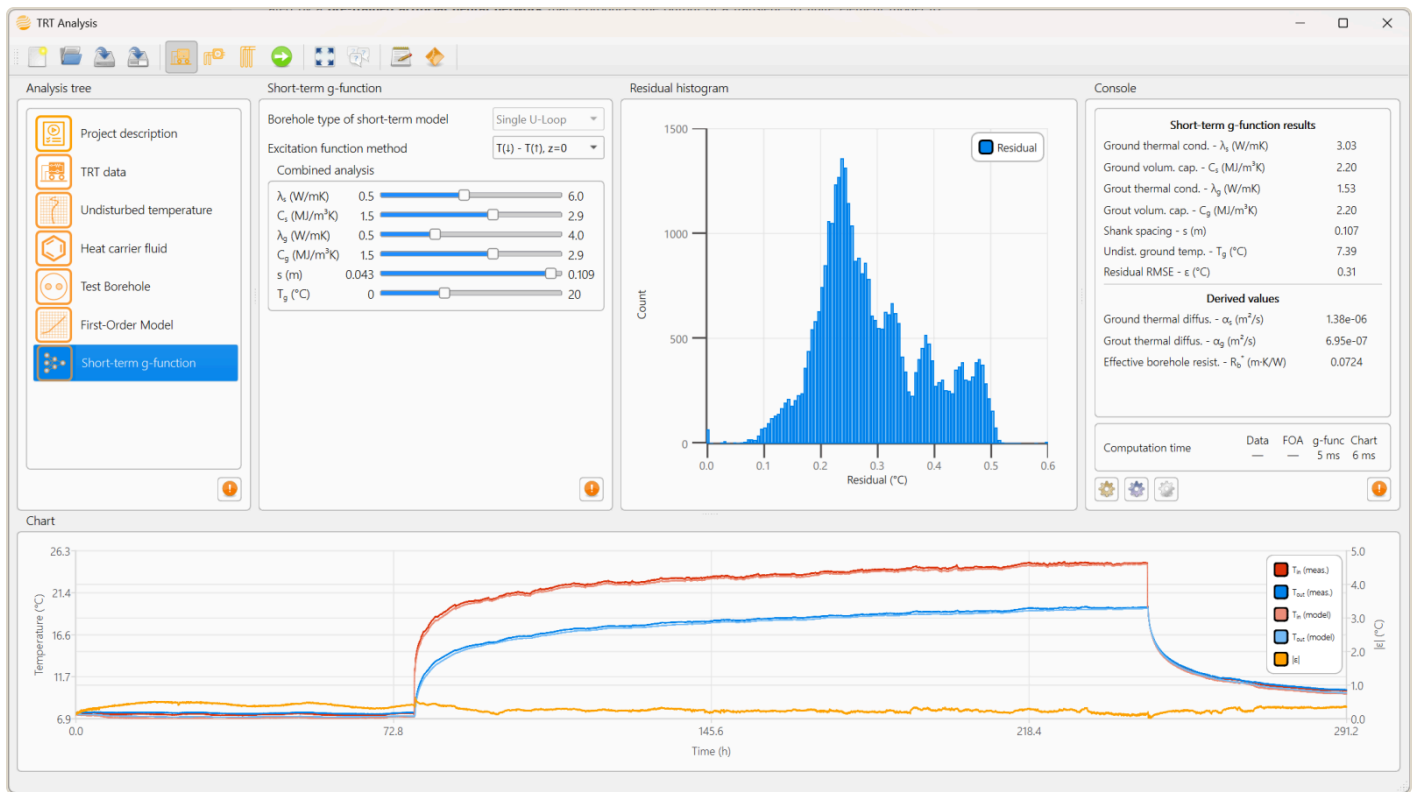


Figure 9 — Short-term g-function chart — measured inlet and outlet temperatures (thick) with the simulated curves (thin) overlaid over the full test, the target of the slider calibration

The ranges of the first four are those of the training envelope: λ_s from 0.5 to 6.0 W/m·K, λ_g from 0.5 to 4.0 W/m·K, and both volumetric capacities from 1.5 to 2.9 MJ/m³·K. T_g runs from -10 to 40 °C, and its handle is placed on the value determined by the *Undisturbed temperature* panel as soon as one is available. s is the shank spacing, the centre-to-centre distance between the two pipes, the same quantity as on the *Test borehole* panel. Its range is derived from the borehole, spanning nearly the full space available without letting either pipe cross the borehole wall, with a step of one micrometre. A way to work through the six sliders is given under *TRT in practice*, below.

