ASTM C177 and Similar Standards

One might argue that the hallmark of a developed civilization is the ability to create, adhere to, and improve standards. If you cannot measure it reliably, you cannot really get a handle on improving whatever it is you are measuring.

Some of the standards that are applicable to the measurement of thermal conductivity are listed below. This is not a comprehensive list and I have left out hot-box methods as they address more complex heat transfer methods such as radiation and convection.

Standard	Title
ASTM C177	Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus
ASTM C518	Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus
ISO 8301	Thermal insulation -- Determination of steady-state thermal resistance and related properties -- Heat flow meter apparatus
ISO 8302	Thermal insulation -- Determination of steady-state thermal resistance and related properties -- Guarded hot plate apparatus
GB 10294	The chinese version of ISO 8302
BS EN 12664, 12667, 12939	Thermal Performance of Building Materials and Products. Determination of Thermal Resistance by means of Guarded Hot Plate and Heat Flow Meter Methods. *Various categories*

There are other methods, such as the hot-wire technique, and other transient methods, but I am focusing on steady-state methods as they tend to be more accurate.

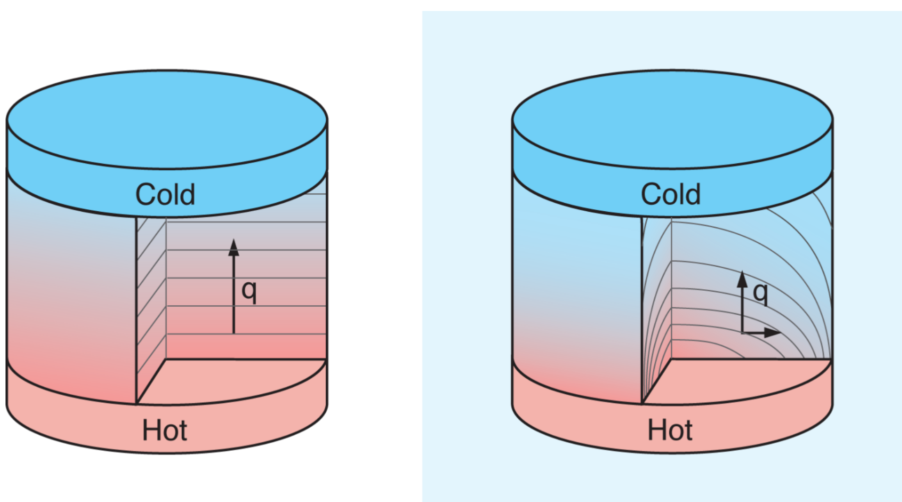
I'll start by unpicking the titles in the above table. Basically, there are two types of measurement used in steady-state thermal conductivity standards. These centre on the phrases 'guarded hot plate' and 'heat flow meter' which I will discuss in the next two sections.

Guarded hot-plate

The steady state procedures listed above rely on measuring the heat flux, $\dot{\mathbf{q}}$, needed to create a temperature gradient across a material of known thickness. Let's recall Fourier's law, and we'll assume that thermal conductivity, *k* is a scalar.

$$\dot{\mathbf{q}} = -k\nabla T \qquad \text{Eq. 1}$$

In the ASTM C177 and ISO 8302 methods heat flows from a hot plate to a cold plate through the material to be tested. Ideally, the heat doesn't leak sideways and get lost (and hence unmeasured). This requires that the isotherms in the specimens be perpendicular to the shortest path through the specimen, and is shown in the diagram below. In the left-hand diagram a hot plate (red) drives heat through a specimen to a cold plate (blue). If the system is perfectly insulated then the isotherms (grey lines) are perpendicular to the shortest path through the specimen. In the right-hand figure, the system is surrounded by a cooler environment, and you can see that the curved skin of the material being tested is cooler than before. Also, you can see that *inside* the specimen, heat is flowing sideways - the horizontal black arrow has a non-zero length, showing that the isotherms are no longer parallel to the plates' faces.



Figures 1 and 2 – showing an idealized (left) and a real-world (right) example of heat transport through a specimen sandwiched by hot and cold plates.

