

# ENERGY CONSERVATION: REFRIGERATION

Dr Steven Bluhm, Frank von Glehn and Ross Wilson  
*Bluhm Burton Engineering*

## INTRODUCTION

Huge quantities of power are consumed by refrigeration equipment in the South African gold and platinum mining industry. At present it is estimated that the total installed refrigeration capacity is of the order of 1350 MW<sub>R</sub> on these mines. In terms of electrical motor ratings, this relates to about 350 MW<sub>E</sub> in refrigerant compressor drives with motor sizes generally ranging from 0.5 MW<sub>E</sub> to 2 MW<sub>E</sub>. In addition, the direct auxiliaries [cooling towers, condenser pumps, etc] will have a total electrical rating of the order of 150 MW<sub>E</sub> with motor sizes ranging from small to about 0.3 MW<sub>E</sub>. Thus, in the South African gold and platinum mining industry, the total electrical name-plate rating for refrigeration equipment is of the order of 500 MW<sub>E</sub>.

The engineering and operation of these systems has evolved over the decades and many highly talented engineers have contributed to the current state-of-the-art and much has been achieved in terms of energy efficiency. However, there still remains great potential to improve on energy conservation and energy management related to designing and operating these systems.

Electrical power costs in South Africa have traditionally been low by international standards and, until fairly recently, there has been a single overall tariff. However, future projections of power costs anticipate significant increases. Fairly recently, power tariff structures have introduced rates that vary throughout the day, differ on Saturdays and Sundays and change between winter and summer. The difference between the lowest and highest tariff is about 1000%, see Figure 1.

The electrical power generation situation in South Africa is such that Eskom is providing incentives [through Government grants] to use power more efficiently and to shift power demand during critical times. Amongst other incentives, the Eskom program provides capital for projects

designed to shift electrical power away from certain peak rate periods. This capital is used to acquire equipment and control systems to allow the energy shifting to be implemented. [The mining company ultimately receives this capital equipment and in addition, the mine benefits from reduced power costs].

All these factors have created the situation where there is a very strong current awareness of all energy related matters in mining. The energy efficiency issues in mine refrigeration systems can be categorized as follows:

- Cooling generation and distribution:  
Including thermal losses and aspects such as pipe insulation, energy recovery, losses in dams, as well as energy efficiency of refrigeration machines and issues such as compressor efficiency, compressor speed optimisation, fouling, heat rejection efficiency, etc.
- Reducing mine heat loads:  
Including issues such as backfill, tunnel insulation, mine layout design, minimising diesel machinery, etc.
- Active cyclical control of refrigeration systems:  
Including issues such as engineered thermal storage [water dams, ice dams], thermal storage effects in cold rock, making best use of diurnal variations, etc.

Because of the large extent of the subject, it is difficult to write an all-embracing definitive paper on the topic. Rather, this paper discusses a number of selected aspects under each of the above categories.

## COOLING GENERATION AND DISTRIBUTION LOSSES<sup>[1]</sup>

The efficiency of cooling distribution by chilled water is dependant on keeping the water as cold as

possible for use at pre-determined strategic sites such as air coolers and in-stope devices. The loss of cooling-potential of the water flow is due to hydraulic losses [friction] and heat gains from external sources.

The losses can be examined at *component* level starting with surface dams and ending with drain water - including cold dams, pipes, energy recovery devices, regulating valves, air coolers, cold water devices in workings, drains, pumps, etc. The thermo/hydraulic characteristics of each component are well documented in standard texts. These standard process calculations for each component can then be analysed interactively on a system-wide basis. Components to be examined should include: dams, air coolers, pipe insulation, in-stope water applications, drains, etc. Because of the very many possible combinations and permutations, it is useful to grade the performance of each of these aspects on a comparative-relative basis [high-medium-low], see below.

The selected components of underground dams, pipe insulation and energy recovery are presented below as examples.

