Drift scale test: Analyze and report

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<td>Editorial change, “CP1” to “CP2”, on page 18. Version number was added on pp. 80 and 83.</td>
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EXECUTIVE SUMMARY

This report summarizes the results of the in situ thermophysical properties measurements as part of the Drift Scale Test (DST) measurement program at Yucca Mountain, Nevada. Thermophysical measurements have been performed with three built-in thermal probes since November 13, 1997 and were expected to continue for three more years until the end of the DST cooling period. The Department of Energy (DOE), under Cooperative Agreement, Number DE-FC28-98NV12081, has funded a research project at the University of Nevada, Reno since November, 1999 titled: “Continuing site characterization and performance verification applications with the REKA method at Yucca Mountain, Task 13.” This project is also referred to as “Drift Scale Tests,” the previous title of a research project that was funded by a different contract from the DOE from 1997 to 1999 under M&O task WBS 1.2.3.14 (123E2265M1). The thermophysical properties include thermal conductivity and diffusivity, each pair determined simultaneously from an in situ temperature field measurement around a single-borehole thermal probe, using inverse modeling. The application of the method and apparatus have practiced U.S. patent 4,933,887, assigned to Sierra Science of Reno, NV. The method is called Rapid Evaluation of K and Alpha (REKA), referring to the determination of thermal conductivity and diffusivity from a single measurement. The application of the REKA method during the project period resulted in the submission of over 330 in situ, effective conductivity and diffusivity pairs during the reported period.

The scope of work for Task 13, approved in 1999, included the design and fabrication of three new thermal probes for the use in the Enhanced Characterization of the Repository Block (ECRB) activity, as well as in subsequent performance verification. The promise of long-term application and measurement continuation at Yucca Mountain served as the basis for waiving the license fee for U.S. Patent 4,933,887 for the project. However, the scope of work for Task 13 was re-defined during the course of the work by DOE and M&O personnel, documented in the Scientific Notebook UCCSN-UNR-013 entries between May 2000 and November 2000. According to the new scope, re-usable REKA probes were needed, as a procurement of the method for the use in the lithophysal rock formation for a third party. Although the protracted decisions regarding the intellectual property issues effectively prevented the completion of the new probes and their application in site characterization, the design of the probes and the method evaluation for lithophysal application have been completed during the reported period.

The in situ measurement results have shown that the effective thermophysical properties variations were moderate with mean values around the expected, conduction-only values, except for the readings taken when the boiling front was at or around the location of Probe 1. Thermophysical properties variations within a 10-20% regime indicate that the heat flow has been conduction-dominated around all three REKA probes in the DST during the study period excluding the time of the boiling front condition at a probe location. Slow, as well as periodic changes in the effective conductivity and diffusivity values were also observed, that may be attributed to convective and evaporative effects as well as moisture content changes. In addition, Probe 1 recorded consistent pool boiling for over a year in an area known to be in the condensate shredding zone.
The in situ measurement results were evaluated using statistical methods, trend analysis, and signal processing. The simple averages as conduction-only equivalent values for each probe are as follows:

<table>
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<tr>
<th>Probe</th>
<th>Average Thermal Conductivity [W/(mK)]</th>
<th>Average Thermal Diffusivity [m²/s]</th>
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<tr>
<td>1 (downward)</td>
<td>2.27</td>
<td>0.95 x 10⁻⁶</td>
</tr>
<tr>
<td>2 (horizontal)</td>
<td>1.98</td>
<td>0.95 x 10⁻⁶</td>
</tr>
<tr>
<td>3 (upward)</td>
<td>2.18</td>
<td>0.95 x 10⁻⁶</td>
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The effective thermal conductivity at the Probe 2 location is only about 10% lower than the readings of the other probes. More difference was expected due to the high rock temperature that was dominantly above boiling during the study period around Probe 2. Therefore, the in situ, effective thermal conductivity measured in assumingly dry, above-boiling conditions does not approximate well the gas-saturated conductivity used in thermal studies and models (BSC, 2002).

A linear trend analysis was also conducted in order to study the significance of variation with time, and to re-establish the initial, baseline properties at the three probes’ locations from the heated measurements. The results are as follows:

<table>
<thead>
<tr>
<th>Probe</th>
<th>Initial (unheated) Thermal Conductivity [W/(mK)]</th>
<th>Initial (unheated) Thermal Diffusivity (10^6) x [m²/s]</th>
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<tr>
<td>1 (downward)</td>
<td>1.97 +/- 0.13</td>
<td>0.78 +/- 0.09</td>
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<tr>
<td>2 (horizontal)</td>
<td>1.85 +/- 0.05</td>
<td>0.69 +/- 0.05</td>
</tr>
<tr>
<td>3 (upward)</td>
<td>2.10 +/- 0.11</td>
<td>0.85 +/- 0.10</td>
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The linear trend was proved to be statistically significant only for Probe 1 with non-zero slope, while the changes in the effective properties at the Probe 2 and 3 locations may not be considered statistically significant versus a zero change. Since variations are observed, the statistics suggest that the changes are either stochastic, or deterministic-periodic, or a combination thereof. Signal processing was used to filter the random effects from the deterministic components, applying low-pass, digital filtering. The results, depicted in the figures for Probes 1, 2, and 3, show a recognizable, periodic variation with a significantly high...
amplitude of about 10% of the mean value. The average cycle time is very close to one year, a
strong indication that all three probes captured annual, periodic variations in the thermophysical
properties. Other variation frequencies, most notably seasonal, may also be identified, but are
not discussed in the report and must be deferred to future studies. The significance of such
variation is not seen much in the basic application of the thermophysical properties in thermal
analysis, since the annual variations would average out. The variation is rather seen to be
significant as an indicator of some underlying events being involved in the coupled processes or
boundary conditions.

Many reasons can be subjected to hypothesis tests for the explanation of such annual (or
seasonal) variations. For example, changes may be explained by moisture content variation due to
changing percolation, barometric pressure pumping, or periodic vapor-phase advection toward
the ventilated part of the drift scale test area. It must be noted, however, that a simple, periodic
heat loss variation through the bulkhead of the heated drift would not result directly in the
variation of the effective thermophysical properties, since no significant, periodic temperature
field variation at the probe's locations has been detected.

The REKA results are complementary to large-scale inverse modeling results such as obtained
for DST by the other investigators studying coupled thermo-hydrologic processes at Yucca
Mountain, fitting model results to multiple sensors data. Periodic variations of the effective
properties as surrogate hydrothermal characteristics can be identified by the REKA probes.
However, such variations may be missed by the simple observation of the temperature field
variation and subsequent inverse modeling. The very small signal changes in a hydrothermally
disturbed area may be masked by thermal and measurement noise, and thus filtered out and lost.
Since the evaluation of the REKA probe readings is self-contained and each probe yields
independent results, the method is straightforward, and sensitive to very small changes. In
addition, the REKA probes have excellent long-term stability and durability. For these reasons,
the method is seen to be efficient for validations and performance confirmation applications.

The application of the single-probe REKA method for lithophysal rock heat conductivity,
diffusivity, and porosity determination from one measurement has been extensively studied as
part of the design activity in Task 13. Although unfunded in the current fiscal year, the
lithophysal application studies using Monte-Carlo computer simulations have shown that the
REKA method is capable of determining effective thermophysical properties from a single-
borehole measurement even if the lithophysae are randomly distributed around the probe's
sensors. In addition, the evaluation of the REKA results yields an average lithophysal porosity,
an added value when considering site evaluation in design applications. The studies regarding
the lithophysal applications are included in the appendices of the report.
Task13 Final Report.

Probe 1

\[ a = 230.41 \]
\[ b/2 = 247.7 \]
\[ (a-b)/2 = 362.90 \]

Filtered
Original

Time in days starting from 4th Dec, 1997

Probe 2

\[ a = 420.51 \]
\[ b = 288.02 \]
\[ c = 328.34 \]
\[ d/2 = 190.09 \]
\[ (a+b+c+d)/4 = 354.267 \]

Filtered
Original

Time in days starting from 4th Dec, 1997

Probe 3

\[ a/2 = 201.61 \]
\[ b = 334.10 \]
\[ c = 278.73 \]
\[ d = 432.03 \]
\[ (a+b+c+d)/4 = 360.02 \]

Filtered
Original

Time in days starting from 4th Dec, 1997

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ACRONYMS AND ABBREVIATIONS

REKA Rapid Evaluation of K and Alpha
DOE U.S. Department of Energy
SIP Scientific Investigations Plan
YMP Yucca Mountain Site Characterization Project
UC University and Community College System of Nevada
### 1.0. SUMMARY OF SUBMISSIONS

Table 1-1: Acquired /developed data submissions

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| 013GD.008 | Q | MO0205UCC013GD.008 | DST REKA probe acquired data for thermal conductivity and diffusivity for the period 01/01/2001 to 03/31/2002 (heated measurements for boreholes 151, 152, and 153.) | 04/05/2002 |
| 013GD.009 | Q | MO0208UCC013GD.009 | DST REKA probe acquired data for thermal conductivity and diffusivity for the period 04/01/2002 to 06/30/2002 (heated measurements for boreholes 151, 152, and 153.) | 07/29/2002 |
| 013GD.010 | Q | MO0208UCC013GD.010 | DST REKA probe developed data for thermal conductivity and diffusivity for the period 03/01/2001 to 06/30/2002 (heated measurements for borehole 153). | 07/30/2002 |
| 013GD.011 | Q | MO0208UCC013GD.011 | DST REKA probe developed data for thermal conductivity and diffusivity for the period 01/01/2002 to 06/30/2002 (heated measurements for boreholes 151, 152) | 07/30/2002 |
| 013GD.012 | Q | MO0211UCC013GD.012 | DST REKA probe acquired data for thermal conductivity and diffusivity for the period 07/01/2001 to 09/30/2002 (heated measurements for boreholes 151, 152, and 153.) | 10/10/2002 |
| 013GD.013 | Q | MO0211UCC013GD.013 | DST REKA probe developed data for thermal conductivity and diffusivity for the period 07/01/02 to 09/30/02 (heated measurements for borehole 153) | 10/10/2002 |
| 013GD.014 | Q | MO0211UCC013GD.014 | DST REKA probe developed data for thermal conductivity and diffusivity for the period 07/01/02 to 09/30/02 (heated measurements for boreholes 151, 152) | 10/11/2002 |
| 013GD.015 | Q | MO0302UCC013GC.015 | DST REKA probe acquired data for thermal conductivity and diffusivity for the period 10/01/2002 to 12/31/2002 (heated measurements for boreholes 151, 152, and 153.) | 01/08/2003 |
| 013GD.016 | Q | MO0302UCC013GD.016 | DST REKA probe developed data for thermal conductivity and diffusivity for the period 10/01/02 to 12/31/02 (heated measurements for boreholes 151, 152, and 153) | 01/08/2003 |
| 013GD.017 | Q | MO0305UCC013GD.017 | DST REKA probe acquired data for thermal conductivity and diffusivity for the period 01/01/2003 to 03/31/2003 (heated measurements for boreholes 151, 152, and 153) | 03/28/2003 |</p>
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Table 1-2: Relationship between measurement/derived data and various evaluation representations in tables and figures in the final report.
2.0. INTRODUCTION

2.1 IN SITU MEASUREMENTS: BACKGROUND AND REVIEW

Representative thermophysical properties of rock are of great importance in the design and operation of underground facilities. The dissipation of heat generated from nuclear waste packages to be emplaced at Yucca Mountain is an important factor of the thermal operation. A recent sensitivity study (NWRPO, 2003) shows that the heat conductivity and diffusivity of the host rock greatly affects the temperature of the subsurface space.

A thermal probe method, called REKA (Rapid Evaluation of K and Alpha), has been used at the DST (Drift Scale Tests) at Yucca Mountain for determining heat conductivity (k) and thermal diffusivity (alpha). The REKA method involves a single borehole probe with an integral heater and a temperature measurement section. An incremental ellipsoidal temperature field is generated by the heater of the REKA probe and the temperature distribution along the length of the probe is recorded at several locations and at given time intervals for a period of 24 hours. A trial-and-error evaluation procedure is used to determine the unknown thermophysical properties by minimizing the root-mean-square error between the measured and the calculated incremental temperature fields with the trial thermophysical properties. Since the REKA method uses incremental temperatures generated by a small incremental heating signal, in situ measurements can be conducted under variable ambient temperatures and hydrothermal conditions. The conductivity and diffusivity results of the REKA evaluation are dependent upon the forward temperature prediction model used for the calculation of the trial incremental temperature fields. The current study involves a conduction-only forward prediction model, therefore, the results presented are of effective thermophysical properties representing all modes of heat transport as conduction in the rock. Other representation of the primary REKA measurement results is also possible using a hydrothermal model for measurement evaluation, as discussed in a previous publication (Danko and Buscheck, 1993). It was proposed and approved by DOE, documented in the Scientific Investigation Plan (SIP) in Appendix 1, to repeat the evaluation of all the primary REKA data files against a NUFT (NUFT, 2000) rock model in order to characterize rock matrix conductivity and diffusivity in situ. However, task modifications by DOE eliminated this study during the course of the research project.

Measurements have been conducted using three independent probes since November 1997 when the DST facility was completed but still at its ambient, unheated condition. Heating of the DST started in December 1997 by in-drift as well as wing heaters. REKA measurements have since been continued under varying temperature and other hydrothermal conditions. The locations of the REKA Probes 1, 2, and 3 shown in Figure 3-1, are in the DST boreholes numbered in the respective order as 153 (9.60 m deep, downward at 45° angle), 152 (10.06 m deep, horizontal, between two wing heater tubes) and 151 (10.06 m deep, vertical, above the drift centerline).

Pre-heated, baseline readings with 9 measurements were taken during November, 1997. During the heated phase between December, 1997 and January, 2002, 223 REKA measurements were performed on Probes 1, 2, and 3. The current, cooling phase has to date yielded 104 measurements on the three probes. The measurement control software was modified in May, 1998, in order to decrease electronic and thermal errors in the measurement. The current report includes the derived data for the period of improved measurements, between May 1998, and June 30, 2003.

In addition to continuing the in situ measurement and evaluation with the three REKA probes at DST in Task 13, other tasks were also proposed and originally approved. Large-scale REKA probes were designed and analyzed for characterizing the effective lithophysal rock properties at
the ECRB facility. This task, however, was eliminated by DOE before the new REKA probes were built, and only the numerical studies of the design were completed (Danko et. al., 2002, 2003).

2.2 OBJECTIVES

There were three original objectives included in the SIP:

1. To continue data gathering, at least once a month, with each of the three REKA Thermal Probes that are built into the drift wall at DST Alcove 5 at Yucca Mountain; to evaluate the primary measurement data against in-situ thermal diffusivity and heat conductivity; and report the changes in these values during the heating phase of the DST.

2. To measure thermophysical properties at new locations in the ESF.

3. To explore the possibility of using the REKA Thermal Probe technique for continuous performance confirmation verification applications regarding hydrothermal/rock drying effects.

During the course of the research project, the scope was reduced by DOE to include only the 1st Objective, however, part of the design and analysis were funded. The results obtained regarding the design and application analysis of the REKA method in lithophysal rock formation are documented in Appendix 2 and 3.
3.0. DESCRIPTION OF REKA METHOD

3.1 INTRODUCTION

The REKA (Rapid Evaluation of K and Alpha) method was developed in order to perform in situ measurement of heat conductivity (K), and thermal diffusivity (α) of rock mass. The REKA method, originally proposed by Danko and Cifka (1985), consists of a specific data collection, and evaluation methodology.

The REKA measurement involves a single borehole probe with a heater and a temperature measurement section. The heater generates an ellipsoidal temperature field; the temperature distribution along the length of the probe is recorded, using a data collection system, at several locations at a specified time interval during the measurement period. The volume of rock involved in the measurement is variable, depending on the duration of the measurement period and the length of the temperature measurement section.

The REKA evaluation software version 1.1 performs inverse modeling of the measured temperatures and input thermal power to determine the heat conductivity and thermal diffusivity of the rock, using trial property values and comparing the temperature field from forward calculations to the measured temperature field.

3.2 MEASUREMENT LOCATION

Three REKA probes were installed at DST in the Exploratory Studies Facility (ESF) tunnel to measure heat conductivity and thermal diffusivity of the rock mass as the tunnel is being heated. The locations of the REKA Probes 1, 2, and 3 are shown in Figure 3-1. These probes are numbered in the respective order as 153 (9.60 m deep, downward at 45° angle), 152 (10.06 m deep, horizontal, between two wing heater tubes) and 151 (10.06 m deep, vertical, above the drift centerline).
3.3 THE THERMAL PROBES

Each DST measurement probe is equipped with a heater section, 0.20 meters in length, and a measurement section covered by uniformly distributed measurement stations. Each measurement station is a combination of two thermocouple sensors placed on two sides of the probe. Figure 3-2 shows the detail of the REKA probe’s layout of heater and measurement thermocouples designed and used at DST. One thermocouple measures the probe’s heater temperature, and 8 thermocouples, 0.05 m apart, starting at 0.2 m from the center of the heater section, measure rock temperature at four distances from the center of the heater section. All thermocouple and heater wires are bundled together. The measurement sensor head is formed to the shape of a hollow cylinder and then inserted into a drill hole. The drill hole is grouted after the insertion of the probe assembly. The installation is permanent and the measurement probe can not be removed.
Figure 3-2. REKA probe at DST, (a) shaped probe, (b) plan view (unwrapped), (c) probe after insertion into a borehole
3.4 REKA DATA ACQUISITION SYSTEM

3.4.1 The DST system

Figure 3-3 shows the REKA data acquisition system installed at DST. The system consists of an HP75000B data acquisition system, connected to the three REKA thermal probes, and an IBM PC with LINUX operating system. The HP unit and the LINUX PC are connected through two serial communication ports, COM1 and COM2. A set of REKA measurement control programs, already developed and installed on the HP unit, conduct a REKA measurement and send the results to the PC serial port. A program, developed and compiled using gcc C compiler on the LINUX PC, receives and writes the data into a user-defined Primary Measurement Input Data (PMID) file. The data file has a fixed structure that is compatible with the REKA evaluation software (Danko, 2001). The DSTR101 software (Danko, 2001) installed on the data acquisition system contains all the control programs needed for these measurements. The IPR-006 procedure (IPR-006, 2002) controls the collection and electronic transfer of measurement data files.

