The Future Mine Collaborative Research Initiative: Making Research Work

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Abstract

The FutureMine Collaborative Research Initiative has been successfully completed after three years of activity. The main objective of this initiative was to provide applications of research previously undertaken in the DeepMine initiative in terms of realistic solutions to problems facing gold mining operations as they reach for depths beyond 3500m below surface.

The FutureMine initiative was sub-divided into four broad streams of technological expertise: rock engineering and seismicity; mining engineering and orebody management; software and communications and ventilation, cooling and refrigeration. This paper presents a summary of research output in this last area of expertise. Broadly, research in mine ventilation, cooling and refrigeration was directed in areas related to the re-circulation of air, cyclical use of ventilation and cooling systems, air scrubbing technology, optimization of chilled water reticulation, obtaining direct cooling at the work-face, improving underground refrigeration system through dry air-cooling and water heat rejection systems and a number of software simulation programs to be used in specific applications and as a tool assisting real-time monitoring of underground environmental conditions.

This paper describes in broad terms the outcomes from this section of the research programme and proposes ways in which some of these technologies may be combined synergistically in novel systems aimed at maintaining acceptable environmental conditions while reducing the impact on the profitability of operations.

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Introduction

The South African Mining Industry greeted the conclusion of the DeepMine collaborative research programme with enthusiasm. The outcomes exceeded expectations and the formula proved effective and successful in directing research to provide useful outcomes. The success of this initiative was recognised even before the end of the research programme and led to the creation of a similar research initiative directed at coal mining (Coaltech 2020). The enthusiasm following such success was driven further by numerous questions posed by some of the results produced by the research. It was therefore not surprising that the research programme sponsors rekindled the initiative by creating the FutureMine research programme.

The objectives of FutureMine were primarily to select findings form the DeepMine initiative with the view of developing new technologies and methods that could assist in bridging any technology gaps to facilitate the progress of mining operations between 3500m to 4000m below surface. The DeepMine initiative was aimed primarily at establishing the needs for mining at a depth of approximately 5000m below surface and to define which technologies needed to be developed to achieve the objectives of such a strategy.

Briefly summarised, the findings of the DeepMine research programme in terms of ventilation, cooling, refrigeration and occupational hygiene, concluded that current technology would have to be advanced and modified to meet the challenges posed by mining operations at this depth.

At these depths, workers would have to be protected from an increasingly hostile environment exemplified primarily by the risk of high ambient temperatures both physically and psychologically. In this respect, the provision of air in sufficient quantity and of adequate quality in all working places was highlighted. This in turn pointed to the need to provide ventilation, cooling and refrigeration systems operating more efficiently and therefore designed to a higher degree of sophistication. The outcomes of this research pointed to changing air distribution strategies, improving the efficiency of cooling water reticulation systems and streamlining the refrigeration system design.

In general terms, the FutureMine initiative was structured along a similar model as its successful predecessors by sub-dividing the research programme in a number of major streams dedicated to:

- mining engineering,
- seismicity and rock engineering,
- mine ventilation, cooling, refrigeration and occupational hygiene,
- software and communications.

The brief of the FutureMine initiative was to develop technologies that would enable the South African gold mining industry to make the next quantum step towards mining beyond 3500m. This paper describes the research activities that were undertaken by FutureMine as part of the mine ventilation, cooling, refrigeration and occupational hygiene research stream.

From ventilation cooling and refrigeration perspectives, the research programme was sub-divided into a number of research thrusts:

- Air distribution strategies.
- Air cooling systems.
- Refrigeration plant technologies.
- Software applications.

Furthermore, the value of this work would be enhanced significantly if affinities and synergies between these facets could be exploited in an integrated design strategy. The links between ventilation, cooling and refrigeration are apparent and the application of custom-developed software would enhance the operation of such systems in conjunction with each other.

Air distribution strategies

As part of this section of the research, the feasibility of controlled air re-circulation was analysed more closely with the view of developing an air scrubber that would allow the operation of a re-circulation strategy. The objective of such a system would be to limit the amount of fresh air drawn into a mine thus limiting the heating effects resulting from auto-compression of the air. This effect may be considerable and will add significantly to the capital and operational costs of operations related to air cooling and refrigeration where the mining horizon is between 2500m and 3500m below surface.