### Underground dams

In underground cold water storage dams, the water level changes with time. This varying water level results in a 'tidal zone', where the rock is cyclically submerged and exposed allowing a regenerative heat transfer from the air to the water via the rock. The total heat flow to the dam water comprises a short-term component [including regenerative effects] and long-term heat flow from virgin rock. Procedures have been developed, and verified by field measurement, for predicting the heat gains to the water from both the air and the surrounding rock for different dam layouts, rock types, air flow scenarios, water flow and temperature and tidal variations. The magnitudes of the cooling losses for typical underground dam scenarios will vary from about 500 kW to 2000 kW depending on dam ventilation, size, shape and temperatures. The cooling losses in underground dams can be reduced by minimising the ventilation within the limits of acceptable practice [depending on specific circumstances]. The only way of reducing long-term heat flow from surrounding rock is to install an insulating layer on the rock. This insulation will reduce long-term heat as well as the regenerative and radiation heat components. For high-heat-flow dams there will be clear financial motivation for insulation should a reasonable product be developed. Cooling losses in underground cold water dams may be broadly grouped as: high -

500 kW per MI, medium - 200 kW per MI, low - 50 kW per MI.

### Pipe insulation

Chilled water pipe insulation systems comprise an insulation medium, vapor barrier and outer mechanical cover. Newly installed insulated pipes can effectively contain cooling losses, but the mining environment is such that the insulation loses its effectiveness with time [sometimes very quickly]. This is because it becomes damaged and even a small hole in the vapor barrier can lead to complete saturation with time. Thus within a mine system there will be varying degrees of insulation performance and the effectiveness of insulation systems can be grouped qualitatively varying from high-medium-low as follows:

<b>High</b>
High quality insulation system with all pipes, flanges and valves fully insulated with a perfect vapor barrier and a protective outer covering. For example, insulation medium would be about 35 mm of high quality insulation of conductivity about 0.03 W / m°C.
<b>Medium</b>
Insulation system either with some pipes or flanges un-insulated or with damaged sections of pipe. Heat transfer will be due to conduction through the insulation as well as some condensation on bare flanges and/or damaged water -logged sections of insulation.
<b>Low</b>
No insulation. Bare pipes, flanges and valves. Condensation freely occurring on all surfaces.

For example a 300 mm, high-quality insulated pipe system would typically lose about 5 kW per 100 m whereas a low-quality insulated pipe system would lose about 200 kW per 100 m. Considering that some mine systems have more than 50 km of chilled water piping, the cooling losses through piping relates to a very significant energy transfer.

In general, existing pipe insulation systems in mines do not perform well; the main problem being mechanical damage and water-logging. Also, often when pipes are replaced, the insulation system is neglected. In older mines there remains a legacy associated with the stripping of pipe insulation after the fires in the 1980s. It is clear that there is a great financial driving force for installing and maintaining high integrity and high quality pipe insulation systems. Significant expenditure in

pipe insulation and its maintenance is a sound investment in the overall context.

### Energy recovery

There has been much debate over the last two decades comparing turbine generator systems to hydro-lift [or three pipe feeder (3PFS)] systems. In addition to the normal analysis which compares the specific characteristics of the equipment, it is informative to examine the losses on an overall mine-wide basis [because of system 'knock-on' effects]. One such study examined the life-cycle present-value cost differences for an entire cooling system<sup>[1]</sup>. Capital estimates included refrigeration plants, dams, pumps, pipes, energy recovery equipment, standby equipment and all related infrastructure. Operating estimates included all power components [plants, pumps, etc], maintenance costs, replacement spares, consumables, water treatment, etc.

Obviously, the comparison of turbines with hydro-lift systems is dominated by the overall effectiveness of energy recovery and pumping efficiency. The band of data for the turbine system in Figure 2 is defined by an effectiveness\* of 70% for the 'upper' scenario and 50% for the 'lower' scenario. But also inherent in this system study is an assumed pumping efficiency of 70%. Thus, in an overall sense, the energy conversion can be considered as 50% and 35% for the 'upper' and 'lower' scenarios respectively. The band of data for the hydro-lift system is defined by a hydro-lift effectiveness\* of 80% for the 'upper' scenario and 50% for the 'lower' scenario. But in this case these values include pumping effects. Also, with the hydro-lifts, the evaluation includes a standby pumping provision. As the depth increases, the hydro-lift system looks more favorable. Indeed it is concluded that if hydro-lift systems can be proven to be reliable in a fully operational sense they will offer significant benefits over turbine systems. Hydro-lift systems deserve detailed consideration and the renewed interest in this concept should soon produce much-needed practical operating histories. While hydro-lift systems are conceptually elegant, a long-term sustained operational effectiveness factor of the order of 80% may be difficult to achieve\* considering the low effectiveness of existing [and past] energy recovery systems and the failure in the past of direct-coupled turbine/pump systems [where 'up' and 'down' water flows needed to be matched].

