8. Thermal Conductivity

8.1. Principles

PHYSICAL BACKGROUND

The coefficient of thermal conductivity, k [W/(m·K)], is a measure of the rate q (W) at which heat flows through a material. It is the coefficient of heat transfer across a steady-state temperature difference ($T_2 - T_1$) over a distance ($x_2 - x_1$), or

$$q = k\,(\Delta T/\Delta x). \qquad (1)$$

Thermal conductivity can be measured by transient heating of a material with a known heating power generated from a source of known geometry and measuring the temperature change with time. The method assumes isotropic materials. Theoretical discussion for measuring thermal conductivity with cylindrical sources is found in Blackwell (1954), Carslaw and Jaeger (1959), De Vries et al. (1958), Von Herzen and Maxwell (1959), Kristiansen (1982), and Vacquier (1985).

For a full-space needle probe, the length L can be assumed to be infinite and the problem is reduced to two dimensions. Given the resistance R of a looped wire in a needle, the generated heat is

$$q = 2\,\mathrm{i}^2\,R / L, \qquad (2)$$

where R/L is the resistance of the needle per unit length. At any time t after heating has started, the temperature T is related to the thermal conductivity k by

$$T = (q / 4\pi k)\,\ln(t) + C, \qquad (3)$$

where q is the heat input per unit length and unit time and C is a constant. A simple way of calculating the thermal conductivity coefficient k is picking T_1 and T_2 at times t_1 and t_2, respectively, from the temperature versus time measurement curve (see also ASTM, 1993):

$$k_a(t) = q / 4\pi\,[\ln(t_2) - \ln(t_1)] / (T_2 - T_1). \qquad (4)$$

$k_a(t)$ is the apparent thermal conductivity because the true conductivity, k, is approached only by a sufficiently large heating duration. This method assumes that the measurement curve is linear and ignores the imperfections of the experiment expressed in the constant C.

In practice, the correct choice of a time interval is difficult. During the early stage of heating, the source temperature is affected by the contact resistance between the source and the surrounding material. During the later stage of heating, boundary effects of the finite length of the source affect the measurement. The position of the optimum interval generally differs from measurement to measurement. The two systems presently available on the ship employ different procedures to select the time interval: the older Thermcon-85 system relies on operator judgment based on visual examination of the $\ln(t)$ vs. T plot; the newer TK04 system uses an algorithm that automatically finds the optimal time interval (Erbas, 1985). More information is provided about each in the following sections.

ENVIRONMENTAL EFFECTS

In situ thermal conductivity is a function of in situ temperature and pressure conditions. Corrections may be applied to laboratory measurements on cores, based on in situ information and theoretical and empirical relationships. Data in the ODP database are not corrected for in situ conditions.

USE OF THERMAL CONDUCTIVITY

Thermal conductivity is an intrinsic material property for which the values depend on the chemical composition, porosity, density, structure, and fabric of the material (e.g., Jumikis, 1966). In marine geophysics, mainly thermal conductivity profiles of sediment and rock sections are used, along with temperature measurements, to determine heat flow. Heat flow is not only characteristic of the material, but an indicator of type and age of ocean crust and fluid circulation processes at shallow and great depths.

8.2. Thermcon-85 System

EQUIPMENT

The Thermcon-85 system consists of the following components:

- Thermcon-85 unit,
- calibrated needle probes,
- personal computer,
- TC-PC control and data reduction program, and
- calibration file for TC-PC.

The Thermcon-85 unit was purchased from Woods Hole Oceanographic Institution. It is under the control of PROM-based programming, and an RS-232 serial interface is available. One to five needle probes can be connected to the rear panel. An eight-channel multiplexer selects the appropriate input for each measurement. See the Thermcon-85 manual for more details.

The needle probes are either assembled at ODP or purchased preassembled. In either case, they contain factory-calibrated thermistors.

The TC-PC program was developed at ODP in 1991 using Quick Basic (v. 4.5) and runs on a PC clone. The following programs are involved:

- TCMENU: controls the overall data acquisition process;
- COLLECT: communicates with the Thermcon-85; performs drift study; collects raw data and writes raw data file; monitors “bad data conditions” (warnings not written to data file);

- PROCESS: allows selection of probe positions; allows for optional correction for temperature drift at drift study termination; allows selection of "optimal" interval; reduces the raw data and calculates thermal conductivity; writes to a results file; and
- PROBES: used to enter thermistor calibration coefficients for new probes and "secondary" probe calibration constants into the PROBES.DAT file.