During research performed as part of the DeepMine initiative, the advantages of controlled air re-circulation were re-affirmed and the project undertaken now by FutureMine would be aimed at designing a unit that could handle between 50 and 150kg/s of air in bulk. The critical functionality of such a unit would be assessed in its ability to handle heat, dust, respirable carbon dust, radon gas progeny, carbon monoxide and sulphur dioxide in a number of integrated air handling stages of the same unit. The design of such a unit would be based on providing liquid sprays or mists that would eliminate solid particulates through impact while providing an adequately large reactive surface for chemical reactions to take place.

The unit would be designed to handle pollutants during the normal production shift. Re-circulation of air would be suspended during the blasting and re-entry periods. The following aspects were covered as primary topics:

- Pollutant definition in terms of air load, toxicity and ease [or difficulty] of air conditioning treatment.
- Review sources of pollutants and their loads
- Review internationally acceptable exposure standards
- Definition of typical or expected capture efficiency for each pollutant
- Production of first order specifications for a typical installation
- Review the status of relevant technologies against these requirements
- Define specific performance criteria and 'scope' of hypothetical installation
- Provide a pre-feasibility [order-of-magnitude] assessment on this concept both in terms of technical risks and financial viability.

Typical capture efficiencies were found to be as follows:

	Attainable	**Future**
Attached Radon Daughters	50%	
Diesel Particulate Matter (DPM)	80%	
Respirable Mineral Dust	90%	95%
Nitrogen Oxide (NO)	70%	75%
Nitrogen Dioxide (NO_2)	85%	90%
Carbon Monoxide (CO)	25%	33%
Sulphur Dioxide (SO_2)	90%	

Design work was undertaken to increase the capture efficiencies to levels reflected in the “Future” column in the table above.

The outcome of this research resulted in the preliminary design for an underground installation that could handle 100kg/s of air and reduce typical pollutant loads to acceptable levels except for CO and radon gas scrubbing. The removal of carbon monoxide was simulated in laboratory and pilot plants using potassium permanganate and hydrogen peroxide. This was found to be ineffective and would require the use of large quantities of dangerous chemicals underground.

The use of gold catalytic converter technology was considered for this purpose but was soon abandoned in terms of system practicalities.

The success of this system is defined by:

- The ability to transport and handle the various chemical reagents for underground use in the air-scrubber.
- The ability to collect handle and remove from the mine considerable masses of salts and solids.
- The ability to dispose of the by-products into the environment in a safe and responsible manner.
- The use of oxidising agents requires the use of non-corrosive materials and components.
- Adequate and regular maintenance are essential to ensure continuous operation at the correct regimes.

- Adequate protective measures have to be in place to offset the hazard posed by underground fires, breakdowns and power failures. This requires the use of stand-by equipment and redundancy in system layouts.

The conclusion from this study was that the construction and operation of such an air scrubber and air conditioner would be feasible as long as the problem of CO scrubbing could be resolved.

Air cooling systems

A number of project were undertaken to improve the performance of air cooling systems both in terms of the “hardware” used (cooling coil technology) and of the strategy that could be adopted to reduce the considerable operational and distribution costs of extensive reticulation networks. The following aspects were considered:

- Cyclical operation of air cooling systems
- Develop a portable and effective in-stope cooler.
- Assess the feasibility of using dry air cooling systems.

The cyclical operation of cooling systems was proposed by findings from the DeepMine research programme. The continuous operation of cooling systems is presently the norm in South African deep level mines and the validity of this practice was questioned seeing that all mines have to observe a four to six hour re-entry period where the stopes are abandoned. This presents an opportunity to reduce the operational costs considerably by turning-off the cooling system when this is not required.

The aim of the study was to consider two mines and study the effect of turning-off the cooling system in the re-entry period. The study was carried-out firstly by computer simulations and secondly by verification of predictions through measurements in a section of the mine.

The advantages of this strategy are perceived to be:

- A reduction in the size and capacity of the refrigeration plants.
- A reduction in the size and capacity of the water pumping systems.
- A reduction in power costs both in terms of refrigeration power and pumping power.

Initially it was thought to include the reduction in airflow as part of this strategy. This suggestion was quickly dismissed as a continuous flow of air through the stopes and airways is essential in scavenging pollutants adequately during the re-entry period and will prevent the build-up of toxic or flammable gases. In addition the continuous flow of air will prevent the excessive rise in temperature and will assist to some extent in removing heat energy from freshly blasted ore - bearing in mid that the rock temperature at these depths is in the region of 60^{o}C.