\* 'Effectiveness' term refers to the product of: availability factor, utilisation factor, hydraulic efficiency, mechanical efficiency, thermodynamic efficiency and electrical efficiency [in case of generator].

### System-wide analyses

In existing hot mines the cooling networks are extensive and the thermal losses are very significant. The success of cold water cooling distribution systems depend on truly cold water being delivered to the correct locations. There is a hierarchy-of-priorities for using cold water. In the deep gold mines, the highest priority will be that of in-stope water [in-stope cooling devices] and critical air cooler sites. Unfortunately, this hierarchy-of-needs is not naturally matched by the cooling distribution systems. It is not possible to provide the coldest water closest to the workings since these are normally at the furthest location from the cooling generation centres. Thus effective design and operation of mine cooling systems is often a compromise between the location of the cooling generation and that of the final point-of-use.

Also, the 'positional efficiency' of the point-of-use of the cold water influences overall effectiveness. The use of cold water within hot workings has high positional efficiency in terms of localised air cooling, and any losses in ventilation thereafter are generally irrelevant. In contrast, surface bulk air cooling does not have a high positional efficiency in relation to stoping because of ventilation leakage and other factors. In carrying out system-loss studies, a spectrum of positional efficiencies for different cold water applications has evolved. These range from 90%+ for in-stope point-of-use down to zero for losses related to regulation valves, hydraulic friction [all of which provide no useful cooling]. For air coolers, drains and cooling losses from pipes and dams the positional efficiency will be of intermediate values as relevant to the specific system under consideration.

All the different components within a cooling distribution system interact, the losses in one affect the next and there is a 'knock-on' throughout the system. As noted, in order to understand the overall in-efficiencies, it is important to examine the losses on a system basis. For this purpose, a modelling and auditing approach is required. Within these models, individual algorithms must calculate the cooling losses due to both hydraulic losses [friction] and external heat flow for each component in an interactive manner. Consider a hypothetical example of a deep mine in the Witwatersrand area with a production of 200 kt/month [reef+waste] from secondary and tertiary shaft systems. The refrigeration generation system will include a surface ice plant supplemented by an underground chiller plant. The cooling distribution system will include the use of in-stope cold water as well as strategically placed bulk air coolers and



tertiary air coolers [coils]. The refrigeration capacity will be of the order of  $100 \text{ MW}_R$  and the breakdown of the cooling-effect is given in Figure 3. Considering the relevant spectrum of positional efficiencies, it is estimated that the actual effective cooling achieved is  $65 \text{ MW}$  or  $65\%$ .

As noted, it is useful to grade aspects such as pipe insulation, air cooler performance, stope water effect, drain effects, etc on a relative basis of high-medium-low. The distribution effectiveness of  $65\%$  above relates to medium grading of each aspect. If high grades were assumed for each aspect, the above effectiveness value would increase to about  $80\%$  while if low grades were assumed for each aspect, it would reduce to about  $50\%$ .

It must be observed that huge quantities of cooling can be lost [and are lost in existing mines]. But it must also be noted that there is considerable potential for minimising these losses with good design and maintenance of high quality systems.

### **Energy efficiency of refrigeration machines**

The energy efficiency of the actual refrigeration machines obviously also plays an important role in overall optimum energy management. Refrigerant compressors are designed and selected for specific optimum energy efficiency points. But, in practice they are often required to operate outside these efficiency bands because of:

- Different-from-expected loads in terms of flow rates and temperatures.
- Poor heat rejection facilities and high condensing temperatures.
- Fouling of heat exchangers.

Sometimes refrigeration machines are moved from one application to another where they are required to operate under conditions that were never considered at the design stage [perhaps some 1 or 2 decades ago]. Where possible, speed changes by modifying gear-sets can be used to minimise these deficiencies. Some of the mining companies make use of refrigeration machines with two-speed gear boxes to beneficial effect. The gear-sets are changed at the change of season to enable efficient operation throughout the year. It is also important to ensure that inter-stage economizers are operated correctly at optimum set points and gas levels.

