EPG 17
Nagoorin, Queensland

Thermal Conductivity Measurements and Heat Production Analysis Results

for core samples taken from Arrow Energy's Boyne River-2C Well

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Introduction

Hot Dry Rocks Pty Ltd (HDRPL) were contracted by Granite Power Ltd (GPL) to undertake measurements of thermal conductivity and heat production on selected core sampled from Arrow Energy's Boyne River-2C well by Granite Power Ltd in August 2008. The attached HDRPL report contains details of the methods and results.

The Boyne River-2C well is in the Boyne River Valley, near Ubobo, Queensland and is located at 331831.819 E, 7301172.695N Zone 56, GDA94. Full details of the well are given in Arrow Energy's well completion report (Author: Brad Pinder, Arrow Energy, 2005).

Samples were selected that were competent enough for testing and that represented th changes in lithology throughout the well. Thirteen samples were selected in total. Samples of whole core were taken of approximately 20 cm in length. For the heat production analysis, the cores were split longitudinally to preserve half the core, with the remainder being used for the analysis.

The following table indicates depth interval of sample, basic lithology and both GPL's and HDRPL's sampling numbering:-

GPL Sample number	Depth from	Depth to	Lithology	HDRPL Sample Number
BR2C-001	108.1	108.31	Carbonaceous mudst	GPL042
BRC2-002	184.79	184.9	Dolomite	GPL043
BRC2-003	207.87	207.98	Shaley coal	GPL044
BRC2-004	221.59	221.71	Carbonaceous shale	GPL045
BRC2-005	230.5	230.64	Dolerite	GPL046
BRC2-006	334.38	334.53	Clay-rich sandstone	GPL047
BRC2-007	467.5	467.68	Claystone	GPL048
BRC2-008	563.85	564.02	Lignite	GPL049
BRC2-009	608.55	608.67	Carbonaceous mudst/coaly shale	GPL050
BRC2-010	626.41	626.6	Coarse gr. sandstone	GPL051
BRC2-011	666.97	666.97	Carbonaceous mudstone	GPL052
BRC2-012	696.42	696.57	Shaley coal	GPL053
BRC2-013	739.39	739.52	Sandstone	GPL054

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Thermal conductivity of core samples GPL042-GPL054

Prepared for Granite Power Limited

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Executive summary

Granite Power Ltd commissioned Hot Dry Rocks Pty Ltd (HDRPL) to measure the thermal conductivity of 13 core specimens delivered in mid August 2008. Measurements were made on the 13 specimens using a steady state divided bar apparatus calibrated for the range 1.4–9.8 W/mK. Up to three samples were prepared from each specimen to investigate variation in thermal conductivity over short distance scales and to determine mean conductivity and uncertainty. All values were measured at a standard temperature of 25°C. The uncertainty for individual samples is ± 3.5%.

HDRPL considers the following points to be important:

- Results are in the range typical for very good to normal thermal insulators, falling in the range of 0.45–3.15 W/mK.
- While the specimens were chosen to represent the cored geological sections from which they came, there is no guarantee that the sections themselves are typical of the overall geological formations.
- It is to be expected that the thermal conductivity of a given formation will vary from place to place if the porosity of the formation varies.
- Thermal conductivity of rocks is sensitive to temperature. This should be kept in mind when developing models of in situ thermal conductivity.

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1.0 Introduction

Thermal conductivity is the physical property that controls the rate at which heat energy flows through a material in a given thermal gradient. In the S.I. system of units, it is measured in watts per metre-kelvin (W/mK). In the Earth, thermal conductivity controls the rate at which temperature increases with depth for a given heat flow. The thermal conductivity distribution within a section of crust must be known in order to calculate crustal heat flow from temperature gradient data, or to predict temperature distribution from a given heat flow. This report describes the results of laboratory thermal conductivity measurements on a series of drill core samples from Company Name.

Granite Power Ltd commissioned Hot Dry Rocks Pty Ltd (HDRPL) to undertake this study. HDRPL took delivery of 13 core specimens[1] from the well Boyne River 2C in August 2008 (Table 1). Thermal conductivity measurements were made on all of these specimens using a steady state divided bar apparatus calibrated for the range 1.4–9.8 W/mK.

Thermal conductivity is sensitive to temperature (e.g. Vosteen and Schellschmidt, 2003[2]), in general decreasing as temperature increases. The measurements contained in this report were made within ±2°C of 25°C.

