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# The Portable Electronic Divided Bar (PEDB): a Tool for Measuring Thermal Conductivity of Rock Samples

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**ABSTRACT**

The thermal conductivity of a geological formation is an essential physical property to be determined when attempting to understand and model heat flow. The Portable Electronic Divided Bar (PEDB) is an effective tool in measuring thermal conductivity, and is currently playing an important in the development of heat flow modelling of Australian geothermal resources.

The PEDB is an electronic apparatus that produces a temperature gradient across a specially prepared rock sample; and with its precision heat flow monitoring system, it allows thermal conductivity of a rock sample to be determined via the application of Fourier's Law. A simple spreadsheet allows direct temperature measurements—utilising thermocouples—to be recorded and interpreted to provide an absolute thermal conductivity value within ±3.5% on a production scale.

In addition to uniaxial thermal conductivity measurements, biaxial and triaxial measurements can be made with the PEDB, allowing for studies of thermal conductivity anisotropy. Cylindrical core as well as irregularly shaped rock samples can be measured.

## INTRODUCTION

The Divided Bar was first described as a steady-state tool used to measure the thermal conductivity of materials by Benfield in 1939 (Beardsmore and Cull, 2001). The Portable Electronic Divided Bar (PEDB) is a development of Benfield's divided bar operating principal, utilizing advancements in technology to achieve a high accuracy (±3.5%), light-weight (less than 10 kg), small size (260 mm x 310 mm x 410 mm) low power consumption (less than 200 W), and low noise production.

Portability makes the PEDB an effective tool for production scale thermal conductivity measurements in a field setting, where it is valuable for measuring rock samples immediately after recovery from drilling, maintaining as closely as possible the rock's *in situ* porosity and moisture content. Mains power is not necessary—it can be powered by a source such as an automobile or a small sine-wave generator.

For use in laboratory settings, the space that is required is the corner of an office desk and a single AC power outlet.

### 1. Thermal Conductivity and Heat Flow

Observing Fourier's Law:

$$Q = \lambda \times \beta \quad (1)$$

Where Q, $\lambda$, and $\beta$ are heat flow (W/m$^2$), thermal conductivity (W/mK), and thermal gradient (K/m), respectively,

the heat flow of a site can be derived by utilising a combination of: 1. thermal conductivity measurements to define λ; and 2. down-hole temperature logging to define β. Determining heat flow requires consideration of the geologic formations from which the thermal conductivity samples came, and so rock samples that are to be tested for thermal conductivity must be carefully chosen to ensure they are appropriately representative of those geologic formations, with attention paid to characteristics such as lithology and porosity.

If thermal conductivity measurements from several geological formations are calculated, it is possible to develop a down-hole profile of thermal conductivity.

## 2. CALCULATION OF THERMAL CONDUCTIVITY

Thermal conductivity of a rock sample, as measured by a PEDB, is determined by:

$$\lambda = \frac{d}{R} \quad (2)$$

$\lambda$ = thermal conductivity

$d$ = thickness of the sample in mm

$R$ = A (ΔT- c)/ a (diameter + b)

A = surface area of sample in mm$^2$

a, b, c, are calibration constants determined during the calibration process.

ΔT is defined by:

$$\Delta T = \frac{T_2 - T_3}{(T_1 - T_2) + (T_3 - T_4)} \quad (3)$$

$T_1$, $T_2$, $T_3$, $T_4$ = temperatures of PEDB plates as shown on Figure 1.

The thermal conductivity of each rock sample is calculated via the measurement of three values: 1) $d$, the sample thickness in mm; 2) A, the sample surface area in mm$^2$; and 3) ΔT, the ratio of the thermal gradient across the sample relative to the sum of thermal gradients across the polycarbonate layers within each plate-pair—a unitless quantity.

The measurements of d and A are made utilising precision calipers; the measurement of ΔT is made utilising the PEDB.

