



Mine cooling and insulation of chilled water transport pipes

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Synopsis

Deep underground mines use refrigeration systems to provide a reasonably comfortable ambient environment to increase productivity and to maintain safety as a priority. Deep level gold mines maintain the environment at an acceptable temperature, i.e. 27°C. However, the increasing cost of doing so through refrigeration is becoming a significant factor in the economic viability of mines.

This paper discusses of the important facet of energy losses in cooling reticulation systems, laying with the specific emphasis on the subject of chilled water transport pipe insulation and its thermodynamic relationships. Aspects relating to the deterioration of open cell-type insulation materials such as polyurethane/styrene foams and the use of Phenolic resins that have good fire retardation properties have been investigated. The thermal conductivities of these insulation media are good (meaning below 0.05 W/°C) However, they are known to be negatively influenced by water vapour ingress and vapour pressure differences that result in the ingress of water into the material by means of absorption, condensation, hygroscopicity, permeability and capillary action, to name a few of many.

The overall effect on mine cooling efficiency takes in the two forms: first by the loss of refrigeration or increased chill in the water temperature arriving in a given section and second, by a loss in transfer efficiency when the gap between the arriving water temperature and the actual air temperature decreases.

Keywords: Conductivity, vapour, insulation, fluid, thermal, temperature, pressure, transport, refrigeration.

Introduction

General issues

If nothing is done to improve chilled water pipe insulation systems, over time the arriving chilled water temperatures in the working sections of mines will increase from an operational norm of 10°C to a norm of 13°C.

The reasons for the use of refrigeration in the hot underground gold mines of South Africa are not disputed. The science of transferring the required refrigeration into water for ease of distribution in mines is accepted practice. However, the techniques associated with the transfer of large quantities

of cold fluid down and through deep and extensive underground mines are unique, and therefore usually require to be designed by specialists.

The water quantities and water pressures involved are high, and distributing water quantities in excess of 1 000 kg/s at pressures of up to 4 000 kPa are fairly common for a large mine distribution system.

The primary method of water reticulation is via suitably sized and selected steel piping. It is often associated with pressure-reducing valves, energy recovery systems and large dams.

The temperature range of the water leaving the refrigeration plants is typically 3 to 5°C, and the arriving temperatures of this water at its final destination is ideally 8 to 10°C, depending on the vertical and horizontal distance travelled.

The reasons for this temperature increase are governed by many factors, such as:

- ▶ Fluid compression with depth (Joule Thomson effect, JT) and the non-use of energy recovery systems
- ▶ Friction losses and therefore the selection of fluid flow rate in the conveying pipes
- ▶ Heat flow from the surrounding rock into the ambient air due to increased geothermal gradient with depth
- ▶ Type and quality of the Chilled Water Pipe (CWP) insulation system
- ▶ Size and insulation system of storage dams
- ▶ Size and maintenance of Chilled Water Pipes
- ▶ Damage to the vapour brake of insulation material.

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The increase in temperature of water as it flows along a pipe is not only due to the reasons given above but a direct loss of the energy that is delivered at the workings (through energy transfer systems/units) in the form of air cooling. Obviously, the mine cooling philosophy plays an important role. Other factors such as positioning and type of refrigeration systems (surface only, surface and underground, ice, ammonia, etc.) must be considered and the mode of water distribution to and from the working is an important factor. The so-called 'open' and 'close' circuit reticulation systems (high and low pressure type) systems are used, and the differences between these and reasoning for the use of either are depends on the system design.

Regardless of the refrigeration or transportation systems used, an increase in the arriving temperature of the chilled water at the working place for the cooling of the ventilation air can be considered a direct loss in generated refrigeration. The formula $kW(R) = M_w (\text{mass flow-kg/s}) \times \Delta t$ (water temperature difference-°C) $\times C_w$ (specific heat or thermal capacity of water-J/kg°C) indicates that the greater the temperature difference (Δt), the more refrigeration is required ($kW(R)$) for a given mass flow (M_w) of water with a C_w of 4,187 kJ/kg°C. In essence, the lower the temperature difference (Δt) between two transfer points (intake and point of application), the lower the amount of refrigeration that needs to be generated and, again, the lower the transport mass of the water which in effect then influences the pipe sizes etc.

