Pre-feasibility investigation of infrared thermography for the identification of loose hangingwall and impending falls of ground

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Project number: GAP706
Date of report: September 2000
Executive summary

This report presents the results of a pre-feasibility study of Infrared (IR) Thermography/Radiometry for detection of loose rock in hard rock mines. The method is based on the temperature difference (gradient) between solid rock and the tip of loose rock due to the heat exchange between loose rock and ventilation air.

Early attempts to introduce this method of loose rock detection took place in the 1970’s in North America. A relatively low temperature difference (5-8 °C) between the solid rock and ventilation air in mines is one of the possible explanations why the method has never been developed to a commercial stage. It was proposed that South African hard rock mine conditions would favour the method due to the high rock temperatures and the relatively low temperature of the ventilation air.

Theoretical evaluation demonstrated that a temperature gradient of as much as 3-5 °C between solid rock and the tip of a loose rock could be expected in local hard rock mines. Four underground tests confirmed that an IR Radiometer with a 0.1 °C resolution could indeed detect loose rock. In practice, the maximum temperature gradient obtained between solid and loose rock was 5 °C.

Further investigation is required to establish a possible correlation between the temperature gradient between solid and loose rock on the one hand and the level of the hazard on the other.

The IR radiometers currently available on the market are not able to provide reliable operation in the harsh underground environment, particularly in deep gold mines. They also cannot be used in a potentially explosive atmosphere. A portable mine-worthy, intrinsically safe IR radiometer should be developed for use in roof and wall scanning before any work is done in a particular area.

It is proposed to use IR Thermography/Radiometry for other aspects of mine safety, such as condition monitoring of mechanical and electrical/electronic equipment.
Acknowledgements

I would like to express my gratitude towards the Kloof and Moab Khotson Gold Mines and Rustenburg Platinum Mine for the perfect organization of the underground tests and full support during implementation of the project.

Special thanks to my colleagues at CSIR Miningtek: Mr B. Spottiswoode and Mr K. Walker whose efforts led to the project being implemented, as well as to Mr R. Hattingh for his assistance.
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### Definitions and abbreviations

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<tr>
<td>IR</td>
<td>Infrared (radiation, spectrum, source, detector, optics etc.)</td>
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<tr>
<td>ε</td>
<td>Emissivity: the ratio of radiant emittance of an object to that of a blackbody at the same temperature</td>
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<tr>
<td>$k_{\text{rock}}$</td>
<td>Thermal conductivity of rock (W/mK)</td>
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<tr>
<td>α</td>
<td>Thermal diffusivity (m$^2$/s)</td>
</tr>
<tr>
<td>θ</td>
<td>Age of the mining (s)</td>
</tr>
<tr>
<td>$d_h$</td>
<td>Hydraulic diameter (m)</td>
</tr>
<tr>
<td>$h_c$</td>
<td>Heat transfer coefficient (W/m$^2$K)</td>
</tr>
<tr>
<td>P</td>
<td>Tunnel perimeter (m)</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Tunnel wall temperature (°C)</td>
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<td>$T_{\text{db}}$</td>
<td>Dry bulb temperature (°C)</td>
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<tr>
<td>$T_{\text{VR}}$</td>
<td>Virgin rock temperature (°C)</td>
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<tr>
<td>Re$_L$</td>
<td>Reynolds number</td>
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<td>V</td>
<td>Air velocity (m/s)</td>
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<tr>
<td>$\mu$</td>
<td>Air viscosity (kg/ms)</td>
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<tr>
<td>$\rho$</td>
<td>Air density (kg/m$^3$)</td>
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<tr>
<td>$P_{\text{slab}}$</td>
<td>Modified slab perimeter - as top of slab not exposed (m)</td>
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<tr>
<td>$A_c$</td>
<td>Cross sectional area of slab (m$^2$)</td>
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<tr>
<td>$k_{\text{air}}$</td>
<td>Thermal conductivity of air (W/mK)</td>
</tr>
<tr>
<td>Tb</td>
<td>Base temperature of the fin</td>
</tr>
<tr>
<td>$R_{ij}$</td>
<td>Thermal resistance (units)</td>
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<tr>
<td>$T_{ij}$</td>
<td>Temperature</td>
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<tr>
<td>$F_0$</td>
<td>Fourier number</td>
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1 Introduction

Falls of ground are a major source of accidents in South African mines. The identification of impending falls of ground would provide an early hazard warning and thereby reduce the risk of accidents.

Due to the exposed surface area, loose sections of ventilated rock should have a lower temperature than solid sections of ventilated rock because they work like cooling fins. The temperature gradient between loose and solid rock depends on the thermal conductivity of the rock, the ventilation conditions, the looseness of the rock and, to a lesser extent, the type of rock and age of mining. Such a gradient could be anything from a tenth of a degree to a few degrees Centigrade.

