METER
ENVIRONMENT

TEMPOS COMPLIANCE TO ASTM AND IEEE STANDARDS

ASTM STANDARD REVISED IN 2022

ASTM D5334-22 is a significantly updated version of the Standard Test Method for Determination of Thermal Conductivity of Soils and Rock by Thermal Needle Probe Procedure. It represents the best practices in accordance with current research in heat and mass transfer. For accurate measurements, it is important to specify and use the most current version of this standard.

ELEMENTS OF TEMPOS COMPLIANCE TO ASTM D5334-22

TEMPOS TR-3 and the KS-3 single-needle probes have sufficient length-to-diameter ratio to simulate conditions for an infinitely long, infinitely thin heating source. TEMPOS provides neither a drilling device nor a balance, but the package does include standard material for accuracy verification and accessories capable of drilling a pilot hole with a diameter and depth equal to the dimensions of the probe needles. Select requirements from ASTM D5334-22 are listed below with an explanation of TEMPOS' compliance to the standard.

6.2 Constant current source—a device to produce a constant current

TEMPOS compliance: meets

> TEMPOS produces a constant voltage and measures the current. Since the probe resistance is constant, the current also remains constant.

6.3 Temperature readout unit or recorder—a device to record the temperature from the thermocouple or thermistor with a readability of 0.01 K or better

TEMPOS compliance: meets

TEMPOS measures temperature with a resolution of 0.001 K.

6.4 Voltage-Ohm-Meter (VOM)—a device to read voltage and current to the nearest 0.01 V and 0.01 A

TEMPOS compliance: meets

TEMPOS uses a linear voltage regulator that precisely regulates voltage instead of measuring but is capable of reading voltage to the nearest 0.01V. TEMPOS reads current to better than the nearest 0.01 milliamp.

6.5 Timer—a clock, stopwatch, digital timer, or integrated electronic timer capable of measuring to the nearest 0.1 s or better for the duration of the measurement

TEMPOS compliance: meets

TEMPOS measures time to better than the nearest 0.01 second.

8.1 The thermal needle probe apparatus shall be calibrated before its use. Perform calibration by comparing the experimental determination of the thermal conductivity of a standard material to its known value.

TEMPOS compliance: meets

TEMPOS calculates thermal conductivity by measuring the power to the heater and the resulting changes in temperature and then applying principles of thermodynamics. We validate each sensor using a standard of known conductivity. We do not compute a calibration factor. The user can take the readings in likely calibration standards and apply a correction, but this will make the reading worse if the differences in media diffusivity are not taken into account.

8.1.1 All subsequent measurements with the thermal needle probe apparatus shall be multiplied by C before being reported. Although calibration is mandatory, it is especially important with large diameter needle probes (that is, d > 2.54 mm) where departures from the assumption of an infinitely thin probe cause potentially significant differences in estimation of the thermal conductivity due to non-negligible heat storage and transmission in the needle probe itself.

TEMPOS compliance: partial (requires external user action)

This adjustment needs to be computed and applied by the user, so that the user can be fully apprised of the effect. Again, METER does not recommend applying a calibration. TEMPOS does not compute, store, or apply a calibration factor.

8.3 Calibration standard—one or more materials with known values of thermal conductivity in the range of the materials being measured, which is typically $0.2 < \lambda < 5$ W/m·K. Suitable materials include dry Ottawa sand, Pyrex 7740, fused silica, Pryoceram 9606 (3), glycerine (glycerol) with a known thermal conductivity of 0.286 W/(m·K) at 25 °C (3), or water stabilized with 5 g agar per litre (to prevent free convection) with a known thermal conductivity of 0.607 W/m·K at 25 °C (3). (See Annex A2 for details on preparation of calibration standards.) The calibration standard shall be in the shape of a cylinder. The diameter of the cylinder shall be at least 40 mm or 10 times the diameter of the thermal needle probe, whichever is larger, and the length shall be at least 20 % longer than the needle probe. On solid specimens, a hole is drilled along the axis of the cylinder to a depth equivalent to the length of the probe. The diameter of the hole shall be equal to the diameter of the probe so that the probe fits tightly into the hole. For drilled specimens, the probe shall be coated with thermal grease to minimize contact resistance.