It thus stands to reason that the 'conservation' of the departure water temperature from a given refrigeration plant is essential in any mine to prevent so-called 'line losses', which result in:

- a Oversized refrigeration plants
- b Oversized water transport piping systems (more chilled water required)
- c Inflated capital and running costs
- d Dramatic changes in the cold water to air transfer efficiencies (cooling coils or bulk air coolers) in the working places when the gap between the arriving water temperature and the actual air temperature is decreased.

The single largest reason for the increase in CWT (chilled water temperatures) in a mine after the JT effect is a poor quality CWP insulation system.

This paper reviews the mine application of CWP insulation and identifies possible reasons for their deteriorating. It also proposes guidelines for the improvement of insulation systems and the upgrading of the general specification in order to satisfy the future needs of deep mines.

The general problem

The aim of using CWP insulation is to contain the valuable energy stored with the reticulation system. For many years, the most commonly-used underground pipe insulation media was polyurethane (PUR). Because of the fire-related problems associated with PUR, in 1989 the gold mines embarked on a systematic removal of polyurethane insulation on chilled water reticulation piping. The mines were only partially

successful and PUR insulation still exists, although various types of fire protection sleeve are now in use.

The quest for a technically and practically viable alternative also started at this time. This explains the popularity of the now fairly widely used fire retardant Phenolic foam. (Note that the available generic specification 'Thermal insulation for chilled water piping' states that polyurethane or polystyrene-based materials shall not be used underground.)

The *in situ* replacement of the stripped PUR insulation with alternatives such as glass fibre wool and, for that matter, half round Phenolic foam insulation sections has proved to be difficult for many practical and cost-related reasons. Consequently, large portions of the older CWPs in the mines remain either uninsulated or poorly insulated.

The newer sections of the mines generally use pipes that have been pre-insulated on surface. These pre-insulated systems come mainly in two forms:

- UPVC (Unplasticised Polyvinyl Chloride) sleeves (maximum thickness 3.0 mm) around metallic pipes that are injected with Phenolic foam to a required thickness and sealed at each end. The vapour barrier in this case is the UPVC sleeve, the ends of which are usually glued into place. The UPVC also acts as a mechanical protection to the foam material
- Pre-cut Phenolic foam half rounds that are encapsulated in a laminated aluminium polyethylene coated foil that acts as the vapour barrier and is kept in place around the foam half round shape by vacuum. The insulation and vapour barrier is then protected by a galvanised or stainless steel sleeve.

Phenolic or, for that matter PUR foams have very good k-values (low thermal conductivity) properties ($k \approx 0.03$ W/mK). They are influenced by water vapour ingress due to the vapour pressure difference that is generated between the actual in-mine atmospheric conditions and the atmospheric conditions at the surface of the CWP.

The ingress of this water vapour into the foam increases the k-value of the insulation material and results in vapour condensing on the outside wall of the insulation when the dew point temperatures are attained. This condensate further penetrates the insulation via physical mechanisms such as hygroscopicity, permeability and capillary action. When the k-value of the insulation reaches that of water ($k = \pm 0.6$ W/mK), the effect of the dew point now results in condensation on the outside of the steel pipe and eventual water logging of the entire insulation system around the steel pipe.

To overcome the ingress of water vapour into the insulation, a suitable water vapour barrier (WVB) is wrapped around the insulation material.

The partial pressure difference between the outside of the insulation and the inside of the insulation (pipe interface) can be as high as 4 000 Pa and, with this driving force, the quality of the WVB must be of the highest standard. Under the driving force of the partial pressure difference, the flow of water vapour will depend on the behaviour of the WVB. If it is totally vapour-tight material such as metal or glass, the vapour ingress will be zero or insignificant. If it is not fitted

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tightly (with the vacuum placed within) and maintained undamaged on the insulating material, the vapour ingress will be significant.

The flow of 1 gram of water through a material of given thickness per square metre of surface area per 24 hours is termed permeance. This is a performance value and not a property of the material. (The generic thermal insulation specification previously referred to calls for 0.2 g/m²/24 hrs.).