The user normally runs TCMENU. Interaction with the COLLECT and PROCESS programs is accomplished via menu selection. The calibration data must be entered into the PROBES.DAT file when appropriate.

CALIBRATION

Power Supply, Digital Volt Meter, and Heater Current

Calibration must be periodically performed by an ODP Electronics Technician. Refer to the Thermcon-85 manual for details.

Needle Probe Resistance

The thermistors in each needle probe are calibrated at the factory over a range of temperatures (usually 15° to 75°C) and fit to an equation of the form

$$T^{-1} = alpha + beta \ln(R) + gamma\,(\ln(R))^3, \qquad (5)$$

where T is the temperature in degrees Kelvin, R is the thermistor resistance in ohms, and *alpha*, *beta*, and *gamma* are constants. The error in this procedure is far smaller than the general uncertainty in thermal conductivity measurements. The constants are available to the data reduction program and are used for conversion of measured resistance into temperature. Electronics Technicians are responsible for entering the constants of a new resistor into the program. Do not attempt to re-calibrate the thermistors—a specialized facility is required.

Needle Probe Secondary Calibration

ODP procedure with the Thermcon-85 system includes a calibration of each needle probe using standard materials of "known" thermal conductivity values (Table 8—1). These values were established on Legs 127, 129, and 131 and on subsequent legs using this same instrument. This calibration should be viewed as a relative one that makes ODP shipboard data a little more consistent.

Table 8—1 Standard materials used for calibrations and control measurements.

Standard material	Thermal conductivity [W/(m·K)]
Black rubber	0.54
Red rubber	0.96
Macor	1.61

The standard measurements must be entered into a separate spreadsheet and the liner coefficients (slope, intercept) determined. The coefficients are then entered into the PROBES.DAT file using the PROBES program utility. The thermal conductivity values returned by the PC-TC program are subsequently corrected using these coefficients.

PERFORMANCE

Precision

About 5%. (Systematic evaluation is required.)

Accuracy

About 5%. (Systematic evaluation is required.)

MEASUREMENT

1. Bring cores to temperature equilibrium (about 4 hr). Hard-rock specimens should be placed in a water bath to equilibrate.
2. Soft sediment: drill holes into core liner. Also drill a small hole in semiconsolidated sediment if necessary. Apply thermal joint compound if necessary. Insert full-space probes carefully into sediment. Rocks: prepare smooth surface on a split-core specimen at least 5 cm long. Treat the needles gently, and store them properly when not in use.
3. Insert one probe into a standard material for a control measurement, to be used for later corrections if necessary.
4. Start the TCMENU program and follow the prompts for parameters. Default values are provided for each prompt.
5. Press the reset button on the Thermcon-85 unit to start the drift study. After a couple of minutes, the drift data will be displayed. The drift study is performed in phases of 25 minutes, the maximum time the box can be programmed. The drift study is terminated if all positions are equilibrated or if the user overrides the drift study.
6. Press the reset button twice to start the process of heating, data acquisition, and creation of the raw data file. Messages will be displayed if there are data or hardware problems.
7. The user has the option of acquiring more data and processing batches of data later or processing the data collected immediately. It is recommended to process the data immediately.
8. Load the PROCESS program from the TCMENU screen. The run just completed will appear as the default run to be processed. Accept or change it.
9. Select the position to be processed and the drift correction. The ln(t) vs. T graph will be displayed.
10. Select the time interval to be processed by moving the cross hairs on the screen. For routine processing, use the same interval used for secondary probe calibration. Adjust if necessary. Press enter to calculate conductivity and the fit parameter. Warnings will come up if the nonlinear component is considered too large, the fit is poor, the segment is considered too short, etc.
11. Press enter twice to write the conductivity of a segment to the Results file.

DATA PROCESSING

Data reduction with the TC-PC program written for the Thermcon-85 system is based on a least-squares fit of the measured temperatures to the following equation, which is a variation of Equation XXX(107?):

$$T = (q / 4¼k) \ln(t) + At + B. \quad (6)$$

The constant *A* is the temperature drift rate (also including edge effect, asymmetry, nonzero epoxy conductivity, etc.) during measurement and is expressed in K/min. The constant *B* represents other imperfections in the experiment. The unknowns in this system are *k*, *A*, and *B*, so when more than three data pairs are acquired the system is overdetermined. Using the previous equation for the rate of heating, the coefficient *k* can be determined at any time increment *dt* as

$$k = [2\, i^2\, R / L\, d\ln(t)] / 4¼\, (dT - At - B)], \text{ or} \qquad (7)$$

$$k = (i^2\, R / 2¼L)\, [d\ln(t) / (dT)]. \qquad (8)$$

The first group of terms in these equations is an instrument constant including generated heat and needle geometry. The second group of terms is calculated for each measurement.