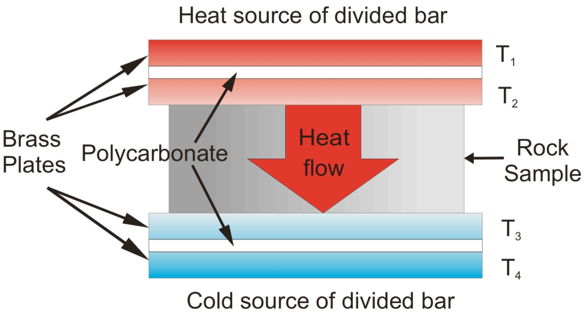


**Figure 1: Diagram showing principal components of the plates of the PEDB. Each brass plate is fitted with a separate thermocouple; ΔT is the ratio of the temperature of the plates of the PEDB: $\Delta T = (T_2\text{-}T_3)/((T_1\text{-}T_2)+(T_3\text{-}T_4))$. The heat source is above the top pair of brass plates, and the cold source is below the bottom pair; the consequence is that heat flows across the rock sample.**

## 3. THE PEDB

### 3.1 Power Supply

The PEDB has a "universal" power supply, capable of being powered by mains sources that are within 100-250 V AC 45-70 Hz. Portability of the PEDB can be achieved by using a suitably rated generator producing a pure sine-wave, or by using a pure sine-wave inverter rated for 200 W connected to a power source such as an automobile.

### 3.1 Plates of the PEDB

Fundamentally, the principles in measuring thermal conductivity using the PEDB are similar to those of traditional (that is, typically large and hydraulically heated/cooled) divided bars. Two pairs of highly thermally conductive plates—brass in the case of the PEDB—are used, each with a layer of polycarbonate in between, comprising a brass-polycarbonate-brass assembly that resembles a sandwich, as shown in Figure 2. Each of these assemblies has a thickness of approximately 7mm and a diameter of 65 mm. One of the assemblies is situated on top of the rock sample—thermally connected to a heat source—and the other assembly is below the sample—thermally connected to a cold source; such an orientation prevents: 1) convection from occurring between the plates and; 2) resultant introduced uncertainties.

Within each of the four brass plates is embedded a thermocouple with its welded joint located in the center of the circular plate. Thus the temperatures of each brass plate can independently be measured and used to determine λ.

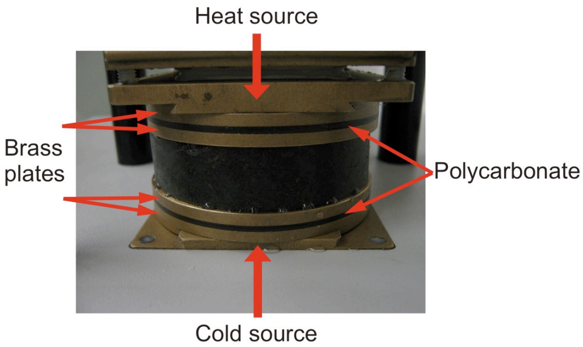


**Figure 2: The plates of the PEDB. A HQ sized rock sample is in place and ready for thermal conductivity measurement. Each pair of plates is brass, with a polycarbonate layer in between. Above the upper plate is a heat source, and below the lower plate is the cold source--a thermal gradient across the sample is created; the ratio of the thermal gradients across each of the polycarbonate layers and the sample is used to determine λ.**

### 3.2 Sample Preparation

The PEDB measures the thermal conductivity of consolidated drill—core. Samples measured for thermal conductivity can be any size up to a diameter of to 65 mm (approximate size of HQ core). The samples should be cut so that the two faces of the sample produced are as parallel as possible, although precise parallelism is not essential, owing to a swivel-head which allows for measurement of samples that are not perfectly parallel (Figure 3); sample preparation is consequently easier than with systems that do not allow for sub-parallel rock samples.

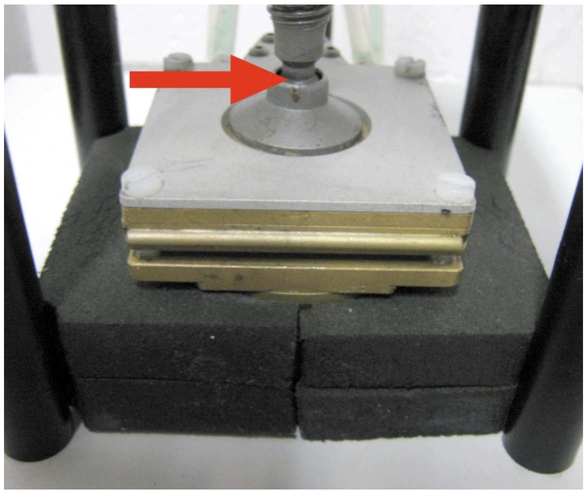

**Figure 3: The swivel head (indicated by arrow) of the PEDB allows for thermal conductivity measurements of samples to be made without necessitating perfect parallelism between sample faces. Additionally, the black insulation shown is effective in minimizing thermal loss from the sample.**

It is however essential that the faces of the rock sample are completely flat. This can be accomplished by using a flat grinding wheel and lap-wheel combination, which has been the preferred method for producing thermal conductivity samples thus far. The system of sample preparation should be standardized. Generally, polishing to a fine grade up to 600-grit is recommended.

