

Rapid Evaluation of Rock Thermal Parameters at the Lucky Friday Mine

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ABSTRACT

In many hot mines a large portion of the total heat load is associated with the surrounding strata. In order to maintain acceptable underground environmental conditions, the mine heat load must be controlled by the ventilating airstream, and in certain cases by mechanical refrigeration. To compute existing, or future heat additions from the surrounding rock, certain parameters must be determined. These parameters include the rock thermal conductivity, thermal diffusivity, and the geothermal gradient (with relation to a virgin rock datum). These rock thermal parameters are typically estimated from published literature, or evaluated by laboratory or in-situ measurements. Presented in the paper are the results from a series of tests conducted at Hecla Mining Company's Lucky Friday Mine. These tests include in-situ measurements of rock thermal conductivity and geothermal gradient, which were performed in highly active sections of this deep silver mine. The results from the in-situ tests are compared with data obtained from laboratory testing of mine core samples. The methodology, measurement equipment, test data, and main results are described.

KEYWORDS

Conductivity, Diffusivity, VRT, Heat Flow, and Lucky Friday Mine.

INTRODUCTION

The Lucky Friday Mine is located near the town of Wallace, Idaho, in the Coeur d'Alene mining district. The mine operator is Hecla Mining Company. The Lucky Friday is an old, deep silver mine, that incorporates active stopes at depths greater than 1,830 m (6,000 ft). In 1996 Hecla Mining Company initiated an engineering study to plan the development and mining of a new orebody, located approximately 1.6 km (1 mile) from the main intake shaft (Silver Shaft). This new orebody was termed the Goldhunter deposit. The total extent of the orebody was unknown, however reserves had been discovered in a zone from 1,234 to 1,981 m (4,050-6,500 ft).

Initial ventilation and heatflow studies suggested that mechanical refrigeration would be required to maintain an acceptable work environment in the Goldhunter section. At this early date it was recognized that additional, more detailed studies were needed to accurately quantify the expected heat load. During the initial heat flow analyses certain assumptions had been made to enable the evaluation of the strata heat load. These assumptions included the

estimation of the rock thermal properties and virgin rock temperatures (VRT) based on published literature. As part of the detailed heat flow study, a series of tests were developed to attempt to quantify the mine rock thermal properties and VRT by direct measurement. It was felt that the accurate determination of these parameters would provide increased confidence in the overall ventilation and cooling design.

The determination of three critical parameters will be discussed in this paper. These were the rock thermal conductivity (k), the rock thermal diffusivity (α) and the geothermal gradient (with relation to a virgin rock datum).

IN-SITU ROCK THERMAL CONDUCTIVITY

The parameter k is a measure of the ability of a material to pass heat. The measurement of an in-situ value for k is quite a complex process, and is often impacted by the non-ideal test conditions experienced in a producing mine.

For steady-state conditions, the k value ($W/m^{\circ}C$) for a straight drift may be obtained from the following relationship (Mousset-Jones, 1988):

$$\frac{(T_2 - T_1)}{\log_e \left(\frac{r_2}{r_1} \right)} = - \frac{q}{2\pi k L} = b \quad (1)$$

Where: r = radius from center of drift (m)
 T = temperature ($^{\circ}C$) at location r
 q = radial heat flow (W)
 L = length of test section (m)
 b = slope of graph of T v. $\log_e r$

In order to calculate k it is necessary to determine the value of the slope (b), and the quantity of heat flow from the rock (q) for a measured length of drift. The following procedure was used to develop a test to measure k :

1. Select a location to conduct the test. The test site should ideally satisfy the following criteria:
 - adequate length of drift with consistent airflow;
 - minor changes in cross-sectional area;
 - infrequent, or no equipment movement;
 - no heat source except the rock;
 - an appreciable increase in air temperature over the test section $>2^{\circ}C$ ($3.5^{\circ}F$).
2. Drill at least three 10 m (33 ft) holes radially out from the rock surface of the drift. Insert temperature-monitoring devices (thermocouples) into the holes to measure the rock temperature at different depths. Allow the rock temperatures surrounding the holes to stabilize, and record the rock temperatures at known depths. From these data determine the average slope (b in Equation 1).
3. At the inlet and outlet stations to the test site measure the air quantity, barometric pressure, dry bulb temperature, and relative humidity. Determine the sigma heat (total heat content) at each station, and by difference evaluate the heat addition from the rock (q in Equation 1). Repeat test over several days.
4. From Equation 1 determine k .

Ideally such tests are conducted in idle areas of the mine, and data acquisition instrumentation is used to monitor and record values over a prolonged period (which may be months). For the Goldhunter study this method of testing was not an option. There was neither the time nor the budget to conduct such a test, and it was decided that data would be manually collected as soon as the rock temperatures had stabilized. If substantial changes were noted in the data, then the test would be extended until stable data were recorded. Measurements of k were recorded in two different

areas of the Lucky Friday Mine, corresponding to two different rock types. These areas were termed Site #1 (Goldhunter rock type) and Site #2 (Lucky Friday rock type).