Range of validity - Because the underlying network was trained over a finite range of conditions, it should be used as an interpolator, not an extrapolator. The training envelope covers the great majority of conventional tests: a ground conductivity from 0.25 to 8 W/m·K and a grout conductivity from 0.25 to 5 W/m·K, volumetric capacities from 1.4 to 3.0 MJ/m³·K, boreholes 50 to 250 m long with a radius up to 0.1 m, pipe inner radii from 12 to 27 mm and outer radii from 15 to 36 mm, a pipe conductivity from 0.3 to 1.0 W/m·K, a fluid volumetric capacity from 3.8 to 4.3 MJ/m³·K, and flow rates from 15 to 35 L/min. The sliders are deliberately narrower than that envelope, so that a normal interpretation stays inside it. The quantities read from the other panels are not checked: a borehole geometry or a flow rate outside these bounds falls outside what the model learned, and its estimates become unreliable. The test must also fit within the 21-day window; a longer record is truncated to it. When inputs sit near these edges, lean on the first-order approximation as a check.

Assumptions and limitations - The assumptions underlying this model are a constant circulation flow rate and the absence of groundwater flow around the GHE. If one or more of these assumptions are not met, it should not be used to analyze the TRT. Two conditions lie entirely outside the training envelope, whatever the slider positions: a layered ground, and groundwater advection. Both are active research subjects, and a network trained on a heterogeneous

medium with advection has since been demonstrated (Rose et al., 2024), but the network shipped here does not carry them.

The network was also trained on **single U-loop** boreholes only, and represents any other test borehole as one, whatever the *Test borehole* panel shows. The first-order approximation has no such restriction.



Summary & charts: the simulated curves, their residuals and the calibrated parameters

Residual histogram, and where the fit is reported - The panel to the right shows the distribution of the residuals, measured minus simulated. The numbers behind it, the current value of each of the six parameters, the ground and grout thermal diffusivities $\alpha = \lambda/C$ they imply, the mean, standard deviation and RMSE of the residuals, and an **experimental** effective borehole resistance R_b^* , computed by the same multipole method as the *Test borehole* panel but from these calibrated parameters instead of the entered ones, are reported on the third page of the console, which selecting this node brings up.

The model predicts **both** fluid temperatures, and both are drawn on the chart: the convolution yields the outlet temperature, and the inlet temperature follows by adding the temperature difference across the borehole.



TRT in practice: a good fit is not proof of the right parameters

Where to start. Set λ_s and T_g from the first-order approximation, then adjust the remaining four sliders to drive the RMSE down. Calibrate the parameters the test is most sensitive to first, typically λ_s and T_g , before fine-tuning the grout properties and the spacing, which influence mainly the early-time response. A good fit reproduces both the heating and the recovery temperatures, not just one of them.

Reading the fit while you calibrate. Unlike those of a least-squares regression, these residuals are not forced to be centred, so their **mean** is informative: a mean away from zero means the simulated curve sits above or below the measurement throughout the test, a bias that usually points at T_g or at the ground conductivity. The **RMSE** is the figure the sliders above are driving down, and the histogram beside it says how: a narrow symmetric bell centred on zero is a fit, a shifted one is a bias, and a broad or double-peaked one says the model follows part of the test only.

Calibrating six parameters against one temperature record is an inverse problem, and inverse problems rarely have a single answer. Several combinations can reproduce the same measurements about equally well: a slightly lower conductivity offset by a warmer T_g , or a poorer grout offset by a wider pipe spacing, can land within a few hundredths of a degree of one another in RMSE. A low misfit therefore shows that a combination is *compatible* with the data, not that it is the right one.

Two habits help. Fix what you can measure independently: take T_g from the *Undisturbed temperature* panel instead of tuning it freely, and hold the geometry to the completion record. Then test the fit: move a parameter away from its calibrated value and check whether the RMSE rises. A parameter the test does not constrain will barely change it, which should be known before quoting it in a report. Where the answer stays ambiguous, report a range and say which parameters were fixed rather than a single set of six figures the data cannot separate.