It was therefore proposed that Infrared (IR), non-contact, surface temperature measurement could be used for the identification of underground hazards. This more expensive method of IR Thermography is able to provide a visualization of the temperatures present on a remote surface. Using a portable IR thermograph or an IR remote temperature-sensing device (a radiometer), it will be possible to monitor roof temperature whilst moving along a road or stope. Areas exhibiting lower temperatures would be indicative of potential hazards.

This is the first time that any attempt has been made to theoretically estimate such temperature gradients. Both theoretical and experimental research have provided evidence supporting the suitability of this method for use in South African mines. It recommended that a mine-worthy, intrinsically safe IR radiometer should be developed in order to conduct the industry-wide investigation. A next step will be the establishment of a relationship between the temperature gradient and the hazard level. A method of hazard elimination will also need to be investigated.

2 Methods of remote non-contact temperature measurement

There are many situations where it is necessary to measure temperature in places that are physically inaccessible or dangerous. Remote non-contact temperature measurement is based on the premise that any physical body with a temperature higher than absolute zero radiates some amount of IR radiation. The higher the body temperature, the higher the level of IR radiation emitted by the body.

A body may lose or gain thermal energy without requiring a physical medium or contact with another body. This loss is due to an electromagnetic emission known as a thermal radiation. Infrared (IR) radiation, which is primarily responsible for thermal radiation, falls within the wavelength range of 0.75 m to about 1000 m. Strictly speaking, some heat transfer also takes place in the visual band of electromagnetic radiation.

Fundamental to an understanding of the thermal emission of solids is the concept of a blackbody. A blackbody is defined as a substance that absorbs all radiation which strikes the body at any wavelength, without reflection or transmission.

The intensity of black body radiation is a function of temperature only. The rate at which energy is emitted per unit area of the emitting surface is given by the Stefan-Boltzmann law:
\[ W = \varepsilon \sigma T^4 \]  

Where  
\( W \) - is the total emissive power;  
\( T \) - is the absolute temperature of the body;  
\( \varepsilon \) - is a universal physical constant;  
\( \varepsilon \) - is the emissivity of a surface, which for a black body is 1.0.

The emissivity \( \varepsilon \) is a numeric whose value lies from zero for a nonradiating object and 1.0 for a blackbody. Emissivity is a function of the type of material and its surface condition and can vary with wavelength and with the temperature of the object.

The emissivity of an object in the visible spectrum is no guide to its emissivity in the IR spectrum. For example, white paint has a low emissivity in the visible light but is nearly equivalent to a blackbody at wavelengths beyond 3 \( \mu \)m. A body which is covered with white paint stays relatively cool in sunlight because it not only reflects the sunlight well, but also reradiates the absorbed part of the energy almost as well as a blackbody.

On the contrary, aluminium plate is actually warmer in direct sunlight, as it has a low emissivity and therefore cannot reradiate the absorbed energy efficiently. Aircraft are painted with a paint based on white titanium dioxide which has \( \varepsilon = 0.94 \), in order to reduce their internal temperatures while they are parked on the ground in hot sun (Hudson, 1986:45), (Jamieson, 1963:15).

The emissivity of human skin is very high \( \varepsilon = 0.94 \) and this value is independent of skin colour. Human skins are equally black beyond 2 \( \mu \)m. Thus human skin is another example of the inadvisability of estimating the emissivity of an object on the basis of its visual appearance (Hadson, 1969:103).

The value \( W \) is dependent upon the temperature of the emitting surface, the material of which the surface is composed and the condition of the surface. The total emissive power comprises all the radiant emission from a surface element, which passes into or through a hemisphere above that surface. The emissive power may have both spectral and directional dependence.

The spectral radiant emissions for a black body at different temperatures are shown in Figure 2.1. The emission at any particular wavelength always increases as the temperature increases. The wavelength \( \lambda_m \), at which the maximum radiation occurs, shifts towards a shorter wavelength when the temperature increases and can be determined as:

\[ \lambda_m T = 2897 \mu K \]  

**Figure 2.1 Spectral radiant emittance of a black body**
The result is known as the Wien displacement law. In Figure 2.1 the family of emission curves demonstrate the law. The variation in the colour of hot objects with temperature is explained by these curves. Near room temperature all radiation is in the IR spectrum. As the temperature increases, more and more of the radiation becomes visible. At first it is at the red end of the spectrum and shifts up towards white as the temperature approaches and then exceeds 5000 °K.

In accordance with the displacement law, the wavelength at which the maximum emission of radiation from, for example, a silicon furnace occurs, given an operating temperature of 1800 °K, is 2.0 m (Figure 2.1). Almost 25% of the radiant energy is emitted at wavelengths of less than m.

In accordance with Lambert’s law, the intensity of radiation is greatest in the direction normal to the plane of the body and decreases with the cosine of the angle between the normal and the direction of observation.