Description Test #1 – 1,494 m (4,900 ft)

Every effort was made to find a location that fit the ideal criteria for a k test, however, in the Goldhunter area there was only one site available. Present development in the Goldhunter was limited to a single drift that was ventilated using duct and auxiliary fans. Using a dead-end heading for the test was certainly not ideal, because there would be heat transfer between the air in the duct and that in the drift, and also because the leakage of air from the duct into the drift would make the test considerably more complex. In addition, the presence of auxiliary fans limited the length and location of the test section to an area that did not contain a fan (which can be a considerable heat source). Another reason why a development heading was not desirable was that there was equipment movement through the area. However, since this was the only available location, a section of the exploration drift (located on the 1,494 m {4,900 ft} level), was chosen for the study. Figure 1 shows the location and layout for Test #1.

A jumbo drill was used to drill 10 m (33 ft) holes into the rock. Four holes were drilled at varying angles into the surrounding rock mass. Ideally the holes should be drilled horizontally into each rib, and vertically into the floor and back. This was not possible due to the limitations of the equipment, and the confined space cramping the operation of the jumbo boom. For this reason the holes were located in each corner of the drift, angled away from the horizontal. Strings of thermocouples were installed into each hole to allow measurement of the rock temperatures. Type "T" (copper/constantin) thermocouples were used. The thermocouple strings were pre-assembled and tested prior to commissioning them in the mine. Foam spacers were installed along the thermocouple strings to prevent convection within the drill holes. The thermocouple beads (actual measurement point) were not held against the rock, and were freely suspended off the main cable (as shown in Figure 1). Each thermocouple was independently wired, and the strings were installed using sections of flexible PVC pipe connected into a 12.2 m (40 ft) length. The thermocouples were held in the holes using specially designed anchors (Mousset-Jones, 1988). These devices connected to the tip of the PVC rod and were pushed to the end of the holes. The thermocouple strings were connected to the anchors using 20 lb. breakable sections of nylon line. This allowed the thermocouple strings to be removed by tugging sharply on the tail end of the string and breaking the line (leaving the anchor in the hole). The original intention was to

conduct the two k tests in the mine simultaneously, using 6 available thermocouple strings. For this reason only three of

the holes were used in the study, with the fourth hole left as a spare.

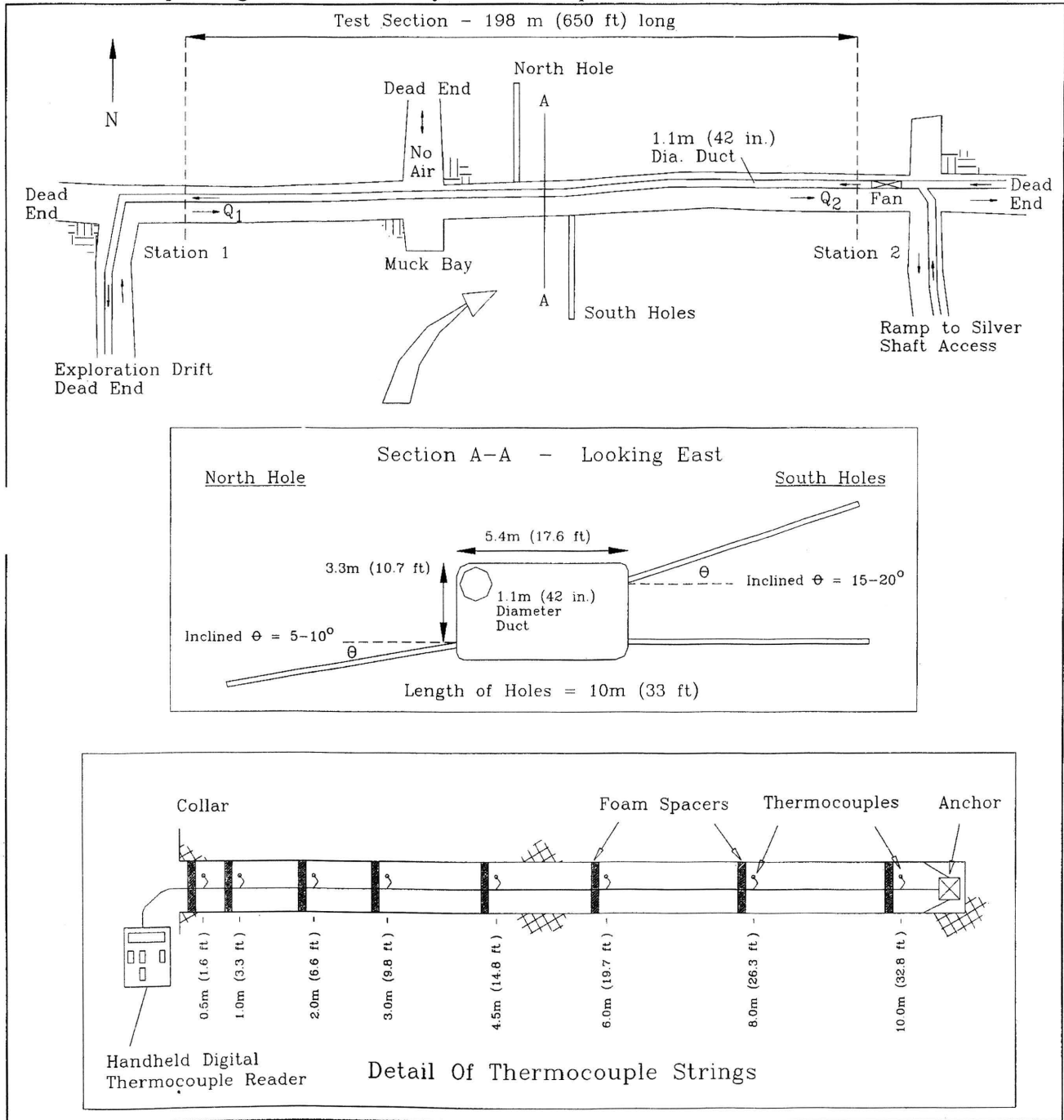


Figure 1. Sketch showing selected site for Test #1.

