Modified transient plane source measurements of Olkiluoto migmatite

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ABSTRACT: Finland is moving forward as the first country to solve the geological final disposal of spent nuclear fuel. Due to the temperature sensitive nature of the used disposal method, thermal design of the repository layout is necessary. This design process requires information of the thermal properties of the rock mass as confining parameters for modelling. As part of this process, modified transient plane source (MTPS) measurements of the thermal properties of Olkiluoto migmatite were carried out between 2019 and 2021. The MTPS method was used to measure simultaneously thermal conductivity and thermal effusivity. Additionally, density measurements were done, allowing the calculation of thermal diffusivity and specific heat capacity. The assumption of normally distributed data was tested using the Shapiro-Wilk test for normality and normal probability plots. Finally, the data were fitted with Gaussians using the maximum likelihood method.

Keywords: geological disposal, thermal properties, thermal conductivity, thermal effusivity. modified transient plane source, MTPS.

1 INTRODUCTION

Posiva Oy is responsible for the final disposal of the spent nuclear fuel of its owners Teollisuuden Voima Oy and Fortum Power & Heat Oy. As part of the disposal process, investigations have been carried out in the ONKALO® facility in Olkiluoto, Western Finland. This paper describes modified transient plane source (MTPS) measurements of thermal conductivity and thermal effusivity carried out in room temperature between 2019 and 2021 as a part of the on-going investigations on rock thermal properties for the needs of thermal dimensioning of the disposal facility. Additionally, measured density values and calculated specific heat capacity and thermal diffusivity values are described. A more comprehensive description of the work done will be published as a Posiva Working Report (Kiuru 2023).

1.1 Background

Due to the temperature sensitive nature of the used bentonite buffer, thermal design of the repository layout is necessary. This design process requires information of the thermal properties of the rock mass as confining parameters for modelling the temperature evolution of the different layout candidates. Studies on thermal properties have been carried out in Olkiluoto since 1989 and include both laboratory and in situ measurements, as well as theoretical studies. Reporting has been project based and, as a result, scattered. A recent effort was made to record all work done on thermal properties between 1992 and 2017 (Kiuru & Kukkonen 2023).

1.2 Location

ONKALO® facility (Figure 1) is situated on the island of Olkiluoto in the municipality of Eurajoki in Western Finland. The bedrock of Olkiluoto is dominated by variably migmatised supracrustal high-grade metamorphic rocks of Paleoproterozoic age. These are intruded by Paleoproterozoic granitic-tonalitic plutonic rocks and granitic pegmatoids. The bedrock of Olkiluoto has been divided into two main lithological units: 1) veined gneiss unit (VGN), and 2) diatexite unit (DGN). Bodies of tonalitic-granodioritic-granitic gneisses (TGG), mafic gneisses (MFGN), mica gneisses (MGN) and granitic pegmatoids (PGR) have been identified in both units as individual lithological objects. (Aaltonen et al. 2016)