2.1 IR radiometry and some related problems of remote temperature measurement

The simplest, well-known radiation optical pyrometer that could be found is used in cases when an object has a temperature of more than 700 °C, or in a temperature range corresponding to visible incandescence. In this pyrometer the electrical bulb filament is colour matched to a high temperature object in the background by adjusting the current through the bulb filament. This means that the temperature of the bulb filament and the object are the same. Knowing the relation between the filament current and its temperature makes it possible to measure remotely the temperature of, for example, melted material in a furnace.

Contemporary radiometers contain at least a system of lenses, an on/off modulating device, a sensitive detector and an amplifier, a reference source and a display. It is possible to obtain a temperature resolution of 0.1 °C and a measuring time of about 0.5-1 s.

From the viewpoint of an industrial application and without presenting too much of the theory on radiometry, which is given by Hudson (1969:432-433, 513), it should be noted that:

- When the object of interest fills the field of view of an IR detector, it is not necessary to know the distance to the object or its area in order to measure its temperature remotely.
- Temperature determined in this way is called equivalent blackbody radiation temperature.

This is correct when the following assumptions are applied:

1. The object radiates as a blackbody.
2. Atmospheric absorption along the line of sight is negligible.
3. The sensitivity of the IR detector is independent of wavelength.

If any of these conditions are not applied, then a correction should be applied. For example, when a practical object is not a blackbody, the true emissivity \( \varepsilon \) of the object should be taken into account during measurement; otherwise, the remotely measured temperature of the object will be lower than the true temperature obtained by a contact measurement.

Such a difference in emissivity can be neglected only when the relative temperature gradient of the same object is the issue of interest. This is true for the case of loose rock detection when the difference between the temperature of the solid and loose part of the same rock is important. At the same time, in order to develop a proper understanding of the heat transfer between ventilation air and rock, data on the emissivity of different rocks should be obtained.
2.2 Infrared thermography

There is no doubt that the great advances in IR technology have been stimulated by military needs. The first commercial system that provided viewing of an object in the IR spectrum was demonstrated in 1942, and was designed to assist tank and truck drivers at night during a blackout.

IR Imaging Systems also provide a temperature resolution of 0.1 °C, which, presented in shadows of grey or in colour, enables very easy identification of areas of different temperature, but at great expense. Some of these systems are not able to operate when the ambient temperature is more than 40 °C. The cheapest IR thermal imaging digital camera costs R118 000 while the best system may cost up to R500 000.

In order to reduce running expenses on the current project, it was decided to conduct an underground investigation using an IR handheld radiometer. If such an instrument were to be developed for mining industry conditions, it would be useful for daily roof inspection.

3 IR remote temperature measurement for industrial application

The very first application of IR radiometry was by astronomers as far back as 1869 when Lord Rosse tried to measure the IR radiation of the moon using a telescope.

Since the end of the 1940’s, IR remote temperature measurement and IR thermography have been widely used in industry for heat radiation monitoring in engines and motors, measuring heat loss in buildings and numerous other applications. A description of these applications would take enormous space, but a good overview is given by Hudson (1969). Only transport applications that could be relevant to the mining industry are presented here.

3.1 Surface transport

IR remote temperature sensing and IR thermography can be used for detection of subsurface anomalies below railroads, airfield runways and motorways.

Such monitoring is based on the premise that heat generated by the sun and the moving wheels of vehicles penetrates into the road surface and near sub-surface. Due to the different thermal conductivity of a road bed structure, mechanical components such as piping, vessels, slabs and piles can be identified (Okomoto, 1995). The method is able to detect buried moisture and erosion voids of railroad track beds (Weil, 1995).

Several factors can cause spurious surface temperature variations, such as screening from the sun and variations in traffic intensity. Therefore, tests are usually conducted after sunset, when the temperature gradient between the different surface areas can reach 5 °C. Variations in traffic flow affect this gradient by approximately 0.1 °C (Gustavsson, 1991).
3.2 Underground roof condition monitoring

It has been claimed that the United States Bureau of Mines (USBM) discovered the concept of IR roof condition detection through tests into methods of determining the strength of limestone pillars (Merrill 1958). During the experiments, a 15 cm layer became detached from the roof. During the removal of this piece of limestone, it was observed that the temperature of this loose rock was lower than that of the solid rock. This was detected simply through feeling with the palm of a hand. At that time, remote sensing technology had not progressed beyond the sensitivity of human touch.

During the next two decades, IR instrumentation was developed to the level where a 0.1 °C resolution was obtained. The practical research demonstrating the possibility of using IR radiometers for detection of loose rock in underground conditions was conducted by Merrill (1970), when the Denver Mining Research Centre of the USBM began tests to detect hazardous or potentially hazardous conditions. An IR radiometer capable of detecting a 0.2 °C temperature difference at distances of 3 m was used for the experiments. In order to provide visualisation of some of the results, an IR scanner supplied by the US Army Electronics Command–s Night Vision Laboratory was used. The scanner provided the same 0.2 °C resolution.