The water vapour diffusion resistance number (μ) is the ratio of the resistance of a layer of material (to water vapour diffusion) to the resistance of a layer of air of the same thickness, under the same conditions of temperature and atmospheric pressure. It expresses how many times better the material resists water vapour passage than air does. As a matter of appreciation, an insulation material will require a μ value of at least several thousand to be satisfactory for most applications, so special means should be used to protect it from moisture penetration and transfer. Phenolic foam has limited resistance with a μ value of 30 to 50. Phenolic foam must, therefore, be protected with a WVB with a μ value of 20 000 to 50 000 such as a thick bitumen, aluminium, polyethylene foil with a thickness of 0.1 mm or a solid steel pipe.

A typical WVB in use on Phenolic insulation material is 152 micro meter thick composite polyethylene (63,5 μ)/aluminium (25 μ)/polyethylene (63,5 μ) [3 layer] foil. Only this product meets the current specification for water vapour transmission of 0.2 g/m²/24hours (SABS tested (ASTM E96) WVB = 0.17 g/m²/24h). UPVC piping with a 3.2 mm thick wall has water vapour transmission rates of ± 2 to 3 g/m²/24 hours!

The puncture resistance of UPVC is good, while the puncture resistance of aluminium polyethylene foil is poor. Portions of the modern Phenolic type insulation in some mines are contaminated with water vapour.

Another important factor affecting the loss of cooling or temperature rise in transported CW is the practice of not insulating the CWP flanges.

The following example is given to illustrate temperature rise over a flange section:

CWP length:	9.1 m
Pipe section insulated:	8.8 m
Uninsulated section:	0.3 m
Pipe size:	250 mm \varnothing
Insulation material thickness:	40 mm
Temperature change over insulated section:	0.0713°C
Temperature change over un-insul. section:	0.0709°C

It can be seen that the temperature rise over the 450 mm un-insulated flange is virtually identical to the temperature rise over the entire 8.8 m of insulated pipe.

The basic cause of unacceptably high arriving chilled water temperatures in the underground workings of mines can be categorized as follows:

Design

- No insulation has been placed on CWPs. (The reason often given is that the cooling losses are transferred into the air, whereas in actual fact the losses manifest as condensate on the steel pipes that falls into the drain and imparts minimal cooling to the actual air)

- Sizing of CWPs in relation to flow rates is incorrect, which results in temperature rises, especially in non-insulated or poorly-insulated pipes when low flow rates are experienced.

Engineering

- The loss or breaching of the vapour barrier on insulated pipes results in an increase in K-value of the Phenolic or PUR insulation
- The non-insulation or poor insulation of CWP flanges
- The poor maintenance of damaged insulation on CWPs.

Management

- The general lack of understanding of the requirements of a good insulation system
- The neglect or limited use of the insulation techniques on chilled water storage dams
- The non-compliance of purchased insulation systems with company specifications.

The compounding effect of all of these factors has resulted in arriving water temperatures at the workings of 12 to 16°C when they should be in the order of to 8 to 10°C.

Basic solutions

The ever-increasing pressure on the gold mines to produce at lower cost has resulted in the review of every component of an underground refrigeration system. The increasing capital and running costs of these large cooling installations and water reticulation systems and the requirement to mine more deeply have made an appraisal of the operating efficiencies of the present and future cooling systems necessary.

The solutions suggested are based on the following set of fundamentals:

- Upgrading the general knowledge of engineers and environmental safety and health managers who are involved in the design and selection of piping and insulation materials.
- Providing supply managers with technical tools that can be introduced in the form of specially designed software that will allow:
 - a The simulation of conditions that insulation materials and vapour barriers will operate under, thereby predicting the water vapour transmission rates needed for compliance with the required specification. The programme also allow the prediction of the life span of a given insulation and WVB under specific water vapour transmission rates, so that systems to be selected in accordance with the expected life of mine
 - b Simulation of the underground environmental conditions in which a chilled water system is operating. This allows the prediction of the arriving water temperature at any specific length when various types or thickness of insulation are considered on a specific pipe type, pipe size and at various water temperature and fluid flow rates. It also considers, the JT effect, pressure reducing valve, energy recovery and water drainage systems

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- c The prediction of the specific life span (owning cost) scenario, with required input parameters such as power, capital, interest rates and life of project by means of a financial model .
- Developing general guidelines that will cover selection, installation, fabrication and maintenance of CWP installation.
- Adopting an updated set of specifications covering the technical facets of a total insulation system with an emphasis on improved WVB strength and
- Compiling a basic list of currently available products that can be used and that comply with the generic specifications.