Immediately after placing the thermocouples in the holes, measurements were taken to determine the rock temperatures. These temperature values were considered to be initial figures, and the holes were then left for an entire shift before re-measuring. A total of three sets of measurements were taken for the thermocouples once the temperatures had stabilized. A small hand-held thermocouple reader

was used to measure the output signal from each probe. Thermocouples are durable devices that respond very rapidly to changes in temperature. During the study certain thermocouples were entirely submerged in the hot groundwater, however, not one of the thermocouples failed. In addition, the hand-held thermocouple reader functioned well in the humid and hot conditions.

Close to the same time that the thermocouples were being recorded, measurements of the drift and duct air dry bulb temperatures and humidities were taken at the inlet and outlet to the test section. Airflow measurements were taken in the drift, and the ambient barometric pressures and differential pressures across the duct were also recorded. These measurements were used to determine the total heat addition to the air from the rock.

Results from Test #1

Additional problems were encountered during the Goldhunter test because a duct chiller unit, outside the test section, was turned off. This resulted in the air temperatures in the duct being considerably higher than normal. It was crucial that steady-state conditions were measured during the test, subsequently the test was extended for two weeks.

The rock temperature measurements taken each day were very similar. The results from one set of these daily measurements are provided on Figure 2. From this graph it can be seen that the thermal gradient in the rock surrounding the drift does vary according to direction. The rock mass adjacent to the south side of the drift has a lower thermal gradient than that on the north side. This is apparent by the trends of the graph, where the north hole starts at a considerably lower temperature value (at 0.4 m {1.3 ft} into the rock), but at 10 m (32.8 ft) into the rock the temperatures are almost the same.

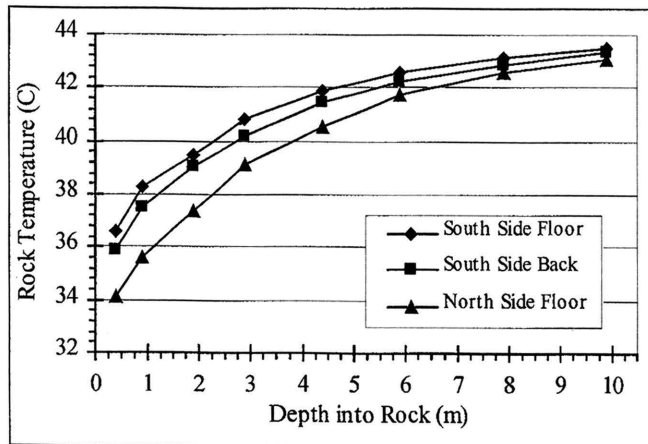


Figure 2. Rock temperature measurements for Test #1.

In order to apply these data to Equation 1, it is necessary to plot the graph of \log_e radius against temperature. This graph is shown on Figure 3. The equation of the lines formed by plotting the radius (\log_e) against rock temperature is of the form $\theta = b \log_e (r + 2.0) + a$, where b is the gradient required for Equation 1. For steady-state conditions the points in Figure 3 should plot as a straight line. In this case there is a slight transition towards the end of each hole,

where the temperatures appear to level out. This would suggest that steady-state conditions were not reached during the test, and that the rock temperatures near the rock/air interface were lower than they should be under true steady-state conditions. However, an averaged value of b was determined in all three holes for each test, and from these slopes an average value of k could be determined. In order to apply Equation 1 it is also necessary to evaluate heat flow from the difference in the total heat content of the air at each station.

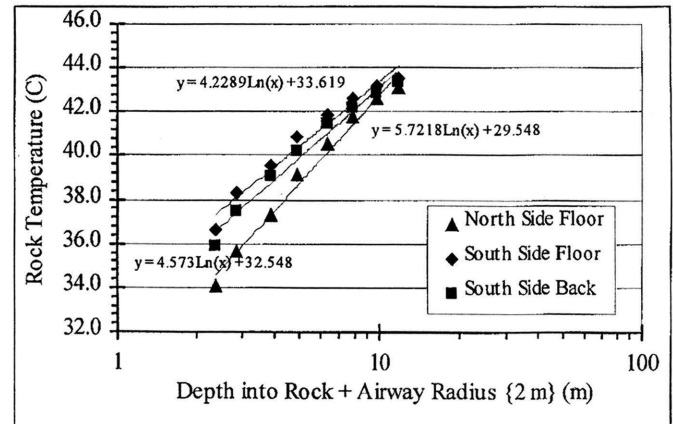


Figure 3. Plot of \log_e radius v. Temperature for Test #1.