The handheld radiometer was used in several mines and the results were as following:

1. With no air flowing and no temperature difference between the air and a tunnel surface, no temperature transition on loose rock was detected.
2. However, after 15 minutes of air flow, the temperature gradient reached between 0.2 °C and 7 °C depending on the air temperature.

Unfortunately, no detailed information on either the air or rock temperature was given. It was estimated that, in one case, the air temperature was between 14 and 19 °C and the rock temperature was between 16 and 17 °C.

An important observation was made when the temperature of a newly blasted face was measured. A temperature gradient of 3 °C per metre of rock was noted. The obtained temperature gradient of the loose rock was about 1.0-1.5 °C, or higher, than in the older mining.

This work provided one of the first confirmations of the applicability of the concept for loose rock detection. No further information on development of the method by the USBM has been found.

More recently, in Yu (1990), a more systematic approach to the problem has been given. The main task of this research was to enhance the temperature gradient between solid and loose rock. Through the use of an IR thermographer, the information was supplied to an operator of a mechanized scaler in order to eliminate potentially dangerous spots. The method was based fully on a previously described concept.

Initial tests were conducted on a 350 kg lump of rhyolite on which there was a loose section. The test piece was enclosed in a plywood box and was subjected to heating and an air flow of different temperature. Two sets of thermocouple wires provided the temperatures of the solid body and the tip of the loose rock. The resolution of the monitoring equipment was 0.2 °C. The laboratory tests provided the expected results that loose rock cools faster than solid rock and provides a temperature gradient of up to 1.7 °C.

Besides spot temperature measurements, laboratory and underground experiments were also conducted with AGA Thermovision 110 and 782 devices. The test rock was observed using an IR scanner in conjunction with a spot temperature measurement, and both numerical and visual data were collected and analyzed for trends. No theoretical research has been done.
Mine monitoring under normal conditions at Kidd Creek Mines confirmed that some loose rocks could be detected using the method. It was also noted that the age of the underground mining excavation tends to influence the detectability of loose rock. In order to enhance the temperature gradient, different methods were tested depending on temperature relations between the rock and air. Information on the type of rock tested is not available.

In the majority of cases observed at Kidd Creek, in locations where the mine air temperature exceeded the rock surface temperature, loose rock tended to be warmer than the adjacent solid rock. In locations where the mine air temperature was lower than the rock surface temperature, loose rock tended to be cooler than solid rock.

Checking, with a scaling bar, areas that were scanned with an IR scanner demonstrated that a significant amount of loose rock was not identified using the IR method.

The following enhancement methods were tested:

1. Hot diesel exhaust from an LHD machine blowing against the roof for 20-30 minutes.
2. Airflow rate acceleration using a local fan.
3. Radiant heat from the IR source.
4. Evaporation of water from the rock surface.

The use of hot diesel exhaust was recognized as the most effective method of gradient temperature enhancement. The authors of the report on the experiment believed that the use of exhaust enhancement in a drier environment would be even more effective than in a humid environment.

Based on the test results, an underground trial was conducted to determine whether an IR scanner mounted on a mechanical scaler is able to assist an operator. It was found that an IR scanner is most effective when directed perpendicular to the surface (roof) being inspected. In order to enhance the temperature gradient, a machine's exhaust was directed at the roof ahead of the machine. The trial demonstrated that, when using the IR scanner, the total miner’s exposure time required for roof checking and scaling was 30.4 minutes per 30 metres of the tunnel, instead of 64.4 minutes for the non-IR technique. This represents about a 50% reduction in risk during the roof conditioning process (Yu, 1990).

### 3.3 Other underground applications

In the 1980’s, an IR radiometer was used in the Ukraine by the MakNII research institute to identify the areas on a longwall that are potentially dangerous in terms of an abrupt outburst of methane and coal. It was proved that the coal temperature in such areas is about 1-4 °C higher than that of the surrounding coal.

Misfires, mine fires, combustion in waste dumps and underground water courses (Merrill 1970) are just a few examples of the wide application that the IR radiometer has found in engineering. Numerous publications are devoted to condition monitoring of mechanical and electrical equipment, where local temperature increases very often result in impending mechanical or electrical failure. For example, IR scanning of electrical cables assists in identifying cable manufacturing defects, bad electrical contacts in connections and a reduction in the effective core cross-section due to mechanical load. The last example is very important in the case of flexible power trailing cables for LHD machines and shuttle cars. Early identification of such problems reduces maintenance and operational cost, and improves safety.
4 Theoretical estimation of heat transfer between a tunnel surface and air flow

4.1 General South African underground environment and the proposed method of loose rock location.

As was noted by Merryll (1970) and Yu (1990), North American underground conditions such as relatively low rock and air temperatures, and their bi-directional relations and low differences, very often limited the application of the method unless a special enhancing technique was used. All enhancing methods dramatically increase IR scanning times and thus detract from the method efficiency, most probably the main reason why the method of IR Thermography has not found commercial application in North America.