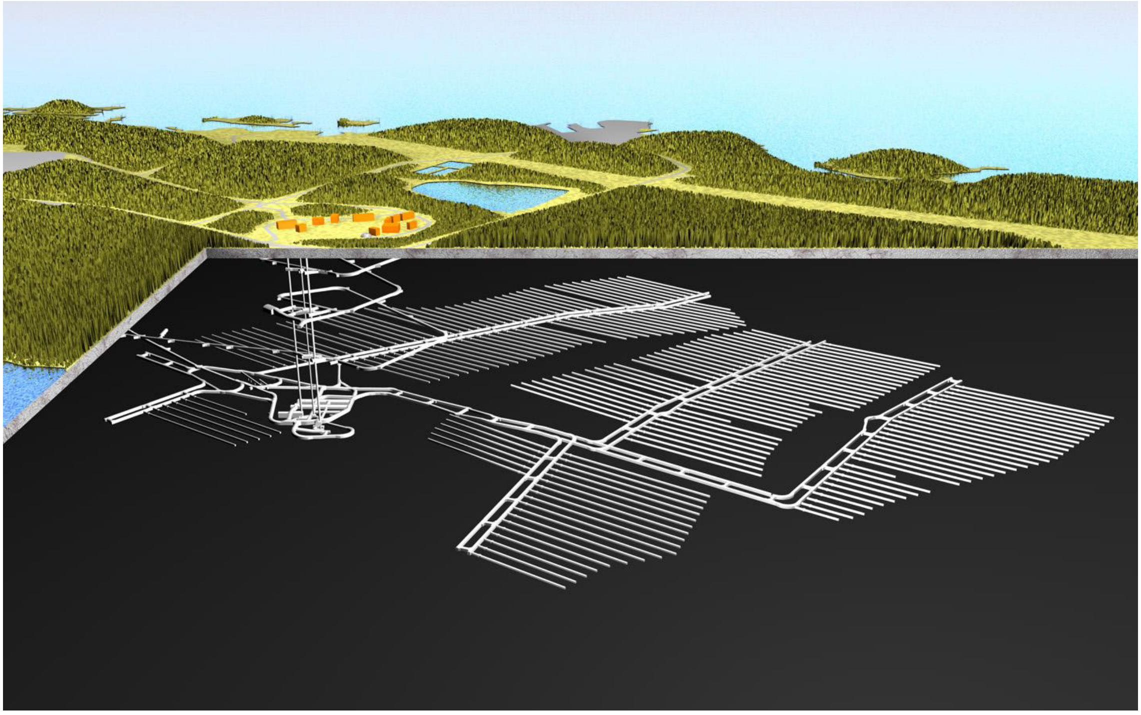

Figure 1. Planned layout of the ONKALO® facility in Olkiluoto, Eurajoki, Finland. Image: Posiva Oy.

2 MODIFIED TRANSIENT PLANE SOURCE (MTPS) MEASUREMENTS

This section describes the methodology of MTPS measurements carried out between 2019 and 2021. A total of 6 measurement campaigns were done for the needs of 5 different projects. (Kiuru 2023)

2.1 Operating principle

The modified transient plane source (MTPS) system used in this study was the patented (Mathis & Chandler 2004) TCi™ Thermal Conductivity Analyzer by C-Therm Technologies Ltd. During the measurement, the heat reflectance sensor applies a momentary constant heat source to the specimen. The sensor is supported on an insulated backing and surrounded by a guard ring that ensures one-dimensional heat flow into the specimen. Heat is generated by applying a current to the sensor's coil. Simultaneously, the rate of the temperature increase is monitored by reading the voltage drop over the sensor, which has been calibrated to the temperature change. (C-Therm 2016)

Effusivity is determined from the voltage data by considering the temperature coefficient of resistivity of the sensor. Thermal conductivity is inversely proportional to the rate of increase of the temperature monitored and is calculated using the patented iterative method of Mathis & Chandler (2004). Temperature change in the material due to the temperature pulse is typically in the range of 0.2°C to 2.0°C, with maximum increase of less than 10°C. (C-Therm 2016)

2.2 Specimen selection and preparation

Specimen selection was done based on the requirements of each project. In general, typical specimens were 50 mm long sections of drill core, with diameters ranging from 50–70 mm. These were cut to length and when necessary, the ends were grinded to remove lips of prominent saw marks. After the physical preparation, all specimens were first dried for 72 hours at 95°C for measurement of dry mass, then saturated in tap water in NTP conditions for at least 30 days for the measurement of saturated mass and thermal properties. A total of 1103 of these specimens were measured. Measurements were taken on both ends of each specimen, resulting in 2206 measurement values. One measured value was later rejected due to erroneous behavior of the sensor during measurement.

Additionally, 200 older specimens were selected for remeasurement. These were 5–8 mm thick disks with a diameter of 40–42 mm that had originally been measured using the divided bar method by the Geological Survey of Finland between 1995–2014. Older specimens were not remeasured for density and porosity, as the small specimen size would have resulted in unacceptably large relative errors. This being the case, only preparation step was saturation in tap water in NTP conditions for at least 30 days prior to the MTPS measurements.