[1] In this report the word "specimen" refers to a raw piece of rock delivered to HDRPL, while "sample" refers to part of a specimen prepared for conductivity measurement. In general, three samples are prepared from each specimen.

[2] **Vosteen, H.-D. and Schellschmidt, R.** (2003). Influence of temperature on thermal conductivity, thermal capacity and thermal diffusivity for different types of rock. *Physics and Chemistry of the Earth*, 28, 499–509.

Table 1. Specimens presented for thermal conductivity measurement.

Sample	Well	Depth From	Depth To
GPL042	Boyne River 2C	108.10 m	108.31 m
GPL043	Boyne River 2C	184.79 m	184.90 m
GPL044	Boyne River 2C	207.87 m	207.98 m
GPL045	Boyne River 2C	221.59 m	221.71 m
GPL046	Boyne River 2C	230.50 m	230.64 m
GPL047	Boyne River 2C	334.38 m	334.53 m
GPL048	Boyne River 2C	467.50 m	467.68 m
GPL049	Boyne River 2C	563.85 m	564.02 m
GPL050	Boyne River 2C	608.55 m	608.67 m
GPL051	Boyne River 2C	626.41 m	626.60 m
GPL052	Boyne River 2C	666.97 m	667.10 m
GPL053	Boyne River 2C	696.42 m	696.59 m
GPL054	Boyne River 2C	739.39 m	739.52 m

2.0 Methodology

Hot Dry Rocks Pty Ltd received 13 specimens of rock from Granite Power Ltd. HDRPL assumed that the specimens were representative of the average lithological composition of the formation being sampled.

Each specimen was prepared for thermal conductivity measurement in a divided bar apparatus[3]. Where possible, three prisms were cut from each consolidated core, each approximately 1/3 to 1/2 the diameter of the specimen in thickness. Three samples were taken to investigate variation in thermal conductivity over short distance scales and to determine mean conductivity and uncertainty. The samples were all of a circular/cylindrical shape. Each sample was ground flat and polished, then evacuated under >95% vacuum for a minimum of three hours. Samples were then submerged in water prior to returning to atmospheric pressure. Water saturation continued at atmospheric pressure for a minimum of three hours, and all samples were left in water until just prior to conductivity measurement.

Values were measured at a standard temperature of 25°C (±2°C). Harmonic mean conductivity (see Figure 1) and one standard deviation uncertainty were calculated for each specimen. Results are presented in the next section.

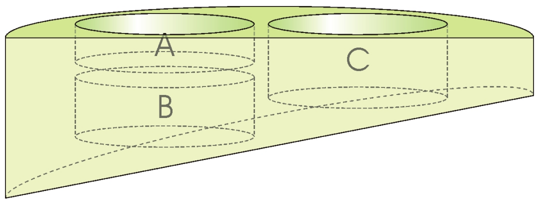

Figure 1. The average conductivity of samples in series (e.g. A and B) is found using the harmonic mean. The average conductivity of samples in parallel (e.g. A and C) is found using the arithmetic mean.

[3] Divided bar apparatus: An instrument that places an unknown sample in series with a standard of known thermal conductivity, then imposes a constant thermal gradient across the combination in order to derive the conductivity of the unknown sample.

3.0 Results

Table 2 displays the thermal conductivity for each individual sample, and the harmonic mean conductivity and standard deviation for each specimen. All values are for a standard temperature of 25°C. The uncertainty for individual samples is approximately ±3.5% for consolidated samples (based on the instrument precision of the divided bar apparatus).

Table 2. Thermal conductivity of samples at 25°C, and harmonic mean and uncertainty[4] for each specimen.

Well	Depth From	Depth To	Sample			Conductivity (W/mK)
				A	0.83	
				B	0.84	
Boyne River 2C	108.10 m	108.31 m	GPL042	C	0.83	0.83 ± 0.01
				A	1.63	
				B	1.67	
Boyne River 2C	184.79 m	184.90 m	GPL043	C	1.59	1.63 ± 0.04
				A	0.56	
				B	0.55	
Boyne River 2C	207.87 m	207.98 m	GPL044	C	0.56	0.56 ± 0.01
				A	0.66	
				B	0.81	
Boyne River 2C	221.59 m	221.71 m	GPL045	C	0.98	0.80 ± 0.16
				A	1.60	
				B	1.58	
Boyne River 2C	230.50 m	230.64 m	GPL046	C	1.58	1.59 ± 0.01
				A	2.63	
				B	2.23	
Boyne River 2C	334.38 m	334.53 m	GPL047	C	2.19	2.33 ± 0.24
				A	1.03	
				B	1.25	
Boyne River 2C	467.50 m	467.68 m	GPL048	C	1.60	1.25 ± 0.29
				A	0.59	
				B	0.59	
Boyne River 2C	563.85 m	564.02 m	GPL049	C	0.53	0.57 ± 0.04

[4] Uncertainty of the thermal conductivity for each specimen is one standard deviation of the measured values.

