



AN APPLICATION OF HIGH MASS FRACTION TUBULAR ICE IN THE DESIGN AND DEVELOPMENT OF COOLING SYSTEMS FOR MINING AT DEPTH

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This paper is dedicated to the memory of Marius de Leeuw. Marius was a colleague who facilitated the mine design and performed the project management of the Phakisa Mine Deeping Project. Marius' strength and faith during the last months of his life gave me a new appreciation for the meaning and importance of friendship. He lived his life well by acting in accordance with his unequivocal faith and reliance upon God. He faced his too early death bravely. During his terminal illness, he remained so positive and was an enormous inspiration to us all.

1. SYNOPSIS

This paper presents a conceptual level discussion on the selection, design and development of a cooling solution for Harmony's Phakisa mine. It describes the increased demand for refrigeration as mines progress deeper and briefly presents the traditional mine refrigeration systems available for selection. The paper explores the thermodynamic advantage of ice compared to chilled water by distinguishing between 'sensible heat' and 'latent heat'. The various methods of producing industrial ice are discussed followed by a brief history of the application of ice for cooling in South African mines.

The second part of the paper is devoted to the feasibility of adopting ice as a cooling solution at the host mine. The constraints which impacted on the selection methodology are presented followed by a description of the actual tubular ice production process at the mine. To appreciate the lead time associated with installing ice plants, the project millstones from business case approval to final commissioning is included.

The ice plants at Phakisa have been in operation since 2010 and certain design shortcomings were identified post commissioning of the plants. The design alternations effected by the mine are included for the reader's consideration when future ice applications are considered.



2. INTRODUCTION

During and post 1970, many underground mines in South Africa reached depths which necessitated cooling to enable safe production. Calm (2011) describes that as mines develop deeper, to reach previously untapped or previously less economic minerals, thermal loads increase. Not only does ambient rock temperature increase at depth but air temperatures also increase due to auto compression (Ramsden and Bluhm, 1985). As a result, the demand for cooling solutions has increased exponentially. This demand stimulated the development of alternative mine cooling systems which, as a business imperative, had to be more efficient and more cost effective (Calm, 2011).

Traditional cooling systems consisted mostly of large refrigeration plants on surface. These refrigeration plants typically cool water down to 4°C, after which the water is dispatched down the mine. Chilled water is used for various methods of air cooling such as Bulk Air Coolers (BAC) and Spot Coolers wherein heat transfer takes place between the hot air and chilled water. However, the dynamics associated with water in a pipe system down a mine results in increases in pressure and temperature. This increase in water temperature affects the positional efficiency (PE) of a cooling system – surface refrigeration plants' PE is generally lower than that of other applications such as underground refrigeration plants. Furthermore, the positional placement of surface refrigeration plants necessitates all the mine water to be pumped back up to surface to be circulated through the cooling cycle. At depth, the electrical power required for the refrigeration (including water pumping) is a considerable part of a mine's power consumption. As suggested by Calm (2011), the cost of electricity increases in many mining locations around the world. This is evident in the recent above inflation increases granted to the power utility in South Africa. As a result, the direct cost of cooling and pumping is escalating at an alarming rate. The principle problem is that the deeper the mine, the higher the pumping costs to circulate water for cooling. In certain cases, energy recovery systems (typically turbines) are installed to recover electric power with the added advantage of a reduction in the increase of water temperature (Ramsden and Bluhm, 1985). Other energy recovery systems such as Pelton Wheels¹ or Three Chamber Pipe Feeder Systems² have also been used but the inefficiencies associated with pumping (depth and distance), and the cost thereof, resulted in underground refrigeration systems becoming the preferred option.

¹ Turbine energy recovery device.

² Recovers the gravitational potential of water entering the mine and uses it to pump water out of the mine.