The optimum time segment for calculating thermal conductivity is selected interactively by the user by placing cross hairs on a ln(*t*) vs. *T* plot of the data. Information on the quality of the fit is updated on the screen as the cross-hairs are moved. The curve-fit parameter is the root mean square of the temperature deviation and should not exceed 0.04°C/min. However, it is more important to choose a consistent sampling time than it is to reduce the drift as much as possible.

DATA SPECIFICATIONS

TC-PC Output Files

At present, the TC-PC data are not integrated in the new ODP database. The following two program output files are archived: the “Processed Data” or “Results” (*.DAT) files and the “Raw Data” (*.TC) files.

Data in the *.DAT files are fixed format, mixed string, and numeric, with one record (line) per position per TC run. If a given position on a run is not processed, then there is no entry in this file. However, if a given position is processed more than once, there are multiple lines in this file for that position. The file name is the hole identifier.

Data in the *.RAW files are free-format in which each line represents an output string from the program. If a position was not used, some strings are omitted and some return zero values. The file name is a combination of hole ID and run number.

Table 8—2 TC-PC “Processed Data” file.

Short description	Description	Data file designations
Leg	Leg	[TC-PC Results 1-4] leg
Site	Site	[TC-PC Results 8-11] site
Hole	Hole	[TC-PC Results 13] hole
Core	Core	[TC-PC Results 15-17] core
Core type	Core type	[TC-PC Results 19] core_type
Section	Section	[TC-PC Results 21-22] section_or_std
Top	Interval top (cm)	[TC-PC Results 24-28] interval_top
Bottom	Interval bottom (cm)	[TC-PC Results 30-34] interval_bottom
Space	Space model	[TC-PC Results 49] full_or_half
Run No.	Run number	[TC-PC Results 51-53] run_number
Probe	Probe number	[TC-PC Results 55-57] probe_number
Position	Position number	[TC-PC Results 59] position_number
TC uncorr.	Uncorr. thermal conductivity. [W/(m·K)]	[TC-PC Results 61-67] calculated_tc

Table 8—2 TC-PC "Processed Data" file.

TC corr.	Corr. thermal conductivity. [W/(m·K)]	[TC-PC Results 69-75] corrected_tc
R2	Standard error R^2	[TC-PC Results 77-87] standard_error
Drift	Calculated drift (°C/s)	[TC-PC Results 89-97] calculated_drift
Lower end	Lower end point used	[TC-PC Results 99-100] lower_end_point
First time	Time at lower end point (s)	[TC-PC Results 102-104] time_at_first_point
Upper end	Upper end point used	[TC-PC Results 106-107] upper_end_point
Last time	Time at upper end point (s)	[TC-PC Results 109-111] time_at_last_point
Drift status	Drift study status	[TC-PC Results 113-126] drift_status
T drift	Temp. at drift study termination (°C)	[TC-PC Results 128-132] drift_temperature
Drift rate	Drift rate at termination (°C/s)	[TC-PC Results 134-142] drift_rate
Drift fit	Least-squares fit for drift	[TC-PC Results 144-151] drift_fit
Run status	Run status (NORMAL, ...)	[TC-PC Results 153-160] run_status
Alpha	Probe alpha constant	[TC-PC Results 162-180] probe_alpha
Beta	Probe beta constant	[TC-PC Results 182-200] probe_beta
Gamma	Probe gamma constant	[TC-PC Results 202-220] probe_gamma
Resistance	Probe wire resistance (ohm/cm)	[TC-PC Results 222-227] probe_wire_resistance
Half space	Probe half-space flag (1 = true)	[TC-PC Results 229-230] half_space_flag
Probe m1	Probe secondary calibration slope	[TC-PC Results 232=238] probe_m1
Probe m0	Probe secondary calibration intercept	[TC-PC Results 240-246] probe_m0
Lower end	Upper end point, probe calibration (s)	[TC-PC Results 248-250] time_at_first_point
Upper end	Lower end point, probe calibration (s)	[TC-PC Results 252-254] time_at_last_point
Drift corr.	Drift correction status	[TC-PC Results 256-268] drift_correction_status
Version	Version of TC-PC program	[TC-PC Results 270-274] tcpc_version
Comment	Comment	[TC-PC Results 276-356] comment