![Diagram of REKA data acquisition system at DST](image)

Figure 3-3. REKA data acquisition system at DST

3.5 THE REKA EVALUATION METHOD

The purpose of REKA1.1 software is to process a single or multiple, electronic, PMID file(s) and evaluate the heat conductivity (k) and thermal diffusivity (α). The PMID contains implicit information about the k and alpha of the rock surrounding a REKA thermal probe. This section describes the mathematical model and evaluation principle.

3.5.1 Evaluation Principle

The unknown heat conductivity (k) and thermal diffusivity (α) are determined by finding the values that satisfy the best least-square-fit between the measured and predicted temperature fields. The evaluation uses all temperature sensors (eight at DST) at all measurement times (400
intervals at DST) during perturbation of temperatures by the REKA heater. The squared RMS error is calculated as follows:

\[
(RMS)^2 = \frac{1}{NS(M - M_1)} \sum_{j=1}^{NS} \sum_{i=M_1}^{M} \left( vma_{ij} - \frac{1}{k} \nu v(\alpha, t_i, d_j) \right)^2
\] (3-1)

Where:

\( vma_{ij} = VM_{ij} - b_j - c t_i \)

\( VM - \) measured temperature field

\( b_j - \) zero-error of temperature measurement

\( t_i - \) time

\( c - \) background temperature evolution (rate of change) due to a remote heater

\( M - \) total number of time divisions

\( M_1 - \) start of heating time index

\( NS - \) number of sensor locations

\( i - \) spatial index

\( j - \) temporal index

\( k - \) thermal conductivity

\( \nu v(\alpha, t_i, d_j) - \) calculated temperature field as a function of time \( t_i \), and position \( d_j \); \( \alpha \) is the thermal diffusivity

To perform the comparison, the software calculates simulated temperatures with assumed \( k \) and \( \alpha \) values using an analytical solution to the transient conduction equation. For convenience, the equation is solved for an initial condition of zero temperature and a far-field boundary condition of zero temperature. The initial and boundary conditions for the REKA measurements depend on the particular situation. To facilitate the comparison between the measured and simulated temperatures, the measured values are adjusted to be consistent with an initial condition of zero temperature and a far-field boundary condition of zero temperature. Minimization of Equation (3-1) is accomplished numerically with respect to \( \alpha \), and analytically with respect to \( k \), the initial temperatures of the eight sensors, and the average rate of change of the temperatures of the eight sensors (in the absence of REKA probe heating).

For an assumed \( \alpha \), the process begins with a trial \( k \). The analytical minimization is achieved by setting the partial derivatives of Equation (3-1) to zero, and then solving the algebraic equations. Equation (3-1) is minimized separately for each of the eight sensors. The resulting initial temperatures and the trial \( k \) are then used in the minimization of Equation (3-1) for the average rate of change of the temperatures. The result is then used to minimize Equation (3-1) for the \( k \) value. If the resulting \( k \) and the average rate of change of background temperature are not sufficiently close to the initially assumed values, the process is repeated, using the previously
calculated values of these two parameters as assumptions. The equations used for the calculation of $k$, $b_j$, and $c$ are given in section 3.5.2.

When the best fit values for the $k$, initial temperatures, and average rate of change of background temperature are found, the software stores and prints the results if the $\alpha$ was provided as an input parameter. For the situation in which the $\alpha$ is also optimized for each individual PMID data file or for a group of PMID files, the $\alpha$ is varied and the above process is repeated. When all of the trials are processed, the best $\alpha$ and the associated $k$ that minimize Equation (3-1) are recorded as the final results.

3.5.2 Analytical Solution

The REKA probe has a short cylindrical heater. Temperature field around the cylindrical probe can be modeled using the superposition of spherical heater's analytical solution to the non-steady-state heat conduction in an infinite solid around a hollow sphere. (Carslaw and Jaeger, 1986) The partial differential equation for temperature, $v$, in polar coordinate system, for this situation is

$$\frac{\partial v}{\partial t} = \alpha \left( \frac{\partial^2 v}{\partial r^2} + \frac{2}{r} \frac{\partial v}{\partial r} \right)$$  \hspace{1cm} (3-2)

The differential equation is subject to the following initial and boundary conditions:

1) the initial temperature in the rock is zero

2) a spherical heat source, with heat flux $q$, is generated on the surface of a hollow sphere of radius $R$

3) the rock volume is infinite, i.e., the temperature is always zero at large distances

Carslaw and Jaeger (1986) show that the solution for the temperature, $v$, is the following:

$$v(t,r,k,\alpha) = \frac{q}{4\pi kr} \left[ \text{erfc} \left( \frac{r - R}{2\sqrt{\alpha t}} \right) - \exp \left( \frac{r - R}{R} + \frac{\alpha t}{r} \right) \text{erfc} \left( \frac{r - R}{2\sqrt{\alpha t}} + \frac{\sqrt{\alpha t}}{R} \right) \right]$$  \hspace{1cm} (3-3)
Where $\alpha$ is the effective thermal diffusivity,

- $k$ is the effective heat conductivity,
- $r$ is the distance to the center of heater,
- $t$ is time,
- $q$ is heat flux, and
- $R$ is radius of hollow sphere.

The REKA heater is a cylindrical source. To use the analytical solution of Equation (3-3), this heater is modeled as a set of overlapping spherical sources, and the resulting incremental temperature changes due to each source are summed up at each sensor location and evaluation time. The number of sources is specified in the probe geometry file, and is 20 for the DST probes. The value of the heat source, $q$, in Equation (3-3), is the measured electrical power of the heater divided by the number of spherical sources superimposed in the analytical solution.

For each trial value of $\alpha$, the REKA Version 1.1 software calculates the temperature field at $(M-M1+1)$ time steps (after heater initiation) and for each of the eight sensors. Since the unknown $k$ is the leading constant, the $v(t, r)$ is first calculated with $k = 1$, and then the resulting temperature matrix, $vv$, is divided by the actual (and changing) value of $k$. This procedure minimizes the number of times that Equation (3-3) must be evaluated. The normalized $vv$ matrix (for $k=1$ and $q=1$) for a user-defined $\alpha$ can be pre-determined for a given probe arrangement by the probe’s developer and copied to the probeID.dat characteristic data file. If activated, the use of this constant $vv$ matrix can further accelerate the evaluation for a given $\alpha$. In addition, this option allows the import of a normalized temperature field calculated by a numerical or hydrothermal code.

In Equation (3-1), the measured temperatures are adjusted to account for the initial temperature of the sensors and the non-REKA evolution of the average temperature in the measurement volume. Equation (3-4) is the adjustment equation, in terms of the parameter names in the software.

$[cvm] = [VM] - \text{ones}(M, NS) * (<sv3> - C * [tii])$  

(3-4)

The variables in equation (3-4) are as follows:

**VM (M,NS):** Measured temperature field- a matrix with M rows for the M time steps and NS columns for the NS sensors, corresponding to $VM_{ij}$ in Equation (3-1.a).
ones (M, NS): **Ones**- a MxNS matrix with each entry being 1.0. It is used to build initial temperature and externally driven temperature evolution adjustments to the measured temperatures.

<sv3> (NS): **Initial temperature**- a diagonal matrix with NS values, corresponding to $b_j$ in Equation (3-1.a). Each element is the initial temperature (just prior to start of REKA heating) of an individual sensor. The product of Ones and <sv3> is an M x NS matrix with each (time) row being the initial (step Mi) temperatures of the eight sensors.

C: **Temperature change rate**- the average background change rate of the temperature of the ensemble of eight sensors, corresponding to $c$ in Equation (3-1.a). This change is due to the presence of non-REKA heat sources or sinks that also affect the temperature evolution.

tii (M, NS): **Time matrix**- each column is the time in seconds. The product of the tii matrix with the constant $C$ is an estimate of how much the average temperature of the sensors would have changed at each time step if the REKA heater had not been energized.

cvm (M, NS): **Adjusted measured field**- This is the measured temperature field, corresponding to $V_{M_0}$ in Equation (3-1.a), with the temperatures adjusted to remove the initial temperature field and the background (non-REKA) evolution of the temperature field. These temperatures should be directly comparable to a simulated temperature field that uses zero temperature initial condition and zero temperature far field boundary condition.

Substitution of Equation (3-4) into Equation (3-1) allows differentiation of the left side with respect to each of the initial temperatures, the rate of background temperature change, and the thermal conductivity. The RMS term in Equation (3-5) denotes the root-mean-square error of fit between the measured and simulated temperature fields. The calculation of these variables is the subject of the following sections 3.5.3 through 3.5.5.

$$\text{(RMS)}^2 = \frac{1}{N} \sum_{j=1}^{NS} \sum_{i=M_i+1}^{M} \left(VM(i, j) - (\text{ones (M, 2NS)} *)<sv3>(i, j) - C \text{tii}(i, j) - \frac{1}{k} \text{vv}(i, j)\right)^2 \quad (3-5)$$

### 3.5.3 Initial Temperatures

Equation (3-5) is initially differentiated with respect to each diagonal term in the <sv3> matrix and set to zero.

$$\sum_{i=M_i+1}^{M} \left(VM(i, j) - (\text{ones (M, NS)} *)<sv3>(i, j) - C \text{tii}(i, j) - \frac{1}{k} \text{vv}(i, j)\right) = 0$$
The above equation is solved for each $j^{th}$ element of $<sv3>$ diagonal matrix. The result is Equation (3-6), in which the eight elements of matrix (b) become the diagonal elements of $<sv3>$.

$$b(j) = \frac{\sum_{i=M_{i+1}}^{M} [VM(i, j) \ wt(i, j) - \frac{1}{k} \ vv(i, j) * wt(i, j) - C * tii(i, j) * wt(i, j)]}{\sum_{i=M_{i+1}}^{M} wt(i, j)}$$  \hspace{1cm} (3-6)

Equation (3-6) includes a set of weighting values, $wt(i,j)$. Inspection of the raw REKA data indicates that energizing the heater causes immediate (small) changes in the temperature sensor outputs; this is probably related to a change in the balance of the electrical instrument circuits, or physical transport processes in the probe's sensor area, not associated with heat conduction. Thus, the initial temperatures should be determined from data after the heater is energized. However, as time proceeds, the sensors will receive heat from the REKA heater, and their temperatures will be a combination of the initial temperature, the background temperature evolution, and REKA heating. Therefore, the weighting factors give preference to data from the earliest times after the REKA heater is energized. The algorithm for the weighting factors used as a standard configuration for DST measurements is $wt = e^{(M_{i+1} - j/30)}$. The weighting factor is 1 at the moment of energizing ($i = M_{i+1}$), and a decreasing value towards zero with increasing $i$.

### 3.5.4 Background Temperature Evolution

Equation (3-5) is next differentiated with respect to the background temperature evolution rate, $C$, and set to zero:

$$\sum_{i=M_{i+1}}^{M} tii(i, j)\left(VM(i, j) - \left<sv3\right>(i, j) - C tii(i, j) - \frac{1}{k} vv(i, j)\right) = 0$$

Solving the above equation for $C$ results in Equation (3-7):

$$C = \frac{\sum_{j=1}^{NS} \sum_{i=1}^{M} [VM(i, j) * tii(i, j) - \frac{1}{k} vv(i, j) * tii(i, j) - \left<sv3\right>(i, j)]}{\sum_{j=1}^{NS} \sum_{i=1}^{M} tii^2(i, j)}$$  \hspace{1cm} (3-7)
In Equation (3-7), the terms are evaluated using the last $M_1$ to $M$ rows and all $NS$ columns. The equation is evaluated with the assumed thermal conductivity and the $\text{<sv3>}$ results.

### 3.5.5 Thermal Conductivity

Finally, Equation (3-5) is differentiated with respect to the thermal conductivity ($k$) and set to zero.

$$
\sum_{i=M_1+1}^{M} v(i, j) \left( VM(i, j) - \left( \text{ones} (M, NS) * \text{<sv3>} \right)(i, j) - C tii(i, j) - \frac{1}{k} v(i, j) \right) = 0
$$

The above equation can be solved for $k$, the result is as follows:

$$
k = \frac{\sum_{j=1}^{NS} \sum_{i=M_1+1}^{M} v(i, j) \left( VM(i, j) - \left( \text{ones} (M, NS) * \text{<sv3>} \right)(i, j) - C tii(i, j) - \frac{1}{k} v(i, j) \right)}{\sum_{j=1}^{NS} \sum_{i=M_1+1}^{M} v(i, j)} \tag{3-8}
$$

The equation is evaluated using the $\text{<sv3>}$ and $C$ values determined in the preceding steps, Equations (3-6) and (3-7). However, only the heated temperature values are used for the evaluation.

### 3.5.6 Convergence

The partial optimization of $b(j)$, $C$, and $k$ according to Equations (3-6), (3-7), and (3-8) needs to be repeated until all converge to a multivariate optimum solution. The computed values of $k$ and $C$ of each iteration cycle are compared to the previous iteration. If the relative differences for $C$ and $k$ are within 0.0000001% and 0.00001% respectively, the iteration is complete. If not, the computed values are used as the starting point for another iteration through Equations (3-6), (3-7), and (3-8). The values of $b(j)$ are calculated every iteration. Only the $k$ and the RMS values are used and recorded as results.

### 3.5.7 Evaluation of Diffusivity

After optimizing the $k$ for the user-specified or the set of trial diffusivities, the error-of-fit (RMS values) are plotted vs. the diffusivity. The software outputs the diffusivity associated with the minimum value of the RMS error function. This last step assures that the optimum set of thermophysical properties is determined.
3.6 THE REMOTE MEASUREMENT AND DATA FILE TRANSFER

The remote DST PC is accessed through a modem connection. The PMID is initially collected on the DST PC attached to the REKA measurement unit. The PMID is copied from the hard drive of the PC onto a floppy disk. The original files remain on the hard drive of the PC. The commands to collect and copy the files are issued remotely through a telephone link. Security is provided electronically for the PC of the REKA measurement unit and the data by password protection and limited access. The files copied onto the floppy are routinely examined remotely to check the completeness and integrity of the files. Integrity is further ensured by the REKA1.1 evaluation software, which will terminate if presented with a PMID file that has improper structure due to a missing or garbled data entry. The initiation and handling of a REKA field measurement and the resulting PMID are documented in an implementing procedure (UCCSN IPR-006). A PMID file contains 400 temperature readings on each of nine thermocouple sensors, as well as heating power in terms of voltage and current, at equal time intervals over a period of 24 hours. During the first 100 readings, the probe’s heater is off and at the 100th reading cycle, the measurement control program turns on the heater, providing a heating power of about 2 watts.

Although this procedure is specifically developed to control and process the REKA measurements at ESF in YMP, identical steps are needed for applying the method elsewhere.

4.0. DESCRIPTION OF THE EVALUATION SOFTWARE

A software version, previously used and qualified in 1997 for the REKA measurement evaluation, called REKA01, was available but rendered un-qualified in 2000 due to new software management requirements. A new software qualification activity was initiated and completed in 2000.

4.1 SOFTWARE QUALIFICATION

The software qualification followed the UCCSN QAP-3.2 procedure, in the UCCSN QA system. The first step was the preparation and approval of Control Point 1 documents (CP1). The CP1 contains five documents as follows:

1. Software Activity Plan (SAP), description of the software and timetable for the completion of qualification.

2. Software Requirements Document (SRD), description of software requirements.

3. Software Design Document (SDD), descriptions of software design to implement the software requirements.

4. Validation Test Plan (VTP), description of the entire test cases to be performed to guarantee the correctness and accuracy of software requirements.

5. Installation Test Plan (ITP), descriptions of the tests required before and after installation to ensure correct installation and the integrity of the software package.
After the CP1 documents were prepared, an independent technical reviewer reviewed them and all the technical comments were resolved. Then, the final versions of the CP1 documents were submitted for ITSMA review and final approval. After the final approval of CP1 documents, preparation of Control Point 2 (CP2) documents commenced. These documents are as follows:

1. Users Manual (UM): This document contains all the information regarding the usage and theory of the model used for the calculations.

2. Validation Test Report (VTR): This document is the major document as it contains the description and the results of the test cases specified in the ITP and VTP documents.

Eleven test cases were designed to ensure the correctness and accuracy of the REKA1.1 evaluation software listed as follows:

Test case 1 was designed to test the design elements of the input and output files, and user interface requirements of kat.m which is the master program. This is to make sure that the user-defined parameters and the input data in accordance with the structures defined in the SDD are used properly without any error.

Test case 2 was designed to check that the single file operation with either a user-defined diffusivity value or an optimized (calculated by the software) diffusivity value is performed correctly with proper data flow between the kat.m and the eva22.m program modules. The results of correct performance are the best estimates for conductivity and (if applicable) diffusivity, i.e., the pair belonging to the minimum error-of-fit between measured and simulated temperature fields.

Test case 3 was designed to test if multiple file operation is performed properly with individual optimization of both conductivity and diffusivity.