Installing refrigeration plants underground has advantages but also some disadvantages. Placing the plants closer to the mine workings has the advantage of reduced pumping cost and reduced thermal losses (higher PE). However, underground refrigeration plants often present challenges in that ventilation quantity limitations reduce the heat rejection capability of such installations which could result in excessive condenser pressures and a lower Coefficient of Performance (COP). Added hereto, the amount of cooling required for a large deep to ultra-deep level mine often require multiple underground cooling plants. The dimensions of refrigeration equipment require large underground excavations to be developed and in certain cases it may even influence the design of winders and shaft dimensions to facilitate transport of such equipment down the barrel. Large underground chambers occupy development resources for extended periods which increase the cost of these chambers. Furthermore, the maintenance work on underground refrigeration plants may be more involved and time consuming than on similar equipment on surface.

These and other challenges associated with the use of surface and underground refrigeration plants advanced the frontiers of knowledge and science towards the development of new alternative cooling options. One such alternative is the application of ice in the design and development of cooling systems for mining at depth.

3. PRINCIPLE: THE THERMODYNAMIC ADVANTAGE OF ICE VS. CHILLED WATER

The three types of heat particular to this paper are sensible heat, latent heat and specific heat.

Sensible heat is associated with a change in temperature whilst latent heat is associated with a change in state (de Leeuw, 2011). In most cases, heating a substance results in an increase in the temperature of the substance. However, in some cases when a substance is heated the substance transforms its state without a temperature increase. To illustrate the concept of sensible heat versus latent heat, consider the process of heating ice from -10 degrees Celsius ($^{\circ}\text{C}$) to water at 10°C . Initially the heating process will increase the temperature of the ice and this will continue up to freezing point at 0°C – this is sensible heat. Whilst at 0°C the heating process will cause the ice to melt to produce water at 0°C – this is latent heat. After the ice has melted the water's temperature will increase to 10°C as a result of the heating process – again sensible heat.

De Leeuw (2011) continues to describe that the quantity of energy required for a certain change in temperature can be derived from a substance's specific heat. Specific heat is defined as the quantity of energy to change the temperature of 1 kilogram (kg) of a substance by 1°C (or 1 Kelvin (K)). The specific heat of water is 4,19 kilojoule/kilogram.Kelvin (kJ/kg.K) whereas the specific heat of ice is



2,09kJ/kg.K. In the case of latent heat the energy required for a change of state is derived from empirical data.

Refrigeration plants that cool water utilise sensible heat. A typical change in temperature of the water being chilled by a refrigeration plant would be around 20°C and therefore one kilogram of water can absorb 83,7kJ of energy. This result can be calculated from the thermodynamic formula:

$$Q = m \times C_p \times \Delta t$$

$$83.7kJ = 1kg \times 4.19kJ/kg.K \times 20K$$

Wherein:

Q represents energy absorbed in kJ,

m represents the mass of water in kg,

C_p represents the specific heat capacity of water in kJ/kg.K,

Δt represents the change in water temperature in K,

In comparison, ice plants produce ice which utilises latent heat. One kilogram of ice absorbs 333kJ as it transforms state from ice to water at 0°C. Thus, ice has the thermodynamic advantage versus chilled water in that it can absorb more energy whilst at 0°C due to the energy being used to transform state instead of increasing temperature – latent heat.

The energy required to pump water from a depth of 2000m to surface at a flow that can be achieved by a typical multistage pump is in the order of 19,6kJ/kg. This is about a quarter of the energy that is typically absorbed by chilled water. Multistage pumps used at mines are typically less than 85% efficient and typical refrigeration plants require around 17% of its refrigeration energy. In the absence of energy recovery systems, this implies that the energy used for pumping exceeds the power used for refrigeration in a surface refrigeration plant application. In the preceding paragraph it was demonstrated that, due to the specific heat and latent heat properties of water and ice, less ice mass than chilled water mass is required for the same amount of cooling. Therefore the pumping cost associated with ice applications is lower than for chilled water applications. Ice plants, however, are in general less efficient than refrigeration plants.



The following table compares the cooling energy of a refrigeration plant with that of an equal amount of cooling energy should the energy have been utilised to produce ice for a pump-head of 2000m (plants installed on surface without energy recovery).