The console reports every number produced by the interpretation. It is organised as three independent pages, reached with the buttons at the bottom of the panel, and the three pages share a common footer reporting computation times. The console updates live: moving a phase boundary or a calibration slider changes the figures below as the mouse moves.

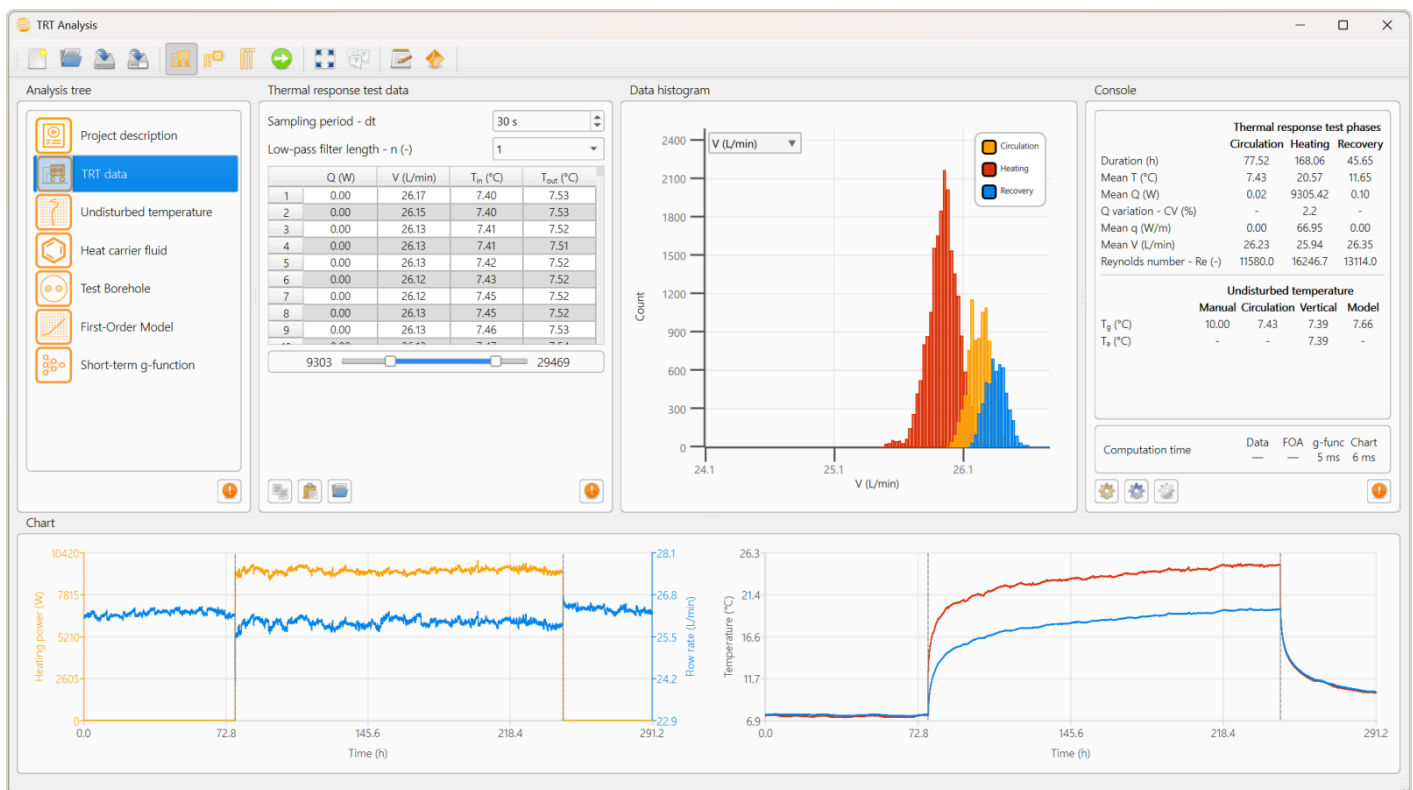


Figure 10 — Console panel — the three result pages (phase statistics with the undisturbed temperatures, FOA regression results, short-term g-function results) selected by the buttons at the bottom, with the shared computation-time footer

The console doubles as the help viewer: clicking the help button ⓘ of any panel replaces the results with the help page of that panel, and clicking one of the page buttons below brings the results back.