Notes: The numbers following the file name (TC-PC Results . . .) are positions in the fixed-space format of the output file. Corrected thermal conductivity is corrected using the secondary probe calibration coefficients m_1 and m_0 obtained from standard measurements. Corrected thermal conductivity is added only if the user selects this option when specifying data reduction. If correction is not selected, the position numbers are reduced by 8 spaces starting with the "Standard error" field.

Table 8—3 TC-PC "Raw Data" file (free format).

Short description	Description	Data file designations
Run parameters		
Title	Title string	[TC-PC Raw 1] title
Run	Run number	[TC-PC Raw 2] run_number
Positions	No. of positions used; length (min.)	[TC-PC Raw 3] no_of_positions_length
Parameters for first position		
Sample ID	ODP sample identification	[TC-PC Raw 4] sample_id
Piece	Piece	[TC-PC Raw 5] piece
Subpiece	Subpiece	[TC-PC Raw 5] sub_piece
Space	Space model	[TC-PC Raw 7] full_or_half
Position no.	Position number	[TC-PC Raw 8] position_number
Alpha	Probe alpha constant	[TC-PC Raw 9.1] probe_alpha
Beta	Probe beta constant	[TC-PC Raw 9.2] probe_beta
Gamma	Probe gamma constant	[TC-PC Raw 9.3] probe_gamma
Resistance	Probe wire resistance (ohm/cm)	[TC-PC Raw 9.4] probe_wire_resistance
Half space	Probe half-space flag (1 = half)	[TC-PC Raw 9.5] half_space_flag
Probe m_1	Probe secondary calibr. slope	[TC-PC Raw 9.6] probe_m1
Probe m_0	Probe secondary calibr. intercept	[TC-PC Raw 9.7] probe_m0
Lower end	Lower end point, probe calib. (s)	[TC-PC Raw 9.8] time_at_first_point
Upper end	Upper end point, probe calib. (s)	[TC-PC Raw 9.9] time_at_last_point
Comment	Position-specific comment	[TC-PC Raw 10] comment
Parameters repeated for other positions[a]		
Drift time	Drift: no. of readings; length(s)	[TC-PC Raw one line, two values]
Drift study for first position		
Drift t-T	String of time-temperature pairs	[TC-PC Raw one line, unlimited pairs]
Drift end	Temp., rate., fit, at end of drift study	[TC-PC Raw one line, three values]
Drift study repeated for other positions[b]		

Table 8—3 TC-PC "Raw Data" file (free format).

Drift status	Drift status (OK; OVERRIDE)	[TC-PC Raw one line, one alpha string]
Data for positions 1–5		
Data	Cycle #; ref. volt; I1 to I5; current	[TC-PC Raw multiple lines, 3-8 values per line)
Data repeated for each meas. cycle[c]		
Run status	Run status (NORMAL...)	[TC-PC Raw one line, one alpha string]

Notes: [a]The probe parameters of lines 4–10 are written for subsequent positions only if the positions were used, otherwise the lines are omitted. [b]The drift study data lines (two lines per position) are always written to the file regardless whether positions were used or not. If a position was not used, all values are zero. [c]Data are written on one line for each measurement cycle. On each line, there are the following readings separated in time by 3 s (hard-coded in the program): (1) cycle number; (2) internal reference voltage; (3) to (7) up to five probe voltage readings (no reading for unused positions); (8) heater current. Total time for one cycle is (2 + <number of positions used>) times 3 s (2 stands for reference and heater current readings). It varies between 6 s (no position used) and 21 s (five positions used).