TEMPOS compliance: meets

TEMPOS probes are validated in a 6 cm diameter, 120 mm long cylinder of glycerine.

8.4 The measured thermal conductivity of the calibration specimen must agree within one standard deviation of the published value of thermal conductivity, or with the value of thermal conductivity determined by an independent method.

TEMPOS compliance: unknown

ASTM D5334-22 does an inadequate job of defining the "standard deviation of the published value of thermal conductivity." If this statement is taken to mean the standard deviation of the thermal conductivity values yielded by repeated measurements with the device, then inherently unstable measurement devices will be more likely to meet the standard than higher quality devices. If this statement is taken to mean the standard deviation of a reference value published in the literature, then it will be impossible to quantify as reference values do not specify a standard deviation.

9.4 Apply a known constant current, for example, equivalent to 1.0 A, to the heater wire such that the temperature change is less than 10 K in 1000 s.
TEMPOS compliance: meets

The current is constant in that it does not change for the duration of the reading, and the current is the same from one reading to the next for a given sensor. The TEMPOS does not verify the temperature rise for each reading. Typical temperature rise for a TR-3 needle over 300 seconds at maximum power in dry silica sand is 4.3 K. Because of the logarithmic nature of the heating curve, the temperature change in 1000 seconds will be less than 10 K.

Typical temperature rise for a KS-3 needle over 300 seconds at maximum power in dry silica sand is 10.9 K. At low power, the KS-3 needle's temperature rise is compliant in dry silica sand. (Note: Dry silica sand is selected as the medium in these examples because of its low conductivity).

The intention of this requirement is to ensure that the temperature change is large enough to measure accurately for precise calculations, but large enough to affect the properties of the medium. TEMPOS includes a low heat mode for low-conductivity media.

9.5 Record time and temperature readings for at least 20 to 30 steps throughout the heating period. The total heating time should be appropriate to the thermal needle probe size. For a small diameter needle (that is, $d < 2.54$ mm), a 30- to 60-second heating duration is sufficient to accurately measure thermal conductivity.

TEMPOS compliance: meets

TEMPOS employs two heating profiles for single-needle probes. In ASTM/IEEE mode the reading duration can be set to five or ten minutes, half of which is heating time. 30 temperature measurements are taken during the heating time. This is longer than the ASTM recommendation but is necessary for accurate readings when using the Infinite Line Heat Source (ILHS) model.

In other modes (Soil, Rock, and Conductivity), the needle heats for the entire 60-second reading duration. 60 temperature readings are taken during that time. The reference model for these modes employs an adjustable start time, which permits accurate results with lower read times.

10.2.3 The data included in the analysis shall be evenly spaced with the logarithm of time (X-axis). If data are collected in even time increments and subsequently plotted on a log time scale, then the distribution becomes uneven, biasing the analysis too heavily toward the long term of the testing period.

TEMPOS compliance: partial (requires external user action)

TEMPOS does not evenly distribute the temperature measurements with the logarithm of time when making calculations. We have not recognized any problems from distributing temperatures evenly in time. TEMPOS provides all data for the user to select temperature measurements according to any desired profile.

TEMPOS COMPLIANCE TO IEEE STANDARD 442/D3

The IEEE updated 442-03 to IEEE 442/D3 in 2017. It is still a draft revision, but it is considered to be a final draft. The previous thorough consideration and revision were in 1981. The theory and techniques called out in the new revision remain mostly unchanged, and TEMPOS complies with all theoretical assumptions upon which IEEE 442/D3 is based.

As the IEEE continues to update this standard, it may be advisable to specify and follow ASTM 5334-14, which better represents current state-of-the-art theory and practice in heat and mass transfer. Inaccuracies may result from explicitly following the field probe dimensions and probe heating times outlined in IEEE 442/D3, as explained below.