Test case 4 was designed to test if multiple file operation is performed properly with a common, user-defined thermal diffusivity and individually optimized conductivity.

Test case 5 was designed to test if multiple file operation is performed properly with a common, group-optimized thermal diffusivity and individually optimized conductivity.

Test case 6 was designed to test the correctness of operations of the data2aa.m and data3aa.m program modules, which read primary data files obtained from REKA measurements.

Test case 7 was designed to test the correctness and accuracy of the eva22.m main engine's inverse modeling capabilities. It uses the forward modeling capabilities to be tested in Case 8.

Test case 8 was designed to test the correctness and accuracy of the eva22.m main engine's forward temperature modeling simulation accuracy.

Test case 9 was designed to check auto-zero with inverse conductivity and diffusivity.
Test case 10 was designed to check variable auto-zero with inverse conductivity and diffusivity.

Test case 11 was designed to check remote heater effect suppression with inverse conductivity and diffusivity.

After the CP2 documents were prepared, reviewed, and the comments were resolved, the final versions of the CP2 documents were submitted for ITSMA review and approval. Upon final approval of the CP2 documents, the software was placed in the Software Configuration Management (SCM) and released for distribution with the software tracking number 10383-1.1-00. A qualified installation was performed on the designated computer at UNR labeled as DST_A_2000 and DST_B_2000 on 3/23/01. All the data collected since 5/22/98 were evaluated using the REKA V1.1 evaluation software in order to produce qualified data. The IPR-006 procedure controls the electronic data transfer as well as the evaluation of measurement files.

4.2 EVALUATION OF MEASUREMENT FILES

There are four different evaluation applications for the REKA evaluation software. Each application type is described in this section.

4.2.1 Standard Evaluation

The first evaluation category is based on the collected REKA probe measurement files. Figure 4-1 and Figure 4-2 show the plots generated by the REKA1.1 evaluation software based on a typical measurement file, prl_1023.dat, collected on 10/23/98. In this figure, the incremental REKA temperature field, \([cvm]\) in Equation (3-4), caused by the REKA heater and the temperature field calculated using the analytical formula, Equation (3-3), are plotted using dots and solid lines respectively. Four distinct, matched curves of dots and solid lines are shown, with respect to 4 different distances from the REKA probe's heater. The closer a sensor location is to the center of the probe's heater, the larger its temperature rise is. The REKA1.1 evaluation reports the optimized effective heat conductivity, diffusivity, and the RMS error of fit in addition to the undisturbed rock temperature at the probe location. Figure 4-2 shows the RMS error of fit vs. the trial diffusivity values. The REKA1.1 evaluation determines the diffusivity value associated with the minimum RMS. Figure 4-3 and Figure 4-4 show the results of the REKA evaluation of the pr2_0116.dat measurement file collected on 01/16/99 using Probe 2. Figure 4-5 and Figure 4-6 show the REKA evaluation of the pr3_0801.dat measurement file, collected on 08/01/98, as an example of Probe 3 measurement.
Figure 4-1. REKA evaluation result of Probe 1 (pr1_1023.dat, 1998, DTN: UN0106SPA013GD.003)

Figure 4-2. REKA evaluation result of Probe 1 (pr1_1023.dat, 1998, DTN: UN0106SPA013GD.003), diffusivity plot
Figure 4-3. REKA evaluation result of Probe 2 (pr2_0116.dat, 1999, DTN: UN0106SPA013GD.003)

Figure 4-4. REKA evaluation result of Probe 2 (pr2_0116.dat, 1999, DTN: UN0106SPA013GD.003), diffusivity plot
Figure 4-5. REKA evaluation result of Probe 3 (pr3_0801.dat, 1998, DTN: UN0106SPA013GD.003)

Figure 4-6. REKA evaluation result of Probe 3 (pr3_0801.dat, 1998, DTN: UN0106SPA013GD.003), diffusivity plot
Selection of the PMID files for submission was based on visual inspection of each individual temperature field as well as the results of the REKA evaluation. Visual inspection of the PMID temperature measurement results occasionally revealed that some of the measurements should be excluded from the evaluation since they may have been influenced by episodic hydrothermal activities or electrical disturbances that distorted the measurements and rendered them insignificant. Figure 4-7 shows an evaluation result of a rejected PMID file, pr3_0117.dat, collected on 01/17/99. This figure reveals a measurement with substantial noise-type fluctuation in the temperature field. These temperature fluctuations may be attributed to an electric noise affecting all the analog signals simultaneously. This disturbance cannot be modeled and filtered out. Therefore, only a poor fit can be obtained between measurement and the evaluation model. This poor fit is evident by examining the RMS error, which is an order of magnitude higher in this case than in the three previous evaluation examples.

In other cases, the disturbance may be caused by episodic hydrothermal effects such as moisture and vapor movements near the sensor locations. This type of disturbance is illustrated in Figure 4-8, using the pr1_0922 measurement file collected on 09/22/00. This interpretation is further supported by the fact that the rock temperature, 91°C, is close to the boiling temperature of water.
Figure 4-8. REKA evaluation result of Probe 1 (pr1_0922.dat, 2000, DTN: UN0106SPA013GD.003)

The effective conductivity, diffusivity, and ambient rock temperature results with respect to time are shown in Figure 5-1 through Figure 5-7. For a time period during which boiling conditions are found at Probe 1, the Nusselt number, instead of the thermal conductivity, is shown in Figure 5-2 as it will be discussed in 4.2.2. The number of days into heating is calculated from the first day of heating the ESF tunnel on 12/04/97. The results may be considered average values for a rockmass of approximately 0.2 m$^3$ in volume around Probes 1, 2, and 3. In addition to the standard results of the REKA software, the effective heat capacitance, $\rho c$, of the rockmass volume is calculated as the ratio of heat conductivity and thermal diffusivity, $k/\alpha$, where $\rho$ is density and $c$ is specific heat. Each thermophysical property displayed is accompanied by a linear regression estimate and a histogram of the relative error between the actual values and the estimated ones.

4.2.2 Evaluation in the Boiling Regime

The second evaluation application is based on a manually trimmed input file focusing on a short time period before and after the start of the probe's heater. This category occurred in Probe 1 location. The effective heat conductivity at the Probe 1 location increases with time. Since the rock is within below-boiling temperature regime, the continuous increase in the effective heat conductivity can only be attributed to a continuously increasing moisture content, or vapor-phase heat transport in the probe's area. During the time period when Probe 1 is around the boiling
temperature of water, the conductivity prediction by REKA V1.1 becomes unreliable due to a very active hydrothermal process of boiling. No meaningful results could be obtained using the standard model and evaluation configuration due to very low incremental temperature change and resulting low signal-to-noise ratio. Careful observation of the REKA temperature fields showed that subsequent to the start of the probe's heater, about 6 hours into measurement, there was a fast temperature rise of less than 0.05 °C followed by a decrease in temperature. This observation led to a hypothesis that boiling of water takes place in the probe's area, and the fast temperature rise is due to convective effects from the heater to the sensor area. In order to capture these effects, a three-hour time domain of measurement evaluation is used, instead of the total time interval of 18 hrs. The truncation of data for the evaluation allows capturing the essential part of the vapor transport while eliminating most of the masking noise. The evaluated effective conductivity here represents an indicator of convection/advection near boiling regime and does not represent a rock mass thermal property. The ratio between the effective, evaluated and submitted, and the theoretical, water-saturated conductivity, assumed to be 2.0 W/(mK), is calculated as a convection-induced increasing factor. This factor, obtained by a simple division of the effective thermal conductivity by 2.0, is considered to be the Nusselt number for porous media advection/convection. The Nusselt number results are used for probe 1 for the time period of boiling between days 1200 and 1750. For the other days, the effective conductivity is used. The average value of Nu is 12.7905 corresponding to a conductivity about 5.6 times the average conductivity at the Probe 1 location.

4.2.3 NUFT-Based Evaluation, Identification

The third type of evaluation applies an imported, simulated temperature field obtained using NUFT 3.0s. This type of evaluation can be used to inverse-identify thermophysical and hydrothermal characteristics. For example, a NUFT based temperature field was used to verify the REKA probe design arrangement and the correctness of the inverse modeling evaluation for lithophysal application, given in Appendix 2 (Danko, et. al., 2002).

4.3 PERIODIC CALIBRATION OF THE MEASUREMENT SYSTEM

The calibration of the measurement system was checked in 2001 and again checked on June 24, 2003. The system components were found to be in the range of specifications on both occasions. An end-point check was performed on the resistance of the current measurement resistor, R_l, which was found to be 1.02 Ohm instead of 0.993 Ohm based on the original reading taken in 1997. The value of R_l is used for the determination of heating power in the evaluation of the PMID files during inverse modeling. The heating power, q, used during the REKA measurement is a scale factor that affects the evaluation result of the thermal conductivity reciprocally, as seen in Eq. (3-3) from the term of q/k in the expression of the temperature field. The heating power, however, does not affect the thermal diffusivity which is optimized independently from conductivity. The deviation in heating power is about 2.7 percent increase which corresponds to a 2.7 percent reduction in the evaluated conductivities for Probe 1 and Probe 2. The heating power for Probe 3 is calculated differently, using the current reading twice, according to the formula q=R_{probe}I^2. The correction for Probe 3 is, therefore, (1.02/0.993)^2 = 1.055, i.e., 5.5% reduction, amid the different evaluation methodology.
Although this change is slight considering the time period of 6 years between the two readings, corrections may be applied to the thermal conductivity results, previously evaluated assuming $R_f=0.993$. The corrections may be linearly applied over time between June, 1997, with zero correction, and June 2003, with a correction of -2.7% for Probe 1 and 2, and -5.4% for Probe 3. Note, that the primary measurement files and the derived thermal diffusivity values are not affected by the current measuring resistor.

Due to the small error, the results already submitted are not corrected, and the systematic change in the measurement resistance is treated as a systematic measurement error. For Probe 1 and 2, the systematic error in the thermal conductivity is +0% and -2.7%, while for Probe 3, it is +0% and -5.4%. The thermal diffusivities are not affected. The nature of the changes in the electrical resistors with time is one-directional, therefore, a smooth change may be assumed causing no fluctuation with time.
5.0. EVALUATION RESULTS OF THE MEASUREMENTS

This section describes the results of statistical analysis of the DST measurement and evaluation results. The goal of this section is to interpret the results and determine if there is any trend in the effective thermophysical properties of the rock mass surrounding the measurement location with respect to time. First, the results of REKA V1.1 evaluation software are presented together with linear regression results. Second, a set of descriptive statistics for all the probes is presented for average values. Third, linear regression and trend t-test results are summarized and discussed, followed by the Boot Strap method (Jenson, 1997) to determine the significance of the observed correlations in the linear regression method as an independent verification.

5.1 REKA V1.1 EVALUATION RESULTS

The results of REKA V1.1 evaluation results are depicted in Figure 5-1 through Figure 5-7. As shown in Figure 5-8, the effective heat conductivity at the Probe 1 location varies with time over the presented measurement period. Since the rock is within a below-boiling temperature regime (see Figure 5-1), the continuous increase in the effective heat conductivity can only be attributed to a continuously increasing moisture content, or vapor-phase heat transport in the probe’s area. A power and subsequent computer hardware failure prevented the continuous monitoring of the thermophysical property variations between days 520 and 650. The loss of the measurements over this time period coincides with an apparent irregularity in the thermal diffusivity just before and after the lost time period (see Figure 5-3a). Probe 1 location went in boiling regime between 08/28/00 and 09/07/02. The data corresponding to this time period is excluded from the statistical analysis.

The results for Probes 2 and 3, depicted in Figure 5-4 through Figure 5-7, show little variation with time for both conductivity and diffusivity. The conductivity range is in acceptable agreement with the value of 2.1 W/(m.K) in the YM database (CRWMS M&O, 1996, and OCRWM 2000). The most stable readings over time are at the location of the horizontal Probe 2. This can be explained by the complete drying of the rock, ambient rock temperature between 120 °C and 169 °C, in the area surrounding the Probe 2 location. It is interesting to note that the rock around the vertical, upward Probe 3 displays an increase in pc product, approximately 100% during the reported time period, shown in Figure 5-3c through Figure 5-7c. The trend is statistically significant. An increase in the pc thermal capacitance can be attributed to an increase in the moisture content. This can be expected for the low-temperature areas of Probe 1, and Probe 3. A statistically significant decreasing trend indicates drying rock around the high-temperature Probe 2 as is depicted in Figure 5-5c.
Figure 5-1: DST REKA Probe 1 evaluation results; (a) temperature, (b) conductivity, (c) relative error histogram (Source: see Table 1-2).

Figure 5-2: DST REKA Probe 1, Nusselt number for porous media advection/convection with the average of 25.5810 (Source: see Table 1-2).
Figure 5-3: DST REKA Probel evaluation results; (a) and (b), conductivity with error histogram; (c) and (d), $\rho c = k/\alpha$ with error histogram (Source: see Table 1-2).
Figure 5-4: DST REKA Probe 2 evaluation results; (a) temperature, (b) conductivity, (c) relative error histogram (Source: see Table 1-2).
Figure 5-5: DST REKA Probe2 evaluation results; (a) and (b), conductivity with error histogram; (c) and (d), $\rho c = k/\alpha$ with error histogram (Source: see Table 1-2).
Figure 5-6: DST REKA Probe3 evaluation results; (a) temperature, (b) conductivity, (c) relative error histogram (Source: see Table 1-2).
Figure 5-7: DST REKA Probe3 evaluation results; (a) and (b), conductivity with error histogram; (c) and (d), $\rho c = k/\alpha$ with error histogram (Source: see Table 1-2).

5.2 DESCRIPTIVE STATISTICS

It is preferred to use a set of average effective properties for each probe location for the purpose of any thermal design activity. Table 5-1 summarizes the results of descriptive statistics, including the average, standard deviation, and 95% confidence interval of the mean of each property, assuming that the data belong to a normally distributed population. The descriptive statistics are used to determine an average effective set of thermophysical properties at each location.
Comparing the average effective properties of three probes together, while taking into account their corresponding 95% confidence interval, reveals that the average effective properties are relatively close to each other. For example, it can be asserted that the average effective conductivity of Probe 3 is also a good estimate of the effective conductivity of Probe 1.

Table 5-1: Descriptive statistics of the effective thermophysical properties at the Probe 1, 2, and 3 locations, (Source: see Table 1-2).

<table>
<thead>
<tr>
<th>Probe</th>
<th>Property</th>
<th>mean</th>
<th>Std</th>
<th>95% confidence interval of the mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe1</td>
<td>Conductivity</td>
<td>2.2655</td>
<td>0.4008</td>
<td>2.1653</td>
</tr>
<tr>
<td></td>
<td>Diffusivity(10^6)</td>
<td>0.9533</td>
<td>0.2684</td>
<td>0.8863</td>
</tr>
<tr>
<td></td>
<td>ρc(10^6)</td>
<td>2.4488</td>
<td>0.4139</td>
<td>2.3454</td>
</tr>
<tr>
<td>Probe2</td>
<td>Conductivity</td>
<td>1.9757</td>
<td>0.1471</td>
<td>1.9481</td>
</tr>
<tr>
<td></td>
<td>Diffusivity(10^6)</td>
<td>0.8090</td>
<td>0.1474</td>
<td>0.7814</td>
</tr>
<tr>
<td></td>
<td>ρc(10^6)</td>
<td>2.4983</td>
<td>0.3500</td>
<td>2.4328</td>
</tr>
<tr>
<td>Probe3</td>
<td>Conductivity</td>
<td>2.1815</td>
<td>0.2738</td>
<td>2.1300</td>
</tr>
<tr>
<td></td>
<td>Diffusivity(10^6)</td>
<td>0.8239</td>
<td>0.2444</td>
<td>0.7779</td>
</tr>
<tr>
<td></td>
<td>ρc(10^6)</td>
<td>2.8401</td>
<td>0.7362</td>
<td>2.7017</td>
</tr>
</tbody>
</table>

5.3 LEAST SQUARE FIT

MATLAB's standard statistical command functions were used to fit linear regression curves to the qualified data. Table 5-2 summarizes the results of the least square linear fit on the effective thermal properties at DST. Column R shows the coefficient of linear correlation for each property. At the Probe 1 location, a very strong correlation is found between the effective conductivity and number of days into heating, while almost no correlation can be found at the Probe 2 locations. Although Figures 5-1 through 5-7 depict slight correlation in each property, the significance of those trends cannot be quantified from the statistical evaluation. Student t-test based hypothesis is used in order to quantify the significance of the linear trends and the slope b, for each effective thermophysical property. The column labeled std shows the standard deviation of error of fit. Columns a and b represent the best-fit coefficients and the corresponding 95% confidence interval. Columns t and P show the results of the null hypothesis test. Column t shows the t statistics for 0.05 significance level and column P shows the probability, P-value, of observing the slope of linear fit to be zero. If the P-value is less than the 0.05 significance level, then the null hypothesis must be rejected, meaning that the trend/slope of the best fit is significantly different from zero. Based on the results of P-value, we can determine quantitatively that the conductivity values for Probe 3 show no significant correlation with the number of days. The results indicate that the observed trend of all the other properties is significant, with 0.05 significance level. Therefore, conclusions based on these trends, presented later in this chapter, can be considered valid. If a significance level of 0.01 is chosen, corresponding to 99% confidence level, then the trend of the Probe 1 diffusivity is considered not significantly different from zero. The column Normality is the result of a known statistical test method Kolmogorov-Smirnov (Jenson, 1997) available in MATLAB function kstest (MATLAB, 2001). The kstest performs a Kolmogorov-Smirnov test to compare the values in the data with a standard normal distribution. It returns the probability of the null hypothesis for
which the data has normal distribution. This test was performed on the relative error of fit for each parameter, using the histogram plots in Figure 5-1 through Figure 5-7, in order to assure that the residuals of linear regression fit are normally distributed, which is also an indication that a linear fit is a reasonable model. The results show that only the diffusivity of Probe 1 has a regression residual which is not normally distributed; the significance of normality is only 0.4%. This can also be seen in Figure 5-3.