Database Model

Table 8—4 Database model

TCON section

tcon_id [PK1] [FK]	
tcon_probe_num [PK2] [FK]	
	top_interval
	bottom_interval
	section_id

TCON control

tcon_id [PK1] [FK]
tcon_probe_num [PK2] [FK]
standard_id [PK3] [FK]

TCON drift raw data

tcon_id [PK1] [FK]	
tcon_probe_num [PK2] [FK]	
tcon_raw_drift_time [PK3]	
	tcon_raw_drift_temp

TCON probe proc. data

tcon_id [PK1] [FK]	
tcon_probe_num [PK2]	
	tcon_comment
	tcon_meas_calib_m0
	tcon_meas_calib_m1
	tcon_meas_calib_time_first
	tcon_meas_calib_time_last
	tcon_meas_drift_lsq_fit
	tcon_meas_drift_rate_final
	tcon_meas_drift_temp_final
	tcon_probe_alpha
	tcon_probe_beta
	tcon_probe_gamma
	tcon_probe_half_full
	tcon_probe_specific_res
	tcon_proc_drift_corr_flag
	tcon_proc_point_first
	tcon_proc_point_last
	tcon_proc_thermcon
	tcon_proc_time_first
	tcon_proc_time_last
	tcon_raw_drift_status
	tcon_raw_pos_num

TCON run

tcon_id [PK1]	
	tcon_run_minutes
	tcon_run_number
	tcon_run_status

TCON cycle

tcon_id [PK1] [FK]	
tcon_cycle_num [PK2]	
	tcon_raw_heater_current
	tcon_raw_heater_curr_time
	tcon_raw_rel_voltage
	tcon_raw_rel_voltage_time

TCON probe cycle

tcon_id [PK1] [FK]	
tcon_cycle_num [PK2] [FK]	
tcon_probe_num [PK3]	
	tcon_raw_time
	tcon_raw_voltage

Standard Queries

The standard queries will be defined once the upload routine has been implemented.

8.3. TK04 System

EQUIPMENT

ODP purchased the TK04 system in late 1995 and deployed it permanently on the ship on Leg 168 (1996). The system was to replace the ailing Thermcon-85 device, built at the Woods Hole Oceanographic Institution (WHOI) and in service on the ship for many years. Currently, both systems are available to the user on the ship.

The TK04 was built by the Berlin company Teka based on an apparatus that had been developed at the Technische Universität Berlin. It was used successfully for thousands of measurements on material from the Continental Deep Drilling Program (KTB). The TK04 consists of

- automatic self-test, heating, and measurement unit TK04,
- full-space (VLQ) and half-space (HLQ) needle probes,
- vice and manual hydraulic pump for half-space contact measurements on rocks, and
- Macor standards for both types of needle probes.

The TK04 measuring system features a self-test at the beginning of each measuring cycle (including probe number validation), registration of the source temperature and its drift, and calculation of the heating power used.

The following executable programs are used to operate the system:

- TKMEAS.EXE to acquire time-temperature data series (creating *.DWL files),
- TKEVA for standard (<5% uncertainty) or special (<2% uncertainty) re-evaluation of data, creating short *.DAT or long *.ERG lists and parameter files, and
- TKGRAPH to display all solutions and assess the quality of the calculated solutions.

In addition, the following parameter files are used:

- TKMEAS.MNU, a list of standard menu settings for TKMEAS.EXE,
- *.INI, list of parameters for probes, where “*” is the number engraved on the probe, and
- TKEVA.INI, list of user-modifiable parameters required for TKEVA.EXE.

Multiple measurements can be taken under identical conditions. The instrument cycles through the measurements automatically, creating files with the user-defined root name (e.g., Core-Section-Interval; only six characters allowed) and a two-digit serial number incrementing by one for each measurement within a cycle. The following files are created by the TK04 system:

- <Rootname-SerialNo>.DWL, (if “Save data” was selected); contains measurement parameters and temperature-time series (raw data), required for extended evaluations; it is not necessary, but strongly recommended, to save the heating curves for routine evaluation. These files allow later extended evaluation and graphical display of the solutions.
- <Rootname->.LST, short list of results from evaluating one root-name-batch of *.DWL files using either the “special approximation method”

(SAM) or conventional (CON) method; contains evaluation parameters and the optimal calculated thermal conductivity value. This is the standard results file.

- TC-LIST.DAT, multiline short list (optional); contains the same information as previous file <Rootname->.LST but for multiple root names. This file is updated as new evaluations are performed. This file is created only by the optional extended evaluation.
- <Rootname>.ERG, long lists of results from evaluating *.DWL files with the SAM method; contains evaluation parameters and all valid calculated thermal conductivity values. This file is optional and required only if graphical evaluation of all valid solutions is desired. It can be created at any time if the *.DWL files are saved. This file is created only by the optional extended evaluation.