Another consideration that is made is the extreme conditions experienced on re-entry just after the cooling system is re-started. In this respect two aspects are to be considered namely the time it takes for the systems to deliver the full cooling power (or system’s “inertia”) and the rate at which cooling may be achieved at the working face. This aspect points to the need for the use of coolers right at the face (in-stope coolers).

Results form the simulations and observations indicated that the cooling of the mine in the on-shift had a positive effect in that some residual cooling could be experienced when the cooling systems were switched-off for a significant period of time. The study also showed that the benefits that could be accrued in the mines analysed could result in a saving of 12% in the power supplied by the surface refrigeration plant while a further saving of 18% of the underground and 3% of the surface refrigeration capacity could be achieved in the second mine. These savings would have to offset the cost of introducing the equipment and control systems necessary to operate these strategies.

The study concluded that the application of such a strategy in existing operations would be marginal for obvious reasons linked to the rigidity of existing system, design of machinery, water distribution networks and control systems. However, the application of cyclical cooling in new sections of mines at these depths is feasible and is likely to be beneficial. In applying these strategies due consideration should be given to:

- The magnitude and significance of transient conditions on stope and development end re-entry need to be considered studied and managed accordingly.
- The design of the mine’s de-watering system particularly in terms of the size of dams, pumping periods, electrical power tariffs, etc.
- Machinery and equipment have to be designed to withstand the stress imposed by daily start-up and shutdown routines.
- Control and remote actuation and modulation systems have to be compatible to this mode of operation in terms of sensitivity, speed of response, accuracy of measurement and reliability.

As mentioned above, the use of an effective in-stope cooler forms an essential part of the strategy required for the successful application of in-stope cooling. More importantly, as recognised in the DeepMine research programme, the temperature increase in stopes operating in these rock temperatures require the intermediate cooling of the air as this ascends through the stope. The need was expressed to develop a lightweight unit that could be used to cool air at a rate in excess of 60kW. Figure 1 shows the concept used for the development of prototype units that were manufactured and tested underground.

An in-stope cooler design had been proposed and constructed as part of the DeepMine programme. However, the challenge was to reduce the size and weight of the unit for ease of transport and installation in stopes.

The objectives were achieved by:

- Splitting the fan and cooling coil sections into two.
- Sourcing adequately sized axial flow fans constructed with polymer casing and impeller.
- Sourcing a high performance, lightweight cooling coil that could be shaped to the required circumference.
- Fitting the coil and water connections in a polymer casing of similar length as the fan.

Each unit is transported to site by two men using the suspension lugs supplied. Once on site the two halves are

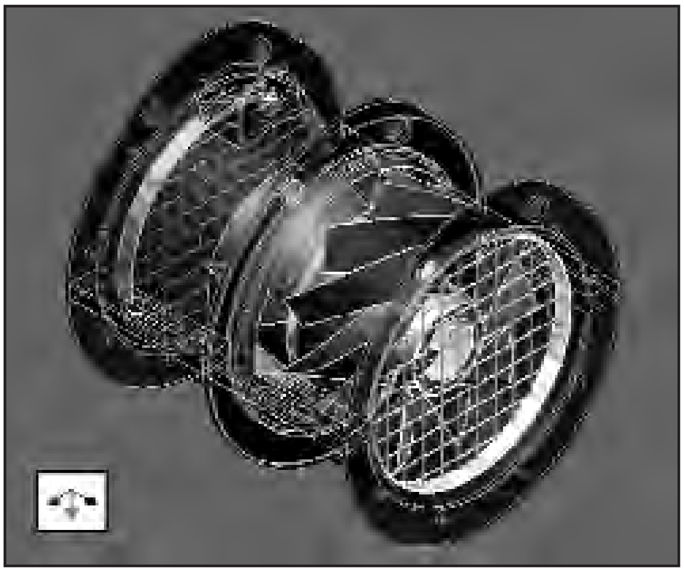

***Figure1**: In-stope cooler concept*

connected by placing nuts and bolts through the common flange. The electrical and water connections are made to render the unit operational.

The units were tested underground at two sites and performed well quickly winning the favour of the workers in the areas where these utilised. The performance matched the design criteria and the units stood-up well to the extreme conditions to which they were subjected. See Figure 2.