On the other hand, the South African gold mining underground conditions favour the method as rock temperatures are high and the temperature of the ventilation air is much lower. It will be demonstrated in Section 4 that even such conditions as low ventilation air velocity actually improve the efficiency of the proposed method.

4.2 Assumptions and initial data

This analysis assumes the slab is infinitely thin and conduction is in one direction only. A fin type analysis has consequently been followed in order to determine the temperature distribution in the slab. The geometry of the slab is as follows:

![A 1-D fin model using theoretical correlations](image)

Before the temperature profile in the fin can be determined, it is necessary to examine the heat transfer process between the rock and the tunnel. The amount of heat flowing from the rock depends on the thermal properties of the rock (conduction effects) and the conditions in the tunnel (convection effects). The heat exchange process is defined by performing an energy balance at the rock/air interface in the tunnel. This process may be described as follows (Mills, 1992):

Heat flow by conduction:

\[ q_{\text{conduction}} = 2\pi k_{\text{rock}} T (T_{\text{VR}} - T_s) \text{ W/m} \]  \hspace{1cm} 4.2.1

where

\[ T = \frac{0.685}{F_0^{0.146}} \]  \hspace{1cm} 4.2.2

\[ F_0 = \frac{\theta \alpha}{d^2} \]  \hspace{1cm} 4.2.3
Heat flow by convection:

\[ q_{\text{convection}} = h_c P (T_s - T_{db}) \quad \text{W/m} \quad 4.2.4 \]

Performing an energy balance at the wall:

\[ q_{\text{conduction}} = q_{\text{convection}} \quad 4.2.5 \]

The heat transfer coefficient is determined as follows:

\[ \frac{h_c d_h}{k_{\text{air}}} = 0.02 Re_L^{0.8} \quad 4.2.6 \]

where

\[ Re_L = \frac{\rho V d_h}{\mu} \quad 4.2.7 \]

The temperature profile along the slab was calculated as follows:

- **Assumptions**
  - Conduction only takes place in one direction
  - The slab is assumed to be a fin
  - The tip of the fin is insulated (no heat transfer across the tip)
  - The base temperature is equal to the wall surface temperature

- **Calculation of the temperature profile in the fin**

\[ \frac{T - T_{db}}{T_b - T_{db}} = \frac{\cosh \beta(L - x)}{\cosh \beta L} \quad 4.2.8 \]

where

\[ \beta^2 = \frac{h_c P_{\text{slab}}}{k_{\text{rock}} A_c} \quad 4.2.9 \]

- **Results of the 1-D model**

To reach a temperature equilibrium between the air, surface of the tunnel and virgin mass of rock, some time is required. This is why the age of the tunnel affects the results considerably. The age of the tunnel has therefore been varied from one day to 10 years to observe the change in the temperature profile in the slab (Figure 4.2.2) and in the tunnel wall temperature (Figure 4.2.3).

Input parameters:

- Velocity 0.5 m/s
- \( T_{\text{VR}} \) 50 °C
- \( T_{\text{db}} \) 30 °C
- Tunnel 3 m x 3 m
- Slab 1 m x 1 m x 0.4 m (length, width, thickness)
Figure 4.2.2 Temperature profile in the slab (1-D fin model)

Figure 4.2.3 Temperature profile from the tunnel wall to the surrounding rock.

These data clearly explain the better results obtained by Yu (1990) in new mining areas than in others. With time, the surface temperature becomes closer to the air temperature which reduces the temperature gradient between solid and loose rock. The first year after mining makes the most difference for the temperature gradient. A conclusion could be made that it is more difficult to identify loose rock in old mining areas.
4.3 Expected temperature gradient

This analysis assumes that heat conduction is in two directions. A numerical method was used to determine the temperature profile in the slab. This method involved numerical formulation by the resistance method. A more realistic geometry was also chosen for the slab.

- **Equations**

  The temperature profile in the slab was calculated by dividing the slab into a number of square blocks, thus producing a mesh. The temperature profile could then be determined using the following equation (valid for 1-D, 2-D and 3-D):

  \[ \sum_j \left( \frac{T_j - T_i}{R_{ij}} \right) = 0 \]  

  4.3.1

  The resistance at each node was found using:

  For conduction \[ R_{ij} = \frac{\Delta x}{\Delta y k_{rock}} \]

  For convection \[ R_{jc} = \frac{1}{h \Delta x} \]

- **Global Assumptions for the 2-D models**

  - The heat transfer coefficient was constant (for the specified velocity).
  - The slab was infinitely wide (conduction in x and y directions only).
  - The gap between the hanging rock and the wall was assumed to be 10 mm.
  - No convection takes place in this region, only conduction.
  - The mesh was assumed to be square.
  - The air temperature was assumed to approach the dry-bulb temperature in one node length (CFD coding would be required to produce more accurate results).