CALIBRATION

No calibration is required. The unit conducts a self-test at the beginning of each measurement cycle. Macor standards are used to confirm the 1.65 W/(m·K) value.

DATA PROCESSING

The Special Approximation Method (SAM)

The main advantage of the Teka data reduction program is the SAM that ensures that only results of physical significance are considered. The critical choice of time interval for calculation of conductivity, selected manually by the user with the Thermcon-85 system, is accomplished by an algorithm that automatically finds the optimal time interval. The solution can be judged in great detail and the data reevaluated with different boundary parameters if warranted. The following explanations are modified from the Teka user manual.

The first evaluation step is an approximation to the solution of a constantly heated line source (Kristiansen, 1982):

$$T(t) = A_1 + A_2\ln(t) + A_3[\ln(t)/t] + A_4(1/t). \tag{9}$$

The coefficients A_i are calculated with the least-squares method. A_1, A_3, and A_4 are related to source geometry and thermal properties. A_2 is calculated by

$$A_2 = q / 4\pi k, \tag{10}$$

where q is the heating power (Wm) and k [W/(m·K)] is the thermal conductivity. If the coefficients A_i are determined, $T(t)$ can be expressed analytically and the apparent thermal conductivity $K_a(t)$ can be calculated by differentiating Equation on page 9 with respect to $\ln(t)$:

$$k_a(t) = dT/d\ln(t) = q/4\pi \, \{A_2 + A_3[1/t - \ln(t)/t] + A_4/t\}. \tag{11}$$

It can be shown that the desired value k is at $k_a(t_{max})$, where t_{max} is the “extreme time.” The requirement for the maximum is

$$d/dt[k_a(t_{max})] = 0, \tag{12}$$

and t_{max} is

$$t_{max} = e^{(2A3-A4)/A3}, A_3 > 0. \tag{13}$$

The logarithm of the extreme time (LET) becomes

$$LET = \ln(t_{max}) = (2A_3 - A_4) / A_3. \quad (14)$$

The time-dependent terms in previous equation are:

$$T(t_{max}) = A_2\ln(t_{max}) + A_3[\ln(t_{max})/t_{max}] + A_4/t_{max}. \quad (15)$$

A_4 can be substituted with (previous) Equation (118?) to give

$$T(t_{max}) = A_2\ln(t_{max}) + 2A_3[\ln(t_{max})/t_{max}]. \quad (16)$$

This equation shows that the purely logarithmic dependence of the approximated temperature (required by the theory) is stronger the larger t_{max} gets. For large t_{max}, the second term in Equation on page 10 approaches zero.

The evaluation procedure approximates the heating curve in as many time intervals as possible and examines each interval for its suitability for thermal conductivity calculation using the following criteria:

1. $k_a(t)$ is located above a given value of time defined by LET,
2. standard deviation of the function for A_2 is below a given value,
3. $k_a(t)$ is a maximum: $A_3 > 0$, and
4. derivation $k_a(t)$ is continuous for $t = t_{max}$: $A_2 t_{max} – A_3$ - 0.

If these criteria are met, thermal conductivity can be calculated as

$$k = q / (4\pi A_2). \quad (17)$$

The evaluation interval is restricted by the dimension of the line source. It must be within the interval of 20 to 80 s to avoid boundary effects, and at least 25 s long for a stable calculation of the coefficients. The input parameters for standard evaluation are

- minimum duration of approximation interval: 25 s,
- start of first approximation interval: 20 s,
- end of last approximation interval: 80 s,
- lower limit for LET: 4, and
- maximum standard deviation of calculated temperature curve from measured heating curve: 0.0003.

With the default parameters, the heating curve is approximated for the following time intervals:

[20,45] [20,46] [20,47] . . . [20,78] [20,79] [20,80]
[21,46] [21,47] . . . [21,78] [21,79] [21,80]
[22,47] . . . [22,78] [22,79] [22,80]
. . .
[53,78] [53,79] [53,80]
[54,79] [54,80]
[55,80]

Among all time intervals that fulfill the listed criteria, the one with the largest LET is used to calculate thermal conductivity. No solutions may be found if the measurement is disturbed by poor sample condition or ambient temperature changes.

Extended Evaluation

An extended evaluation is required if

- the valid solutions are to be plotted against the calculation parameters to judge the results graphically, or
- the measurements are to be reevaluated with different parameters (e.g., a stronger criterion for the LET).