TEMPOS COMPLIANCE WITH IEEE P442™/D3

METER has developed TEMPOS to provide accurate thermal property measurements of soils, backfill, concrete, and a host of other materials.

TEMPOS includes an ASTM/IEEE mode that intends to meet the IEEE 442/D3 standard as closely as possible without compromising the accuracy of the measurements, acknowledging that the laws of soil physics are certain and inviolable, and measurements can be accurate only by recognizing the bounds set by nature. METER recommends using the other TEMPOS modes that use improved methods for measuring conductivity and diffusivity because they are faster and more accurate. However, for applications that still require IEEE compliance, TEMPOS is compliant with the IEEE 442/D3 standard, with the exception of the self-contradicting guidance IEEE 442/D3 gives in regard to needle specification.

Select requirements from IEEE 442/D3 are listed below with an explanation of TEMPOS' compliance to the standard.

FACTORS INFLUENCING MEASUREMENTS (PAGE 12, SECTION 3.1)

Bullet 1: "Migration of the soil moisture away from the probe during the test can result in higher soil thermal resistivity measurements. This migration may be significant and normally takes place when the input power per unit length of the probe is sufficiently high to drive the moisture away from the probe."

TEMPOS compliance: N/A

No requirement is specified; however, TEMPOS makes every effort to avoid this pitfall by employing a low probe power input and a shorter heating time. Lower probe power input results in a smaller temperature rise, so TEMPOS needs high-resolution temperature measurements in order to make an accurate reading.

Bullet 5: "Power supply stability shall be maintained throughout the test. The power dissipated in the probe shall be controlled so that variation in the magnitude of heat flux is kept within ±1%."

TEMPOS compliance: meets

Heat flux, or heat transfer per rate unit area, is calculated from the heat transfer rate, *Q*, and the Area *A. A* is constant for the TEMPOS system; *Q* is measured in units of energy per unit time, such as BTU/hr or Watts. The formula for the heat transfer rate is $Q=I^2R$, where *I* is the current and *R* is the resistance of the probe heater. The current '*I*' is the only component of *Q* that varies over the course of a measurement; power varies with I^2. Measured values of power variation over a reading follow:

	Average	Maximum
Power Variation	±0.041%	±0.306%

Table 1. Measured values of power variation over a reading

LABORATORY THERMAL PROBE (PAGE 13, SECTION 4.2.1)

"Laboratory measurements use a small stainless steel probe with length to diameter ratio of 50 to 1."

TEMPOS compliance: met with TEMPOS TR-4 needle, but not met with TEMPOS KS-3 and TR-3 needles.

For conductivity calculation techniques to be effective, a probe needs to approximate a line heat source or an infinitely thin and infinitely long sensor. IEEE 442/D3 apparently judges that a length to diameter ratio of 50:1 is ideal to approximate this theoretical model; however, neither of the examples in the specification has a 50:1 ratio. The laboratory example in section 6.2, Figure 1, has an aspect ratio of 37.5:1. Annex B single-sensor laboratory probe has a ratio of 67:1. TEMPOS uses the TR-3 and the KS-1 for measurements requiring IEEE compliance, which have aspect ratios of 41.7:1 and 46.2, respectively. These values fall between the two examples in the IEEE specification and are nearer to 50:1.

Length/diameter ratios are listed below for all TEMPOS probes. Note that field probes (e.g., the METER RK-3) have no recommended ratio of length to diameter. All TEMPOS probes are made from stainless steel.

Needle	IEEE-1	IEEE-2	TR-3	TR-4	KS-3	RK-3
Length (mm)	100	120	100	100	60	60
Diameter (mm)	1.5	3.2	2.4	1.9	1.3	3.9
Length/Diameter	67:1	37.5:1	41.7:1	56.2:1	46.2:1	15.4:1

Table 2. Length/diameter ratios for all TEMPOS probes

POWER SUPPLY/POWER MONITOR (PAGE 14, SECTION 4.2.2)

"An adjustable regulated DC power supply is required with the capability of providing at least 20 Watts. Alternatively, power meter (digital or analog) of up to 20 Watts can be used in place of power supply for the power input to the thermal probe."