The page follows the node. Selecting a node in the analysis tree brings up the console page that belongs to it: *TRT data* and *Undisturbed temperature* both open the first page, *FOA model* the second, *Short-term g-function* the third. The buttons can still select any page at any time.

Page 1, Phase statistics and undisturbed temperature - Reached with the ⚙ button. The upper block characterises each of the three phases of the test, circulation, heating and recovery, in its own column: the duration (h), the mean fluid temperature (°C), the mean heating power (W), the coefficient of variation of that power (Q variation, CV, in %), the mean unit power (W/m), the mean flow rate (L/min) and the Reynolds number. The mean fluid temperature is the average of the inlet and outlet readings over the phase, and it is the temperature at which the fluid properties of that

phase, and with them the resistance breakdown of the test borehole, are evaluated. Q variation, CV , is the standard deviation of Q over the phase divided by its mean, reported as a percentage. It is computed on the **measurements as imported**, not on the smoothed signal, since a low-pass filter of n samples reduces the scatter by roughly $\sqrt{n}$. The mean, which the filter does not change, is taken from the filtered signal.

The Reynolds number is that of one downward leg of the test borehole, so it accounts for the pipe configuration entered on the *Test borehole* panel: a double U-loop splits the flow between two legs, and a coaxial probe carries it in the annulus. It is the same value as on the *Heat carrier fluid* panel for the same phase.

The lower block, under the separating rule, reports the undisturbed ground temperature T_g ($^{\circ}\text{C}$) and, where a vertical profile has been analysed, the mean annual ground temperature T_a ($^{\circ}\text{C}$). It carries **four columns**: the first three are the three determination methods of the *Undisturbed temperature* panel, *Manual*, *Circulation* and *Vertical*, shown side by side whichever one is currently selected. A method that cannot produce a value on the loaded data shows a dash; the *Circulation* column, in particular, stays empty when the test has no circulation phase or when both fluid probes are hidden. The fourth column, *Model*, shows the T_g value its slider currently carries. Manual entry and the short-term g-function produce no T_a , so those cells stay blank.

Page 2, FOA regression results - Reached with the  button. Presents, side by side, the results of the heating-phase and recovery-phase regressions: the ground thermal conductivity λ_s (W/m·K), the effective borehole resistance R_b^* (m·K/W) and the critical time t_{cr} (h), which is the value marked by the red line on the regression charts. The recovery column carries no borehole resistance, since R_b^* is recovered from the heating-phase intercept and the recovery phase supplies only a slope.

A further row, **Residual RMSE**, reports the root mean square of the regression residuals over the fitted window, in $^{\circ}\text{C}$. The residual histogram of the FOA panel shows their distribution; their mean and sample standard deviation are given in the CSV export.

Page 3, Short-term g-function results - Reached with the  button. Lists the current value of every calibrated parameter, λ_s (W/m·K), C_s (MJ/m³·K), λ_g (W/m·K), C_g (MJ/m³·K), the shank spacing s (m) and T_g ($^{\circ}\text{C}$), each conductivity/capacity pair followed by the thermal diffusivity $\alpha = \lambda/C$ (m²/s) it implies. Below that, an **experimental** effective borehole resistance R_b^* (m·K/W), computed by the same multipole method as the *Test borehole* panel but from these calibrated values rather than the entered ones, and a **Residual RMSE** row giving the root mean square of the residuals between the measured and the simulated fluid temperature, in $^{\circ}\text{C}$. As on the previous page, their mean and sample standard deviation are exported to CSV rather than shown here.

A single set of statistics describes the two predicted temperatures. With the default excitation both depart from their measurement by the same amount; with the **$Q/(V \cdot C_f)$** excitation the two departures differ and the statistics describe their mean. The residual histogram in the model's panel shows the same residuals as a distribution.

Computation time - The footer shared by every page reports the wall-clock time of each stage of the interpretation pipeline. **Data** covers building the time vector, applying the low-pass filter and splitting the record into its phases; **FOA** covers the two linear regressions; **g-func** covers the spectral convolution of the borehole's response with the measured heat-injection history; and **Chart** covers redrawing the temperature series. The labels are drawn in red while a computation is running and turn black once it completes.



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