Financial implications

The savings that can be derived from improving the quality of the total insulation system of a given mine can best be demonstrated by an example.

The prevention of 1°C temperature rise in 1 litre of water in an underground chilled water reticulation system is equal to:

$$\begin{aligned} \text{Duty} &= M_w \times \Delta t \times C_w \text{ kW(R)} \\ &= 1 \times 1 \times 4,187 = 4.187 \text{ kW(R)/l/s} \end{aligned}$$

The electrical input power to generate 4,187 kW(R) is $\pm 0.963 \text{ kW(E)}$ ($\pm 23\%$ per kW(R)). The present value (PV) of this power cost over 20 years at 10% is 8.5, giving the PV of running costs of $(0.963 \times 8.5 \times R 1,600)$ i.e. R 13,118/°C/l/s (present day electrical power costs are $\pm R 1,600/\text{kW/-annum}$).

The capital cost of a total refrigeration plant and reticulation system is estimated at R 8500/kWR and thus constitutes a one-off payment of $\approx R35,600/^\circ\text{C/l/s}$ (8500×4.187).

The total owning cost of a l/s of water transported with a loss/gain of 1°C over a typical refrigeration system is, thus, $\approx R 49,000$.

On a mine reticulating, say, 1,000 L/s of chilled water, the cost implication would be a (1,000 \times R 49,000 = R 50 million), saving or loss of $\approx R 50$ million over a project period of 20 years.

An improvement in arriving water temperature of 1°C is easily attainable if good total insulation systems are used, but improvements of at least 2°C and more should be aimed for. With the present estimated cost of insulation at around 5% of the capital cost of a refrigeration system, the justification for good and maintained insulation is self-evident.

Causes of refrigeration losses in chilled water reticulation systems

Basic reasons

The more descriptive reasons for poor performance of chilled water reticulation systems are categorized as follows:

Pipe size selections

Note that the higher the quality and effect of the insulation, the lower the consequence of water velocity considerations.

The simulation allows the effect of any selected velocity to be analyzed in relation to the pipe wall thickness and other selection parameters, e.g., insulation type and thickness, etc. (Figure 1).

Non-insulation of chilled water pipes (CWP)

It has been suggested that non-insulated CWPs impart cooling to the surrounding air and that there is no need to insulate CWPs that run in intake airways. This claim concerning cooling transfer from non-insulated pipes was tested during field trials and found to be false.

Non-insulation of flanges on CWPs

The rationale for the non-insulation of flanges on CWPs is the same as discussed in the section 'The general' problem. Insulation of pipe flanges must be to the same high standard as for the normal length of pipe.

Loss of thermal insulation properties

The single most significant reason for the loss of thermal conductivity in an insulant is the ingress of water vapour and water into the insulation material.

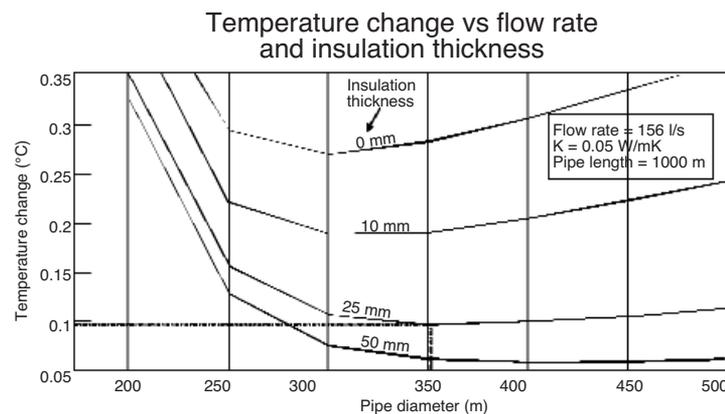


Figure 1—Pipe diameter selection

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The water vapour transmission flow through a typical insulation material such as PUR or Phenolic is $\pm 83 \text{ g/m}^2/24$ hours (tested) under normal underground conditions. This transmission is some 415 times greater than the standard WVB requirement of $0.2 \text{ g/m}^2/24$ hours. Under these conditions the k-values of the insulation increase rapidly and within days, the insulation will contain $\pm 40\%$ vapour and the insulation material's k-value will increase from 0.05 W/mK to 0.25 W/mK .