The results for the evaluation of heat flow and k from measured air psychrometric properties and rock temperature gradients are provided on Table 1. Due to the presence of the duct it was necessary to evaluate the sigma heat of the air in the drift and duct at both stations. The heat generated from the rock (q) was computed as the difference between the total heat content of the air at stations 1 and 2, having subtracted the heat addition from the duct (air leakage into the drift). Results are presented for two sets of tests. The heat flow determined for the initial measurements (12/7/96) was 38.9 kW (2,212 Btu/min), and for the second test was 22.4 kW (1,272 Btu/min). Average values for the airflow quantity were used to determine the mass flow at each station. Average values were used because except for short-duration fluctuations, the airflow through the test area changed very little during the test period. From the airflow measurements it can be seen that there was a large amount of leakage out of the duct along the test section. This added a substantial amount of heat to the drift as a result of the increase in the mass of the air, rather than from heat transfer. For this reason the heat addition from the strata only represented a small percentage of the total heat gain between stations 1 to 2 (average was 3.5%). Such a low heat gain from the rock certainly reduces the degree of confidence in the results, due to the questionable accuracy of the heat gain term (q).

The results from the tests are certainly within the range

of what is considered “typical” for the in-situ rock type found in the Goldhunter area. However, it was considered prudent that a study be conducted to evaluate the sensitivity of the rock heat flow to changes in wet bulb temperature. It was found that increasing all of the duct or drift wet bulb temperatures by 0.1 °C (0.18 °F) had no significant effect

(in the range of air temperatures recorded during the test). This temperature increment was chosen because it was the resolution of the digital temperature/humidity probe used to collect the data. However, increasing or decreasing either the drift or the duct wet bulb temperatures by 0.1 °C (0.18 °F) resulted in an 11% deviation in the heat flow.

Table 1. Rock thermal conductivity results for Test #1.

Measurements taken 12/7/96

Location	Quantity* (cfm)	Quantity (m ³ /s)	<i>T_{wbin}</i> (C)	<i>T_{dbin}</i> (C)	<i>Inlet BP</i> (Pa)	<i>esw</i> (Pa)	<i>X_s</i> (kg/kg)	<i>L_w</i> (J/kg)	<i>Sigma Heat</i> (J/kg dry)	<i>X</i> (kg/kg)	<i>e</i> (Pa)	Act. Den (kg/m ³)	App. Den (kg/m ³)	Mass Flow (kg dry/s)	Total Ht. (kJ/s)
Drift Inlet - Stn 1	29160	13.76	30.6	34.3	106390	4379.8	0.02665	2429584	95470	0.02503	4124.0	1.190	1.161	16.38	1563.9
Drift Outlet - Stn 2	45739	21.59	30.7	33.7	106624	4415.0	0.02687	2429250	96122	0.02557	4209.7	1.192	1.163	25.74	2474.6
Total Heat Pick-up by Air:															910.8
Duct Inlet - Stn 2**	-	-	29.9	36.0	107982	4205.3	0.02521	2431278	91280	0.02256	3778.7	1.201	1.174	25.74	2350.0
Duct Outlet - Stn 1**	-	-	29.5	35.4	107345	4131.0	0.02489	2432018	90233	0.02237	3726.9	1.196	1.170	16.38	1478.1
Total Heat Loss by Duct:															871.9
Total Heat Pick-up by Air - Total Heat Loss by Duct = Heat Addition from Surrounding Rock :															38.9

Measurements taken 12/18/96

Location	Quantity* (cfm)	Quantity (m ³ /s)	<i>T_{wbin}</i> (C)	<i>T_{dbin}</i> (C)	<i>Inlet BP</i> (Pa)	<i>esw</i> (Pa)	<i>X_s</i> (kg/kg)	<i>L_w</i> (J/kg)	<i>Sigma Heat</i> (J/kg dry)	<i>X</i> (kg/kg)	<i>e</i> (Pa)	Act. Den (kg/m ³)	App. Den (kg/m ³)	Mass Flow (kg dry/s)	Total Ht. (kJ/s)
Drift Inlet - Stn 1	29160	13.76	29.3	31.9	108795	4064.9	0.02414	2432686	88136	0.02300	3880.2	1.226	1.198	16.87	1486.9
Drift Outlet - Stn 2	45739	21.59	29.2	31.0	108870	4043.9	0.02399	2432900	87693	0.02321	3915.7	1.230	1.202	26.56	2328.8
Total Heat Pick-up by Air:															841.9
Duct Inlet - Stn 2	-	-	27.4	30.7	110228	3650.8	0.02131	2437100	79473	0.01990	3417.1	1.249	1.225	26.56	2110.5
Duct Outlet - Stn 1	-	-	26.6	30.1	109550	3481.4	0.02042	2439032	76527	0.01892	3234.2	1.245	1.221	16.87	1291.0
Total Heat Loss by Duct:															819.4
Total Heat Pick-up by Air - Total Heat Loss by Duct = Heat Addition from Surrounding Rock :															22.4

*Averaged values over entire test period.

**Averaged values over 3 day test period (12/7/96-12/9/96).

Input data shown in italic - Remainder of values are calculated.