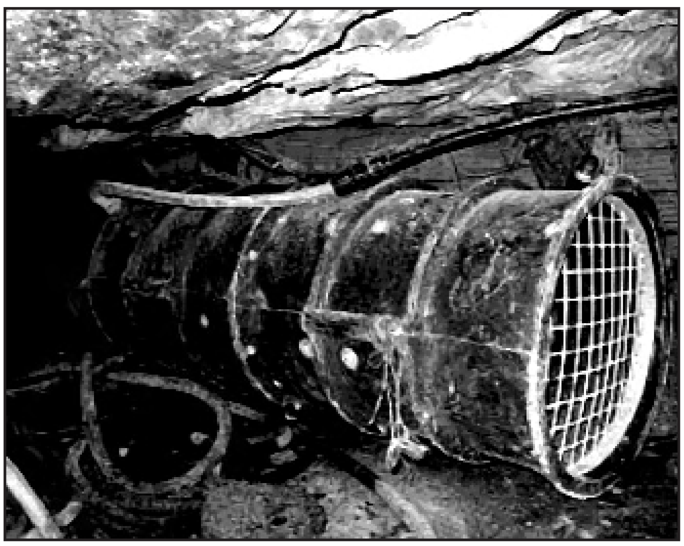

***Figure 2:** In-stope cooler installation in a strike gully.*

Another strategy postulated as part of the DeepMine initiative and taken-up in the FutureMine programme of activities, is the feasibility of adopting dry air cooling. The aim of this research project was to investigate and develop a viable dry-air cooling system for mining bulk air cooling applications. The work was structured in two parts, namely experimental prototype testing and practical viability.

Dry-air cooling involves cooling the air by removing moisture from the air (through latent cooling or dehumidification) from the air. This will decrease the enthalpy of the air while the dry-bulb temperature is maintained as high as possible. This limits the heat flux between the rock and the downstream air to a minimum thus reducing the heat energy pick-up and temperature increase as the air flows through the haulage. The wet-bulb temperature, enthalpy, cooling potential and the comfort index of the dry-air remain virtually the same as those produced in conventional cooling systems. The only difference is the dry-bulb temperature and moisture content of the air. There are two important observations that are relevant in the implementation of this strategy. Firstly, the criteria defining the acceptability of environmental conditions are based on wet bulb temperature limits. Secondly, the heat energy absorption potential between the rock and the air is proportional to the temperature difference between the rock and the dry-bulb temperature of the air. The rock temperature increases with depth while the temperature range within which operations are allowed remains constant (around 30,0^{O}C). Therefore, increasing the dry bulb temperature without penalising the wet bulb temperature will reduce the heat energy absorbed by the air. This consideration is important in reducing the heat energy absorbed in a drive over two thousand metres long.

The scope of the work was to test the experimental prototype based on practical considerations and use the results to design a full-scale system for a mine application. A feasibility study would show the practical potential and cost benefits of such a system. This report contains the main findings from this work.

The prototype was tested at the CSIR-Mingtek laboratories and proved the concept to acceptance. Consequently, a full-scale system could be developed from this data. The experimental work showed a good correlation between the expected results and the actual measured values. Figure 3 shows the layout of the prototype unit tested at CSIR-Miningtek.

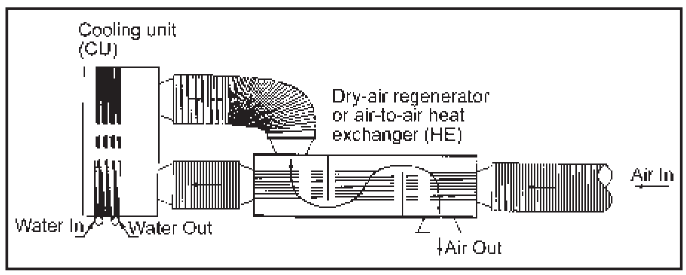

***Figure 3**: Layout of dry-cooling prototype.*

The full-scale design was based on a mine in the West Wits line. An important part of the study was to highlight practical constraints and limitations and to investigate options. The purpose of the study was to investigate the feasibility of retrofitting or installing a dry-air cooler at a bulk air cooler of a mine and to identify potential practical problems with such an installation.