- **Results**

  Four different scenarios were examined for one-year old mining:

  1. Velocity (0.5 m/s), slab (0.8 m x 1 m x 0.4 m) – Figure 4.3.1
  2. Velocity (1 m/s), slab (0.8 m x 1 m x 0.4 m) – Figure 4.3.2
  3. Velocity (5 m/s), slab (0.8 m x 1 m x 0.4 m) – Figure 4.3.3
  4. Velocity (0.5 m/s), slab (0.8 m x 1 m x 0.3 m) – Figure 4.3.4

  Figure 4.3.5 presents one-month old mining to compare with Figure 4.3.3.
(1) Hanging slab case 1

Assumptions and boundary conditions

- $T_{VR}=50 \, ^\circ C$
- $V=0.5 \, m/s$
- $T_{db}=30 \, ^\circ C$
- $h_c=1.872 \, W/m^2K$
- Slab height=0.4 m
- Slab length=0.8 m
- Slab width=1 m
- Spacing between wall & slab=10 mm
- $T_S=38.23 \, ^\circ C$

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Figure 4.3.1 Results for case 1 (slab=1x1x0.4 m, air velocity=0.5 m/s)

The temperature gradient is 3.47 °C.

(2) Hanging slab case 2

Assumptions and boundary conditions

- $T_{VR}=50 \, ^\circ C$
- $V=1 \, m/s$
- $T_{db}=30 \, ^\circ C$
- $h_c=3.259 \, W/m^2K$
- Slab height=0.4 m
- Slab length=0.8 m
- Slab width=1 m
- Spacing between wall and slab=10 mm
- $T_S=35.73 \, ^\circ C$
(3) Hanging slab case 3
Assumptions and boundary conditions
\( T_{VR} = 50 \degree C \)
\( V = 5 \text{ m/s} \)
\( T_{db} = 30 \degree C \)
\( h_c = 11.81 \text{ W/m}^2\text{K} \)
Slab Height=0.4 m
Slab Length=0.8 m
Slab width=1 m
Spacing between wall and slab=10 mm
\( T_s = 31.99 \degree C \)

Hanging slab - corrected mesh, velocity=5 m/s

The temperature gradient is 3.26 \degree C.

Figure 4.3.2 Results for case 2 (slab=1x1x0.4 m, air velocity=1 m/s)

The temperature gradient is 1.75 \degree C.

Figure 4.3.3 Results for Case 3 (slab=0.8x1x0.4 m, air velocity=5 m/s)
(4) Hanging slab case 4

Assumptions and boundary conditions
\( T_{VR}=50 \, ^\circ \text{C} \)
\( V=0.5 \, \text{m/s} \)
\( T_{db}=30 \, ^\circ \text{C} \)
\( h_c=1.872 \, \text{W/m}^2\text{K} \)
Slab height=0.3 m
Slab length=0.8 m
Slab width=1 m
Spacing between wall and slab=10 mm
\( T_S=38.23 \, ^\circ \text{C} \)

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**Figure 4.3.4 Results for Case 4 (slab=0.8x1x0.3 m, air velocity=0.5 m/s)**

The temperature gradient is 3.72 \(^\circ \text{C}\).

Hanging slab - corrected mesh, velocity=5 m/s, 0.8x1x0.4 m (one-month old)

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**Parameters used**
\( T_{VR}=50 \, ^\circ \text{C} \)
\( V=5 \, \text{m/s} \)
\( h_c=11.81 \, \text{W/m}^2\text{K} \)
Slab=0.8 m x 1 m x0.4 m
\( T_S=32.75 \, ^\circ \text{C} \)

**Figure 4.3.5 Results for one-month old mining**

The temperature gradient is 2.48 \(^\circ \text{C}\), which is higher than in case 3.
5. Experimental evaluation of heat transfer

In order to provide for experimental evaluation of heat transfer in underground conditions, two gold and platinum mines were selected. Current mining and old mining sites were identified for the experiments.

5.1 Methodology used

It is obvious that the position of loose rock in a roof or wall does not affect the temperature gradient of the rock. At the same time, loose pieces of rock in a wall are more accessible for measuring their dimensions and estimating the temperature gradient than those in a roof. Therefore, it was decided to scan both sidewalls and the roof to obtain the required information.

The following information was recorded at each site:

1. Cross section of the tunnel.
2. Ventilation air velocity.
3. Air temperature.
4. Rock temperature.
5. Age of mining.

After obtaining information on the temperature of the solid and loose rock, loose rocks were removed (where it was possible and safe to do this) to determine the degree of attachment of the loose rock to the solid rock.