2.3 Calibration and uncertainty

Factory calibration of the TCi-3-A system is based on measurements of multiple reference materials with varying thermal properties. These span a thermal conductivity range of roughly 0.06–400 W/m·K and an effusivity range of roughly 145–37 000 $J/m^2 \cdot K \cdot s^{1/2}$. In addition to the thermal property calibration, the factory calibration includes a temperature coefficient of resistivity (TCR) calibration. Regular verifications of the calibration of the system during the campaigns were done using Pyrex® and Pyroceram® as reference materials. Calibration measurements were taken daily before and after each measurement batch. Calibration measurements were also taken upon restart if the system was turned off.

Reported accuracy of the system is better than 5 %, reported precision better than 1 % and reported reproducibility better than 3 %. Reported values are stated for a temperature range from 0°C to 50°C. Outside of the given temperature range, total system accuracy of < 10 % is reported. (C-Therm, 2016)

Major contributors to measurement error were identified and accounted for. These include 1) heat losses from the system, 2) errors in the temperature measurement, 3) contact resistance between the specimen and the sensor, and 4) heat transfer by convection in air surrounding the specimen. For details on uncertainty, please see the Posiva Working Report (Kiuru 2023).

3 STATISTICAL METHODS

This section describes the statistical analysis methods used with the data. Please note that throughout this paper ‘sample’ is reserved for a statistical sample, while a ‘specimen’ refers to the physical rock samples. Major goal of this paper was to test the applicability of the Central limit theorem and the following assumption of normality to Olkiluoto migmatite.

3.1 Descriptive statistics

Basic description of the data is done using descriptive statistics of minimum, maximum, first and third quartile, median and interquartile distance (IQR). For the sake of saving space, these are given only as standard boxplots. In the standard box plot, the box is defined by first and third quartile values, with the length of the box being the interquartile distance. Median value is represented by a line inside the box, and the whiskers represent minimum and maximum values as long as they are within a distance of 1.5 x IQR from the box. If there are values falling outside of the 1.5 x IQR distance from the box, these are represented as outliers, and the whiskers represent the 1.5 x IQR distance.

3.2 Testing for normality

As we assume the data to be normally distributed to allow for the fit of a Gaussian, it seems necessary to test this assumption. This was done by testing for the normality of the data using the Shapiro-Wilk test (Shapiro & Wilk 1965). For the Shapiro-Wilk test, the null hypothesis is that a sample x = (x1, x2, …, xn) came from a normally distributed population. The null hypothesis is accepted if the p value of the test is more than the chosen significance level α. It must be noted that at large sample sizes, the Shapiro-Wilk test may respond to trivial departures from normality. When necessary, this was reviewed using normal probability plots.

3.3 Maximum likelihood method for fitting a normal distribution to the data

Fitting of a normal distribution to the measured data was done exactly (i.e., without invoking the law of large numbers) utilizing likelihood theory. To grossly simplify the process, we start with the likelihood function and the corresponding log-likelihood function for $X \sim N(\mu,\phi)$. We then simply derive the corresponding maximum likelihood estimates of the mean and variance. For details of the method, see the Posiva Working Report (Kiuru 2023).

4 RESULTS AND DISCUSSION

This section shortly presents some of the results of these projects. Due to the restricted space, only thermal conductivity results are described. For the full results, as well as comparisons to other data sources, please see the Posiva Working Report (Kiuru, 2023).

Descriptive statistics of all MTPS measurements from Olkiluoto are given below as standard box plots for each major rock type and combined (Figure 2). It can be seen here that variation between rock types is relatively small, with the exception of TGG.