Table 5-2: Summary of the linear regression results for Probes 1, 2 and 3 with intercepts (at 150 days into heating), slopes, and mean values for diffusivity and conductivity according to \( v_a = a + b(x-150) \), (Source: see Table 1-2).

<table>
<thead>
<tr>
<th>Probe</th>
<th>Conductivity</th>
<th>Diffusivity (10^5)</th>
<th>( \rho c ) (10^6)</th>
<th>( t )</th>
<th>( P )</th>
<th>( R )</th>
<th>Normality- ( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3271</td>
<td>1.9689 ± 0.1321</td>
<td>3.64E-04 ± 1.2739E-04</td>
<td>5.7108</td>
<td>0.0000</td>
<td>0.5871</td>
<td>0.209</td>
</tr>
<tr>
<td></td>
<td>0.2301</td>
<td>0.7755 ± 0.0930</td>
<td>2.18E-04 ± 8.9623E-05</td>
<td>4.8659</td>
<td>0.0000</td>
<td>0.5257</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>0.4098</td>
<td>2.5465 ± 0.1655</td>
<td>-1.20E-04 ± 1.5960E-04</td>
<td>1.5017</td>
<td>0.1382</td>
<td>0.1873</td>
<td>0.664</td>
</tr>
</tbody>
</table>

| 2     | 0.1307       | 1.8511 ± 0.0510      | 1.25E-04 ± 4.4977E-05 | 5.5269 | 0.0000 | 0.4662 | 0.205 |
|       | 0.1330       | 0.6911 ± 0.0518      | 1.19E-04 ± 4.5741E-05 | 5.1397 | 0.0000 | 0.4400 | 0.027 |
|       | 0.3253       | 2.7398 ± 0.1268      | -2.43E-04 ± 1.1191E-04 | 4.3032 | 0.0000 | 0.3796 | 0.750 |

| 3     | 0.2711       | 2.0966 ± 0.1074      | 8.53E-05 ± 9.4910E-05 | 1.7814 | 0.0776 | 0.1682 | 0.170 |
|       | 0.2452       | 0.8458 ± 0.0971      | -2.20E-05 ± 8.5841E-05 | -0.5081 | 0.6124 | 0.0486 | 0.278 |
|       | 0.7389       | 2.8950 ± 0.2927      | -5.51E-05 ± 2.5865E-04 | -0.4224 | 0.6735 | 0.0404 | 0.140 |

1. var -- dependent property
2. std -- standard deviation of the least square fit
3. t -- t statistics
4. P -- probability of NULL hypothesis, a or b being zero, being true. Assume 0.05 being the critical value associated with 95 percent confidence.
5. R -- R-square statistic
6. Normality - probability of residual being a normal distribution
\( x \) -- number of days into heating of the DST tunnel
\( \rho c=\kappa/\alpha \) ratio

\( a \) and \( b \) are linear regression coefficients with 95% regression confidence interval.

It is important to know whether the slope \( b \) from the best fit for each property is significantly different from a constant \( b' \). If the error of fit is normally distributed and the observations are uncorrelated, \( b \) also has a normal distribution (Jenson, 1997). To test if the slope estimate and the constant are different, the t statistic can be calculated from the equation:

\[
t_b = \frac{|b - b'|}{S_b^2}
\]

where \( S_b \) is the standard deviation of the \( b \) coefficient.

The \( t_b \) statistic has a t distribution. The computed value of \( t_b \) is used to calculate the corresponding confidence level \( \alpha \) at which the \( t_b \) becomes significant. From the Student t table, a level of significance can be obtained at which the slope \( b \) becomes significant. The proposed value \( b' \) and the estimated value \( b \) are different at the \( \alpha \) probability if \( t_b \) is greater than the critical, tabulated value. The question is at what confidence level the trend slope is considered.
significantly different from zero. The probability at which the estimated slope is considered significantly different from zero is \(1 - (P\text{-value})\). Therefore, the probability for the trend slope of thermal conductivity of Probe 2 and Probe 3 is about 23% and 58%, respectively, therefore, slopes are not significantly different from zero.

The effective rock thermal properties obtained for all the REKA probes during the DST heating phase are not compared to the results obtained previously for the unheated period of 11/3/97 to 12/3/97 in this report. The reasons for reporting the two sets of results separately is that different measurement control programs were used, namely the "100"-code and the "101"-code measurements. The "100"-code measurement energizes the probe's heater from the beginning of the measurement, while the "101"-code measurement turns on the probe's heater after 100 reading batches, about 6 hours into the 24-hr probe measurement cycle. The measurement results used in this report are based on the "101"-code measurement. The results reported as the baseline initial thermal properties used the "100"-code measurements.

Measurements were collected during the early stage of the DST heating phase, 12/4/97 to 7/31/98. These measurements included both "100" and "101" type results. It was shown that the "101"-code measurements resulted in considerably less fluctuation in both \(k\) and \(\alpha\) values, than did the "100"-code measurements. Therefore, it was concluded that the effective thermal properties obtained from "101"-code measurements are more precise and reliable than are the ones obtained from the "100"-code measurements (SN, 1998).

In order to predict the baseline thermal properties using the results reported, each regression line for a thermal property is calculated at \(x = (-150 \text{ days})\) as the linear fits were obtained by shifting the independent variable, the number of days into heating by 150 days. The results of this comparison are summarized in Table 5-3. The first column includes the 95% confidence interval by including the error component into the regression estimates. This shows that 95% of new observation points fall within this interval. The second column used the confidence interval of the regression meaning that 95% of new estimated points fall within this interval. The third column was calculated using the variations of the slope and intercept, which also verifies the direct results of regression analysis. The fourth column reports the previously reported initial thermal properties of the unheated period at the three REKA probes locations. Comparing these values with the ones calculated, using the regression of the heated period, shows a good agreement. Therefore, it can be concluded that the least square fit is a reasonable model even when it is used to extrapolate the initial values from the heated period results.
The next section will employ the Bootstrap method of the correlation coefficient, R, of each parameter in order to verify the trend analysis performed in this section based on regression results.

5.4 TREND EVALUATION WITH THE BOOTSTRAP METHOD

The Bootstrap method (Jenson, 1997) uses a procedure that involves choosing samples from a data set randomly with replacement and analyzing each sample population the same way. Sampling with replacement means that every sample is returned to the data set after sampling. In other words, a particular data point from the original data set could appear multiple times in a given bootstrap sample. The number of elements in each bootstrap sample equals the number of elements in the original data set. Using the range of sample estimates, the uncertainty of the quantity under examination can be established.

From the regression analysis of thermal properties of each probe location, it became clear that there are apparent trends in the data. The significance of the trend is of a great importance in order to use the trend for interpolation as well as for forward or backward extrapolation.

The results of the MATLAB bootstrap method analysis (MATLAB, 2001) are summarized in Table 5-4 which compares the estimated correlation coefficient with the least square results. For each bootstrap population, the corrcoef MATLAB function is executed automatically, that returns the corresponding correlation coefficient. A histogram of 1000 correlation coefficient values is then plotted. The 95% confidence intervals are summarized in Table 5-4. If a confidence interval includes the zero, it can be concluded with a 95% confidence level that the no-correlation hypothesis cannot be rejected. These results agree with the regression and t-test results. Figure 5-8(b) shows the results of the Bootstrap method histogram and it can be seen
clearly that the variation of correlation coefficient excludes zero, whereas Figure 5-10 shows that the zero cannot be excluded and the slight slope of the trend is not significant.

Table 5-4: Least Square correlation coefficient and the Bootstrap method comparison, (Source: see Table 1-2).

<table>
<thead>
<tr>
<th></th>
<th>LSQ R</th>
<th>Bootstrap R</th>
<th>Bootstrap R 95% confidence interval</th>
<th>no-correlation hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Probe1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conductivity</td>
<td>0.5871</td>
<td>0.5860</td>
<td>0.4599 0.7122</td>
<td>rejected</td>
</tr>
<tr>
<td>Diffusivity(10⁻⁶)</td>
<td>0.5257</td>
<td>0.5473</td>
<td>0.3860 0.7086</td>
<td>rejected</td>
</tr>
<tr>
<td>ρc(10⁵)</td>
<td>-0.1873</td>
<td>-0.1848</td>
<td>-0.3685 -0.0011</td>
<td>rejected</td>
</tr>
<tr>
<td><strong>Probe2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conductivity</td>
<td>0.4662</td>
<td>0.4688</td>
<td>0.3361 0.6014</td>
<td>rejected</td>
</tr>
<tr>
<td>Diffusivity(10⁻⁶)</td>
<td>0.4400</td>
<td>0.4561</td>
<td>0.2474 0.6648</td>
<td>rejected</td>
</tr>
<tr>
<td>ρc(10⁵)</td>
<td>-0.3796</td>
<td>-0.3863</td>
<td>-0.5478 -0.2247</td>
<td>rejected</td>
</tr>
<tr>
<td><strong>Probe3</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conductivity</td>
<td>0.1682</td>
<td>0.1630</td>
<td>-0.0071 0.3330</td>
<td>accepted</td>
</tr>
<tr>
<td>Diffusivity(10⁻⁶)</td>
<td>-0.0486</td>
<td>-0.0382</td>
<td>-0.2541 0.1777</td>
<td>accepted</td>
</tr>
<tr>
<td>ρc(10⁵)</td>
<td>-0.0404</td>
<td>-0.0427</td>
<td>-0.2290 0.1435</td>
<td>accepted</td>
</tr>
</tbody>
</table>

Figure 5-8. Boot Strap method; histogram of Probe1 results, (Source: see Table 1-2).

Figure 5-9. Boot Strap method; histogram of Probe2 results, (Source: see Table 1-2).
5.5 EVALUATION WITH SIGNAL PROCESSING

Variations are observed in the thermal conductivity and diffusivity results with respect to time, and the statistics suggest that the changes are either stochastic, or deterministic-periodic, or a combination thereof. In order to filter out the random effects from the deterministic components, signal processing was used, applying low-pass, digital filtering. The Signal Processing Toolbox facility of MATLAB was used that provides standard filter application to time-series data.

The "cheby1.m" MATLAB macro filter was selected, realizing a Chebyshev Type I filter design (MATLAB, 2001). The MATLAB command \[ [B,A] = \text{CHEBY1}(N,R,Wn) \] applies an Nth order lowpass digital Chebyshev filter with R decibels of peak-to-peak ripple in the passband. Cheby1 returns the filter coefficients in length N+1 vectors B (numerator) and A (denominator). The cutoff frequency \( Wn \) is \( 0 < Wn < 1.0 \), with 1.0 corresponding to half the sample rate. Cheby1(N,R,Wn,'s') applies analog Chebyshev Type I filter. In this case, \( Wn \) is in [rad/s] and it can be greater than 1.0.

The Chebyshev lowpass filter was applied to both the conductivity and diffusivity measurement results of Probes 1, 2, and 3. The MATLAB macro is given in Appendix 4, describing the filter parameters, their application, and the generation of the original as well as the filtered variations with time in graphical format. The MATLAB macro is commented, and self-explanatory. The end results, i.e., the graphs of the original and the filtered data, can be visually checked for acceptance. Since the filter parameters are user-defined, the filtered results are also user-dependent. The goal of filtering is to discover a pattern, i.e., a deterministic signal variation in a seemingly random field of data. The freedom of choice of the user-dependent filter parameters provides the necessary flexibility for the discovery process. However, some objective outcomes of such a subjective examination are highly desirable. In the present application, one independent outcome is expected to be the dominant frequency of a periodic variation in the thermophysical properties values with time.

Only the filtered conductivity results are used in this report, shown in Figures 5-11, 5-12, and 5-13 for Probes 1, 2, and 3. A dominant periodic variation with a cycle time of nearly exactly one
year can be seen in the figures. The thermal diffusivity results have given very similar periodic variations with time, therefore, are omitted from the report since they provide no new information.

The periodic variation shows a significant, high amplitude of about 10% of the mean value. The average cycle of one year is a strong indication that all three probes captured annual, periodic variations in the thermophysical properties. Other variation frequencies, most notably seasonal, may also be identified, but are not discussed in the report and must be deferred to future studies. More in situ measurement data would also be required for the identification of such variations during the long cooling phase. Probe 1, for example, was highly disturbed during the heated phase due to boiling conditions that effectively prevented any fine variations to be detected for about two years. Probe 1 now operates in the below-boiling regime and provides excellent results for analysis.

The significance of periodic variation is not seen much in the basic application of the thermophysical properties in thermal analysis, since the annual variations would average out. The variation is rather seen to be significant as an indicator of some underlying events being involved in the coupled processes or boundary conditions.

![Figure 5-11. Original and lowpass-filtered effective conductivity variation with time for Probe 1, (Source: see Table 1-2).](image-url)
Figure 5-12. Original and lowpass-filtered effective conductivity variation with time for Probe 2 (Source: see Table 1-2).

Figure 5-13. Original and lowpass-filtered effective conductivity variation with time for Probe 3, (Source: see Table 1-2).
Many reasons can be subjected to hypothesis tests for the explanation of such annual (or seasonal) variations. For example, changes may be explained by moisture content variation due to changing percolation, barometric pressure pumping, or periodic vapor-phase advection toward the ventilated part of the drift scale test area. It must be noted, however, that a simple, periodic heat loss variation through the bulkhead of the heated drift would not result directly in the variation of the effective thermophysical properties, since no significant, periodic temperature field variation at the probe's locations has been detected.

The REKA results are complementary to large-scale inverse modeling results such as obtained for DST by the other investigators studying coupled thermo-hydrologic processes at Yucca Mountain, fitting model results to multiple sensors data. Periodic variations of the effective properties as surrogate hydrothermal characteristics can be identified by the REKA probes. However, such variations may be missed by the simple observation of the temperature field variation and subsequent inverse modeling. The very small signal changes in a hydrothermally disturbed area may be masked by thermal and measurement noise, and thus filtered out and lost. Since the evaluation of the REKA probe readings is self-contained and each probe yields independent results, the method is straightforward, and sensitive to very small changes. In addition, the REKA probes have excellent long-term stability and durability. For these reasons, the method is seen to be efficient for validations and performance confirmation applications.

5.6 SUMMARY OF THE IN SITU MEASUREMENT RESULTS

The in situ measurement results have shown that the effective thermophysical properties variations were moderate with mean values around the expected, conduction-only values, except for the readings taken when the boiling front was at or around the location of Probe 1. Thermophysical properties variations within a 10-20% regime indicate that the heat flow has been conduction-dominated around all three REKA probes in the DST during the study period excluding the time of the boiling front condition at a probe location. Slow, as well as periodic changes in the effective conductivity and diffusivity values were also observed, that may be attributed to convective and evaporative effects as well as moisture content changes. In addition, Probe 1 recorded consistent pool boiling for over a year in an area known to be in the condensate shredding zone.

The in situ measurement results were evaluated using statistical methods, trend analysis, and signal processing. The simple averages as conduction-only equivalent values for each probe are given in Table 5-5.
Table 5-5: Time-average effective thermophysical properties, (Excerpt from Table 5-1).

<table>
<thead>
<tr>
<th></th>
<th>Probe 1 (downward)</th>
<th>Probe 2 (horizontal)</th>
<th>Probe 3 (upward)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Thermal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conductivity [W/(mK)]</td>
<td>2.27</td>
<td>1.98</td>
<td>2.18</td>
</tr>
<tr>
<td>Average Thermal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diffusivity [m²/s]</td>
<td>0.95 x 10⁻⁶</td>
<td>0.81 x 10⁻⁶</td>
<td>0.82 x 10⁻⁶</td>
</tr>
</tbody>
</table>

A linear trend analysis was also conducted in order to study the significance of variation with
time, and to re-establish the initial, baseline properties at the three probes' locations from the
heated measurements. The results in Table 5-6 are as follows:

Table 5-6: Initial, extrapolated effective thermophysical properties from linear trend, (Excerpt
from Table 5-2).

<table>
<thead>
<tr>
<th></th>
<th>Probe 1 (downward)</th>
<th>Probe 2 (horizontal)</th>
<th>Probe 3 (upward)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial (unheated)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Conductivity [W/(mK)]</td>
<td>1.97 +/-0.13</td>
<td>1.85 +/-0.05</td>
<td>2.10 +/-0.11</td>
</tr>
<tr>
<td>Initial (unheated)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Diffusivity 10⁶ x [m²/s]</td>
<td>0.78 +/-0.09</td>
<td>0.69 +/-0.05</td>
<td>0.85 +/-0.10</td>
</tr>
</tbody>
</table>

The linear trend was proved to be statistically significant only for Probe 1 with non-zero slope,
while the changes in the effective properties at the Probe 2 and 3 locations may not be
considered statistically significant versus a zero change.