With the constant changing of loads and with the large quantities of energy involved, it is very important that careful operational measurements are taken and that machine performance is checked regularly and accurately. Water treatment and fouling are aspects that are often seriously ne-

glected. These issues have direct and significant energy implications and must be treated with a very high level of respect. For example, the difference between a cleaned and fouled machine can relate to COP differences of up to  $20\%$ . Extrapolating from this for the  $350 \text{ MW}_E$  total rating noted earlier, gives a measure of the serious importance of these aspects.

Apart from fouling, the application of non-optimum process flow conditions can also cause low evaporating temperatures and low COPs. For example, many systems use very-cold water [say  $1^\circ\text{C}$ ] in air coolers to produce not-so-cold air [say  $12^\circ\text{C}$ ]. A much improved process scenario would use about  $6^\circ\text{C}$  water [at higher flows] and allow the refrigeration compressors to operate in an 'easier' condition. Note that COPs can be improved by  $10\%$  to  $15\%$  by increasing evaporating temperatures by about  $3^\circ\text{C}$ . Advantageous COPs can also be achieved, through improved evaporating temperatures, by arranging plant evaporators in series rather than parallel. In some cases, arrangements of up to three plants in series have been justified. Also, the use of a back-pass of chilled water around the evaporators, which is often applied for chilled water temperature control, artificially lowers the evaporating temperature. While this approach is used as a very practical control mechanism, it is done so at the expense of compressor energy and the back-pass flow quantities should be kept to a minimum.

Considering the machine efficiency factors noted above and other similar issues, it is suggested that attention to these issues alone can probably improve overall average efficiency in terms of energy consumption by  $10\%$  to  $20\%$ . Again, extrapolating from this for the  $350 \text{ MW}_E$  noted earlier, gives a measure of the serious importance of these factors.

### **REDUCING MINE HEAT LOADS<sup>[2]</sup>**

Numerous methods for the reduction of heat flow have been identified. These include the use of backfill; the insulation of intake airways; the design of stoping layouts, the cyclical cooling of ventilation control zones and minimizing diesel equipment.

The reduction of heat load and improved ventilation control are an important benefit of backfill. Backfill reduces heat loads because it seals off worked-out areas and thus minimizes the area of exposed hot-rock surface. Backfill enhances the utilization of ventilation by either enabling higher air velocities at the face for the same quantity or by allowing a reduced overall air flow rate.

Theoretical models have been developed which can be used to analyse the effects of backfill on a

mine-wide scale. Over the last two decades these models have been validated by underground field measurements. The mine-wide use of backfill can reduce the overall mine heat load by between 10% and 25%. Heat reduction from backfilling depends on the extent of backfill [percentage filled], mean fill-to-face distance and on specific stope criteria such as face advance. Heat conduction through backfill is not significant because of the relatively low conductivity of the newly placed fill.

Over the last two decades, the thermal benefits of coating the surfaces of intake tunnels with insulation have been thoroughly investigated. These investigations have included a number of underground trials and much computer simulation work. It has been established that this heat flow can be reduced by up to 50% when the surfaces of the tunnel are coated with approximately 40 mm of high quality insulation. But this heat flow saving will halve when, for example, the footwall of the tunnel is not insulated.

However, notwithstanding these driving forces, the development of suitable materials has been disappointing. Materials used for the insulation of the intake tunnels should, in addition to having a low thermal conductivity, be durable economical and safe to use. Mechanical strength properties which enable the material to provide some degree of support are also an important requirement. However, in general all good insulators lack mechanical support and vice versa. Many different insulation materials including phenolic foams, mineral wools, perlite, cement-based and hybrid products have been evaluated. But to date none of these satisfy all of the ideal requirements entirely. However, given the strong financial driving forces, it is anticipated that an insulation material suitable for implementation will be developed in the near future.

Alternative mining methods and layouts also have the potential to improve the thermal environment markedly. The stope heat flow per ton of rock mined is closely related to the total length of working face and an effective means of reducing the heat flow is to minimize the total length of face. Consequently, the aims of heat flow reduction and face mechanization for higher production are complementary. An important aspect is the relationship between the rate of face advance and stope heat flow. VUMA models have been developed [and verified by measurement] to enable this relationship to be confidently predicted for different conditions and effective mine design teams now take full cognizance of these issues.