If the samples being measured for thermal conductivity were saturated with water *in situ*, all efforts should be made to preserve the inter-pore water within the core sample. If this is not practicable, then the sample should be re-saturated before measurement via vacuum saturation; in such cases the samples are subjected to a vacuum for a standardized time before being submerged in water and returned to atmospheric pressure for a standardized time, whereafter they can be measured for thermal conductivity.

3.2.1 Relevance of Sample Preparation Quality

It has been observed that samples prepared with sub-flat faces or surface irregularities can provide significantly lower measured thermal conductivity values. Examples of surface irregularities that have shown significant decrease in apparent thermal conductivity are:

- Convex sample faces resulting from poor grinding and polishing practices.
- Grooved sample faces left over from the rock-sawing process; chips that have fractured from the sample during cutting.
- Pitted surfaces resulting from preparation of weakly consolidated rocks susceptible to "plucking" of grains.
- Fractures and/or joints having a horizontal component.

As zones of low thermal conductivity and high water/air content that are created either within the sample itself or along the sample/plate contact, these irregularities effectively impede the heat flow across the sample. Careful efforts—implemented during sample selection, preparation, and measurement—are essential for producing accurate thermal conductivity results. The overwhelming majority of core samples that have been encountered by the author during conductivity measurement have been able to provide useful samples for accurate thermal conductivity measurements, when carefully prepared.

3.2.2 Relevance of Size and Shape of Samples tested in the PEDB

The dimensions of a rock sample that must be measured when calculating thermal conductivity are thickness and surface area. Thickness is measured with precision calipers, and surface area can be calculated two ways: 1) assuming the sample is from cylindrical core, the diameter of the core can be measured and from this the surface area derived; and 2) the outline of an irregularly shaped sample can be traced and from this tracing the surface area can be measured either digitally (via scanner and digital graphics software) or on to grid paper. Experiments have shown that variations in results of measurements made via the tracing method and via the calculation from diameter method are within 0.7% variation from the mean.

Irregularly shaped rock samples can be measured since the PEDB uses surface area and thickness, and not a standardized shape and size, to calculate thermal conductivity. The accuracy of thermal conductivity measurements is independent of sample shape so long as thermal loss around the perimeter of the sample is minimized. Generally, the thermal loss that may exist for a sample would increase as its perimeter increases, but this tendency is effectively controlled with the use of thermal insulation around the PEDB plates and rock sample (Figure 3).

Figure 4 and Figure 5 demonstrate the PEDB's ability to measure thermal conductivity of irregularly shaped samples. In both cases, samples were ground flat, polished, and were of a variable siltstone lithology. Variation in thermal conductivity was 5% or less from the mean in both cases.

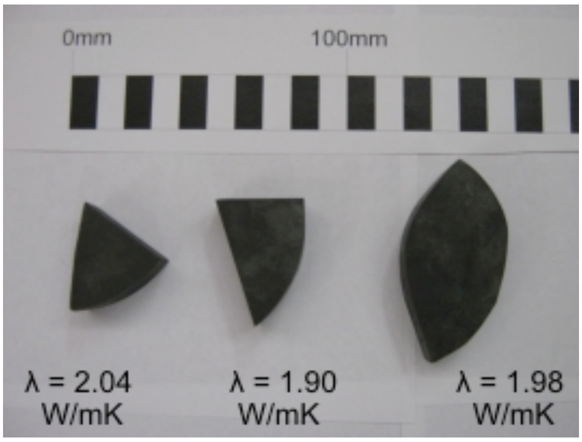


**Figure 4: Although varying significantly in size and shape, these samples—which were taken from the same specimen—still provide consistent results. Their conductivities are 2.04, 1.90, and 1.98 W/mK respectively, resulting in a variation of 3.5% from the mean conductivity of 1.97 W/mK.**