An air-to-air heat exchanger was sized according to the mine's current requirements. Various options were considered with advantages and disadvantages. This part of the study showed some of the constraints in developing a dry-air cooling system when retrofitting this to a current cooling system s opposed to building a new system.

None of the options investigated offer a truly feasible solution in terms of benefits for the mine selected for the study. This was mainly as the result of constraints and limitations placed by the existing infrastructure and by the fact that the system had to be retrofitted in an operating shaft. However, this conclusion may vary for different mines. The study does show that there is potential for net financial benefits in using a dry-air cooling system, but this is dependent on the project's constraints - the application of this strategy to a new section of the mine being the most promising option. The study highlighted a number of practical problems that could be encountered whenever a system like this is retrofitted to any operating mine. This provided useful information that was incorporated in the final report and that may be used by practitioners for future reference.

Refrigeration plant technologies

The tendencies highlighted in the DeepMine research pointed to the use of ice plants on surface and maximised use of underground refrigeration plants as a strategy for reducing operational and capital costs for the provision of chilled water for air cooling processes. FutureMine therefore concentrated efforts in this area of expertise to perform studies in this direction.

Much of this work was performed in conjunction with the School of Mechanical Engineering of the University of the Witwatersrand. As such this highlighted one of the objectives of the FutureMine initiative: that of providing opportunities for students to benefit from this initiative in terms of participation and experience. Over and above this, the Management and Sponsors of the FutureMine donated some of the equipment used in the research to the university for further use in research and educational applications.

In terms of ice plant technology, studies were performed at the School of Mechanical Engineering's laboratories and at the Mponeng mine to analyse the flow of slurry ice in horizontal and vertical pipes. The outcome of this study was a set of design procedures and guidelines that would assist engineers in the design of pipelines on surface and underground.

The research involving ice plant was dedicated at establishing whether hard ice could be generated from mine (process) water. Hard ice is considered to be a better product and the manufacture of the ice itself is deemed to be less complex not requiring the use of large high speed compressors using water as a refrigerant as is the case for slurry or vacuum ice. Hard ice may be generated relatively easily on surface using ammonia refrigeration units. This implies considerably lower capital and running costs. The transportation of this type of ice is also deemed to be easier than slurry ice.

Up to now it was thought that hard ice could be produced effectively only by using potable water thus adding to the cost of production and of excess water disposal. The use of process water within the mine's circuit would reduce these costs.

The study consisted in defining a number of "test" water prototypes that were obtained by analysing water samples over a long period of times from mines in the Carletonville, Klerksdorp and Welkom areas. The samples were tested for dissolved solids, suspended solid content, acidity (pH), scaling tendency, hardness and freezing point depression. The samples were used to formulate a number of water batches that were prepared an used in a pilot plant application.

The project team sourced and re-located a hard-ice machine from the Johannesburg produce market to the Driefontein mine. Figure 4 shows the pilot plant at the mine.

***Figure 4**: Pilot plant at Driefontein Mine*

Numerous runs were made using the batched water together with a potable control batch. The results showed consistently that process water can produce hard ice with a dryness fraction in excess of 90% for the three process water batches used as compared to an ice fraction of 99% for potable water. This is deemed to be suitable for mine applications.

As a last part, the ice plant was transferred from the mine site to the University of the Witwatersrand School of Mechanical Engineering Laboratory. The unit was re-constructed and re-commissioned and will be used for undergraduate and post-graduate research and tutorial work. Figure 5 shows the commissioned unit in the laboratory.

In order to improve the efficiency of cooling systems utilising underground refrigeration plants, a study was performed on the feasibility of using process water being pumped out of the mine in order to increase the heat rejection capacity of underground refrigeration plants. This concept's feasibility was proposed previously and required verification against real mining parameters.