5.2 Instrumentation used for underground experiments

A measuring tape was used for dimensional measuring. Ventilation air velocity and temperature were measured using a SKYMATE (Serial No5470) by Speedtech (USA).

An IR radiometer MINIRAY100 (Serial No34468) by Eurotron (Italy) was selected for use. This radiometer provides a temperature resolution of 0.1 °C and spatial resolution of 30 mm at 1 m distance between the instrument and rock. The measuring spectral band is 8-14 µm, which corresponds to the required temperature interval.

Both instruments are designed for normal industrial application.

5.3 Results of tests in gold mines

5.3.1 Moab Khotsong mine

Two tests were conducted at 11 shaft, 70 level (depth of 2400 m) at the same site, at two week intervals, in order to verify the effect of age of mining on the temperature gradient.

Site 1.
At 8 m from the face the stope was about two weeks old. The site has a very unstable hangingwall and the tips of the loose rock were about 10-30 mm thick. During the experiments, the air velocity was 1-1.1 m/s and the air temperature was 29.8 °C. The average solid rock temperature was 30.1 °C. The maximum measured temperature gradient between the tip of the loose rock and the solid rock was 0.5 °C.
Site 2.
The haulage was two years old. Air velocity during the experiment was 0.7 m/s and the air temperature was 29.8 °C. The maximum measured gradient was 0.3 °C.

The obtained low temperature gradient is due to the nearly equal air and solid rock temperatures.

These tests were repeated at the same sites a week later in order to check the consistency of the measurements. The obtained results were practically the same. Tests were also conducted at new sites.

5.3.2 Kloof Gold Mine

Tests were conducted at No 4 Shaft, 43 level, 43/51 North development. The site depth is 3216 m. The air temperature was 35 °C with variations of ±0.1 °C. Measured air velocity at the face was 1.3 m/s. The age of the mining face was two days. The entire surface of the tunnel from the face to 20 m back was scanned. Three typical situations of roofbolted loose rock are presented. Points marked with (*) refer to solid rock temperature. Points marked with (•) refer to the tips of the loose rock.

In Figure 5.3.2.1 the measurement was taken about 10 m from the face. The measured solid rock temperature was 37.8 °C and the tip temperature was 35 °C or equal to the air temperature. The temperature gradient was 2.8 °C.

![Figure 5.3.2.1 Site one](image)

In Figure 5.3.2.2 the measurement was taken 5 m from the face. The temperatures of solid rock and the tip of the loose rock were 40 °C and 35 °C, respectively. The outlet of the ventilation tube was about 3 m from the tip of the loose rock. The temperature gradient was 5 °C.
In Figure 5.3.2.3, a very similar scenario to the previous one is presented. The main difference is that measurements were taken about 20 m from the face which means that the age of this mining was about three weeks; therefore, a lower temperature gradient could be expected. The measured temperatures of the solid rock and the tip of the loose rock were 38.5 °C and 36 °C, respectively. This results in a 2.5 °C temperature gradient as compared with the 5 °C in the previous case.

This confirms that older mining provides solid rock temperatures close to the air temperature and, therefore, the temperature gradient between the solid and loose rock is lower than in recent mining.

5.4 Results of tests in platinum mines

Tests were conducted at Rustenburg Platinum Mines (Amplats) Townland shaft at 14 level. The test site was at a depth of approximately 570 m. The calculated virgin rock temperature at this depth was $20.8374 + (570 \times 0.021949) = 33.34833 \degree C$.

Site 1.
The site is in close proximity to the shaft and mining is about 30 years old. Due to the very good ventilation, the temperature of the air and rock was very similar: 18 °C and 19 °C, respectively. Because of both the age and ventilation, the temperature gradient between the loose and solid rock was practically undetectable. Only the fallen rock resting on a protective steel mesh had a
temperature about 0.2 °C lower than the solid rock.

Site 2.
This 30-year old site is about 300 m from the shaft. The air temperature was 21 °C, with a velocity of 2.6 m/sec. A temperature gradient of about 0.2 °C was registered on loose rock. The temperatures of the solid rock exposed to the ventilation air and in a cubby with a 0.1 m/s air velocity were 18.6 °C and 19.9 °C, respectively.

Site 3.
This three-month old site is about 500 m from the shaft. The site is in an upper gully, which was developed for mechanized shortwall mining. The air temperature was 22.3 °C with a velocity of 0.7 m/s. A piece of loose rock, 200 mm x 200 mm, with a 1 mm air gap, produced a 1.2 °C temperature gradient.

Site 4.
This site is in the same upper gully at a distance of about 600 m from the shaft. The age of mining was about one month. The air temperature and velocity were 25.5 °C and 0.1 m/s, respectively. A piece of rock, 300 mm x 500 mm with a 2 mm crack on the longer side, provided a 1.8 °C temperature gradient.