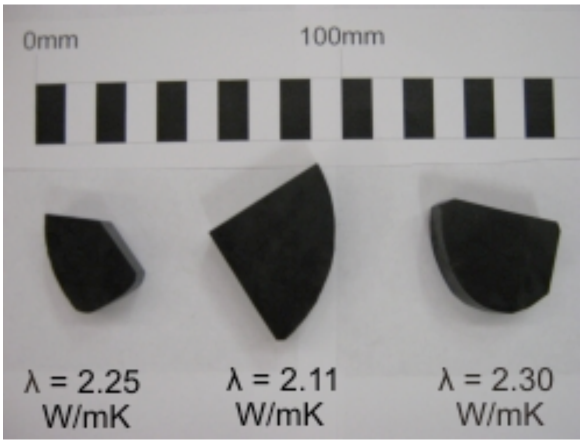


**Figure 5: Although varying significantly in size and shape, these samples—taken from the same specimen—still provide consistent results. Their conductivities are 2.25, 2.11, and 2.30 W/mK respectively, resulting in a variation of 5% from the mean conductivity of 2.22 W/mK.**

### 3.3 Thermocouple/Computer Interface

Thermocouples are used to determine the temperatures of the four plates of the PEDB. The working ends of the thermocouples are imbedded within the brass plates, while the other ends—the plug ends—are connected to an interface that allows the variation in voltage across each of the thermocouples (voltage is measured on the scale of millivolts) to be translated into temperature data and interpreted on a computer. Each thermocouple is monitored on a separate channel.

### 3.4 Equilibration Process

Once the sample is placed between the plates of the PEDB and slight pressure is applied to the sample via the hand-operated clamp, a temperature gradient is imposed across the sample and state of thermal equilibrium typically occurs within 5–15 minutes. The time required is dependant upon sample thickness and surface area and upon the thermal characteristics of the rock sample. A sample will equilibrate relatively quickly if it is thin, and has a high surface area and thermal conductivity. Alternatively, a sample will take longer to equilibrate if it is very thick, and has a low surface area and thermal conductivity. Figure 6 and Figure 7 represent data from the same thermal conductivity measurement.

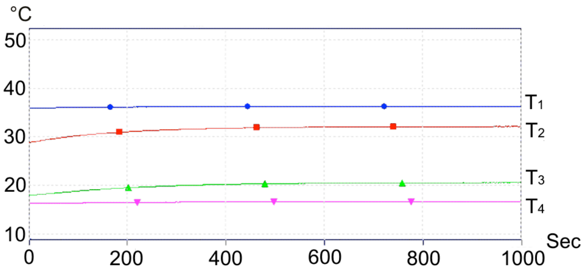


**Figure 6: Example of data collected during thermal conductivity measurement; the horizontal axis is time, measured in seconds, and the vertical axis is temperature measured in °C. Each plot represents the temperature of a plate of the PEDB, $T_1$–$T_4$, where the hot plate ($T_1$) in this case is approximately 35°C, the cold plate ($T_2$) is approximately 17°C, and the intermediate plates ($T_3$ and $T_4$), after having a rock sample placed in between them, gradually increase in temperature until thermal equilibrium is reached.**

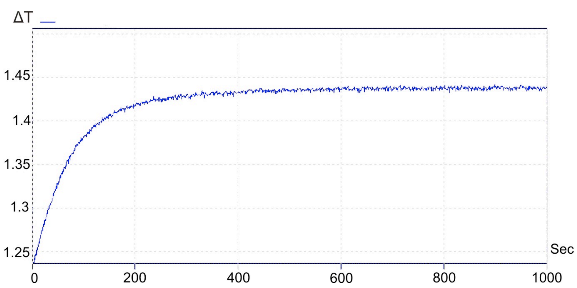


**Figure 7: Example of data collected during thermal conductivity measurement; the horizontal axis is time, measured in seconds, and the vertical axis is ΔT. In this example, the sample measured for thermal conductivity is fully equilibrated after approximately 600s, to a ΔT value of 1.44.**

### 3.5 Calibration of the PEDB

The PEDB is calibrated by using a set of standards with known thermal conductivity (Figure 8). These standards are of differing thicknesses and surface areas, enabling the PEDB to be used for measuring diversely shaped samples, and samples with a range of thicknesses and surface areas.

**Figure 8: Example of standards used for calibrating the PEDB.**

During calibration, these standards are placed in the PEDB individually and measurements are made of the four plate temperatures $T_1$–$T_4$ and the derived ΔT value once the standard has reached a state of thermal equilibrium, and the thicknesses and surface areas of the standard used.

### 3.6 Mean Sample Temperature of the PEDB

The PEDB operates most efficiently when the mean sample temperature of the sample being measured is near the environmental air temperature. To facilitate accurate field measurements, the PEDB is capable of operating at range of mean temperatures, from approximately 15°C–35°C, and has a indication system showing when the mean temperature nearest to environmental temperature has been reached.