TEMPOS compliance: meets

This IEEE requirement is perhaps incomplete and inadequate. Power is computed as the product of Voltage and Current, or Voltage^2 divided by the resistance. The TEMPOS power supply is capable of providing 20 Watts into a 1.25 W resistance (Voltage^2/Resistance = $5^2/1.25 = 25/1.25 = 20$W).

With regard to the stated alternative of using a power meter, we are not exactly sure what that means. TEMPOS measures (meters) the power input to the thermal probe, which power meter is up to (but never exceeding) 20 W. It appears that TEMPOS also meets the alternative requirement.

More importantly, the power capacity/metering requirement and the calculation of power are largely irrelevant. The power per unit probe length is the important parameter, as addressed with the compliance to section 5.2.2.

TEMPERATURE MONITOR (PAGE 14, SECTION 4.2.3)

"A multipoint portable digital instrument designed to measure temperature with a resolution of better than 0.1 °C is preferred for lab use."

TEMPOS compliance: meets

TEMPOS is portable and digital. The temperature-measuring circuitry in TEMPOS and the thermistor used in all TEMPOS probes work together to measure temperature with a resolution of better than 0.001 °C.

We are not sure what 'multipoint' means. Our best guess is that it harks back to 1960's vintage strip chart recorders. TEMPOS is not multipoint in any way we can reasonably justify, but it does have the desired temperature resolution.

TEST PROCEDURE FOR LABORATORY PROBE (PAGE 16, SECTION 5.2.2)

"An input of between 10 W/m and 30 W/m is usually applied to the thermal probe. The heat input selection depends on the resistivity of the soil..."

TEMPOS compliance: meets

Note the use of the word "usually", in place of a strict requirement. TEMPOS applies a current to the TR-3 sensor of 82 mA to 90 mA (depending on the properties of the particular probe) or 4.1 W/m to 4.5 W/m. TEMPOS' low power improves on the lower end of the suggested power level, to the end of avoiding the overheating pitfalls listed in IEEE 442/D3 section 3.1 Factors Influencing Measurements. High heat drives water in the soil away from the probe, distorting the reading. The temperature sensitivity of TEMPOS probes enables TEMPOS to make an accurate reading from the smaller temperature rise that results from a lower probe power input.

"...Temperature data is recorded at 15-second intervals for 10 minutes...."

TEMPOS compliance: meets

TEMPOS temperature data are recorded at ten-second intervals for ten minutes, exceeding the requirement. TEMPOS takes readings for ten minutes. The first five minutes is heating and the second five minutes is cooling. Each phase produces a slope that contributes to the final result.

"…If at any time, the probe temperature reaches 25 °C above ambient soil temperature, the test should be terminated."

TEMPOS compliance: meets

TEMPOS affords the user the opportunity to make an informed decision to discard a reading after viewing the result. TEMPOS does not check to ensure that the temperature rise does not exceed 25 °C. This check is unnecessary because of TEMPOS' low probe power input.

ANALYSIS OF TEST RESULTS (PAGE 17, SECTION 6)

"[ ] To simplify the resistivity calculations, extend the straight-line section of the curve to intersect at least one cycle on the semi-log graph. By recording the temperature change over one logarithmic cycle, the resistivity of the computation reduces to: …"

TEMPOS compliance: meets

The word choice makes extending "the straight-line section of the curve" an instruction, but for the sole sake of simplifying a calculation. This simplification is not necessary if the computer has the capability to calculate logarithms or if one uses least squares curve fits, a common practice in this century.