Assessment of Thermal Conductivity (k)

Length Test Section = 198 m

Location	Thermal Gradient (C/m)				Heat from 12/7/96	Heat from 12/18/96
	12/7/96	12/8/96	12/9/96	Average	k (W/mC)	
South Side Floor:	4.209	4.212	4.229	4.217	7.41	4.27
South Side Back:	4.646	4.591	4.573	4.603	6.79	3.91
North Side Floor:	6.320	5.775	5.722	5.939	5.26	3.03

Average k for test = 6.48 3.74
Overall Average k = 5.11

The evaluated k values shown on Table 1 highlight the fact that significant errors can be introduced with relatively small variations in the collected data. The average k value measured on 12/7/96 was 6.5 W/m°C (3.8 Btuft/ft²h°R) compared to only 3.7 W/m°C (2.1 Btuft/ft²h°R) on 12/18/97. This variation was largely thought to result from the poor location of the test site. Using values from both tests, the average k for the Goldhunter rock mass was determined to be 5.11 W/m°C (2.95 Btuft/ft²h°R). This is higher than typical laboratory references for a conglomerate type deposit, however in-situ values can be as much as two to three time higher than laboratory measurements. The reason for in-situ values being higher is that the small

laboratory samples frequently do not fully represent the entire rock mass. Heat conduction along bedding planes and fractures, and through groundwater courses is considerably different to that within the solid mass, and laboratory testing fails to measure these factors.

Description of Test #2 – 1,661 m (5,450 ft)

A second k test was planned in the Lucky Friday section of the mine. Both tests (in the Goldhunter {#1} and Lucky Friday {#2}) were to be conducted at the same time to expedite the procedure. As with Test #1, it was difficult to find an ideal site within the existing mine workings. A site

was selected in the ramp system between the 1,646 m (5,400 ft) and 1,676 m (5,500 ft) levels. Although this drift was neither straight nor level, the elevation change over the test section was small enough that the discrepancy in thermal gradient due to this factor was considered insignificant (the change in elevation can be taken into account by incorporating the elevation term in the Steady-Flow Energy Equation). This test section was located in an older, established section of the mine, and one of the main concerns was whether the rock had cooled down to the point that the strata heat addition was too low for accurate measurement. The redeeming features concerning the site were that it was in a relatively non-active area (very little vehicular travel), and that the only heat source was the rock.

Initially, considerable problems were experienced in drilling the holes (using a jumbo machine). Unexpected equipment malfunction delayed the drilling of the holes, and when they were finally drilled the holes were not acceptable for the test. Due to boom clearance restrictions the holes had been drilled approximately 45° off perpendicular with respect to the rock surface. The small drifts in the Lucky Friday Mine were another factor that placed a severe restriction on site selection, because the location had to accommodate the boom of the jumbo drill (the only means available to drill the holes). Four acceptable holes were eventually drilled, and thermocouple strings were placed in three of the holes. The "downholes" were both collared at floor elevation into the wall, and the "upholes" were collared 2.4 m (8 ft) above the floor into the wall. All of the holes were angled 25° from the horizontal plane. The total distance between the two stations (defining the test section) was 128 m (420 ft). The airway profile between the two stations was very regular, with the exception of a single dead-end heading.

Results from Test #2

As with Test #1, the rock temperature profile did not change significantly during the test. Some data from the test are presented in Figure 4 (rock temperatures against depth) and Figure 5 (rock temperatures against \log_e radius).

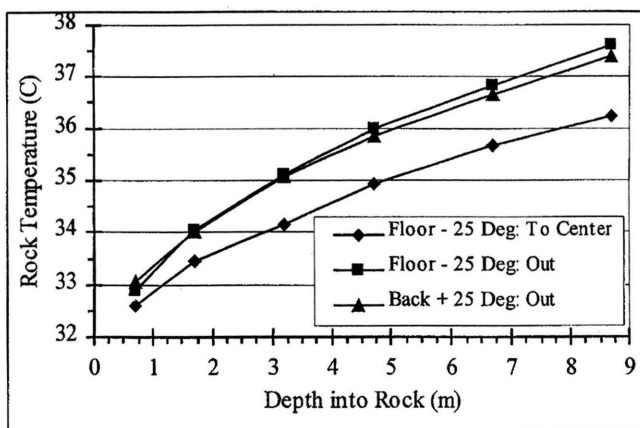


Figure 4. Rock temperature measurements for Test #2.

The results are somewhat unusual in that the rock temperatures are significantly lower than those measured in Test #1, even though the second test site was located at a greater depth. However, Test #1 was conducted in near virgin ground conditions, whereas the rock had obviously cooled down considerably in the area selected for Test #2. This is also apparent from an examination of the thermal gradient at each location. The slope of the lines in Figure 3 (Test #1) are considerably steeper than those of Figure 5 (Test #2). Also of interest is the fact that the one hole angled towards the center of the ramp, rather than pointing radially out, reported considerably lower temperature values. This is to be expected, because transfer of heat into the surrounding airway (analogy to a cooling coil) will gradually cool the rock mass contained within the center of a ramp system. The linearity of the data series in Figure 5 are much better than those seen in Test #1, which would suggest that true steady-state conditions were achieved in the second test.