Thermal conductivity is a physical property that, for rocks, is dependant upon temperature. It has been observed that rocks generally become less thermally conductive with increasing temperature at a rate of approximately 0.16% per °C (Vosteen and Schellschmidt, 2003). This must be kept in mind when determining the thermal conductivity of geological formations, where the *in situ* temperature can be significantly greater than that at which the laboratory tests were made.

## 4. MEASUREMENT OF THERMAL CONDUCTIVITY ANISOTROPY

Anisotropy is the characteristic of a material to behave differently with respect to one direction than with respect to another. Rocks can be thermally anisotropic, and in so being can exhibit thermal properties with respect to one direction differently than another.

Typically, thermal conductivity measurements are made uniaxially, so that a single thermal conductivity measurement is made along the long axis of a core specimen. It is the expectation of the heat flow modeler that the core specimen was taken from a bore that was drilled nearly vertically, and therefore was sufficiently parallel to Earth's heat flow that the need for understanding how heat travels across the length of the core specimen is negated.

Testing for thermal conductivity anisotropy of a rock sample involves biaxial or triaxial measurements. The preparation of cube-shaped samples allows thermal conductivity to be measured across each axis of the same sample; thus, one sample can provide the minimum data required for the creation of an ellipsoidal thermal model. Alternatively, three orthogonally oriented samples can be prepared from a common specimen, collectively providing data for the creation of an ellipsoidal thermal model.

For foliated meta-sedimentary specimens, the tendency has been observed (Figure 9) for thermal conductivity to be greater where samples are measured for thermal conductivity with heat flow parallel to the foliation than with heat flow perpendicular to the foliation. In this paper, $\lambda_1$ is nominated as the axis of greatest thermal conductivity, while $\lambda_2$ is nominated the axis of least thermal conductivity, and it is assumed that there is an elliptical gradation between $\lambda_1$ and $\lambda_2$.

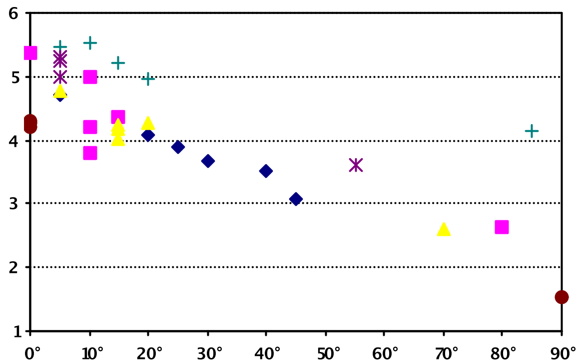


**Figure 9: Summary of thermal conductivity data from six meta-sedimentary rock specimens; the six differently shaped symbols indicating the different specimens studied. Each specimen was measured for thermal conductivity at several angles with respect to the specimen's foliation and the direction of heat flow imposed across it by the PEDB. The vertical axis is thermal conductivity in W/mK; the horizontal axis is the angle between the foliation of the rock sample, and the direction of heat flow across the rock sample while within the PEDB, measured in degrees (°). The general trend observed is that, for the specimens studied, a relationship exists between the magnitude of thermal conductivity and the direction of heat flow with respect to the specimen's foliation.**

### 4.1 Results of Anisotropy Testing

4.1.1 Thermally Anisotropic Rock Specimens

The results of the two most extreme cases of rock specimens displaying thermal conductivity anisotropy shown in Figure 9 are discussed below.

A foliated meta-sediment, Specimen A was measured to have a mean conductivity of 4.26 W/mK with heat flow parallel to foliation, and a mean conductivity of 1.44 W/mK with heat flow perpendicular to foliation. That is a variation of 50% from the mean conductivity of 2.85 W/mK.

Another foliated meta-sediment, Specimen B, was measured to have a mean conductivity of 5.37 W/mK with heat flow parallel to foliation, and a mean conductivity of 2.65 W/mK with heat flow perpendicular to foliation. That is a variation of 34% from the mean conductivity of 4.01 W/mK.

In both cases, $\lambda_1$ was parallel to the rock specimen's foliation, while $\lambda_2$ was perpendicular to the rock specimen's foliation. In addition, $\lambda_1$ and the foliation were within 5° of parallel to the bore in both cases. Since the bores that these samples originated from were vertical, the thermal conductivities that would be most relevant to the heat-flow modeller—for the location within the geological formation from which the specimens came—would be those that were parallel to Earth's heat flow, and in these cases parallel to $\lambda_1$. The conductivities values most relevant for heat flow modelling of geological formations represented by specimens A and B, would be 4.26 W/mK and 5.37 W/mK respectively.