***Figure 5**: Ice plant at Wits University*

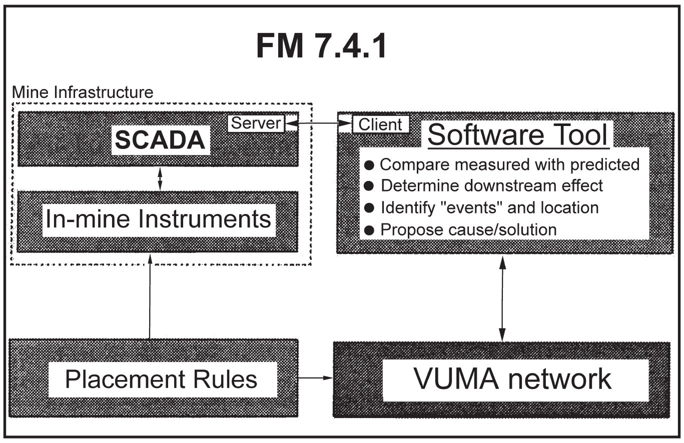

Figure 6: *Real time monitoring software system design.*

The intention of this strategy is to make use of water being removed from the mine as an additional heat sink. The study was aimed at testing previous postulates in this respect and at stating the viability of such a strategy in real applications. For this reason the application of such a strategy to the cooling system of the TauTona mine in the Carletonville area was studied in depth.

The study showed that the practicalities involved in retrofitting this system at TauTona would negate any cost benefits. In the first instance, the operational temperatures of the pipes would increase beyond the design limit and would induce destructive stresses in the horizontal and vertical sections of the pipelines. Insulation of the condenser water pipes would be required to prevent re-heating of the fresh air where the pipes occupy intake airways. The reduction in condenser water temperature would not increase the efficiency of the compressors as these are operating at peak efficiency - determined by the present system's operating points. The fluctuation of return mine water availability in diurnal pumping cycles would result in system instability and requires "smoothing" in terms of water management and condenser throughput.

Notwithstanding these findings pertaining to the TauTona pilot site, the study concluded that the strategy may be viable provided that the following issues are addressed:

- Refrigeration plants, pumps, dams and piping have to be selected and arranged in a way that would suit the use of return water in the condenser water circuit both in terms of temperature, quantity (fluctuating) and quality (suspended and dissolved solids).
- In addition the operational parameters of the pipeline in term of thermal stresses and transmission of heat energy to fresh air need to be considered.
- A series of operational hazard studies have to be identified and performed to address risks in specific applications.
- The reduction in power consumption that could be achieved in adopting this strategy may be significant enough to convince the electricity supplier to co-fund the system's alterations.

Software applications

Two software applications were developed as part of this thrust within the FutureMine programme. The first application consisted of developing a system that could be used in the real time monitoring of conditions underground while providing certain predictive features that could assist in trouble-shooting.

The system was developed to run off the VUMA simulation software platform in conjunction with a SCADA data collection system. The work was performed in conjunction with the School of Mechanical Engineering of the University of the Witwatersrand and formed part of a postgraduate research programme. The philosophy adopted in completing this work is outlined schematically in Figure 6.

The project consisted in developing a platform that would bring together the predictive output of a real mine network modelled using the VUMA software and the continual data flow from underground provided from the SCADA system. The development of a data exchange protocol that would set the two systems on the same dynamic base proved to be a challenging task. This resulted in the development of an interactive comparative tool that:

- can compare conditions measured by the SCADA system with conditions at the same point as predicted by the VUMA model,
- can determine or predict the effect of changes downstream of key environmental measuring stations,
- can identify the location and nature of certain events and
- can provide an explanation as to the cause of the problem and the solution thereto.

Essential in achieving the predictive properties of the software tool is the definition of "placement rules" that will be utilized in the various decision algorithms. These rues have to be established as part of the system's simulation procedure. The rules have been structured to guide expert users in generic terms when the model is structured. The correct structuring of the rules is essential to maximise the accuracy of predictions and proposed solutions. Given the nature of the systems being utilised by this software application, the VUMA model, software tool and placement rules have to be reviewed at regular intervals.

The software was designed and tested successfully with data obtained from the SCADA system operated at the Beatrix mine. The outcome from this work is a workable system that will require some refinement in order to make it more widely accessible and more user friendly. Issues around the program's stability under intense transient data flow has to be resolved but the concept has proved its worth and robustness for application in real life situations.

The second software tool developed as part of the FutureMine imitative consisted in devising a package for the simulation of underground chilled water network design. This tool has been designed to take into account the thermodynamic properties of the pipe network, the heat exchangers used in the air cooling systems and the environment surrounding these. This is seen as a first generation Windows-based software modelling tool that has the potential of integrating data from other software tools - in particular VUMA - in order to form an amalgamated system of data and simulation tools that will model automatically the interaction between air and the cooling processes for steady-state conditions.