In order to filter out the stochastic, or chaotic, variations from any deterministic-periodic
variations, signal processing was used, applying low-pass, digital filtering. The results, depicted
in Figures 5-11, 5-12, and 5-13 for Probe 1, 2, and 3, show a recognizable, periodic variation
with a significantly high amplitude of about 10% of the mean value. The average cycle time is
very close to one year, a strong indication that all three probes captured annual, periodic
variations in the thermophysical properties. Other, higher variation frequencies, most notably
seasonal, can also be recognized in the figures, but are not discussed in the report.
6.0. REKA PROBE DESIGN FOR LITHOPHYSAL APPLICATION

Scoping calculations and preliminary measurement error analysis were made for lithophysal application of the REKA method as part of the approved task. The first draft of the design is documented in UCCSN-UNR-013 Volume 2, Scientific Notebook pp.60-68 in May 2001. Due to change in scope, however, the progress of this part of the task was delayed and later the task was not funded. The design of the lithophysal probe is described in a paper (Danko, et. al., 2002), followed by a more detailed performance analysis (Danko, et. al., 2003), given in Appendices 2 and 3.
7.0. CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

- The in situ, effective thermophysical properties generally agree well with the expected values for Alcove 5 (BSC, 2002). However, Probe 2, which has operated at well above boiling temperatures in supposedly dry rock most of the time, show little effect of thermal conductivity decrease due to drying.
- The in situ thermophysical properties measurements are shown to be sensitive enough to detect fine variations due to varying temperature and hydrothermal effects during the heated and cooling phases at the Drift Scale Test, Yucca Mountain. Based on the measurement results, conclusive trends can be obtained using statistical methods.
- The fluctuations in the effective thermophysical properties results are seemingly random, but may be due to stochastic or deterministic hydrothermal disturbances caused by the effect of rockmass heating. The self-induced, incremental heating of the REKA probes generates very low incremental temperatures (less than 0.3° C) in order to avoid self-generating hydrothermal disturbances. This design constraint has caused far from optimal conditions for the measurements for robust statistical trend analysis, but provided for the detection of hydrothermal process disturbances.
- Statistical analysis of the effective thermal properties with respect to the number of days into DST heating showed that the effective thermal conductivity results of Probe 2 do not change significantly. This proves that the measurement system, common for all three probes, does not bias the measurement results with time to any significant level.
- The random variation of the effective thermophysical properties appears to be decreasing during the cooling phase when compared to the heating phase. It is, however, not clear whether the decrease in variation is due to the general cooling of the rock, or the decreasing nature of disturbing measurement and other activities at DST.
- Digital filtering can eliminate the high-frequency fluctuations and yet determine an underlying signal trend. Such signal trends show significant annual variations in both the thermal conductivity and diffusivity over time for all three probes. The periodic trends do not seem to disappear during the cooling phase.

7.2 RECOMMENDATIONS

- It is recommended to continue the measurements with the three REKA probes at DST until the end of the cooling period in order to investigate long-term changes in the values of the thermophysical properties caused by a thermal cycle.
- Another use of the continuing measurement results is the analysis of periodic variations in the thermophysical properties.
- It is recommended to analyze the periodic variations of the effective thermophysical properties against three working hypotheses as follows:
  1. Hypothesis 1. The effective thermophysical properties as surrogate hydrothermal characteristics are dependent upon the ambient barometric pressure variation, showing a strong connection between the rockmass and the outside conditions.
2. Hypothesis 2. The effective thermophysical properties as surrogate hydrothermal characteristics are dependent upon moisture/vapor transport, affected by the relative humidity of the ventilating air delivered through ventilation to Alcove 5.

3. Hypothesis 3. The effective thermophysical properties as surrogate hydrothermal characteristics are dependent upon the variation of water percolation flux, affecting periodically the saturation level of the rockmass around the REKA probes.

- Based on the results shown in Appendices 2 and 3, it is recommended to apply the single-borehole REKA method for effective lithophysal thermal conductivity and porosity measurements at YM in the design and performance verification activities.
- It is recommended to use the REKA methodology in the performance verification activities of the future thermal tests at YM. Somewhat higher incremental temperature generation is recommended for increased signal-to-noise ratio, and thus for supporting a more robust trend evaluation in the variation of the thermophysical properties with time.
- It is recommended to use the in situ, effective thermophysical properties from the REKA method as surrogate system responses to hydrothermal processes during repository operation. Such an application, converting effective thermophysical properties variations to hydrothermal processes, is described in a previous publication (Danko and Buscheck, 1993).
8.0. REFERENCES


APPENDIX 1. Scientific Investigation Plan

University and Community College System of Nevada (UCCSN)
Scientific Investigation Plan (SIP)

Task Title: Drift Scale Test: Analyze and Report

Document Number: SIP-UNR-002

Revision: 0

Effective Date: 07/24/00

Author: Davood Bahrami

Approvals:

Original signed by George Danko
Principal Investigator 04-27-00  Approval Date

Original signed by Deborah Barr
Technical Task Representative 07-13-00  Approval Date

Original signed by Amy J. Smieciinski
UCCSN QA Manager 07-24-00  Approval Date
### REVISION HISTORY

<table>
<thead>
<tr>
<th>Revision Number</th>
<th>Effective Date</th>
<th>Description and Reason for Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>07/24/00</td>
<td>Initial Issue</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

This task is a continuation of work performed under M&O task WBS 1.2.3.14 (123E2265M1). This task is now funded as Task #13 by UCCSN/DOE cooperative agreement DE-FC08-98NV12081. A three-year continuation research project is proposed to monitor the changes in the rock thermophysical properties, mountain-scale hydrologic effects and rock water content during heating and cooling at the ESF facility at Yucca Mountain. Three REKA thermal probes have been operated at Alcove 5 since November, 1997 by the Mining Engineering Department, University of Nevada, Reno. It is proposed to continue the in situ measurements during the rest of the heating and the subsequent cooling periods, and to evaluate the primary in situ measurement data against the hydrothermal model NUFT. The results of the work will be directly applicable to evaluate/verify current conceptual/theoretical DOE models that are needed to transform small-scale laboratory sample data into thermophysical design input data that include the rockmass effects upon heat conductivity and diffusivity. In addition, the REKA method will be evaluated as low-cost and reliable performance confirmation technique to monitor rock drying.

2. SCOPE, OBJECTIVES, AND SUBTASKS

2.1. Scope

The project task is to continue the REKA Thermal Probe measurements during the heating phase of the Drift Scale Test (DST) and document the results in a letter to the YMSCO Technical Lead for thermal Testing Data Analysis and Reporting. In addition, three Quarterly, and one Final Report will be submitted each year.

2.2. Objectives

The objectives of the project are as follows:

- To continue data gathering, at least once a month, with each of the three REKA Thermal Probes that are built into the drift wall at DST Alcove 5 at Yucca Mountain; to evaluate the primary measurement data against in-situ thermal diffusivity and heat conductivity; and report the changes in these values during the heating phase of the DST.
- To measure thermophysical properties at new locations in the ESF.
- To explore the possibility of using the REKA Thermal Probe technique for continuous performance confirmation verification applications regarding hydrothermal/rock drying effects.

2.3. Subtasks:

Deliverables listed for each subtask are submitted in accordance with the cooperative agreement to the Administrative Task PI for submission to the DOE.

2.3.1. Primary REKA Probe measurements

Measurement data files will be generated at least once a month with three independent probes.

Deliverable: Primary in situ measurement data files will be submitted through the
2.3.2. Evaluation of the primary measurement data

The primary, quality affecting data will be evaluated using the current evaluation software REKA1.0.

Deliverable: Thermal conductivity and diffusivity values with respect to time, a minimum of 36 values per year. The results will be submitted to the YMSCO Project Manager for Thermal Testing Data Analysis in a letter format. In addition, four Quarterly, and one Final Report will be submitted each year to the Administrative Task PI for submission to the DOE.

2.3.3. Development of a NUFT-based primary measurement evaluation procedure

NUFT will be used to re-evaluate the current and future primary measurement results.

Deliverable: Thermal conductivity, diffusivity, and hydrothermal characteristics trends with respect to time, included in the Final Report.

Schedule: FY00-FY03, continuous

2.3.4. Fabrication of new REKA Thermal Probes for site characterization at new locations

New probes will be built to support thermal site characterization activities.

Deliverable: Three new REKA probes with the computer-controlled measurement data acquisition system and driving software.

2.3.5. In situ performance confirmation and monitoring applications

The REKA method will be evaluated for long-term monitoring applications using computer simulations.

Deliverable: Conceptual arrangement for performance confirmation applications; numerical case studies.
3. APPROACH

3.1. Continuation of the current measurement program with three REKA probes at Alcove 5, ESF, Yucca Mountain

The REKA measurements with three built-in probes will be continued throughout the life cycle of the Drift Scale Heater Tests being conducted at Alcove 5. A thermal probe method, called REKA (Rapid Evaluation of K and Alpha) has been used for determining rock thermal conductivity (K) and diffusivity (Alpha) to support the site characterization program of the proposed high-level nuclear waste repository at Yucca Mountain. The REKA method involves a single borehole probe with a heater and a temperature measurement section. An elliptical temperature field is generated by the heater, and the temperature distribution along the length of the probe is recorded at several locations and at given time intervals for a period of 24 hours.

3.2. Evaluation of the primary measurement data

A trial-and-error evaluation procedure is used to determine the unknown thermophysical properties (K and Alpha) by minimizing the root-mean-square error between the measured and the calculated temperature fields. The current, Quality Assured evaluation software, REKA1.0, applies a conduction-only thermal model for the determination of the thermophysical properties that include the resultant rockmass and the moisture effects, representing effective properties. In addition to using REKA1.0, it is proposed to apply a hydrothermal model, namely NUFT, for the evaluation of the difference between the effective and the rock matrix thermophysical properties, in order to relate the measurement results to hydrothermal characteristics and saturation level of the host rock.

3.3. Investigate the trends in the thermophysical properties

Three REKA probes were built into the drift wall at the Drift-scale Heater Test site at Yucca Mountain. Measurements with the probes have been conducted since November 1997. Results of conductivity and diffusivity have been monitored to investigate the variation of these properties with time and the hydrothermal processes generated by heating of the drift wall. The measurements will be re-evaluated for all the results obtained since November 3, 1997 (approx. 120 individual data files corresponding to 24 hrs. records to date) using NUFT.

3.4. In situ measurements of the thermophysical properties at new locations in the ESF

Further measurements will be made with new REKA probes at new sites, other than the DST at Alcove 5, to support site characterization and design input data verification programs.

Two previous, successful applications of the REKA method were made at Yucca Mountain. A reusable REKA probe was used in the Exploratory Studies Facility (ESF) to measure conductivity and diffusivity of the host rock at five locations. Permanent REKA probes grouted in the insertion holes were used at the Fran Ridge Large Heated Block Tests bed at three different locations. Measurements were conducted over eight months with the probes to monitor the change in the thermophysical property values due to heating and drying. Results to date from the REKA applications show that the in situ probe measurements agree very well with the expected values at both Fran Ridge and in the ESF. The Fran Ridge results indicate
that the method is sensitive enough to detect convective effects.

3.5. In situ performance confirmation and monitoring applications using the REKA method

The REKA method will be evaluated as low-cost and reliable performance confirmation technique to monitor rock drying. The hardware, the measurement technique, and the best measurement parameters will be evaluated using the experiences with the REKA probes being applied at Yucca Mountain. The evaluation of the REKA method for monitoring rock drying will be made using numerical simulation applying the thermal/ventilation models MULTIFLUX and NUFT.

4. STANDARDS

ASTM-traceable thermometer standards will be used for calibration verification of factory-made thermocouples used for constructing new REKA probes for task 3.4.

5. IMPLEMENTING PROCEDURES/SCIENTIFIC NOTEBOOKS

The new REKA probe calibration will follow the calibration procedure IPR-005 (which is being written and will meet the requirements of QAP-12.0, “Control of Measuring and Test Equipment” and will be completed by 9/30/00).

The measurement data transfer method, previously approved as meeting QARD Supplement V, will be written as procedure IPR-006 and will be completed by 5/15/00.

6. EQUIPMENT

- Two HP75000 measurement units, one unit being a backup unit located at UNR. Each unit contains the following items:
  1- mainframe controller
  2- multimeter
  3- 16 channel thermocouple relay matrix
  4- RS-232/422 communication module

- Three REKA probes previously installed in Alcove 5 of the Exploratory Studies Facility (ESF) at Yucca Mountain, Nevada.

Three new REKA probes will be built and installed in the ESF tunnel for the purpose of supporting site characterization in new locations at YM. The probe calibration will be performed with IPR-005 and is a one-time action before installation. Permanent installation prevents removal of probes for re-calibration, which is the case for the Drift Scale Test.
7. HOLD POINTS/DECISION POINTS

There are no hold points/decision points as defined in the UCCSN QA Program for this work.

8. RECORDS

QA Records produced as a result of the IPs and the UCCSN QA Program will be handled in accordance with QAP-17.0. Those QA records that must be submitted directly to the Local Records Center as listed in the implementing procedures and in this SIP will be handled in accordance with AP-17.1Q.

9. VERIFICATIONS AND REVIEWS

Evaluation results determined in section 3.2 are submitted to the HRC Administrative Task PI who will submit them to DOE for review. Data must be labeled “preliminary” unless they have undergone a technical review.

10. SOFTWARE

The Qualified software REKA 1.0 will be used for measurement evaluation. New software version will be qualified in accordance with QAP-3.2 and parallel to the YMP requirements. A qualified version of NUFT (Non-Equilibrium, Unsaturated-saturated Flow and Transport code, developed at Lawrence Livermore National Laboratory) will be used in task 2.3.3.

11. INTERFACE CONTROLS

The involved personnel in this project that are listed below along with their responsibilities:

Internal Interfaces

11.1. Principal Investigator

Position description:
- Scientific Notebook entries
- Supervision of investigators
- Participation in periodic reports
- Design and development of NUFT-based previous measurement evaluation software
- Design of new REKA probes

11.2. Investigator

Position description:
- Remote measurements
- Data transfer/record
11.3. Investigator

**Position description:**
- a- File system, and data copy for evaluation
- b- REKA measurements
- c- Statistical evaluation
- d- Participation in periodic reports

**External Interfaces**

11.4 DOE Technical Task Representative: Paul Harrington

11.5 Project Manager: Robin Datta

12.0 OTHER REQUIREMENTS

12.1 Determination of Precision, Accuracy, and Representativeness of Results

Error of fit parameters is generated by the evaluation software REKA1.0. Other quality characteristics will be evaluated as conclusions.

12.2 Potential Sources of Error

The technical content of the result report must address potential sources of error associated with the particular submission.

12.3 Uncertainty

Uncertainty evaluation is addressed as a response to technical review.

12.4 Data Recording, Reduction, and Analysis

Project activities are recorded in the SN. In situ measurements are recorded in the Measurement Record notebook. Evaluation results from Section 2.3.2 are inserted in the scientific notebook.
APPENDIX 2. Lithophysal Paper 1, “For Corroborative Use Only”

EVALUATION OF LITHOPHYSAL CONDUCTIVITY, DIFFUSIVITY, AND POROSITY MEASUREMENTS USING THE REKA METHOD

George Danko, Nipesh Shah, and Davood Bahrami
Mackay School of Mines
University of Nevada, Reno
Reno, NV 89557
(775) 784-4284

ABSTRACT

A method is presented, based on the NUFT and REKA V1.1 software packages combination, to study the nature of non-steady-state heat flow during a single-borehole REKA thermal probe thermophysical measurement in solid as well as lithophysal rock formation. The results prove the principle of the REKA method application in lithophysal formation. The numerical evaluation results, based on the use of two qualified software packages, show that the presented REKA probe arrangement is correctly modeled and that the effective heat conductivity and the lithophysal porosity can be evaluated correctly using the REKA probe method.

INTRODUCTION

Site Recommendation design for Yucca Mountain [1] locates approximately 70% of the active emplacement and heat dissipation area of the potential repository in lithophysal rock formations. It is necessary to evaluate the thermophysical properties (heat conductivity, k, and thermal diffusivity, α) as well as the lithophysal porosity (φl) to support temperature and humidity calculations for both pre-closure and post-closure performance verifications at Yucca Mountain (YM).

In situ thermal probe measurements involving a large rock volume and mass provide valuable information about the lithophysal formation where the lithophysae distribution and the complex geometry has a primary effect upon the flow of heat. The single-borehole, in situ Rapid Evaluation of K and Alpha (REKA) method, that has been used successfully at other locations at YM since 1995 [2,3,4], is a natural candidate for lithophysal application using a proper probe size and measurement time interval for receiving thermal response from a large enough, representative rock volume. A single-borehole installation is (a) simpler than a two- or multiple-borehole unit, (b) the relative positions of the temperature sensors to the heater(s) are fixed by the body of the probe, thus, they are precise and require no in situ surveying, (c) due to (a) and (b), significant cost-saving per measurement installation can be accomplished. In addition, the single-borehole method applies a relatively compact, ellipsoid-type temperature field that can be fitted into a relatively small, finite volume that is kept within the intact rock, away from a disturbed, open boundary surface.
This paper describes the measurement concept and the proof-of-principle tests of the lithophysal application of the REKA method based on numerical simulation. Support analysis for the design is carried out based on emulated temperature fields, using the Non-equilibrium, Unsaturated-Saturated Flow and Transport (NUFT) software [5]. The reason for using emulated measurements is that controlled conditions can be provided. The input properties that specify the rock model and formation in NUFT (e.g., heat conductivity, lithophysal porosity, lithophysal distribution) are known input for creating the time-dependent temperature field in the rock. A "blind" evaluation of the temperature field, representing a computer-emulated measurement, is made with the REKA V1.1 software in which the temperature field is used as an input, and the conductivity and lithophysal porosity are inverse-evaluated as output. Conclusions are drawn based on comparing the known inputs of NUFT to the blindly evaluated outputs of REKA V1.1 software. The only connection between NUFT and REKA V1.1 is provided by (a) the known geometry of the REKA probe, (b) the probe's heating power, and (c) the emulated temperature field with space and time.