Traditionally, mine cooling systems have been such that the entire mine is cooled continuously. Heat flow and cooling costs can be greatly reduced if cooling systems are controlled such that the

cooling was only provided when and where men work. Also the degree of cooling provided must be appropriate for the prevailing heat load which varies on a daily, weekly and seasonal basis. This is discussed further below.

## **ACTIVE CYCLICAL CONTROL OF REFRIGERATION SYSTEMS**

The active cyclic control of mine cooling systems has great potential for energy management and reduction of power costs. Again this is a very wide subject and the possible applications are many and varied. In this paper two examples of cooling-on-demand and engineered thermal storage are discussed.

### **Cooling-on-demand<sup>[3]</sup>**

Analogies of domestic hot water systems and room air-conditioners are useful in explaining the principles of mine cooling-on-demand systems. Firstly, consider a domestic hot water system. There are incentives to switch-off domestic geysers to save energy because lowering the temperature of the contents reduces thermal losses. The energy required to bring the contents back up to temperature is less than that required to maintain the temperature. There is however an inconvenient delay in restoring the desired temperature and power has to be switched back-on some time before hot water is required. There is an associated phenomenon when hot water is delivered to the distribution system. First, the residual [cold] water has to be purged from the pipe-work and then, when hot water arrives at the tap, the temperature only increases gradually as the heat from the hot water first heats the pipe and surrounding plaster.

The situation with room air conditioners is slightly different. Air conditioners are not normally left running overnight because they are capable of bringing the air temperature down quickly when required and also because they are high power consumers. It is not necessary for the room itself [walls, ceiling etc.] to be cold only the air inside the room during the period that it is occupied. Keeping the room colder than the external environment again increases the thermal losses. The same logic may be applied to mine cooling systems. But a common mindset that hinders the implementation of cooling-on-demand is the perception that if cooling is stopped, even for an hour, it takes days to restore the original conditions. It will be shown that this mindset is not correct.

There are ways of efficiently controlling and directing mine cooling effort. Instead of cooling all-the-mine-all-the-time, consider for example operating coolers at higher duties for less time in selected areas and experience the same, or even better, conditions underground during the 'on-period'.

During the 'off-period', air temperatures will be above normal and heat flow from the rock surface will reduce [or even reverse]. This approach is examined by running the on/off models for numerous cycles so that the short term effects diminish and stable conditions can be observed. In designing and modelling these systems some important questions to be considered include:

- What is the reduction in overall cooling demand?
- How much more cooling is needed in the on-period?
- What are time delays before downstream conditions are achieved?

In the following example, the thermodynamic behaviour of the rock was modelled using finite-element techniques and the air-side calculations were performed using the features of the VUMA-transient software. The models were regularly tested and refined to ensure the sensitivity and accuracy of response to the most important parameters.

For this case study, the mine ventilation, cooling and refrigeration systems were modelled in a suite of integrated modules that calculated the performance of all the major components in the network. The example relates to a 2000 m intake airway with airflow of 43 kg/s in rock of virgin temperature of 50°C. Air arrives at a cooler at the start of the tunnel at 27°Cwb and is cooled down to 20°Cwb - a duty of 1000 kW. The temperature of the air at the end of the 2000 m tunnel is 26.7°Cwb. The 1000 kW cooler is assumed to operate on a cycle of 18 hrs on and 6 hrs off. Figure 4 shows the effect on the wet-bulb temperature at the end of tunnel. The original steady-state conditions [with 1000 kW continuous] are given by the horizontal reference line. Operating the same cooler intermittently causes the delivered air temperature at the end of the on-period [18 hrs] to increase to 27.2°Cwb. This is because the tunnel is now subjected to less overall cooling and will be slightly warmer. To fully compensate for this effect, additional cooling will be required during the on-period. This can be calculated as the additional cooling required at the end-point to achieve the original steady-state conditions. In this particular example this is 100 kW [43 kg/s from 27.2°C to 26.7°Cwb] – an additional 10%.

However the cooling of 1100 kW is only applied for 18 hrs which translates to a refrigeration related power saving of 17% when compared to the 24 hr cooling scenario. Figure 4 also shows that when the cooler is turned on again, the cold air arrives within 1°C of the temperature achieved at the end of the on-period [although it takes about 10 minutes to physically travel the 2000 m]. This

delay is shorter than the travelling time for personnel to the same destination and should not be an inconvenience [unlike the delay in the hot water example]. It is also worth noting that the temperature at the end of the off-period using the air cooler in cyclical mode is only 2.5°C higher than the base-line.