The software was born out of the need to provide a simulation tool that would facilitate and expedite “what-if” simulations in the design of chilled water reticulation networks. In addition, the tool will allow the optimization of the design of these systems in a much reduced time period and with greater accuracy.

The software programme considers the type and condition of piping, pipe insulation and air coolers together with the ambient air conditions at locations where these are installed to predict the heat energy absorbed in the system, the performance of the systems and to highlight any inefficiencies and anomalies.

The interaction with an environmental predictive tool such as VUMA that will utilize and generate thermodynamic inputs and outputs is a logical step. To this end the owners of the VUMA software agreed to integrate a number of platforms and sub-programs to give the final product features very similar to the VUMA program in order to give this new software an immediately familiar "feel" for new users. Figure 7 shows a screen replication from the new software program showing the familiar VUMA look of the package.

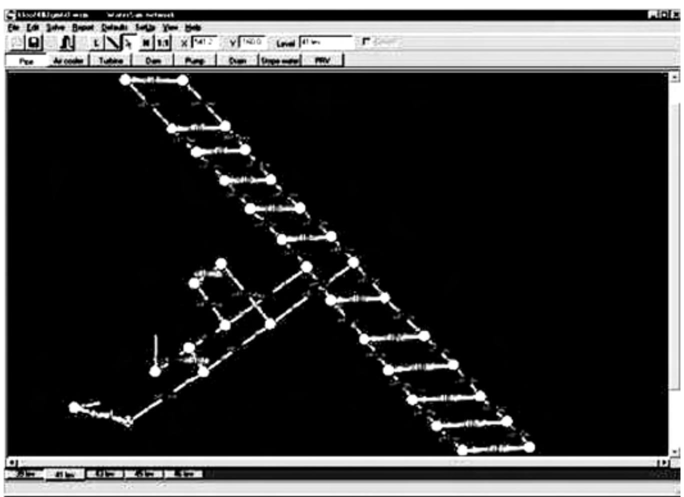

***Figure 7**: Chilled water network simulation.*

As part of this development, the completed package was tested by simulating the Kloof mine’s No.4 Shaft closed loop chilled water distribution system. The predicted conditions were compared with actual measurements by the project team. The results showed a remarkable correlation that rendered the team confident of the validity of their work. In addition the results were also used to make recommendations to the system operators in an effort to improve performance and efficiency. This software tool requires certain refinements in order to make it more user friendly and facilitate integration with VUMA even further.

Discussion and conclusion

From a purely ventilation cooling and refrigeration perspective this research has delivered very valuable results. First and foremost perhaps is the need to move away from steady-state frame of mind into a more dynamic real-time view of systems. This is dictated by the increasingly harsh conditions and the need to provide cost effective and reliable solutions.

On a more pragmatic note, the interaction between ventilation, cooling and refrigeration system will become more critical in the future. The design and selection of different components of these systems is becoming more intimately inter-dependent. Good design practice requires consideration of these aspects in the early stages of design.

As an example, the introduction of controlled re-circulation of air would curtail seriously the ability of using underground refrigeration plants due to the limited heat rejection capacity. Now the system designer is faced with the dilemma of introducing return water heat absorption systems (are these sufficient of adequate?) or of using surface ice plants. As a further example, the introduction of cyclic cooling strategies requires adequate and dynamic monitoring and diagnostic tools that could well be in the guise of the software described in this paper.

More importantly is the way in which concepts postulated in the DeepMine research initiative were developed by FutureMine into prototype and pilot plant applications. This has allowed desktop research results to be developed into systems, tools and hardware can be utilised in the field. A number of projects did not deliver in line with expectations mainly because of the difficulties encountered in retrofitting these concepts into existing applications. However, in all cases the lessons learned were recorded and disseminated in the form of guidelines for users. These will be valuable to engineers and practitioners should they decide to investigate or implement these design options.

The most important lesson that can be taken from this exercise is the need to focus and manage research in a constructive and consistent manner. In this respect the management and sponsors of the FutureMine must be saluted for having displayed extensive understanding and leadership in keeping the programme on track and on budget. The outcomes from this initiative are deemed to be useful and will be developed further by individual sponsors so that the products may be tailored to their specific needs. In this respect it is not unconceivable that interested parties will structure electively funded projects in order to develop industrially viable products.

Acknowledgements

The authors extend their gratitude to the management and sponsors of the FutureMine collaborative research initiative for motivating this paper and allowing its presentation at this Congress.