With time and depending on the dew point temperature, the water vapour starts to condense on the outside of the CWP, and water starts to accumulate between the insulation and the pipe. In time, the insulation starts to absorb the water to a point where the insulation becomes waterlogged and the overall k-value of the system increases to that of still water at $\pm 0.6 \text{ W/mK}$.

Tests conducted underground on $300 \text{ mm } \varnothing$ by $2\,000 \text{ m}$ long CWP that was insulated with a Phenolic foam product and encapsulated in a foil-type WVB and protected occasionally by a spiral wound galvanised iron and UPVC half section sleeves, revealed that some insulation section k-values were indeed as high as 0.23 W/mK where the WVB was damaged. Where the WVB was intact and not damaged, the k-value of the insulation was measured at $\pm 0.05 \text{ W/mK}$. When the k-value 'equivalent' of the entire length of the pipe system is calculated, the average figure of $\pm 0.5 \text{ W/mK}$ is obtained. This increased k-value is attributed to the poor insulation systems at flanges and the degree of insulation damage along the pipe systems.

The lack of, or poor maintenance of, water vapour barriers

The water vapour resistance or μ value of normal foam-type insulation is low (30–50). (Cellular glass is an exception and has a μ value of +50 000 which is comparable to the μ value of a good WVB such as aluminium polyethylene coated foil, as previously indicated.)

In order to protect these foam-type forms of insulation such as Phenolic against water vapour ingress, they are usually wrapped or encapsulated in a WVB which has an μ value at least $\geq 50\,000$.

A WVB with such a high μ value and a thickness of only $\geq 0.1 \text{ mm}$ (resistance to water vapour ingress) will allow a minimal water vapour flow rate of $\pm 0.2 \text{ g/m}^2/24$ hours. In this way, the insulation is protected because with this low water vapour flow rate, the insulation will absorb moisture/water very slowly. This slow absorption of water gradually alters the k-value of the insulation until it eventually reaches $\pm 0.25 \text{ W/mK}$. This process can take up to 20 years, as confirmed by the simulation model generated. It is the most likely reason why $0.2 \text{ g/m}^2/24$ hours was chosen as a flow rate, 20 years being the average life span of most projects.

When the insulation reaches its maximum water loading capacity and the k-value has degraded to, say, 0.25 W/mK , occurs condensation, on the outside of the WVB and further increases the energy losses from the CWP system.

From the above rationale, it is fairly obvious that a section of pipe that is well-insulated has its WVB intact should suffer minimal cooling loss for a long period. However, when the WVB is broken or breached by even the smallest pin-hole, the resistance to water vapour flow almost instantly decreases from a μ of 50 000 to 50. The water vapour flow rate increases 400-fold from $0.2 \text{ g/m}^2/24$ hours to $\pm 80 \text{ g/m}^2/24$ hours. Within a short time, the k-value rises from $\pm 0.05 \text{ W/mK}$ to 0.25 W/mK and the amount of condensate on the outside of the insulation increases because of the lower temperature at this point.

Not only does this condensate manifest in loss of cooling but the condensate flows under the WVB and often fills the WVB bag with water. This 'soggy bag' condition exacerbates the deterioration of the foam insulation material, increasing the amount of water it can hold and, further raising its k-value until it reaches that of still water at $\pm 0.6 \text{ W/mK}$. (How long this takes is unknown, but one must assume that because of the often low pH values associated with the condensate coming in contact with the insulation material, the deterioration of the foam takes between one and three years. Examples of the deteriorated insulation were noted at the mines during tests conducted.

Because there is a linear relationship between the resistance value Φ and the thickness of a WVB, the thickness of a UPVC sleeve would have to be at least 12 mm to limit the water vapour flow rate to $0.2 \text{ g/m}^2/24\text{h}$.

Water vapour barrier protection

The protection of a WVB is usually accomplished with a metallic sleeve. Alternatively, the WVB may be protected by its thickness and inherent strength, as in the case with UPVC. Where metallic protection is used, the majority of installations are the Galvanised Iron type that is spirally wound, using a joint locking technique to form the pipe. This type of protection sleeve, when used with a WVB such as aluminium-coated polyethylene, is a major cause for concern, because when applied over the pipe, it causes minute 'rips' in the WVB material, which damage the WVB before installation.

General insulation assembly problems

Figure 2 depicts a section of a typical 9.144 m underground CWP length with its 1.0 m long WVB covered insulation sections. The illustration below is used to highlight areas that can adversely affect the quality of the insulation protection.