				A	2.02	
				B	1.70	
Boyne River 2C	608.55 m	608.67 m	GPL050	C	1.77	1.82 ± 0.17
				A	2.72	
				B	2.44	
Boyne River 2C	626.41 m	626.60 m	GPL051	C	2.29	2.47 ± 0.22
				A	1.71	
				B	1.81	
Boyne River 2C	666.97 m	667.10 m	GPL052	C	1.72	1.74 ± 0.06
				A	0.48	
				B	0.46	
Boyne River 2C	696.42 m	696.59 m	GPL053	C	0.42	0.45 ± 0.03
				A	3.40	
				B	3.40	
Boyne River 2C	739.39 m	739.52 m	GPL054	C	2.74	3.15 ± 0.38

4.0 Discussion and conclusions

In most cases, the measured values agree closely for samples taken from the same specimen. This implies that variation in thermal conductivity for these specimens is not significant over the scale of centimetres for these specimens. However, specimens GPL047, GPL048, and GPL054 are exceptions, showing 12%, 23%, and 14% variation from the mean conductivity respectively. This indicates that thermal conductivity may be significant over the scale of centimetres for specimens GPL047, GPL048, and GPL054. Given that there is about 114% variation from the mean conductivity (about 1.5 W/mK) across specimens, variation on the kilometre scale through that sequence also appears significant

The conductivities recorded from these specimens are in the low to normal range for sedimentary sequences. The results suggest that the formations assessed in this study could act as attractive thermal insulation for geothermal systems.

The following additional points must be considered if extrapolating the results in this report to in situ formations:

1. The samples upon which the thermal conductivity measurements were made are only several square centimetres in surface area. While the specimens were chosen to represent the geological sections from which they came, there is no guarantee that the sections themselves are typical of the overall geological formations. This is especially true for heterogeneous formations. This introduces an unquantifiable random error into the results.

2. Porosity exerts a primary influence on the thermal conductivity of a rock. Water is substantially less conductive than typical mineral grains[5], and water saturated pores act to reduce the bulk thermal conductivity of the rock. Gas-filled pores reduce the bulk conductivity even more dramatically. Results reported in this document are whole-rock measurements. No adjustments were made for porosity. It is to be expected that the thermal conductivity of a given formation will vary from place to place if the porosity of the formation varies (conductivity decreases with increasing porosity).

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[5] **Beardsmore, G.R. and Cull, J.P.** (2001). *Crustal heat flow: A guide to measurement and modelling*. Cambridge University Press, Cambridge. 324pp.

3. Thermal conductivity of rocks is sensitive to temperature[2], typically decreasing at a rate of around 0.16% per °C. This should be kept in mind when developing models of *in situ* thermal conductivity.

Granite Power Whole Rock Fusion Results GPL042-GPL054						
Sample Number	Density	Uranium [ppm]	Thorium [ppm]	Potassium [%]	Heat Generation [μW/m^3]	±
GPL042	1.868	1.3	5.2	0.48	0.52	0.01
GPL043	2.678	0.5	1.2	0.38	0.25	<0.01
GPL044	1.54	1.1	4	0.37	0.35	0.01
GPL045	1.757	5.1	12.5	0.53	1.48	0.02
GPL046	2.679	0.5	1.2	0.47	0.26	<0.01
GPL047	2.149	2.8	8.5	1.19	1.15	0.02
GPL048	2.232	2.2	8.8	0.78	1.05	0.02
GPL049	1.537	<0.1	0.1	0.02	<0.02	<0.01
GPL050	2.823	0.9	3.5	0.27	0.53	0.01
GPL051	2.481	0.4	1.1	0.29	0.19	<0.01
GPL052	2.383	1.4	4.2	0.48	0.63	0.01
GPL053	1.447	4.8	22.9	0.97	1.59	0.03
GPL054	2.469	1.9	6.8	0.97	0.98	0.01