4.1.2 Calculation of Variability in Thermal Conductivity

But what if the bores, foliation, and the direction of $\lambda_1$ discussed in section 4.1.1 were NOT parallel to Earth's heat flow, and happened to be dipping at 45° instead, as it might in a steeply-dipping mineral exploration bore? In such a case, Earth's heat flow is now no longer parallel with the bore, but is 45° to it; and consequently, the thermal conductivity vector of the rock specimen most relevant to the heat flow modeller is not that which parallel to the bore, but that which is parallel to the direction of Earth's heat flow. Using an elliptical thermal conductivity blending model, where $\lambda_1$ and $\lambda_2$ are the vectors representing the greatest and lowest thermal conductivities respectively, the resultant thermal conductivity vector for 45° can be determined.

The elliptical model is derived beginning with the equation for an ellipse:

$$1 = \frac{x^2}{a^2} + \frac{y^2}{b^2} \qquad (4)$$

Inserting variables allowing for the model to operate in terms of degrees:

$x = \lambda \cos \theta$

$y = \lambda \sin \theta$

$a = \lambda_1$

$b = \lambda_2$

$\lambda$ = thermal conductivity of rock sample in direction of Earth's heat flow

$\lambda_1$ = value of greatest thermal conductivity

$\lambda_2$ = value of least thermal conductivity

$\theta$= angle in (°) between the direction of Earth's heat flow and $\lambda_1$

Substituting the above variables into equation (4) gives:

$$1 = \frac{\lambda^2 \cos^2 \theta}{\lambda_1} + \frac{\lambda^2 \sin^2 \theta}{\lambda_2} \qquad (5)$$

Solving for $\lambda$ in Equation (5) gives:

$$\lambda = \sqrt{\frac{1}{\frac{\cos^2 \theta}{\lambda_1} + \frac{\sin^2 \theta}{\lambda_2}}} \qquad (6)$$

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By inserting the measured $\lambda_1$ and $\lambda_2$ data from section 4.1.1, in addition to inserting 45° for $\theta$ into the equation (6), the thermal conductivity of rock samples A and B in the direction of Earth's heat flow can be determined:

Sample A:

$\lambda_1$ = 4.26 W/mK and $\lambda_2$ = 1.44 W/mK

The resultant $\lambda$ when $\lambda_1$ is dipping at 45°: 1.93 W/mK

Sample B:

$\lambda_1$ = 5.37 W/mK and $\lambda_2$ = 2.65 W/mK

The resultant $\lambda$ when $\lambda_1$ is dipping at 45°: 3.36 W/mK

4.1.3 Significance of variability in Thermal Conductivity

The resultant $\lambda$ of sample A and B at 45° is 1.93 and 3.36 W/mK respectively. These values are significantly different than either of their respective $\lambda_1$ or $\lambda_2$ values.

Sample A

55% variation from $\lambda_1$ 4.26 W/mK

34% variation from $\lambda_2$ of 1.44W/mK

Sample B

37% variation from $\lambda_1$ of 5.37 W/mK

27% variation from $\lambda_2$ 2.65 W/mK

When entered into a heat flow model, this variation in measured thermal conductivity may result in significant variation of calculated heat flow.

While bores drilled purposefully for geothermal energy exploration may as a rule be vertical, bores such as those used for minerals exploration may be significantly non-vertical owing to the efforts of the exploration program to maximize the likelihood of hitting a target lode. Thus, care should be taken when utilizing core from non-vertical bores for geothermal data, ensuring that thermal conductivity anisotropy is accounted for when developing heat flow models.

## 5. LIMITATIONS OF THE PEDB

The PEDB is not calibrated for measuring conductivities of samples larger that the plates, or 65mm in diameter. This can however be accommodated by cutting the core or field samples into a size that fits within the PEDB's 65 mm diameter plates.

The PEDB provided thermal conductivity measurements at mean temperatures from 15°–35°. For geological formations that have had specimens undergo thermal conductivity measurement, considerations of the geological formation's *in situ* temperature and adjustments to the measured thermal conductivity should be made, since thermal conductivity in rocks is a property that generally decreases with increasing temperature.

## CONCLUSION

The PEDB is effective in measuring thermal conductivity:

- On a production scale
- In remote locations
- Using variable power supplies
- In the laboratory
- Of samples that are of non-standardized size
- Of samples with irregularly shaped perimeters
- Triaxially, for thermal conductivity anisotropy studies

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