In both cases, the *.DWL files containing the temperature-time data are required. The *.ERG files (long result lists) that can be created contain all valid solutions for the thermal conductivity, and a line entry in the TC-LIST.DAT file is created with the asymptotic (optimal) thermal conductivity value. There are three options for extended evaluation:

- single evaluation: typing <TKSAM> prompts for filename,
- batch mode with filename as parameter: typing <TKSAM filename> starts evaluation using the standard parameters (no *.ERG file is created), and
- Batch mode evaluating a sequence of data files: after typing TKSAM, type return instead of a filename; all *.DWL files in the directory will be evaluated.

The manufacturer's manual should be consulted for details in regard to file path requirements, data quality issues, etc.

Graphical Evaluation

The program TKGRAPH can be used to visualize and judge the quality of all valid SAM evaluation results for thermal conductivity. *.ERG files are required for plotting. Four graphs are presented for each measurement:

- thermal conductivity vs. LET,
- thermal conductivity vs. interval duration,
- thermal conductivity vs. start of interval, and
- thermal conductivity vs. end of interval.

A series of files can also be viewed. Consult the manufacturer's manual for system configuration, practical hints, guidance for the judgment of results, etc.

Evaluation with Conventional Method

Under certain experimental circumstances (e.g., porous material, high water content) the SAM evaluation may not accept any results because the measurements are too disturbed for the sensitive approximations. In these cases, results may be obtained using the conventional evaluation method in which thermal conductivity is calculated from the inverse slope of the heating curve in a section of logarithmic linearity. In general, a heating duration > 80 s becomes necessary. Accuracy of conventional evaluations is not as good as that of SAM evaluations and the quality cannot be verified graphically.

The program TKCON.EXE is used for the conventional evaluation. The structure and application is similar to the TKSAM.EXE program. The configuration file TKCON.INI includes the following standard parameters:

- minimum duration of interval: 30 s,
- start time: 30 s,
- end time: 120 s, and
- standard deviation of fit: 0.003.

Existing data can be evaluated later with the conventional method (i.e., after the SAM method has failed to yield solutions). Automatic Evaluation with TKCON can be set by typing

TKMEAS/EVA=CON

or if the option

TKMEAS/DCL=20/EVA=CON

is entered. Calling TKMEAS without the /EVA option invokes evaluation with TKSAM.EXE.

A short list of results is created by TKCON with similar structure as the file created by TKSAM. The difference is that instead of LET the standard deviation is reported. The evaluation method used (SAM; CON) is indicated in each line of the file. A long list of results for each measurement can be produced by typing, prior to starting TKMEAS:

set TKCON=ON

The long list includes the calculated values of thermal conductivity, standard deviation, and the start, duration, and end of each interval.

Half-Space Measurements

For the half-space needle probe (HLQ) it is expected that the total amount of produced heat penetrates into the sample. The thermal conductivity is thus calculated with twice the heating power used for the full-space solution. This assumption is justified if the thermal conductivity of the samples is not lower than about 1 W/(m·K); at lower values an error arises because some of the produced heat is penetrating the probe half-space, in which case it is necessary to determine correction factors to compensate for the heat loss.

PERFORMANCE

Precision

Extended evaluation, using special parameters adapted to circumstances, yields an uncertainty of less than 2%. This is clearly smaller than variations caused by sample preparation and inhomogeneities in rocks and sediments, and special evaluations are appropriate only for standard materials and fundamental material investigations.

Accuracy

Random variations of thermal conductivity in natural materials such as sediments and rocks typically give an uncertainty of about 5%. Routine evaluation using the TKEVA.EXE has an accuracy of about 5% and is therefore appropriate.

MEASUREMENT

Standard Settings for Data Acquisition

1. Bring cores to temperature equilibrium (about 4 hr). Hard-rock specimens should be placed in a water bath to equilibrate.
2. Soft sediment: drill holes into core liner. Also drill a small hole in semiconsolidated sediment if necessary. Apply thermal joint compound if necessary. Insert full-space probes carefully into sediment. Hard-rocks: prepare smooth surface on a half-core specimen at least 5 cm long. Treat needles gently, store them properly when not in use.

3. On the computer, change to directory containing the TKMEAS.EXE file, press enter.
4. Type TKERG = ON, press enter.
5. Type the command tkmeas, press enter.
6. Set the parameters on the screen. Heating power should be about 5 W/m (adjust if necessary); measuring time should be about 80 s; enter Y to save time-temperature data.