- i) *Insulation/WVB—thermal short-circuiting*
The radial joints between each length of insulation half round (Phenolic) protected by the foil WVB should be sealed with a suitable sealer, like the longitudinal gaps.
- ii) *Insulation—flanges*
The need to insulate flanges deserves the same attention as the insulation of the straight pipe sections. The open area of non-insulated flanges constitutes only 3.4% of the total pipe length, but can contribute to 50% of the cooling loss of a 9.144 m pipe length if not insulated.

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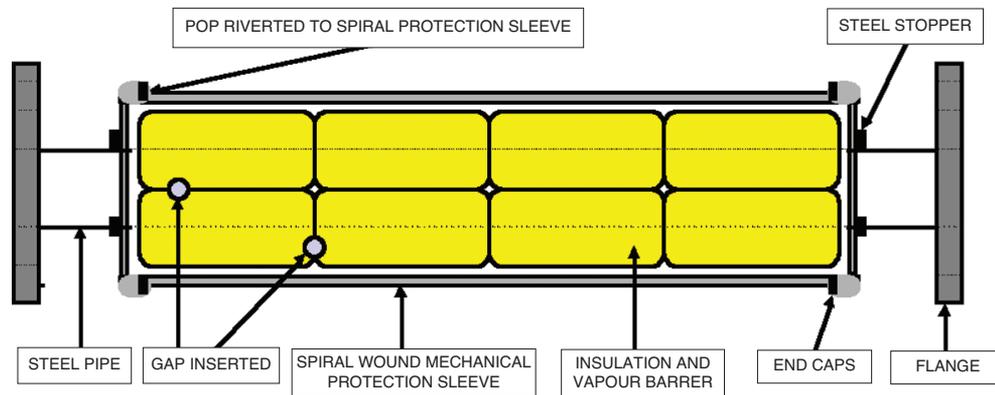


Figure 2—Typical pipe including insulation and sleeve

Installation of insulated CWP

There is no getting away from the space constraints associated with underground mine shafts and haulages. The installation of insulated CWPs will always be competing for space with other service installations such as those carrying compressed air, service water, electricity, etc. Therefore, adequate spacing should be designed for the type of installations required.

General problems

- i) *Damage during transportation of insulation*
Transporting the insulation systems from the factory or from the fabrication facilities at a mine can cause damage to the highly important WVB. The identification of a damaged foil type WVB is easy and manifests as a 'ballooning effect' around the Phenolic half round sections as a result of a loss of vacuum. The transportation problems from the store or fabrication yard to the shaft bank and then down the mine can be termed in-house problems and are numerous. Solutions require complex engineering responses.
- ii) *Wear and tear*
Apart from the natural ageing of the WVB and insulation systems, the only other detrimental activity that can affect CWP insulation systems *in situ* is physical damage caused by collision with the pipe and vibration. Collisions are a safety aspect and the causes are usually well known.
- iii) *Planning and pipe size selection*
The consequence of incorrect pipe size selection in relation to the water flow rates through a given pipe system can, over the life of the system, cause arriving water temperatures to a section to rise above desirable levels. The *in situ* insulation of CWP flanges, valves, etc must be carried out before cold water is allowed to flow through pipes. The secret to good *in situ* insulation is 'keep the pipe dry'. The Design of pipe sizes should take into account the period of use, i.e. the peak demand life time required, the flow rate requirement and then the reduced requirement as production decreases (Two smaller pipes might do a specific job better than one large pipe).

iv) Training and education

All personnel involved in the selection, purchase, quality assurance, fabrication, transport installation and maintenance of underground insulation systems need to be trained in the requirements of a CWP system.

v) Quality assurance

The technical specifications for the purchase of insulation and WVB materials must be sound to ensure that these items are of sufficiently high quality.

Findings, conclusions and recommendations

General findings

The impact of the systematic removal of polyurethane insulation from the chilled water piping (to reduce fire hazard) has been minimal. Environmental engineers confirm that there has been no significant change in wet bulb temperatures after this extensive stripping exercise. That the arriving temperatures did not drop, as expected, clearly indicate that the insulation applied at the time had already deteriorated significantly. There is general acceptance of higher arriving water temperatures of $\pm 12^{\circ}\text{C}$, in the workings has been brought about by the introduction of the chilled service water concept. The use of high-pressure water to remove blasted rock from the face has dramatically increased the service water quantities in use on some mines, has further entrenched the workers' reluctance to accept very cold water for operational use.