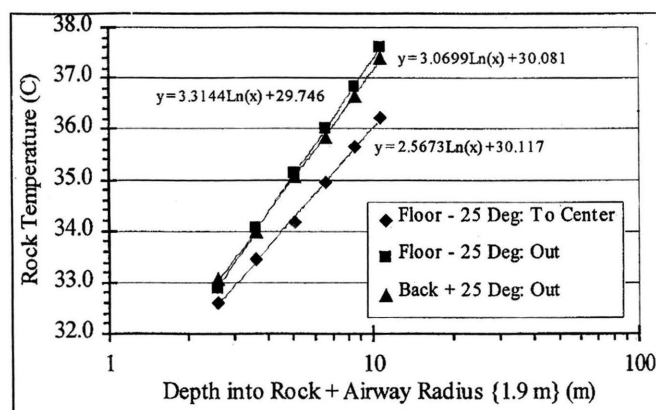


Figure 5. Plot of \log_e radius v. temperature for Test #2.

Table 2 in this case the data from two sets of psychrometric measurements are averaged with rock thermal measurements taken over three days. There is less scatter in the data when compared to Test #1. The large fluctuations

the data when compared to Test #1. The large fluctuations in the heat flow that were seen in Test #1 were not noted, and an average k of 7.05 W/m°C (4.07 Btuft/ft²h°R) was computed.

values. The other two tests were selected in order to allow α (m²/s) to be determined. This parameter may be calculated from the following relationship:

$$\alpha = \frac{k}{\rho \times C} \tag{2}$$

Laboratory Tests for Rock Thermal Parameters

During December, 1996, various rock samples were sent to a laboratory for testing (Anter Laboratories, Inc., Pittsburgh, Pennsylvania, USA). Three sets of rock samples were submitted from both the Goldhunter area and from the Lucky Friday rock mass. The intention was to have tests conducted on each set of samples to determine average parameters for both areas of the mine. Tests to measure k, specific heat (C) and bulk density (ρ) were conducted. The k test was selected to provide a check against the in-situ

Where: ρ = Rock density (kg/m³)
C = Specific heat of rock (J/kg°C)

Hence, from the in-situ measurement of k, α can be determined using the laboratory values of bulk density and specific heat (which should be very similar to the in-situ values for ρ and C). The results for these laboratory tests are shown in Table 3.

Table 2. Rock Thermal Conductivity Results for Test #2.

Measurements taken 1/7/97

Location	Quantity (cfm)	Quantity (m ³ /s)	T _{wbin} (C)	T _{dbin} (C)	Inlet BP (Pa)	esw (Pa)	X _s (kg/kg)	Lw (J/kg)	Sigma Heat (J/kg dry)	X (kg/kg)	e (Pa)	Act. Den (kg/m ³)	App. Den (kg/m ³)	Mass Flow (kg dry/s)	Total Ht. (kJ/s)
Station 1	11460	5.41	24.4	28.8	109635	3060.8	0.01786	2444210	68215	0.01601	2751.6	1.253	1.233	6.78	462.3
Station 2	11200	5.29	25.6	29.9	109866	3272.0	0.01909	2441538	72293	0.01724	2963.7	1.250	1.229	6.61	477.8
Total Heat Pick-up by Air:															15.4

Measurements taken 1/10/97

Location	Quantity* (cfm)	Quantity (m ³ /s)	T _{wbin} (C)	T _{dbin} (C)	Inlet BP (Pa)	esw (Pa)	X _s (kg/kg)	Lw (J/kg)	Sigma Heat (J/kg dry)	X (kg/kg)	e (Pa)	Act. Den (kg/m ³)	App. Den (kg/m ³)	Mass Flow (kg dry/s)	Total Ht. (kJ/s)
Station 1	11390	5.38	24.8	28.5	108889	3119.9	0.01835	2443447	69704	0.01676	2856.5	1.245	1.225	6.69	466.6
Station 2	11200	5.29	25.9	29.8	109065	3332.6	0.01961	2440798	73841	0.01793	3055.6	1.241	1.219	6.56	484.4
Total Heat Pick-up by Air:															17.8

Input data shown in italic - Remainder of values are calculated

Assessment of Thermal Conductivity (k)

Length Test Section = 128 m

Location	Thermal Gradient (C/m)				Heat From 1/7/97	Heat From 1/10/97
	1/7/97	1/8/97	1/10/97	Average	k (W/mC)	
Floor -25 Deg: Center	2.456	2.503	2.567	2.509	7.66	8.83
Back +25 Deg: Out	3.086	3.129	3.070	3.095	6.21	7.16
Floor -25 Deg: Out	3.313	3.332	3.314	3.320	5.79	6.67

Average k for test = 6.55 7.55
Overall Average k = 7.05

Table 3. Laboratory results for rock samples.

Sample	Thermal Conductivity (W/m°C)	Bulk Density (kg/m ³)	Specific Heat Capacity (J/kg°C)
Ave. Site #1	4.76	2,740	754
Specimen 1	4.14	2,710	670
Specimen 2	6.10	2,780	796
Specimen 3	4.03	2,720	796
Ave. Site #2	4.44	2,740	712
Specimen 1	4.92	2,670	754
Specimen 2	4.46	2,750	628
Specimen 3	3.94	2,800	754

Using the in-situ value for k, and the laboratory values given in Table 3, values of 2.5 × 10⁻⁶ m²/s (2.7 × 10⁻⁵ ft²/s) and 3.6 × 10⁻⁶ m²/s (3.9 × 10⁻⁵ ft²/s) are obtained for α from test sites #1 and #2 respectively.