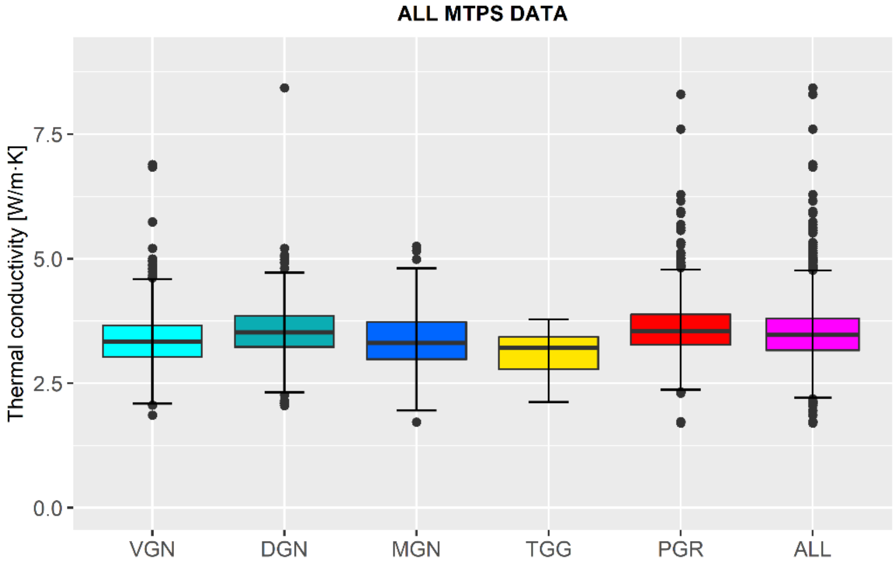

Figure 2. Standard box plots of thermal conductivity for each rock type and combined.

Visually, the fits of the normal distribution seem mostly reasonable (Figure 3). However, all of the rock types except for MGN (p = 0.1052), as well as the data combined, fail the Shapiro-Wilk test at a confidence levels of 95 % and 90 %.

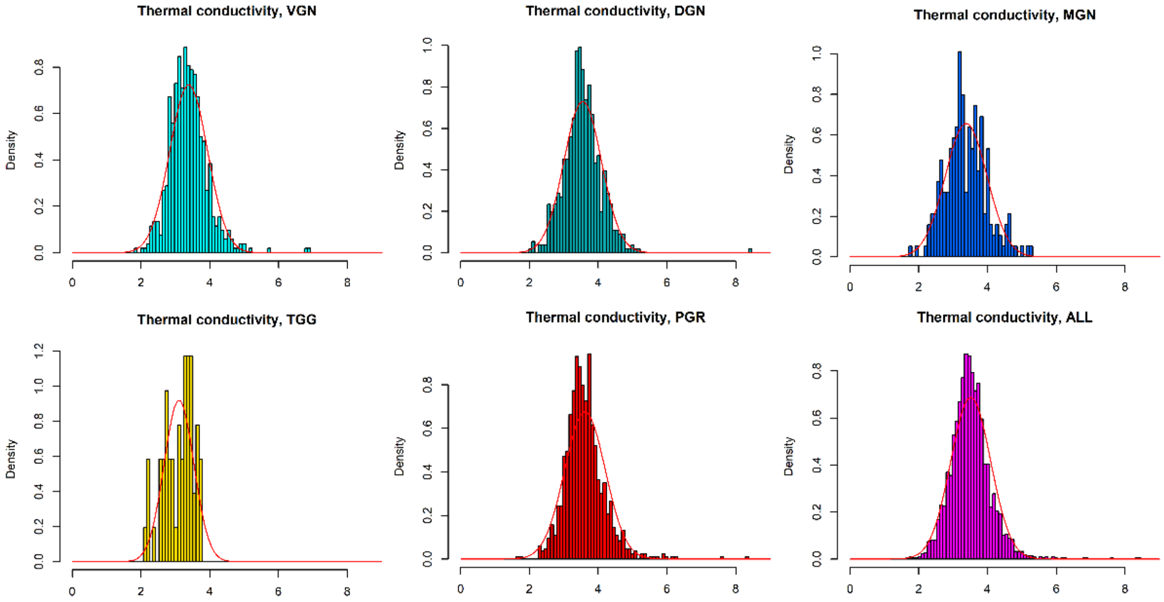

Figure 3. Histograms of the observed thermal conductivity data for each rock type and combined, overlayed with the MLE based Gaussian fits.