THE REKA METHOD IN LITHOPHYSAL APPLICATION

The REKA method involves a single borehole probe with an integral heater and a temperature measurement section. The lithophysal REKA probe applies a twin-heater arrangement with a 1 m-long measurement section on a straight line between two short heater elements spaced 3m apart. The twin-heater arrangement is effectively two single-heater REKA probes comprised within one embodiment. This arrangement was found advantageous during the preliminary method analysis for lithophysal application [6] in order to integrate the uneven heat flow in the scattered rock formation. The probe arrangement is simplified for the present study, representing the short heaters with point sources and applying six temperature sensors, shown in Fig. 1. An incremental, spherical temperature field is generated by each heater of the lithophysal REKA probe. The temperature distribution along the length of the probe is recorded at the six locations hourly for 160 hrs. A trial-and-error evaluation procedure, according to the qualified REKA V1.1 software that includes the twin-heater option [7], is used to determine the unknown thermophysical properties by minimizing the root-mean-square error between the measured and the calculated incremental temperature fields with the trial thermophysical properties. Since the REKA method uses incremental temperatures generated by a small incremental heating signal, in situ measurements can be conducted under variable ambient temperatures and hydrothermal conditions.
In Situ Measurement Emulation

In situ measurements are emulated using NUFT by calculating the temperature field generated by the REKA heaters shown in Fig. 1. The simulation is performed on a rock block of 9 m by 6 m by 6m, which is sub-divided into 45 X 30 X 30 elements, giving 40,500 cubes with sides of 0.20 m. This rock block size is found sufficiently large enough to contain the temperature disturbance caused by the heaters of the REKA probe without raising the temperature on the boundaries for a 160 hour time period. The rock model domain is initially filled with a double-porosity material with matrix and fracture porosities, typical for Yucca Mountain welded tuff. The matrix and fracture elements are named m-tsw35 and f-tsw35. Three cases (Case 1, 2, and 3) are analyzed by emulating three hypothetical REKA measurements using the rock without any lithophysal cavity in it. These initial cases are analyzed for checking the inverse modeling accuracy of the REKA method arrangement for this emulated measurement. The input rock hydrothermal properties and conditions are given in Tables I-IV. The goal of Cases 1-3 is to back-identify the known input rock properties from the simulated measurement fields with the REKA inverse method for baseline comparison.

Seven cases (Case 4 through 10) are analyzed with the introduction of lithophysal cavities in the rock block. The cavities are gas-filled cubic void spaces with hydrothermal properties close to that of still air, specified by the names f-dr and m-dr in Tables II, III and IV.

Cases 4 and 5 apply a regular cavity pattern shown in Fig. 2(a) for two different layer arrangements. The black squares represent cavities, while the white squares depict rock. The patterns correspond to a 0.25 lithophysal porosity, and they avoid overlap of the air cavities. A similar pattern of 0.25 lithophysal porosity but with shifted cavity positions is applied alternately in the z-direction in order to avoid overlap of the air cavities. The difference between Case 4 and 5 is in the REKA probe's position relative to the fixed cavity lattice: the two REKA heaters are...
at nodes 15 and 30 in Case 4, and at nodes 16 and 31 in Case 5, representing a different relative lithophysal formation to the probe. The pattern corresponds to a 0.25 lithophysal porosity. The effective, equivalent heat conductivity of the pattern shown can be calculated in linear heat flow using elementary formulas known for layered material. Using the values for rock (m-tsw35 plus f-tsw35) conductivity of 2.0 and air (m-dr plus f-dr) conductivity of 0.026, the equivalent conductivity for the regular pattern (including both rock and air) is 1.0213 W/(m K). The goal of Cases 4 and 5 is to back-identify the effective lithophysal rock properties from the simulated measurement fields with the REKA inverse method for comparison with the expected values for lithophysal porosity (0.250) and effective conductivity (1.0213).

Cases 6 through 10 apply random cavity patterns generated according to a geometrical random cavity distribution with an average lithophysal porosity of 0.25. Fig. 2(b) is an illustration of random distribution. Although the patterns correspond to 0.25 average lithophysal porosity for the entire block, random variations are expected around the REKA probe. There is no closed solution for the effective, equivalent heat conductivity for the random patterns, but it is expected that the average of large number of evaluations is around the value of the regular pattern. The goal of Cases 6-10 is to back-identify the effective lithophysal rock properties from the simulated measurement fields for the random patterns with the REKA inverse method for comparison.

**Table I. Initial properties**

<table>
<thead>
<tr>
<th>Cases</th>
<th>Initial Barometric pressure</th>
<th>Initial Saturation</th>
<th>Initial Temperature</th>
<th>Lithophysal pattern</th>
<th>Lithophysal porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case1</td>
<td>91000</td>
<td>0.5 0.01</td>
<td>20</td>
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<td>0</td>
</tr>
<tr>
<td>Case2</td>
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<td>0.962 0.01</td>
<td>20</td>
<td>None</td>
<td>0</td>
</tr>
<tr>
<td>Case3</td>
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<td>24</td>
<td>None</td>
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<tr>
<td>Case4</td>
<td>88720</td>
<td>0.001 0.001</td>
<td>24</td>
<td>Regular</td>
<td>0.25</td>
</tr>
<tr>
<td>Case5</td>
<td>88720</td>
<td>0.001 0.001</td>
<td>24</td>
<td>Regular</td>
<td>0.25</td>
</tr>
<tr>
<td>Case6</td>
<td>88720</td>
<td>0.001 0.001</td>
<td>24</td>
<td>RP1</td>
<td>0.25</td>
</tr>
<tr>
<td>Case7</td>
<td>88720</td>
<td>0.001 0.001</td>
<td>24</td>
<td>RP2</td>
<td>0.25</td>
</tr>
<tr>
<td>Case8</td>
<td>88720</td>
<td>0.001 0.001</td>
<td>24</td>
<td>RP3</td>
<td>0.25</td>
</tr>
<tr>
<td>Case9</td>
<td>88720</td>
<td>0.001 0.001</td>
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<td>RP4</td>
<td>0.25</td>
</tr>
<tr>
<td>Case10</td>
<td>88720</td>
<td>0.001 0.001</td>
<td>24</td>
<td>RP5</td>
<td>0.25</td>
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</table>
## Hydrothermal properties:

### Table II. Matrix Properties of the Units

<table>
<thead>
<tr>
<th>Cases</th>
<th>Permeability</th>
<th>Porosity</th>
<th>Van Genutchen ((\alpha))</th>
<th>Van Genutchen ((\beta))</th>
<th>Residual saturation</th>
<th>Satiated saturation</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>m-tsw35</td>
<td>m-dr</td>
<td>m-tsw35</td>
<td>m-dr</td>
<td>6.44e-06</td>
<td>0.236</td>
</tr>
<tr>
<td>Case1</td>
<td>3.04e-17</td>
<td>0.5e-08</td>
<td>1.31e-01</td>
<td>0.495</td>
<td>6.44e-06</td>
<td>0.236</td>
</tr>
<tr>
<td>Case2</td>
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<td>0.5e-08</td>
<td>1.31e-01</td>
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<td>6.44e-06</td>
<td>0.236</td>
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<tr>
<td>Case3</td>
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<tr>
<td>Case5</td>
<td>3.04e-17</td>
<td>0.5e-16</td>
<td>1.31e-01</td>
<td>0.495</td>
<td>6.44e-06</td>
<td>0.236</td>
</tr>
<tr>
<td>Case6</td>
<td>3.04e-17</td>
<td>0.5e-16</td>
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<td>6.44e-06</td>
<td>0.236</td>
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<tr>
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<td>1.31e-01</td>
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<td>6.44e-06</td>
<td>0.236</td>
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<tr>
<td>Case8</td>
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<td>1.31e-01</td>
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<td>6.44e-06</td>
<td>0.236</td>
</tr>
<tr>
<td>Case9</td>
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<td>1.31e-01</td>
<td>0.495</td>
<td>6.44e-06</td>
<td>0.236</td>
</tr>
<tr>
<td>Case10</td>
<td>3.04e-17</td>
<td>0.5e-16</td>
<td>1.31e-01</td>
<td>0.495</td>
<td>6.44e-06</td>
<td>0.236</td>
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### Table III. Fracture Properties of the Units

<table>
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<tr>
<th>Cases</th>
<th>Permeability</th>
<th>Porosity</th>
<th>Van Genutchen ((\alpha))</th>
<th>Van Genutchen ((\beta))</th>
<th>Residual saturation</th>
<th>Satiated saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f-tsw35</td>
<td>f-dr</td>
<td>f-tsw35</td>
<td>f-dr</td>
<td>6.44e-06</td>
<td>0.236</td>
</tr>
<tr>
<td>Case1</td>
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<td>6.44e-06</td>
<td>0.236</td>
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<td>Case2</td>
<td>1.29e-12</td>
<td>0.5e-08</td>
<td>1.1e-02</td>
<td>0.495</td>
<td>6.44e-06</td>
<td>0.236</td>
</tr>
<tr>
<td>Case3</td>
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<td>1.1e-02</td>
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<td>6.44e-06</td>
<td>0.236</td>
</tr>
<tr>
<td>Case4</td>
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<td>1.1e-02</td>
<td>0.495</td>
<td>6.44e-06</td>
<td>0.236</td>
</tr>
<tr>
<td>Case5</td>
<td>1.29e-16</td>
<td>0.5e-16</td>
<td>1.1e-02</td>
<td>0.495</td>
<td>6.44e-06</td>
<td>0.236</td>
</tr>
<tr>
<td>Case6</td>
<td>1.29e-16</td>
<td>0.5e-16</td>
<td>1.1e-02</td>
<td>0.495</td>
<td>6.44e-06</td>
<td>0.236</td>
</tr>
<tr>
<td>Case7</td>
<td>1.29e-16</td>
<td>0.5e-16</td>
<td>1.1e-02</td>
<td>0.495</td>
<td>6.44e-06</td>
<td>0.236</td>
</tr>
<tr>
<td>Case8</td>
<td>1.29e-16</td>
<td>0.5e-16</td>
<td>1.1e-02</td>
<td>0.495</td>
<td>6.44e-06</td>
<td>0.236</td>
</tr>
<tr>
<td>Case9</td>
<td>1.29e-16</td>
<td>0.5e-16</td>
<td>1.1e-02</td>
<td>0.495</td>
<td>6.44e-06</td>
<td>0.236</td>
</tr>
<tr>
<td>Case10</td>
<td>1.29e-16</td>
<td>0.5e-16</td>
<td>1.1e-02</td>
<td>0.495</td>
<td>6.44e-06</td>
<td>0.236</td>
</tr>
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</table>

### Table IV. Thermal Properties of the Rock Domain

<table>
<thead>
<tr>
<th></th>
<th>Solid Density Case1-10</th>
<th>Specific Heat Case1-10</th>
<th>Wet conductivity Case 1-2</th>
<th>Wet conductivity Case3-10</th>
<th>Dry conductivity Case 1-2</th>
<th>Dry conductivity Case 3</th>
<th>Dry conductivity Case 4-10</th>
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</thead>
<tbody>
<tr>
<td>f-tsw35</td>
<td>2.82e+01</td>
<td>900</td>
<td>2.22e-02</td>
<td>0.01</td>
<td>1.31e-02</td>
<td>0.01</td>
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<tr>
<td>m-tsw35</td>
<td>2.89e+03</td>
<td>900</td>
<td>1.996</td>
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<tr>
<td>f-dr</td>
<td>5.92e-01</td>
<td>1006</td>
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<td>0.01</td>
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<tr>
<td>m-dr</td>
<td>5.92e-01</td>
<td>1006</td>
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<td>0.013</td>
<td>0.013</td>
<td>0.013</td>
<td>0.013</td>
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</table>
Fig 2. Lithophysal Cavity Patterns: (a) Regular Pattern of a Layer (Case 4 and 5).
(b) Random Pattern in Three Dimensions.
Evaluation Concept of Lithophysal Porosity, $\varphi_l$

The lithophysal porosity can be obtained from a single in situ REKA measurement if the baseline, non-lithophysal rock properties are known. Based on the measured temperature field $TM(x,t)$ acquired by the REKA probe, and using the REKA V1.1 software with the built-in conduction-only forward prediction model, the effective thermophysical properties can be determined:

$$ TM(x,t) \rightarrow \begin{cases} \kappa_{\text{eff}} \\ \alpha_{\text{eff}} \end{cases} $$ (1)

Since $\kappa_{\text{eff}}$ is evaluated from a measured temperature field, $TM(x,t)$, the effect of heat radiation across cavities, a significant transport component when the cavity size is large, is included in the in situ value. Note that the simulated temperature fields in this paper do not include these effects.

The ratio of conductivity to diffusivity is $(\rho_c c_p)_{\text{eff}}$. Using the definition of the lithophysal volumetric porosity, and assuming that the lithophysae are filled with gas, the following equation can be written:

$$ (\rho_c c_p)_{\text{eff}} = \frac{\kappa_{\text{eff}}}{\alpha_{\text{eff}}} = (\rho c_p)_{\text{rock}} (1 - \varphi_l) + (\rho c_p)_{\text{gas}} \varphi_l, $$ (2)

Since the density of gas is negligible when compared to that of rock, Eq. (2) can be simplified by eliminating the last term in the right-hand side. Through this simplification, the lithophysal porosity is:

$$ \varphi_l = 1 - \frac{(\rho c_p)_{\text{eff}}}{(\rho c_p)_{\text{rock}}} = 1 - \frac{\kappa_{\text{eff}}}{\alpha_{\text{eff}} (\rho c_p)_{\text{rock}}} $$ (3)

In order to evaluate $\varphi_l$, rock density and heat capacity need to be given for $(\rho c_p)_{\text{rock}}$ into Eq. (3). This term may be available from laboratory measurement results. Note that $\varphi_l$ is affected by both conductivity and specific heat, showing the complexity of the thermal behavior of porous media.

Numerical Method Verification

The method of analysis used in this study is verified based on Cases 1 through 3. (For these study cases, both the calculations and the lithophysal porosity are 2D values.) The results of the emulated measurement temperature field obtained using NUFT as inputs and the inverse-modeled temperature field for Case 3 is shown in Fig. 3(a) and 3(b). The thick lines are temperature curves from NUFT using the input values of thermal conductivity and diffusivity, while the thin lines are the temperature curves calculated using the thermal conductivity and diffusivity obtained from the best fit to the NUFT temperature field, as determined, while the thin lines are the curves calculated, as best fit, by the REKA V1.1 inverse modeling software.
The graphs are standard outputs of the software. The effective thermal conductivity and diffusivity values are depicted in Fig. 3, and summarized for all cases in Table V.

### Table V. Results after post processing the results obtained from Reka v 1.1

<table>
<thead>
<tr>
<th>Cases</th>
<th>Conductivity (W/m.k)</th>
<th>Diffusivity (m²/s)</th>
<th>T_{AV} (degree C)</th>
<th>RMS error (degree C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case1</td>
<td>1.5477</td>
<td>6.2450e-07</td>
<td>20.00</td>
<td>2.4184e-003</td>
</tr>
<tr>
<td>Case2</td>
<td>1.9779</td>
<td>7.1750e-07</td>
<td>20.00</td>
<td>1.6094e-003</td>
</tr>
<tr>
<td>Case3</td>
<td>2.0010</td>
<td>8.9347e-07</td>
<td>24.000</td>
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<tr>
<td>Case4</td>
<td>1.0367</td>
<td>6.2200e-07</td>
<td>24.0070</td>
<td>4.3171e-002</td>
</tr>
<tr>
<td>Case5</td>
<td>1.0367</td>
<td>6.2200e-07</td>
<td>24.0070</td>
<td>4.3167e-003</td>
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<tr>
<td>Case6</td>
<td>0.8412</td>
<td>5.5039e-07</td>
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<tr>
<td>Case7</td>
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<td>Case8</td>
<td>0.7128</td>
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<td>24.0100</td>
<td>2.5494e-002</td>
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<tr>
<td>Case9</td>
<td>1.0259</td>
<td>5.8745e-07</td>
<td>24.0042</td>
<td>5.5671e-003</td>
</tr>
<tr>
<td>Case10</td>
<td>0.9489</td>
<td>6.3343e-07</td>
<td>24.0060</td>
<td>1.2274e-003</td>
</tr>
</tbody>
</table>

The expected conductivity for Case 1 is 1.59, corresponding to a saturation of the rock at around 50%. This value is similar to the 1.55 result from the REKA V1.1 evaluation. The expected conductivity for Case 2 is 1.97 for a saturation of 96%. This value is also in agreement with the REKA V1.1 result of 1.98. The expected conductivity for the low-saturation Case 3 is 1.99 since both the dry and wet conductivities were set to that value in the NUFT input deck. The result from the REKA V1.1 software is almost identical, 2.00. These results show that the probe arrangement is correctly modeled and the domain as well as time discretization are acceptable. Case 3 is used as a baseline case and for supplying the $(p_c p)_{rock}$ value for the lithophysal evaluations. It was selected to avoid uncertainties associated with the movement of water in the system being modeled.

### Measurement Arrangement Verification

The lithophysal REKA measurement arrangement is verified based on Cases 4 and 5. The result of the emulated measurement temperature field obtained using NUFT as inputs and the inverse-modeled temperature field for Case 4 is shown in Fig. 4(a) and 4(b) as an example. The expected conductivity for Cases 4 and 5 is 1.0213 as discussed in the foregoing. This is in excellent agreement, within 1.5%, with the results of 1.0367 from the REKA V1.1 software for Cases 4 and 5. This agreement verifies that the measurement arrangement although based on two superimposed spherical temperature fields, closely represent a linear heat flow case. This verification justifies the design arrangement with the relatively widely spaced heaters and the 1m minimum distance between the center of the heaters and the closest temperature sensor station.