Note that the subsequent section, 6.1 Sample Calculation, paragraph 2, presents a completely different, superior method for calculating the conductivity/resistivity: least squares curve fitting. Modern computers lend themselves to the least squares curve fit method, eliminating the need to simplify computation by extending the length of the temperature measurement and thus enabling a shorter duration measurement. TEMPOS' highly accurate temperature measurement enables accurate results from shorter duration readings with lower temperature rises.

TEMPOS implements the least squares curve fitting method.

SAMPLE CALCULATION (PAGE 17, SECTION 6.1)

"[ ] It should be noted that since the time span required to make a field resistivity measurement is longer than when using a laboratory-scale probe, the time elapsed shown on the x-axis should be increased to at least 30 minutes."

TEMPOS compliance: meets

METER does not recommend using field-scale probes. It is important to note that IEEE recommends that measurement duration depend on the probe parameters, rather than on the physical location of the measurement. The accuracy of TEMPOS measurements in ASTM/IEEE mode relies on probes that approximate a line heat source; thus, TEMPOS employs the shorter reading time associated with laboratory-scale probes.

Field measurement requirements are largely irrelevant for TEMPOS. Because IEEE P442/D3-defined field probes differ significantly from a line heat source, METER recommends using laboratory probes for taking readings in the field, as allowed by IEEE 442/D3 section 4.1.2. Laboratory test procedures follow laboratory equipment in accordance with IEEE 442/D3 section 6.1.

Thermal resistivity readings need to be short in order to avoid, or at least to minimize, environmental effects, and they need to be low power in order to avoid the concerns stated in IEEE 442/D3 section 3.1. In order to take short readings, probes also need to have a high-temperature sensitivity and resolution. METER testing has shown that the ambient temperature of a sample does not affect the reading; avoiding temperature drift in the sample is a comparatively larger concern for field measurements.

The following points may be moot if the laboratory procedure is followed, but they should be explicit.

EQUIPMENT REQUIRED FOR FIELD MEASUREMENTS (PAGE 13, SECTION 4.1)

TEST PROCEDURE FOR FIELD PROBES (PAGE 15, SECTION 5.1)

"5.1.2 d) Select a power that will give at least 3 °C to 4 °C temperature rise over approximately one logarithmic cycle of time … If the probe temperature reaches 50 °C at any time, the test should be terminated immediately."

1. In saturated sandy loam, the TEMPOS TR-3 temperature rise is ~0.7 °C over one logarithmic period (period = e = 2.71828). A 3 °C to 4 °C temperature rise measured with a precision of 0.1 °C, as specified in IEEE 442/D3 section 4.2.3, yields a less accurate reading than that from a 0.3 °C to 0.4 °C temperature rise measured with a precision of 0.001 °C such as the TEMPOS provides.

2. The maximum probe temperature (50 °C) should be specified relative to ambient temperature, not absolute. Step g) of section 5.1.2 contains an example appropriately limiting the temperature rise based on the ambient soil temperature.

TEMPOS temperature measurement is accurate over the range of -50 °C to 150 °C. Within reasonable limits, the absolute temperature of the sample is not detrimental to the accuracy of the reading so long as it is holding constant for the duration of the reading.

5.1.2 Step g) and step h) specify a measurement of 35 to 45 minutes, "…or until the logarithmic temperature rise becomes linear."

1. Readings taken near the surface experience measurable environmentally induced temperature drift (diurnal variation) in a 45-minute span of time, which drift corrupts the reading (see Section 3.1. Factors Influencing Measurements) and causes the logarithmic temperature rise to be nonlinear. Note: METER has found that a temperature drift as small as 0.002 °C/sec may affect a reading.

2. TEMPOS' sensitive temperature probe (0.001 °C) and reading computation method allow TEMPOS to make shorter duration readings that effect a smaller temperature rise.

3. TEMPOS does not check the linearity of the logarithmic temperature rise prior to terminating a reading; rather, TEMPOS keeps the reading time short in order to help avoid temperature drifts in the sample that impact the linearity. TEMPOS relies on the user to check the linearity of the logarithmic temperature rise so that the user can deduce the ambient conditions and make informed decisions on subsequent readings.