Finally, normal probability plots (Figure 4) show light tailed distributions for all rock types except TGG, and for the data combined. This means that high thermal conductivity values are less common than would be assumed for normally distributed data. MGN and TGG show some signs of bimodality, but their effect on the entire sample population is limited. It should also be noted that TGG has a relatively small sample size.

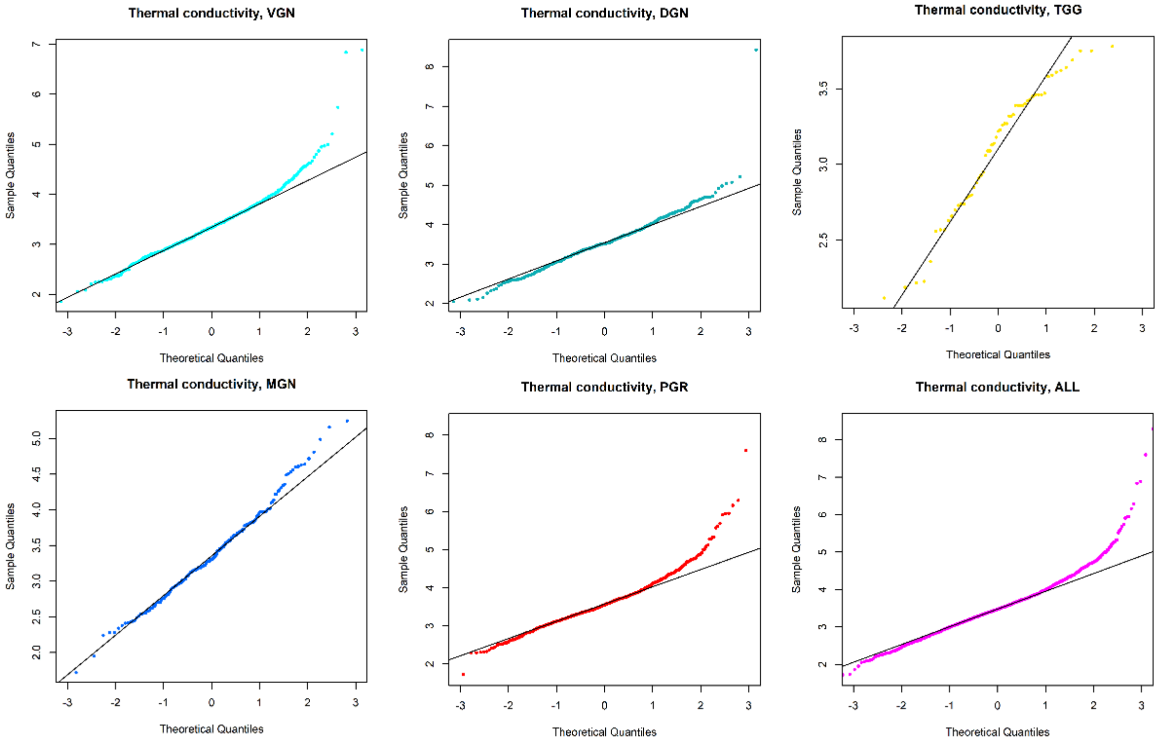
Thermal conductivity, VGN
Thermal conductivity, DGN
Thermal conductivity, TGG
Thermal conductivity, MGN
Thermal conductivity, PGR
Thermal conductivity, ALL

Figure 4. Normal probability plots of the thermal conductivity data for each rock type and combined.

5 CONCLUSIONS

Based on this study, the following conclusions were made:

- Variation in thermal conductivity between the rock types is relatively small
- High thermal conductivity values are less common than they would be, if the values were normally distributed
- There is not clear bimodality on the population level

ACKNOWLEDGEMENTS

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