The significant findings arrived at are as follows:

- a) The historic and current failure to appreciate the technical importance of a WVB has allowed inferior products to be used in the mines. When a WVB is damaged, for whatever reason, the detrimental effect on the insulation itself is not fully understood, and thus the motivation for corrective action has been lacking.
- b) The fact that water vapour can easily penetrate most insulation materials owing to the very high driving force generated by the partial vapour pressure differences across these insulation systems is not fully appreciated. The concept of a closed cell structure of insulation material can be confusing. It is often assumed that insulation is impervious to both water and water vapour. Both Phenolic and isocyanurate based cellular plastics, although they have closed cell structures, easily 'breathe'

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and thus transmit moisture vapour in the same manner as wood and naturally-occurring cellular products.

As mentioned, the partial pressure difference calculated is between 3 kPa and 4 kPa across an insulation system. This can easily force water vapour into the cell structure, where it is quickly condensed into water, which dilutes and replaces the fluorocarbon gases that provide the low k-values associated with these materials. The consequence is a increase in k-value that raises the resistance within the insulation. This in turn promotes further condensation and loss of cooling owing to increased latent heat transfer.

- c) The important need to seal or bond together the longitudinal, radial and end piece joints of WVBs in encapsulated insulation half-rounds is not recognised or acted on. These half rounds are held together by tape bound around the system at certain intervals, and then covered by a protective sleeve. Water vapour ingress via these many unsealed gaps can easily occur, and explains why condensate drips out at the ends of these pipe systems. When flanges are insulated, bonding or sealing of the joints is seldom undertaken. That omission almost nullifies the benefits obtained from flange insulation. Note that the bonding or sealing compounds must have the same water vapour transmission characteristics as the WVB itself (0.2 g/m²/24 hrs and a μ value of at least 50 000).
- d) The quality of underground insulation systems outside the general refrigeration plant areas is poor. The non-insulation of flanges coupled with the poor maintenance of damaged sections add to the low overall efficiency of the chilled water reticulation systems.
- e) The effectiveness of mine air cooling devices such as stope cooling cars (fin and tube), in-stope coolers and, for that matter, direct water to air coolers are all dependent on temperature differentials of $\pm 20^{\circ}\text{C}$ wet-bulb air in—water temperature inlet. This means that with typical air inlet temperatures of 29°C wet-bulb to the cooling coils, the inlet water temperatures to these cooling systems should be between 8 and 10°C . For each degree of increase in water inlet temperature, the efficiency of the cooling device decreases by 5% and the duties by $\pm 10\%$. These decreased efficiencies are calculated for clean fins and tubes on the cooling coils. The loss of efficiency can be even higher when fins and tubes are fouled.
- f) The compounding consequence of all of these detrimental factors is the ever-increasing refrigeration capacities that are installed to overcome these so-called 'line losses'. The technology to produce more cost-effective refrigeration such as ice making, and the overcoming of the JT effect by the use of energy recovery turbines and three-chamber pipe-feeder systems has been vigorously pursued. However, the development of technology to conserve the cooling produced has fallen behind. With increased mining depths the heat loads in the mines will obviously increase, and refrigeration needs will have to be fully optimized. Part of this optimization will be reduction of temperature increases in chilled water along supply pipes to the workings.

Financial implications of these findings

- a) The descriptive simulation indicated some of the required information needed to construct a water temperature change model and an owning cost model for a given typical underground section.
- b) The model (not fully detailed here) represented an underground situation where chilled water is delivered to a level from a chilled water storage dam. The station arriving water temperatures are shown as covering a temperature range of 6.15°C – 7.15°C – 8.00°C . On passing through a pressure-reducing valve they increase to 8.02°C – 9.01°C and 10.01°C respectively.
- c) The nominal pipe sizes selected are in accordance with the quantities of water required in the section to satisfy cooling needs and calculated arriving water temperature. The optimum flow rates through the selected pipes are dictated by the overall assumed insulation k-values over the length of the pipe system, and the actual insulation thickness. An example of such an optimisation process is a 300 mm diameter pipe 1,000 m length with an optimum velocity of 2.15 m/s and insulation material thickness of 25 mm when the system has an overall k-value of 0.25 W/mK.
- d) The total savings indicated that it is financially beneficial to opt for a good overall k-value with due regard for the optimal insulation thickness. The annual cost savings per metre of insulated CWP are not provided here. However, calculations indicate that the annual cost per metre saving brought about by good insulation (0.05 W/mK) is 2.5 times the cost of the original insulation at around R 200/m (25 mm thickness). This relates to about a five-month payback period. In the case of poor insulation (0.25 W/mK plus uninsulated flanges) the payback is more than one year.