Table 1 – Comparison: Ice versus water as cooling media (de Leeuw, 2011)

Item	Unit	Water	Ice
Cooling energy	kJ	83.7	83.7
Percentage cooling energy required	%	17%	26%
Cooling plant input energy	kJ	14.0	21.5
Cooling per mass	kJ/kg	83.7	333
Mass	kg	1	0.251
Pumping energy	kJ	19.6	4.93
Pumping efficiency	%	0.85	0.85
Pump input energy	kJ	23.06	5.80
Total input energy	kJ	37.01	27.26

4. METHODS OF PRODUCING INDUSTRIAL ICE

Ice has well known applications in the food and beverage industry but also found application in the mining industry as a cooling media. In this section, the concept of Ice Mass Fraction (IMF) and the methods of producing different types of industrial ice are discussed.

4.1 Ice Mass Fraction (IMF)

Ice is categorised according to IMF. IMF is defined as the ratio of the mass of ice to the total mass of water and ice (de Leeuw, 2011). For the purpose of this paper, ice with an IMF of greater or equal to 90% delivered directly from the ice maker is defined as hard ice. Ice with an IMF of less than 75% delivered directly from the ice maker is defined as slush ice.

4.2 Types of ice and production method

4.2.1 Slush Ice

Slush ice contains less mass of ice to the total mass of water and ice in comparison to hard ice.

IDE Technologies markets a product that produces slush ice using a vacuum process (IDE Technologies limited, no date). Ice is produced by reducing pressure to the point where water boils and freezes at the same time – this condition is also known as the triple point of water. The process takes place at a very low pressure and requires vapour compression equipment. One could describe



it as a pot wherein ice crystals are formed in the water and the water boils to release water vapour. Compressing the very low pressure vapour produced by this process require large compressors operating at high speeds. The installation footprint for this equipment is relatively large. Furthermore, the production of ice crystals (rather than sheet ice) requires salt to be added which reduces the freezing point and changes the structure of the crystals. Salt increases corrosion and increases the need for regular maintenance. The water ice slurry at an IMF of about 9% is pumped to a concentrator where the ice floats to the top and the brine is drained from the concentrator. The ice, at an IMF of approximately 70%, is harvested from the concentrator.

PAM Refrigeration markets a flow-ice called MicroICE® (PAM Refrigeration, November 2006). The system consists of a large number of encased tubes with a scraper inside. Refrigerant, at low temperature, is circulated on the outside of the tubes while water is pumped through the tube. A scraper driven by an electrical motor is installed inside the tube and with a screw effect scrapes off the ice forming in the tube and flushes it to ice concentrator. The ice floats on the water and as the concentrator tank fills it is pushed out at the top and collected for harvesting. Water is added to the circulating water in the system in order to keep producing ice.

4.2.2 Hard Ice

Hard ice contains more mass of ice to the total mass of water and ice water in comparison to slush ice. Hard ice provides more cooling capability than slurry ice of equal mass due to the latent heat that can be absorbed by the ice. Irani (2013) describes the different types of hard ice and the respective production methods:

Block ice systems consist of water in moulds that are placed in brine tanks. The brine is cooled by refrigerant coils which cause the water to freeze. When the block has frozen completely the ice is released from the moulds by heating the moulds.

Plate ice is very similar to block ice with plates functioning as the moulds onto which ice is formed. Plates are generally immersed in water. Cooling through the plates can be achieved directly with refrigerant or indirectly with brine. Once ice has reached the designed thickness the plates are thawed and the slabs of ice releases. Typically gravity is utilised to break the slabs into smaller chunks.

Tube ice machines generally have vertical freezing sections that drop ice onto harvesting cutters. Inside the freezing section are multiple tubes. The tubes are surrounded by liquid refrigerant during the freezing cycle which freezes water running inside the tubes. Once the ice reaches the desired



thickness, hot gas (refrigerant) is used to displace the liquid refrigerant. This thaws the outside of the ice tubes and as a result the tube ice releases from the freezing tube.

There are a number of different methodologies to produce flake ice. Most systems make use of ice forming on a cylinder with some form of mechanical means for ice harvesting. The mechanical means can consist of cutters or even movement of the cylinder itself.