However, in general a system is weakly in contact with the laboratory. If the lab' is cooler than the hot plate then heat flows sideways, is not monitored, and leads to a higher figure for the thermal conductivity because more power is needed to establish a given temperature difference between the hot and cold plates. Remember the heat flow is a vector quantity, is always perpendicular to the isotherms, and is shown in the above figures as a pair of orthogonal black arrows. Rather than adding insulation till the problematic heat leak becomes insignificant, a neater solution is to surround the hot plate with a so-called 'guard' plate.

This plate is held at the same temperature as the hot plate, but is not in contact with it. The guard plate reduces the horizontal temperature gradient in the specimen above the hot plate, ensuring that the horizontal flow of heat is reduced. This is shown in figure 3, where it is readily seen that above the central disc-shaped plate the isotherms are parallel to the face of that plate - much more so than was the case in the right-hand diagram of figure 2.

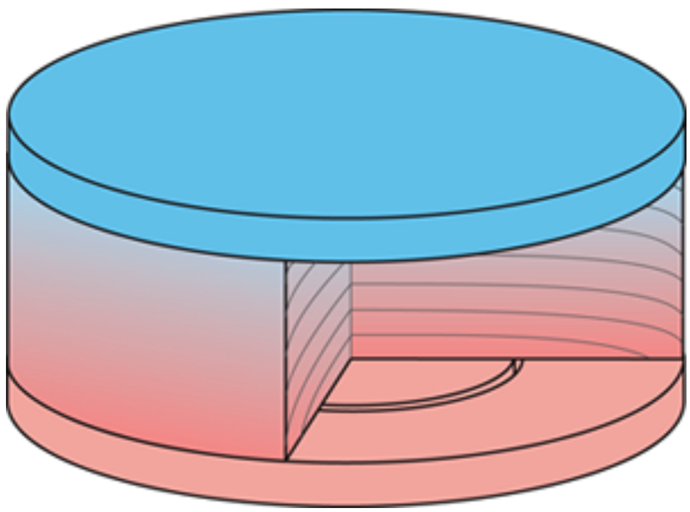


Figure 3 – showing how the addition of a separately heated guard plate around the hot plate reduces the horizontal flow of heat.

In this arrangement the heat, $\mathbf{q}$, that passes through the specimen above the hot-plate is, essentially, the power developed by the central heater of that plate. That power is readily and accurately measured from the voltage difference across the heater and the current flowing through it.

Heat flow meter

Instead of directly measuring the power developed by a hot-plate and ensuring that the heat flow is unidimensional (as in C177), methods such as C518 use something called a heat-flow meter. This involves measuring the temperature difference across a sliver of material that has a well-characterized thermal conductivity and working backwards to deduce the power that must be flowing through that material.

The accuracy of this method is dependent on knowing the thermal conductivity of the material within the heat flux meter. It is therefore classed as a secondary test method as it relies on an absolute measure, such as C177, to calibrate the heat flux meter.

Many manufacturers of insulations use ASTM C518 to qualify their materials. When performed by a professionally-run test laboratory that regularly calibrates the heat flux meter, this is a fine standard to adhere to. But that need for regular calibration means that an extra layer of uncertainty is unavoidable – and a prudent customer always should ask for an error analysis document of the test process.

Finally, a word of caution about the C518 method. It does not mandate the use of a guard element, and so one often finds this procedure used for testing materials with relatively high thermal conductivities at room temperature. The absence of a guard element does not invalidate the utility of this procedure but caution should be exercised when assessing data taken at very high or low temperatures if there is no mention of a guarding plate being used.

Summary

Thermal conductivity is measured through two fundamentally different methods. The ASTM C518 and ISO 8301 methods rely on a pre-calibrated heat-flow meter. The ASTM C177, ISO 8302, and BS EN 12667 methods employ an accurate determination of the heating power needed to establish a given temperature difference. These last three standards rely only on the ability to measure voltage and current to high standards of accuracy and even inexpensive laboratory equipment can determine these quantities to better than one part in 10^6.

If a customer seeks a test that relies on the fewest links in the calibration chain, then the guarded hot-plate methods (ASTM C177, ISO 8302, and BS EN 12667) should be considered. These three standards differ significantly only in the qualification work needed for the system, and are essentially identical in normal use.

The whole purpose of testing a material's properties is to bring understanding and reduce uncertainty. Although every test process relies on a chain of calibration, errors are cumulative and their sum unavoidably grows with each extra link.