The expected lithophysal porosity for Cases 4 and 5 is 0.25 as discussed in the foregoing. For comparison, it is necessary to process the results in Table V using Eq. (3). The $(p_c p)_{rock}$ value for the rock without the lithophysae is conveniently taken from the baseline Case 3 as the ratio of conductivity to diffusivity, giving $(p_c p)_{rock} = 2.24 \times 10^6$. Using this value in Eq. (3), the lithophysal porosities are evaluated and given in Table VI.
Table VI. Lithophysal Porosities using Eq. (3)

<table>
<thead>
<tr>
<th>Cases</th>
<th>$\rho_C$</th>
<th>$\phi_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 3</td>
<td>2.24e+06</td>
<td>0</td>
</tr>
<tr>
<td>Case 4</td>
<td>1.67e+06</td>
<td>0.256</td>
</tr>
<tr>
<td>Case 5</td>
<td>1.67e+06</td>
<td>0.256</td>
</tr>
<tr>
<td>Case 6</td>
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<td>0.318</td>
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<td>Case 7</td>
<td>1.46e+06</td>
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</tr>
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<td>Case 8</td>
<td>1.515e+06</td>
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</tr>
<tr>
<td>Case 9</td>
<td>1.75e+06</td>
<td>0.220</td>
</tr>
<tr>
<td>Case 10</td>
<td>1.50e+06</td>
<td>0.331</td>
</tr>
</tbody>
</table>

The post-processed lithophysal porosity from the REKA method is in excellent agreement, within 2.5%, with the expected value. This agreement further verifies the methodology and justifies the measurement arrangement.

**Study of the Effect of Random Lithophysal Patterns**

Little is known about the nature of non-steady-state heat and moisture flow in lithophysal rock formation. Encouraged by the efficiency of the NUFT and REKA V1.1 combination to study a variety of arrangements, a Monte-Carlo analysis has commenced as a university research project to gain a better understanding. Cases 6 through 10 are sample results of this effort. A different, random cavity pattern is generated for each case with an average lithophysal porosity of 0.25 for the whole rock domain. The result of the emulated measurement temperature field obtained using NUFT as inputs and the inverse-modeled temperature field for Case 10 is shown in Fig. 5(a) & 5(b) as an example. The conductivity results, given in Table V, show a slight variation around an average of 0.953. This value is within 6.5% of the expected value for the same lithophysal porosity, but with a regular cavity pattern. The lithophysal porosity evaluation values, given in Table VI, vary around an average of 0.308. This value is within 23% of the expected value for the entire volume in the domain. The results for the five random samples are encouraging. Although too few in number for drawing conclusions about the statistics, they serve as demonstrations of the uncertainties of the single measurements when the active measurement area is surrounded with a random pattern of the lithophysae.

**CONCLUSIONS**

A method is presented, based on the NUFT and REKA V1.1 combination, to study the nature of non-steady-state heat flow during a single-borehole REKA thermal probe thermophysical measurement in solid as well as lithophysal rock formation with a regular and a random lithophysal pattern. The results prove the principle of the REKA method application in lithophysal formation.

The numerical evaluation results, based on the use of two qualified software packages, show that the presented REKA probe arrangement designed for lithophysal thermophysical properties identification is correctly modeled and the domain as well as time discretizations are acceptable.
The REKA probe arrangement can be used to inverse-identify the effective heat conductivity and thermal diffusivity, and through these values, the lithophysal porosity of a regular lithophysal cavity pattern can be determined. This numerical verification justifies the design arrangement with the relatively widely spaced heaters and the 1m minimum distance between the center of the heaters and the closest temperature sensor station.

A method is presented, based on the NUFT and REKA V1.1 combination, to study the nature of non-steady-state heat in lithophysal rock formation with a random lithophysal pattern. A Monte-Carlo analysis is needed to increase the number of random samples for statistical evaluation. The five sample results presented are encouraging.

REFERENCES


(a) Thick dotted lines are the inputs to REKA V1.1 from NUFT. Thin lines are best-fitted curves generated by REKA 1.1. (b) Error of fit curve generated during inverse optimization by REKA V1.1.
Fig. 4. Inverse evaluation results of Case 4 (Regular Lithophysal Pattern)
(a) Thick dotted lines are the inputs to REKA V1.1 from NUFT. Thin lines are best-fitted curves generated by REKA V1.1.
(b) Error of fit curve generated during inverse optimization by REKA V1.1.
Fig. 5. Inverse evaluation results of Case 10 (A typical random lithophysal pattern).
(a) Thick dotted lines are the inputs to REKA V1.1 from NUFT. Thin lines are best-fitted curves generated by REKA V1.1.
(b) Error of fit curve generated during inverse optimization by REKA V1.1.
APPENDIX 3  Lithophysal Paper 2, “For Corroborative Use Only”

Monte Carlo Analysis of In Situ REKA Lithophysal Properties Identification

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University of Nevada, Reno, Reno, NV 89557, danko@unr.edu

Abstract -Bulk thermophysical properties are studied in lithophysal rock formation characteristic to the host area for the proposed nuclear waste repository at Yucca Mountain (YM). Using numerical simulation based on NUFT, temperature fields are calculated in a large rock block of 6x6x9 m that has random lithophysae distribution varying both in space and connected cavity shape, but providing an average lithophysal porosity of 0.25. Thirty temperature fields are generated for evaluating backward thermal conductivity, diffusivity, and lithophysal porosity using the single-borehole REKA (Rapid Evaluation of K and Alpha) thermal probe arrangement and inverse evaluation method. The statistics of the thermal conductivity results from the REKA method are compared with the results of a linear, steady-state evaluation method for verification. The statistics of the lithophysal porosity from the REKA method are compared with the evaluation of the lithophysal porosity in smaller sub-domains of the large block. Four simple, analytical thermal conductivity models are also presented for obtaining envelopes for expected values assuming regular, lithophysal lattice patterns. The numerical and analytical results are all in good agreement, indicating an expected bulk lithophysal thermal conductivity of 1.03W/(mK) for the example characteristic to YM.

I. INTRODUCTION

Recent conceptual design indicates that approximately 70% of the active emplacement and heat dissipation area of the proposed repository will be built in lithophysal rock formations. It is necessary to evaluate the thermophysical properties (heat conductivity, k, and thermal diffusivity, α) as well as the lithophysal porosity (φ_l) to support temperature and humidity calculations for both pre- and post-closure design and performance verifications at Yucca Mountain (YM).

The lithophysal formation with air cavity distribution involves a complex geometry that has a primary effect upon the flow of heat. A sensitivity analysis of input thermophysical properties showed that heat conductivity strongly affects temperature, with a relative sensitivity approaching 100%. In situ measurements are direct and efficient ways to evaluate rock thermophysical properties. Due to the statistical nature of lithophysae distribution, a sufficiently large number of measurements may be needed to obtain representative and reliable averages. Two in situ methods have been considered for application at YM: (1) the single-borehole, in situ REKA (Rapid Evaluation of K and Alpha) technique, that has been used in several locations at YM since 1995, and (2) a new, multiple-borehole method. The REKA measurement configuration, including the probes, has been designed for lithophysal application, but the application at YM has not been implemented. A new, multiple-borehole method has been used at YM for over a year and three measurement results have been reported. These results (k = 1.74, 2.03-2.18, 1.73-1.76 W/m.K) are still too few in number and uncertain in range to be conclusive. In addition, the multiple-borehole site preparation, instrumentation and data acquisition are far more labor-intensive as well as more expensive than the single-borehole REKA method with re-usable probes. Therefore, it is advantageous to further study the single-borehole REKA method for lithophysal thermophysical properties measurement applications at YM.

The current work is a numerical analysis to study the effect of statistical distribution of lithophysae upon the thermophysical properties. The method of study is based on applying NUFT for the calculation of temperature fields in randomly distributed lithophysal formations with a controlled, average lithophysal porosity of 0.25, and rock matrix conductivity of 2.0 W/(mK), and 2.5 W/(mK). The temperature field is inverse-evaluated using the REKA heater and sensor configuration and evaluation methodology, available as a base-lined software, REKA V1.1.
lithophysae; however, only four random samples were included, rendering them statistically inconclusive. The lithophysae is modeled in NUFT as an air-filled rectangular block. The regular cavity pattern in the previous work$^9$ was studied for comparison with a simple, analytical bulk thermal conductivity model, with which excellent agreement was found, obtaining 1.03 W/(mK). In addition, the inverse evaluation of the lithophysal porosity from the REKA method also agreed excellently with the known, input cavity configuration used in NUFT.

As a follow-up, a Monte Carlo analysis of statistical distribution of the inverse REKA thermal conductivity and lithophysal porosity has been conducted. Normal statistical procedure of the probability density function requires comparison of at least 20 different test data for a safe estimate of normal distribution. In the present case, 30 simulated lithophysae samples were used in the evaluation.

II. DESCRIPTION OF THE METHOD

The domain of the numerical study is a 6x6x9 m rock block with thermally insulated boundaries. Within this domain, 60x60x90 cubes with 0.1 m edges are modeled in NUFT. A white-noise random lithophysae generator is used to determine coordinates of the air cavities, rounded to the closest mesh coordinates, until 25% of the total volume is filled with air cavities. The cavities may coalesce, forming larger lithophysae during the random pattern generation. Therefore, both the center coordinates and the size of the cavities are random.

The lithophysal REKA measurement using a twin-heater arrangement is shown in Fig. 1. A 1.1 m-long measurement section on a straight line is used between two 0.6 m long heater elements spaced 3 m apart. The twin-heater arrangement represents two single-heater REKA probes comprised within one embodiment. This arrangement was found advantageous during the preliminary method analysis for lithophysal application$^9$ in order to integrate the uneven heat flow in the lithophysae rock formation. The probe arrangement was simplified in the previous study, representing the short heaters with point sources; the present work is a more accurate representation, including finer block mesh of 0.10 m cubes applying eleven temperature sensors.

The temperature distribution along the length of the probe is simulated using NUFT. The evolution of the temperature field is recorded at the eleven locations hourly for three time periods of 160 hrs, 320 hrs and 480 hrs respectively to investigate the effect of measurement time on the results. A trial-and-error evaluation procedure, according to the qualified REKA V1.1$^8$ software that includes the twin-heater option, is used to determine the unknown thermophysical properties by minimizing the root-mean-square error between the measured and the calculated incremental temperature fields with the trial thermophysical properties.

Cases 1 through 30 apply random cavity patterns which are generated according to a geometrical random cavity distribution with an average lithophysal porosity of 0.25. Fig. 2 is an illustration of a random distribution. Although the patterns correspond to 0.25 average lithophysal porosity for the entire block, random variation is expected around the REKA probe. There is no closed solution for the bulk, equivalent heat conductivity for the random patterns, but it is expected that the average of a large number of evaluations is around the value of the regular pattern. Four analytical models of bulk conductivity for regular cavity patterns are given in the Appendix for comparison with the numerical results for random pattern.

The goal of Cases 1-30 is to back-identify the bulk lithophysal rock properties from the simulated measurement fields for the random patterns with the REKA inverse method for comparison. The bulk thermal conductivity and diffusivity results for each of the 30 samples are obtained directly from the REKA V1.1$^8$ software. It is possible to use the independent pairs of thermal conductivity and diffusivity for
obtaining the lithophysal porosity. The formula for the lithophysal porosity $\varphi_l$ based on the bulk REKA evaluation results of each sample and the known solid properties is as follows:

$$\varphi_l = 1 - \frac{(k / \alpha)}{(k / \alpha)_{\text{solid}}}$$

where $(k / \alpha)$ in the numerator is the ratio of thermal conductivity and diffusivity obtained from the REKA V1.1 inverse evaluation, and $(k / \alpha)_{\text{solid}}$ is the ratio of thermal conductivity and diffusivity of the solid rock with or without moisture in the matrix.

III. RESULTS

III. A. Bulk Thermal Conductivity, Diffusivity, and Lithophysal Porosity From the REKA Inverse Evaluation

Figure 3. Sample evaluation results from the inverse REKA 1.1 software; (a) error-of-fit minimization with varying bulk thermal diffusivity, and (b) the input and trial temperature variations with time for an emulated REKA measurement with optimized bulk thermal conductivity and diffusivity.
A sample evaluation using the REKA 1.1 software is given in Figure 3. Figure 3(a) shows the result of the inverse evaluated bulk thermal diffusivity as an optimum value for the minimum error-of-fit between the input temperature field from NUFT and the one calculated by the REKA software for a trial bulk thermal diffusivity and conductivity. Figure 3(b) shows the input and output temperatures of the REKA evaluation for the best-fit bulk thermal conductivity and diffusivity.

![Probability Density Functions](image)

Fig. 4. (a) Conductivity, (b) Diffusivity and (c) Porosity distribution using three different evaluation time intervals

Since the temperature variation is stochastic in the random lithophysal samples, the bulk thermal conductivity and diffusivity are also stochastic. The results of the statistical evaluation of the random samples are evaluated using histograms. The probability distribution for conductivity, diffusivity, and lithophysal porosity are shown in Figure 4.

Table 1 shows the expected and the obtained values of average lithophysal porosity $\phi_l$, $k$ and $\alpha$ for all different volumes for an input rock conductivity of 2.0 W/(mK). The table includes different simulation and evaluation time periods of 160 hrs, 320 hrs and 480 hrs respectively. As shown, increasing evaluation time improves the statistical prediction by decreasing the standard deviation of the evaluation. However, the mean values for all properties appear to be much better at 160 hrs than at 480 hrs. It must be noted that the increasing deviation in the mean values with longer time periods is due to the finite size of the rock domain which does not contain the temperature field inside the boundaries at longer time periods, and a slight temperature rise appears on the surfaces. Consequently, a larger rock domain would be needed to correctly model the 320 hrs and 480 hrs time periods in order to avoid the increasing mismatch between the model conditions used in the forward NUFT model (adiabatic on the block surfaces), and inverse REKA V1.1 model (infinite rock domain). Since the limitation in available memory size of 4 GB restricts the domain to its present size, the results in Table 1 have to be used with the notion that the excellent match reached between the evaluated and expected values at 160 hrs time period would remain the same if increasingly larger model domains were used. In order to decrease the standard deviation, i.e., the uncertainty interval of a single evaluation, the longer time period is the better.

III. B. Lithophysal Porosity Evaluation From Geometry

A range of volumes around the measurement segment was considered to study spatial variation of the geometrical porosity in the modeled block of rock. Six volumes were taken around the centerline of the measurement segment as follows:
1. $0.1 \times 0.1 \times 1.1$
2. $0.3 \times 0.3 \times 1.1$
3. $0.5 \times 0.5 \times 1.1$
4. $0.7 \times 0.7 \times 1.1$
5. $0.9 \times 0.9 \times 1.1$
6. $1.1 \times 1.1 \times 1.1$
The geometrical lithophysal porosity \( \varphi_g \) was calculated for each volume of all 30 random patterns:

\[
\varphi_g = \frac{V_v}{V_t},
\]

where: \( V_t \) is the total void volume, \( V_i \) is the total volume within the sample volumes.

Table 1. Lithophysal bulk conductivity, diffusivity, and porosity from 30 simulated samples using the REKA 1.1 inverse evaluation.