TEST FOR VIRGIN ROCK TEMPERATURE AND GEOTHERMAL GRADIENT

The increase in the VRT of strata (unaffected by mining) with respect to depth is known as the geothermal gradient of the rock. If this value is inverted the geothermal step

may be determined, which is the linear increase in depth for each unit increase in temperature. The geothermal step varies according to the k of the local material, and the depth of the earth's crust in those areas. In order to evaluate strata heat flow in subsurface environments it is vital that the geothermal step and VRT be determined. There were no data available on these parameters for the Lucky Friday Mine; hence a study was conducted to measure these values.

To measure VRT it is necessary to obtain data on the natural rock temperature at a known elevation. Ideally a deep hole should be drilled from an advancing drift into a rock mass that is unaffected by any other mining. This should be conducted on at least two different levels to allow the geothermal step to be determined. For the Lucky Friday Mine two locations were selected based on availability. One

site was selected on the 1,494 m (4,900 ft) level, at the face of the advancing exploration drift in the Goldhunter area (near Site #1). The second site was selected on the 1,780 m (5,840 ft) level, where a new stope provided a fresh rock face in which to measure the VRT. For each location a hole was drilled into the fresh face as soon after a blast as possible, and a probe was inserted to measure the rock temperature. The probe was specially designed, and is shown in Figure 6.

The probe was designed in three sections, and joined to form a continuous 2.7 m (9 ft) long unit. This represents a fairly short probe for VRT measurements however, since the rock face was very fresh the probe was considered adequate. The diameter of the probe was approximately 4 cm (1.5 inch) which allowed the foam surface of the probe

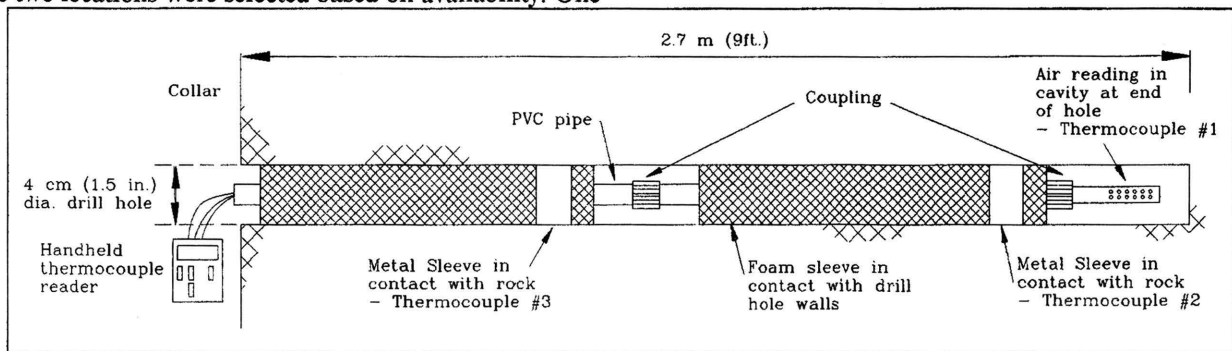


Figure 6. Virgin rock temperature measuring probe.

to fit tightly against the drill hole. This tight fit prevented convection of air within the hole. Three temperature measuring devices were mounted on the probe. A thermocouple was installed in a section of PVC pipe that was within the cavity formed at the end of the drill hole. A second thermocouple was mounted on the surface of the probe near the end of the hole. A metal sleeve was wrapped around the foam and the thermocouple was sandwiched within this sleeve. This ensured that the second thermocouple recorded the actual surface rock temperature near to the end of the probe. A third thermocouple was installed in a similar sleeve located near to the middle of the hole, which provided a check on the other temperature readings.

Every effort was made to insert the probe into the face as soon after a blast as possible, such that actual VRT values were measured. The probes were left in place for at least one full shift, at which time the rock temperature values were noted to start dropping (having been cooled by the ventilating air). The energy absorbed by the rock during blasting (in the form of heat) was not considered sufficient enough to significantly raise the temperature of the rock mass at the end of the hole (2.7 m {9 ft}).

The results from the VRT tests are shown on Figure 7.

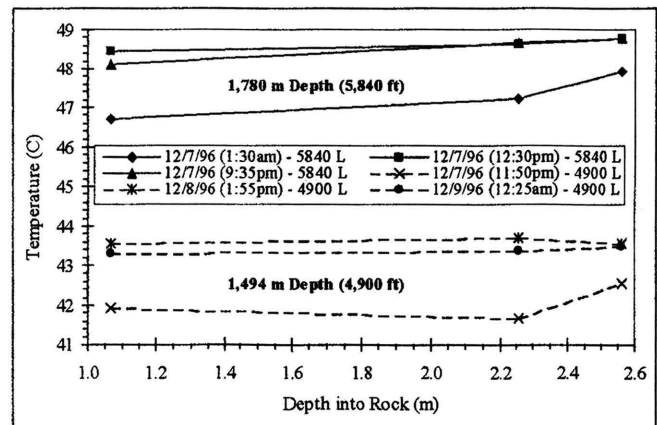


Figure 7. Results from VRT Tests.