DATA SPECIFICATIONS

TK04 Output Files

Currently, TK04 data are not integrated in the new ODP database. The following program output files are archived.

Table 8—5 TK04 "raw data file": <Rootname-Serial>.DWL.

Short description	Description	Data file designation
Header		
Filename	Root name (custom sample id), serial	[TK04 Raw Data] rootname_serial
Probe	Probe ID, TK04, date	[TK04 Raw Data] probe
Comment	Comment, used to identify sample	[TK04 Raw Data] comment
Heat	Heating power (W/m)	[TK04 Raw Data] heating_power
Fit	Slope, Std. dev., temperature	[TK04 Raw Data] fit
?Something	?'Reserved'	[TK04 Raw Data] ?something
?Value1	?Some (drift?) value 1	[TK04 Raw Data] ?value1
?Value2	?Some (drift?) value 2	[TK04 Raw Data] ?value2
Data		
Temp	Temperature (°C)	[TK04 Raw Data] temperature
Time	Time (s)	[TK04 Raw Data] time
Resistance	Resistance (ohm)	[TK04 Raw Data] resistance

Table 8—6 TK04 "results short list": <Rootname>.LST (one rootname batch).

Short description	Description	Data file designation
Filename	Root name + serial (sample ID)	[TK04 Results] rootname_serial
TC	Calculated thermal conductivity	[TK04 Results] calculated_tc
LET/STD	LET (SAM) of std. dev. (CON)	[TK04 Results] let_or_sd
Solutions	No. of solutions found	[TK04 Results] solutions
Start time	Start of approx. time interval (s)	[TK04 Results] time_start
Time	Length of approx. time interval (s)	[TK04 Results] time_length
End time	End of optimal time interval (s)	[TK04 Results] time_end
Eval.	Evaluation method (SAM or CON)	[TK04 Results] eval_method
Hints	Comments (from *.DWL file)	[TK04 Results] hints

*Table 8—7 *TK04 "appended results short list": <Rootname>.LST (all rootnames).*

Short description	Description	Data file designation
Filename	Root name + serial (sample id)	[TK04 Results] rootname_serial
TC	Calculated thermal conductivity	[TK04 Results] calculated_tc
LET/STD	LET (SAM) of std. dev. (CON)	[TK04 Results] let_or_sd
Solutions	Number of solutions found	[TK04 Results] solutions
Start time	Start of approximate time interval (s)	[TK04 Results] time_start
Time	Length of approx. time interval (s)	[TK04 Results] time_length
End time	End of optimal time interval (s)	[TK04 Results] time_end
Eval.	Evaluation method (SAM or CON)	[TK04 Results] eval_method
Hints	Comments (from *.DWL file)	[TK04 Results] hints

*Table 8—8 *TK04 “extended results file”: *.ERG files.*

Short description	Description	Data file designation
Header:	SAM Evaluation Parameters	TKSAM.EXE
Filename	Root name + serial (sample ID)	[TK04 Results] rootname_serial
Comment	Comment, used to identify sample	[TK04 Raw Data] comment
Time	Time interval minimum (s)	[TK04 Results] eval_interval_min
Start time	Start of evaluation (s)	[TK04 Results] eval_time_start
End time	End of optimal time interval (s)	[TK04 Results] eval_time_end
LET	Nat. log. of time	[TK04 Results] eval_let
Std. Dev.	Limit of std. dev. (optional; 0.0003)	[TK04 Results] eval_limit_sd

Table 8—9 Valid solutions.

Short description	Description	Data file designation
TC	Calculated thermal conductivity	[TK04 Results] calculated_tc
LET	Natural logarithm of time at max. therm.al condition	[TK04 Results] let
Start time	Start of approx. time interval (s)	[TK04 Results] time_start
Time	Length of approx. time interval (s)	[TK04 Results] time_length
End time	End of optimal time interval (s)	[TK04 Results] time_end
Std. Dev.	Standard deviation of fit	[TK04 Results] std-deviation

Notes: *ERG files are optional. They are created by extended evaluation and are required only for graphical evaluation. They can be recreated from *.DWL files at any time.

Database Model

A database model and integration into the database are difficult to implement without writing an ODP sample identification routine linked to the TK04 output. A better approach is to write an entirely new user interface for the system, preferably for an upgraded version with multiple-channel capability.