<table>
<thead>
<tr>
<th>Length of Time Period</th>
<th>K [W/m.K]</th>
<th>( \alpha [\text{m/s}] \times 10^6 )</th>
<th>Lithophysal Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Expected</td>
<td>Standard</td>
</tr>
<tr>
<td>160 hrs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deviation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>320 hrs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>480 hrs</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Random Pattern ID</th>
<th>Lithophysal Porosity(%)</th>
<th>k [W/m.K]</th>
<th>( \alpha [\text{m/s}] \times 10^6 )</th>
<th>( \rho e-k/a \times 10^6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>160 hrs</td>
<td>480 hrs</td>
<td>160 hrs</td>
<td>480 hrs</td>
</tr>
<tr>
<td>Solid</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>14.96</td>
<td>25.59</td>
<td>1.2448</td>
<td>0.6423</td>
</tr>
<tr>
<td>2</td>
<td>24.53</td>
<td>26.51</td>
<td>0.9396</td>
<td>0.5463</td>
</tr>
<tr>
<td>3</td>
<td>25.62</td>
<td>29.24</td>
<td>0.9356</td>
<td>0.5843</td>
</tr>
<tr>
<td>4</td>
<td>20.64</td>
<td>27.34</td>
<td>0.9844</td>
<td>0.4783</td>
</tr>
<tr>
<td>5</td>
<td>19.54</td>
<td>23.06</td>
<td>1.0085</td>
<td>0.4866</td>
</tr>
<tr>
<td>6</td>
<td>29.54</td>
<td>20.93</td>
<td>0.707</td>
<td>0.4053</td>
</tr>
<tr>
<td>7</td>
<td>27.07</td>
<td>27.79</td>
<td>0.9568</td>
<td>0.4818</td>
</tr>
<tr>
<td>8</td>
<td>34.3</td>
<td>32.71</td>
<td>0.8812</td>
<td>0.4783</td>
</tr>
<tr>
<td>9</td>
<td>15.64</td>
<td>16.96</td>
<td>0.9195</td>
<td>0.4783</td>
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<tr>
<td>10</td>
<td>36.94</td>
<td>32.54</td>
<td>0.8204</td>
<td>0.4783</td>
</tr>
<tr>
<td>11</td>
<td>21.09</td>
<td>24.42</td>
<td>0.9768</td>
<td>0.4783</td>
</tr>
<tr>
<td>12</td>
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<td>25.59</td>
<td>1.2448</td>
<td>0.6423</td>
</tr>
<tr>
<td>13</td>
<td>23.44</td>
<td>27.05</td>
<td>1.0344</td>
<td>0.4783</td>
</tr>
<tr>
<td>14</td>
<td>24.91</td>
<td>27.38</td>
<td>0.9369</td>
<td>0.5463</td>
</tr>
<tr>
<td>15</td>
<td>25.67</td>
<td>30.97</td>
<td>1.056</td>
<td>0.4783</td>
</tr>
<tr>
<td>16</td>
<td>29.01</td>
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<td>0.8907</td>
<td>0.4783</td>
</tr>
<tr>
<td>17</td>
<td>15.36</td>
<td>24.67</td>
<td>1.1821</td>
<td>0.4783</td>
</tr>
<tr>
<td>18</td>
<td>9.6</td>
<td>19.88</td>
<td>1.1603</td>
<td>0.4783</td>
</tr>
<tr>
<td>19</td>
<td>20.05</td>
<td>24.86</td>
<td>1.0761</td>
<td>0.4783</td>
</tr>
<tr>
<td>20</td>
<td>20.03</td>
<td>26.08</td>
<td>1.0872</td>
<td>0.4783</td>
</tr>
<tr>
<td>21</td>
<td>38.38</td>
<td>28.76</td>
<td>0.6921</td>
<td>0.4783</td>
</tr>
<tr>
<td>22</td>
<td>21.6</td>
<td>24.6</td>
<td>1.04</td>
<td>0.4783</td>
</tr>
<tr>
<td>23</td>
<td>23.69</td>
<td>26.99</td>
<td>1.0295</td>
<td>0.4783</td>
</tr>
<tr>
<td>24</td>
<td>32.43</td>
<td>29.19</td>
<td>0.8593</td>
<td>0.5572</td>
</tr>
<tr>
<td>25</td>
<td>24.25</td>
<td>27.27</td>
<td>0.9968</td>
<td>0.5572</td>
</tr>
<tr>
<td>26</td>
<td>35.97</td>
<td>30.99</td>
<td>0.7875</td>
<td>0.5572</td>
</tr>
<tr>
<td>27</td>
<td>18.87</td>
<td>26.73</td>
<td>1.1596</td>
<td>0.5572</td>
</tr>
<tr>
<td>28</td>
<td>32.93</td>
<td>29.88</td>
<td>0.8477</td>
<td>0.5572</td>
</tr>
<tr>
<td>29</td>
<td>34.86</td>
<td>32.34</td>
<td>0.8207</td>
<td>0.5572</td>
</tr>
<tr>
<td>30</td>
<td>22</td>
<td>27.17</td>
<td>1.0722</td>
<td>0.5572</td>
</tr>
<tr>
<td>Average</td>
<td>24.79</td>
<td>26.86</td>
<td>0.9731</td>
<td>0.5572</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>(7.25)</td>
<td>3.62</td>
<td>(0.1354)</td>
<td>0.0542</td>
</tr>
<tr>
<td>Expected Values</td>
<td>25</td>
<td>25</td>
<td>1.0367</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Document number: TR-03-016
Figure 5 shows the probability distribution of the lithophysal porosity for each volume. Table 2 shows the results of estimated lithophysal porosity for all 30 random patterns based on REKA calculations using 11 sensors and evaluation times of 160 hrs for the mean values and 480 hrs for the standard deviation.

The results of REKA evaluation for 160 hrs. are used for the mean values since the longer time periods have caused numerical simulation error due to the finite size of the rock block applied in the NUFT simulations. The truncation error does not affect the statistical distribution; therefore, the standard deviation results for 480 hrs are used. At least 480 hrs or longer evaluation time period is recommended for field tests in order to decrease statistical uncertainty. A large, undisturbed measurement volume is needed to avoid volume truncation and edge-effect errors in the field. This can be accomplished by placing a REKA probe into a 10 m-deep borehole perpendicular to the surface of the access drift. The probability density function based on 480 hr. measurement evaluation is as shown in Fig. 5.

It can be seen from the plot in Figure 5 that the lithophysal porosity distribution in a 0.3x0.3x1.1 m volume agrees well with the conductivity distribution function. A hypothesis can be raised that perhaps such a volume is represented in one REKA evaluation. An additional numerical test was carried out to prove or reject this hypothesis using a steady-state heat conduction evaluation along the 9 m length in the rock domain.

IV. A STEADY-STATE LITHOPHYSAL HEAT CONDUCTION MODEL AND EVALUATION

IV.A. Average Bulk Thermal Conductivity

The lithophysal random pattern #12 was selected for steady-state, mainly one-dimensional heat conduction simulation. NUFT was configured with a constant-temperature boundary condition of 24 °C on the 6x6 m end surface at x=9 m, and a 40 W constant surface heater boundary condition at x=0, defining a heat flux density of 1.1111 W/m². The steady-state temperature field was simulated using 1 million years for stabilization. The temperature field at x=0 is shown in Figure 6; the average of the varying temperature due to the random cavities is 34.1031°C. The edges are colder than the inside domain by about 3% due to the fact that a 0.1 m solid rock layer is
bounding the block with no open lithophysal cavities on the surfaces. The average, bulk thermal conductivity for the entire 6x6x9 m lithophysal block is calculated from the heat conduction equation:

\[
k = \frac{1.1111}{(10.1031/9)} = 0.9898 \text{ W/(mK)}
\]

(3)

The bulk lithophysal thermal conductivity from Eq. (3) agrees excellently with the expected value of 1.0367 W/(mK) from the previous study. A significant decrease is obtained in thermal conductivity from the non-lithophysal conductivity value of 2.0 W/(mK) due to a random lithophysal porosity of 0.25. The example shows that the volumetric scaling law for conductivity, expressed with the lithophysal porosity and proposed for YM in a recent model report, does not provide correct results for this example. Volumetric scaling with air and rock conductivities of 0.026 and 2.0 would give a much higher bulk thermal conductivity for 0.25 lithophysal porosity as follows:

\[
k_{\text{volumetric-scaled}} = k_{\text{air}} + k_{\text{rock}} (1 - \phi) = 0.026 + 2.0\times0.75 = 1.526 \text{ W/(mK)}
\]

(4)

Approximate scaling models for bulk lithophysal conductivity can be derived analytically assuming periodic cavity patterns. Four such models are given in the Appendix, expressing the effective thermal conductivity from networks of thermal admittances in series and parallel connections.

The results of these models are summarized in Figure 7 providing further comparisons for verification of the numerical results.

**IV. B. Statistical Variation Of the Bulk Thermal Conductivity**

The lithophysal temperature field in the rock block was evaluated along x-directional lines, emulating a series of measurements, using a linear thermometer array such as applied in the study of the REKA method. The bulk thermal conductivity was re-evaluated from the temperature field using a least-square linear fit to the data along each line. An example fit is shown in Figure 8(a). The statistical evaluation result of 58x58 sample lines across the block is shown in Figure 8(b). The standard deviation for the samples was 0.04, a very close value to that of 0.054 obtained for the REKA method. Therefore, it can be concluded that the standard deviation from the REKA method is close to that of the characteristically linear heat flow case, and not related to a reduced volume of influence. The summary of results for the block and the REKA probe arrangement is given in Table 3. Results for simulations with both 2.0 and 2.5 W/(mK) input rock conductivities are shown in Table 3.

<table>
<thead>
<tr>
<th>Input Rock Conductivity</th>
<th>Expected Lithophysal Conductivity (25% lithophysal porosity)</th>
<th>Block Arrangement Identified conductivity in volume(m)</th>
<th>REKA probe arrangement, Identified values in 0.3x0.3x1 m. volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.1x0.1x1</td>
<td>0.3x0.3x1</td>
</tr>
<tr>
<td>2.0</td>
<td>1.06</td>
<td>0.9906</td>
<td>0.9898</td>
</tr>
<tr>
<td>2.5</td>
<td>1.26</td>
<td>1.2356</td>
<td>1.2346</td>
</tr>
</tbody>
</table>

Table 3. Comparison between identified conductivity, diffusivity and lithophysal porosity for input matrix conductivities of 2.0 and 2.5 W/m.K.
Figure 6. Steady-state temperature field at the heated layer of the rock block $x=0$.

Figure 7. Comparison of bulk lithophysal thermal conductivity results from numerical simulations, approximate analytical models, and three in situ measurements conducted by BSC at YM.
V. CONCLUSIONS

1. The numerical results of 30 random lithophysal samples provide close-to-normally-distributed variations for inverse evaluated bulk lithophysal conductivity, diffusivity and porosity, using the REKA methodology.

2. Excellent agreement was found between the expected and inverse-evaluated thermophysical properties. Long measurement time interval over 480 hrs. is recommended in a sufficiently large, undisturbed rock formation.

3. The average of the random lithophysal conductivity of 0.97 W/m.K agrees within 6.1% with the expected bulk conductivity of 1.03 W/m.K.

4. The average of the random lithophysal diffusivity of 0.57 x 10^{-6} m/s^2 agrees within 8.6% with the expected bulk diffusivity of 0.62 x 10^{-6} m/s^2.

5. The average of the random lithophysal porosity of 24.79% agrees within 0.8% with the expected bulk porosity of 25%.

6. The expected bulk lithophysal conductivity of 1.03 W/m.K for 25% lithophysal porosity, or the evaluated 0.97 W/m.K bulk lithophysal conductivity simulated based on two qualified software does not seem to be in good agreement with field measurements in the 1.73 - 2.18 W/m.K regime. Therefore, further verification of bulk, field lithophysal conductivity is recommended at YM.

VI. REFERENCES


VII. APPENDIX

The standard technique of heat conduction network analysis is used to derive the bulk, effective thermal conductivity of periodic patterns of air cavities in a rock formation. Four patterns are analyzed with periodic patterns given in Fig. A1 a-e. The bulk, lithophysal conductivity $k_I$ is expressed as a function of $k_a$, air, $k_r$, rock, and $\varphi_I$, lithophysal porosity.

1. Symmetrical, cube-in-cube pattern. The pattern is given in Figure A1 (a). The bulk lithophysal conductivity is:

$$k_I = \frac{k_a k_r (1 - \varphi_I^{1/3} + \varphi_I) + k_r^2 (\varphi_I^{1/3} - \varphi_I)}{k_a (1 - \varphi_I^{1/3}) + k_r \varphi_I^{1/3}}$$

(A-1)

2. Cube-in-cube pattern, shifted in y direction. The pattern is given in Figure A1 (b). The bulk lithophysal conductivity in y direction is:

$$k_I = \frac{\varphi_I^{2/3} k_a k_r}{\varphi_I^{1/3} (k_r - k_a) + k_a} + (1 - \varphi_I^{2/3}) k_r$$

(A-2)

3. Alternating rock and air cubes, used in a previous study shown in Figure A1 (e). The bulk lithophysal conductivity is:

$$k_I = \frac{\varphi_I (k_a k_r - k_r^2) + \varphi_I^{1/2} (k_r^2 - k_a k_r) + k_a k_r}{k_a + \varphi_I^{1/2} (k_r - k_a)}$$

(A-3)

4. Cube-in-cube pattern, shifted both in x and y directions. The pattern is given in Figure A1 (c). The bulk lithophysal conductivity in x direction is:

$$k_I = k_r (1 - \varphi_e^{1/3}) +$$

$$\frac{k_a k_r}{\varphi_I^{2/3} (k_r - k_a)^2 + 3 \varphi_I^{1/3} k_a (k_r - k_a) + 2 k_a^2}$$

(A-4)
Fig. A1. Periodic cavity patterns used in simplified, analytical, bulk lithophysal conductivity models.
APPENDIX 4  Digital Filter MATLAB Macro: filtering.m v1.0

% filtering.m v1.0
% To filter out the high frequency content in conductivity and diffusivity
% in probes 1, 2, and 3:

% Use Chebychev low pass filter for filtering in all the cases
% cheby1 command gets the polynomial coefficients and filter command uses
% these coefficients to do the filtering

% The current Working Directory should be
% 'C:\c\Users\task13\reports\final\todanko'

% Probe 1:

load prl.dat

t1=prl(:,1);
t11=t1(1:22);
t12=t1(23:45);
t13=t1(46:64);

k1=prl(:,2);
k11 = k1(1:22);
k12 = k1(23:45);
k13 = k1(46:64);

[b,a] = cheby1(5,1,0.1);
K1=filtfilt(b,a,k1);
K11 = K1(1:22);
K12 = K1(23:45);
K13 = K1(46:64);

figure(1)
plot(t11,K11,'-',t11,k11,':',t12,K12,'-',t12,k12,':',t13,K13,'-
',t13,k13,':');
legend('Filtered','Original');
xlabel('Time in days starting from 4th Dec, 1997');
ylabel('Conductivity');
title('Probe 1');

alpha=prl(:,4);
alpha11 = alpha(1:22);
alpha12 = alpha(23:45);
alpha13 = alpha(46:64);

[b,a] = cheby1(5,1,0.1);
ALPHA=filtfilt(b,a,alpha);
ALPHA11 = ALPHA(1:22);
ALPHA12 = ALPHA(23:45);
ALPHA13 = ALPHA(46:64);

figure(2)
plot(t11,ALPHA11,'-',t11,alpha11,':',t12,ALPHA12,'-
',t12,alpha12,':',t13,ALPHA13,'-',t13,alpha13,':');
legend('Filtered','Original');
xlabel('Time in days starting from 4th Dec, 1997');
ylabel('Diffusivity');
title('Probe 1');

% Probe 2:
load pr2.dat

t2=pr2(:,1);
t21=t2(1:23);
t22=t2(24:111);

k2=pr2(:,2);
k21 = k2(1:23);
k22 = k2(24:111);

[b,a] = cheby1(5,0.2,0.1);
K2 = filtfilt(b,a,k2);
K21 = K2(1:23);
K22 = K2(24:111);

figure(3)
plot(t21,K21,-',t21,k21,:',t22,K22,-',t22,k22,:)')
legend('Filtered','Original');
xlabel('Time in days starting from 4th Dec, 1997');
ylabel('Conductivity');
title('Probe 2');

alpha2=pr2(:,4);
alpha21=alpha2(1:23);
alpha22=alpha2(24:111);

[b,a] = cheby1(5,0.2,0.1);
ALPHA2 = filtfilt(b,a,alpha2);
ALPHA21=ALPHA2(1:23);
ALPHA22=ALPHA2(24:111);

figure(4)
plot(t21,ALPHA21,-',t21,alpha21,:',t22,ALPHA22,-',t22,alpha22,:')
legend('Filtered','Original');
xlabel('Time in days starting from 4th Dec, 1997');
ylabel('Diffusivity');
title('Probe 2');

% Probe 3:
load pr3.dat

t3=pr3(:,1);
t31=t3(1:22);
t32=t3(23:111);

k3=pr3(:,2);
k31=k3(1:22);
k32=k3(23:111);
\[ [b, a] = \text{cheby1}(5, 1, 0.1); \]
\[ K3 = \text{filtfilt}(b, a, k3); \]
\[ K31 = K3(1:22); \]
\[ K32 = K3(23:111); \]

\texttt{figure(5)}
\texttt{plot(t31, K31, '-', t31, k31, ':', t32, K32, '-', t32, k32, ':')}
\texttt{legend('Filtered', 'Original');}
\texttt{xlabel('Time in days starting from 4th Dec, 1997');}
\texttt{ylabel('Conductivity');}
\texttt{title('Probe 3');}

\[ \texttt{alpha3} = \text{pr3}(:, 4); \]
\[ \texttt{alpha31} = \text{alpha3}(1:22); \]
\[ \texttt{alpha32} = \text{alpha3}(23:111); \]

\[ [b, a] = \text{cheby1}(5, 1, 0.1); \]
\[ \texttt{ALPHAS} = \text{filtfilt}(b, a, alpha3); \]
\[ \texttt{ALPHAS1} = \text{ALPHAS}(1:22); \]
\[ \texttt{ALPHAS2} = \text{ALPHAS}(23:111); \]

\texttt{figure(6)}
\texttt{plot(t31, ALPHAS1, '-', t31, alpha31, ':', t32, ALPHAS2, '-', t32, alpha32, ':')}
\texttt{legend('Filtered', 'Original');}
\texttt{xlabel('Time in days starting from 4th Dec, 1997');}
\texttt{ylabel('Diffusivity');}
\texttt{title('Probe 3');}
APPENDIX 5  Digital Filter MATLAB Macro, filtering.m v1.0, Verification

The filtering.m MATLAB macro is a script that conveniently executes a set of consecutive MATLAB commands. The input of the macro is qualified, derived data, the output are graphs. The output figures include the graphs of the input data as well as the graphs of the filtered results. Since the macro produces graphs and not numbers, the validation is also based on graphical evaluation, that is, the comparison of curves.

Step 1. The input data used for the evaluation with signal processing was compared with the original, derived data. Specifically, comparisons between conductivities in Figures 5-12, and 5-13 were compared with conductivities in Figures 5-2b, 5-4b, and 5-6b, respectively. The comparison can be reproduced by visual evaluation of the graphs depicted in the corresponding figures.

The conclusion of the verification is: pass

Step 2. The filter output curves were compared with the filter input curves, which depict the conductivities being analyzed and verified in step 1. The results of the macro were visually inspected and it was concluded that the filtered curves do follow the input data trend and are sufficiently smooth as the high frequency noise is removed by the filter. Comparing visually the original and the filtered curves in Figures, 5-11, 5-12, and 5-13, prove the validity of the filtering macro. The quality of the filtering.m macro is accepted since the filtered curves show less fluctuation in amplitude while the average trends of the conductivities are sufficiently matched.

The conclusion of the verification is: pass