An alternative scenario is to achieve better on-period conditions by applying the original 24 hr cooling over the shorter 18 hr duration. In this particular example, the 1000 kW cooler becomes a 1330 kW cooler and the end-point temperature after 18 hrs drops to 25.6°Cwb - an improvement of 1°C, see Figure 5. This provides an additional 230 kW of cooling power with high positional efficiency. The maximum off-period temperature in this case will be 28.9°Cwb.

The practice of cooling-on-demand can be used to reduce the size of refrigeration machinery, reduce power consumption and/or improve conditions. In summary the observations from the modelling are that the tunnel heat/cooling power requirement reduces by 17%. Only 10% additional cooling is required during the on-period [which is 75% of time] to achieve similar conditions. The time delays before downstream design conditions are achieved are negligible.

Other similar studies, with the on/off control of underground recirculation based cooling systems, have indicated savings in refrigeration related power consumed of up to 20%.

### **Engineered thermal storage**

Another versatile approach makes use of thermal storage dynamics to damp the effect of unloading the refrigeration plants at certain times. The thermal storage effects can be in the form of:

- Ice banks located in storage dams.
- Cold water in storage dams.
- Mechanisms that occur in the cold rock mass and shaft steel work.

The engineered systems using ice-banks create, by far, the most powerful controlled thermal storage approach. However, where water storage dams exist, the practical convenience and economic factors make this approach attractive. The passive cyclical thermal storage in the static rock mass and shaft steel components can contribute a very useful and inherent effect, if correctly exploited, as noted above.

Cold water dams in mines have been used for thermal storage for many years, however over time, the original control logic has often been lost. With the renewed strong current awareness of all

energy related matters in mining the application of the existing dams is coming under close scrutiny.

Perhaps more significantly, there has been some success in the use of ice for thermal storage in mine cooling systems<sup>[4]</sup>, see Figure 6. In these systems, a single refrigeration machine is operated on glycol and serves an ice-coil bank facility. In the ice bank, ice is formed on the outside of tube bundles during certain parts of the day and then melted by the circulating water in strategic times of the day when the refrigeration compressors can be un-loaded. This approach will allow load shifting [and provide 'free' cooling in the critical warm periods and provide ultra-cold water to underground or to enable production of ultra-cold air]. This use of ice in mine cooling systems differs from the current applications at ERPM and Mponeng where ice is the product transported into the mine for cooling purposes. The ice thermal storage system at Impala<sup>[4]</sup> and has been working for about five years successfully implementing thermal load damping. At present, plans are well advanced to re-programme the control logic at this system for load-shift purposes to satisfy Eskom's needs [the versatility of control options enabled by this approach is to be noted].

Another example of this application is shown in Figures 7 + 8. The refrigeration system includes 5x10 MW<sub>R</sub> capacity of refrigeration machines. The total installed rated power [including auxiliaries] is 12 MW<sub>E</sub> and the chilled water produced by this system is used for air cooling and as cold feed water to the mine. One of the refrigeration machines will operate on a glycol-water solution which will serve a large ice-bank to be installed in a storage dam. Ice will be formed on the coil bank during standard and off peak tariff periods and subsequently this ice will be melted [from the outside] by diverting the water flow to the ice coils to provide cooling. This system will allow, for example, a load shift of 3 MW<sub>E</sub> to 10 MW<sub>E</sub> depending on the season and allow the mining company a reduction in power costs of greater than R 2 million per annum.

## REFERENCES

1. S J Bluhm et al, Generation and distribution of refrigeration for ultra-deep mining: new challenges and insights. *Proceedings of FRIGAIR 2000 International Conference*, Midrand, South Africa, March 2000.
2. S J Bluhm et al, Current research and development in environmental engineering. South African Institute of Mining and Metallurgy, Ventilation and Refrigeration School, Johannesburg, South Africa, July 1990.
3. R E Gundersen et al, Improving the efficiency of mine ventilation and cooling sys-

tems through active control, *Proceedings of the Eighth International Mine Ventilation Congress*, Brisbane, Australia, July 2005.

4. R W Wilson et al. Thermal storage and cyclical control of mine cooling systems. *Journal of the Mine Ventilation Society of South Africa*, Oct/Dec 2005, pp 117-121.