For both test locations the VRT temperatures can be seen to peak approximately one shift after the probe was installed, after which they begin to drop as the rock cools. From the measured data the following results were obtained:

VRT 1,494 m (4,900 ft) depth = 43.6 °C (110.4 °F)
 VRT 1,780 m (5,840 ft) depth = 48.8 °C (119.8 °F)

Geothermal Gradient = 1.8 °C/100 m (1.0 °F/100 ft)

Geothermal Step = 55 m/°C (100 ft/°F)

DISCUSSION AND CONCLUSIONS

Problems were encountered in locating ideal sites to conduct in-situ k measurements. In new areas of the mine, within fresh rock formations (such as the Goldhunter), it was particularly difficult. The presence of a duct and vehicular interference impacted the first test (Test #1), and the degree of confidence in the result is not so high as Test #2. Substantial variations in the rock heat flow were computed in Test #1, which resulted in a large discrepancy in the k values (Table 1). However, the averaged in-situ k value for Test #1 (5.11 W/m°C {2.95 Btuft/ft²h°R}) was similar to that determined from laboratory testing of core samples (4.76 W/m°C {2.75 Btuft/ft²h°R}). Furthermore, even with an ideal test site and an extended measurement period, it is typical that the data obtained from in-situ tests be scattered (Mousset-Jones and McPherson, 1986).

The location for Test #2 was superior to that used for the first test. The only drawback to this site was that the drift was curved and inclined, however, the fact that it was a ramp may not have been a disadvantage. Taking measurements in a curved airway ensures that the general orientation of bedding and fracture planes and the direction of groundwater migration are not the same throughout the drift. This should provide for a result that is more representative of the entire three-dimensional rock mass. The in-situ value for the k at Site #2 was considerably higher than the laboratory measurement (55 %). However, large discrepancies between laboratory and in-situ measurements have been noted in previous studies (Mousset-Jones, 1988). The difference is probably the result of the in-situ rock being under considerable stress, and from groundwater migration through cracks and fissures (the transfer of heat within the rock mass is not purely conductive).

The laboratory measurement of bulk density produced the same average value for each test site. The specific heat of the rock at each site was similar, differing by approximately 5%. The α value determined for Site #1 was significantly lower than that calculated for Site #2 (approximately 30%). This is attributable to the variation in k , since α is directly proportional to k (Equation 2). The k and α values used in the heat flow study for the Goldhunter project were 5.11 W/m°C (2.95 Btuft/ft²h°R) and 2.5×10^{-6} m²/s (2.7×10^{-5} ft²/s). Although there was more confidence in the data obtained from Test #2, the results of Test #1 were used due to the differing rock masses between the sites. Test #1 was conducted in the actual Goldhunter rock mass, whereas Test #2 was conducted in a rock mass more typical of the lower Lucky Friday Mine. The values estimated from published literature (Hartman, 1982) and used in the initial ventilation and refrigeration study were

3.0 W/m°C (1.73 Btuft/ft²h°R) and 1.1×10^{-6} m²/s (1.2×10^{-5} ft²/s). These assumed values are much lower than those measured during the tests.

Throughout all of the k tests, the measurement of rock temperature was relatively simple. The drill hole temperatures appeared to stabilize within one shift, and there was almost no change in rock temperature throughout the test. This would suggest that it is not necessary to keep the thermocouples within the rock for an extended period of time, and that acceptable data may be collected over a span of about one week. The main difficulty was encountered in obtaining accurate and representative air temperatures. These temperatures tended to fluctuate, which resulted in discrepancies in the computed heat flow.

The measurement of VRT and geothermal gradient was successfully completed within a single 24-hour period. The custom-made probes allowed three rock temperatures to be measured along the length of the holes, which provided redundancy in the data, and allowed the impact of the cooling rock face to be evaluated. The VRT for the Lucky Friday Mine was considerably higher than that estimated from published literature for the nearby Star Mine (Marks, 1980). From the publication by Marks, the VRT on the 1,494 m (4,900 ft) level was initially estimated to be 33.9 °C (93.0 °F) with a geothermal gradient of 1.5 °C per 100 m (1.0 °F per 120 ft). These values are lower than those measured at the Lucky Friday Mine (VRT on the 1,494 m {4,900 ft} level was 43.6 °C {110.4 °F}), and the measured geothermal gradient was 1.8 °C per 100 m {1.0 °F per 100 ft}).

The results show that it is very important to obtain accurate data concerning rock thermal parameters when conducting heat flow studies. This is not always possible with new mines, however when planning the extension of an existing mine these parameters can be measured rapidly without expending too much time and money. For the Goldhunter expansion the measured data were used to plan a new refrigeration system, utilizing chilled water and multiple small spray chambers. This system has been installed, and preliminary indications on the heat load suggest that the refrigeration system is of an adequate, but not excessive size. Furthermore, the airflow quantity through the area is within 4% of that planned using ventilation network modeling. For the Lucky Friday Mine it did prove cost effective to conduct the studies and surveys necessary to accurately determine all of the parameters required for ventilation and heat flow modeling. This allowed the ventilation and refrigeration systems to be designed for the actual expected demand, rather than having to incorporate additional capacity to hedge against uncertainty.

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