At the same site another loose rock, 500 mm x 500 mm with a smaller than 1 mm crack, was exposed to a 0.4 m/s air velocity. In this case the temperature gradient was 0.6 °C.

Site 5.
The most interesting results were obtained in the development of the lower gully, which was only one day old. The test took place at a time of scaling the hanging and installation of temporary wooden props before roof bolting. The measured air temperature and velocity were 24.1 °C and 2.0 m/s, respectively. The solid rock temperature was between 22.8 °C and 23.5 °C.

Three places that were supported and selected for scaling or supporting were inspected with the IR radiometer. The temperatures of loose rock tips were between 20.2 °C and 21 °C, providing a temperature gradient of up to 2.8 °C.

Three mine officials present during the test were satisfied with the results. It was suggested by them that every team should be equipped with an IR radiometer to scan the roof before starting work in any area.

6. Comparison of theoretical and practical results

The main objective of this pre-feasibility study was to demonstrate that a theoretically expected temperature gradient could be obtained during an underground investigation.

As loose rocks are irregular with non-predictable shapes and thicknesses, it is very difficult to make a direct comparison between theoretical and practical results. Therefore, only cases where the loose rocks had more or less regular shapes were used in this evaluation.

All underground measurements were done assuming that the rock emissivity is 0.93. The main problem in a comparison of theoretical and practical results is the unknown emissivity of the tested rock. While the obtained results on the temperature gradient are correct, an absolute rock temperature depends on its emissivity and, therefore, the data on solid rock temperature cannot be used for a comparison of theoretical and practical results without correction.

It is obvious that the results obtained at Rustenburg Platinum Mines, where the air temperature was always higher than the solid rock temperature but the tips of loose rock were always cooler than the
solid rock, do not correspond with theory and even common sense. A similar situation was indirectly described by Yu (1990:48). The data from Kloof Mine are the most reliable and consistent due to the significant difference between the air and solid rock temperature.

During the underground experiments, it was noted that the hot and moist air created drift and "latching" of the measurements from the IR radiometer. In some cases, numerous subsequent measurements were required on the same spot to obtain stable results. It was suggested that this was related to environmental conditions. In order to reduce the negative impact of the harsh underground environment, particularly the moisture, the IR radiometer was wrapped in a plastic bag with a silica-gel inside.

Considering the effect, which a plastic cladding around the instrument could make on measurements, it should be noted that polystyrene and polyethylene show good IR transmission until 3-4 µm when they are about 0.1 mm thick. They also have good transmission in the region beyond 20 µm and in the very far IR spectrum (Fröhlich, 1957:359). Transmission in the 8-14 µm range depends significantly on the quality of the material and manufacturing process; therefore, an effect on absolute temperature results could be expected. This does not affect the relative temperature gradient measurement.

7. Conclusion and recommendations

From the results of a worldwide IR Thermography/Radiometry survey, a theoretical evaluation of the method and the underground tests in South African mines, the following conclusions have been drawn:

* The method of non-contact remote temperature measurement using the emission of IR radiation by physical objects has found very wide industrial application.

* Research on loose rock detection based on this method started in the 1970’s in North America but never became a commercially available option.

* A possible problem that has been identified is the effect a relatively low temperature difference between rock and ventilation air has on reducing the temperature gradient on loose rock.

* A theoretical evaluation of the method’s applicability in South African hard rock mines demonstrated that South African underground conditions, where solid rock and air temperatures differ by at least a few degrees, should favour the method.

* Underground investigations confirmed that the method could be used for loose rock detection, particularly in newly mined areas. When mining is older than a year, the method loses its effectiveness because the expected temperature gradient on loose rock is reduced by as much as two times.

* There is no available information on rock emissivity in the IR spectrum, therefore, only a relative temperature difference between solid rock and the tip of loose rock was obtained.

* There is no mine-worthy IR Radiometer on the market and instruments developed for normal industrial application should not be used underground due to their low reliability.

* The method of remote temperature measurement offers many advantages for the mining industry, ranging from machine and equipment condition monitoring to loose rock detection.
In order to enable a wider study of the implementation of the IR Thermography/Radiometry method for improving safety in mines, the following recommendations are formulated:

1. A portable, mine-worthy, intrinsically safe IR radiometer should be developed to use in roof and wall scanning before and during any work in an area.

2. Such an IR Radiometer should provide simultaneous measurement of the air temperature and airflow, as well as of the temperature gradient in the roof. It should also process information based on the results obtained in recommendation 4 below, in an attempt to provide an early warning of an impending fall of ground.

3. The main types of rock should be tested and a database on the IR emissivity of the rock should be created to provide true information on air/solid rock temperature differences, which will enable a proper theoretical evaluation and practical processing of obtained results.

4. Further investigations are proposed to establish a possible correlation between the magnitude of the temperature gradient of loose rock and ventilation parameters, and the level of the potential hazard presented by the loose rock.
References