These costs indicate that even poor insulation is highly beneficial when compared to no insulation but also highlights the massive saving between poor and good insulation systems. Over 20 years a saving of R 6.1 million for one level alone; for four main intake levels the saving is \pm R 50 million (applicable to this case only).

Conclusions

Technical specification

There are major economic benefits to be derived from the insulation of chilled water piping (including return water pipes) and strict compliance with the insulation standards currently in place.

The need to insulate all pipe flanges to ensure the long-term integrity of the WVBs around insulation is seen as the single most important technical hurdle that must be overcome in an underground mining environment.

Other alternatives can be considered, such as encapsulating the insulation in a WVB that is stronger, such as steel (the pipe within a pipe concept). If UPVC is to be considered as a WVB, it must be sufficiently thick to contain water vapour transmission, and pre-made insulation half rounds must be inserted inside the gap between the steel pipe and the UPVC WVB/protection sleeve.

Mine cooling and insulation of chilled water transport pipes

Planning, measurement and management

There is a need to plan refrigeration requirements on the basis of the lowest arriving chilled water temperatures possible in order to minimise the amount of chilled water circulated and, thus, the size and cost of refrigeration plant and infrastructure. This explains the long-term aim to convey 'ice' right up to the workings. In the interim, the loss of cooling due to poor chilled water reticulation practices (such as lack of correct pipe size selection, poor or non-insulation of pipes, non-insulation of flanges, loss of conductivity values of insulation, loss of WVB protection, etc.) must be curtailed.

Recommendations

- a) The financial evidence clearly shows that designing and operating refrigeration systems that cater for line losses or inefficiencies of more than 40% (mainly because of practical or technical constraints) can no longer be tolerated. Should this practice continue, the future capacity of refrigeration systems will place huge financial burdens on the mines, as mines become deeper and heat loads increase.
- b) The use of insulation materials that have low μ values (high water vapour transmission rates) should be considered only where the WVB is strong enough to withstand the rigours of the harsh underground conditions over a given period. The need to protect both the insulation and the WVB must be considered. (The pipe within a pipe concept has much merit).
- c) Planning for long-term chilled water insulation needs should be based on materials that are themselves WVBs, i.e. have high μ values. These materials would then require sleeves only for physical protection and not form part of a WVB protection requirement.
- d) Materials that do not burn independent of their fire-retardant properties) should be given preference. These products eliminate the need for fire breaks and special precautions during transport, storage and installation.
- e) All CWP's including their flanges and valves, etc. must be insulated. The philosophy should be to tolerate only losses of up to 10% and less.
- f) The need to bond/seal all insulation joints and critical pipe/steel contact areas must be incorporated into the overall chilled water insulation system. Its importance,

though immense often ignored is in mine insulation systems.

- g) Only insulation and WVBs that comply with a mines specification, i.e. 'thermal insulation system for CWP' should be considered.
- h) The size, complexity and financial ramifications of the insulation problem in the mines require a commensurately well-qualified planning, design and control infrastructure.
- i) The underground *in situ* insulation methodology should be used only for new refrigeration plant installations, pipe joints and repair/maintenance work. All run-of-mine pipes used for chilled water reticulation (shafts and horizontal) should be insulated on the surface. The temptation to undertake *in situ* re-insulation of old piping on levels that are almost worked out should be resisted. The payback would not normally justify the expense, and the quality of the insulation cannot be guaranteed. It is preferable to concentrate on the new pipe installations and demand the highest quality.
- j) The typical underground CWP insulation conditions of each mine should be simulated, starting at the refrigeration plant outlet, through the dams, down the shafts and into the levels, and along the haulages to the stope cross-cuts. In this way, the management of each mine can construct their own financial models and determine their own returns on any capital outlay.

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