5. HISTORY OF ICE IN DEEP SOUTH AFRICAN MINES

There are three documented cases of the use of ice in the South African mining industry. The concept of ice for cooling at depth originated as early as the mid to late 1970s from the then Rand Mines Group. The Rand Mines Group constructed the first large capacity (1 000tons (t) per day) ice plant, at its Harmony mine, in the late 1970s.

Following the application of ice at its Harmony mine, Rand Mines commissioned the world's largest ice plant at East Rand Proprietary Mines (ERPM) in Boksburg, at one stage one of the deepest mines in the world. The 5 000t of hard ice per day icemaker built at the Far East shaft of ERPM has been decommissioned after successfully operating for about 15 years.

The then Anglo American Corporation later installed an ice-cooling system at what was then known as the Western Deep Levels South shaft, currently named Mponeng and now part of AngloGold Ashanti. This IDE VIM slush ice plants produces up to 27 megawatt of cooling.

6. FEASIBILITY OF ICE PLANTS AT PHAKISA MINE

Phakisa mine is located near the towns of Odendaalsrus and Welkom in the Free State. Sinking commenced by Anglo American Corporation in the 1990s but the sinking project was delayed from time to time prevailing economics. Harmony acquired the asset during 2002 and concluded a feasibility study to recommence the sinking of the shaft. The shaft sinking was completed up to 2357m below collar. The Phakisa shaft was originally designed as a service shaft for Tshepong shaft to its north hence it was designed to be only 7,1m in diameter. The dimension of the shaft imposes constraints such as limited winding capacity, limited space for equipping services in the shaft and also limited intake air capacity. Harmony turned Phakisa into an independent mine by incorporating Nyala shaft, the old Freddie's Three shaft and Eland shaft into the business unit. Services (compressed air, vertical rock transport etc.) are provided from Nyala shaft whilst Three Shaft and Eland both serve as outlet for return air – albeit both are not optimally placed for this need.

The ventilation and cooling design of Phakisa has been subject to many revisions. Initial reports from Anglo American proposed the use of surface cooling plants supplemented with excess cooling



from Tshepong. In 2003, Harmony's design considered cooling to be installed at the Nyala shaft. Bluhm Burton Engineering, during 2004, proposed two underground cooling complexes at Phakisa (Marx, 2005). Despite the work performed during 2004, the most likely cooling solution for Phakisa still involved the use of surface refrigeration plants at Nyala shaft. An internal review revealed that the solution would be less efficient due to inherent losses and that extensive capital expenditure would be required to develop, install and repair the associated infrastructure as well as to construct and install additional multiple dams, kilometres of piping, high pressure shaft columns and turbines.

Ice plants were initially disqualified as a cooling solution on the basis of the plant capital cost which are generally multiples more expensive than water refrigeration plants per kilowatt refrigeration (kW_r). However, due to thermodynamic advantage of ice over water, the mining depth (pumping cost), limited capacity for underground heat rejection as well as the lead time and cost associated with developing underground chambers to house underground refrigeration plants, this was re-evaluated and proved to be the preferred option for a section of the total required cooling at Phakisa mine.

6.1 Selecting the type of ice

Hard ice (high IMF) provides more cooling per mass than slush ice. On the basis of this thermodynamic advantage and a relatively simple transportation solution for hard ice was selected as the preferred ice type. Ice would be dropped down a low pressure (1,6 megapascal) pipe in the shaft, deflected on 54 level through a lined annex hole and be discharged into an ice dam near the shaft on 55 level.

Eight enterprises were approached to supply equipment for producing 2200t of hard ice per day. The solutions available at the time were either flake ice or tube ice. Final evaluation was based on:

- The initial procurement cost of tube ice plants was lower than the cost of flake ice plants.
- Tube ice had a marginally higher Coefficient of Performance (COP).
- Tube ice required a smaller plant footprint, and
- Tube ice is less prone to lumping than flake ice.

Phakisa opted for tube ice as its preferred hard ice option.



7. PHAKISA'S ICELINGS TUBE ICE PLANT

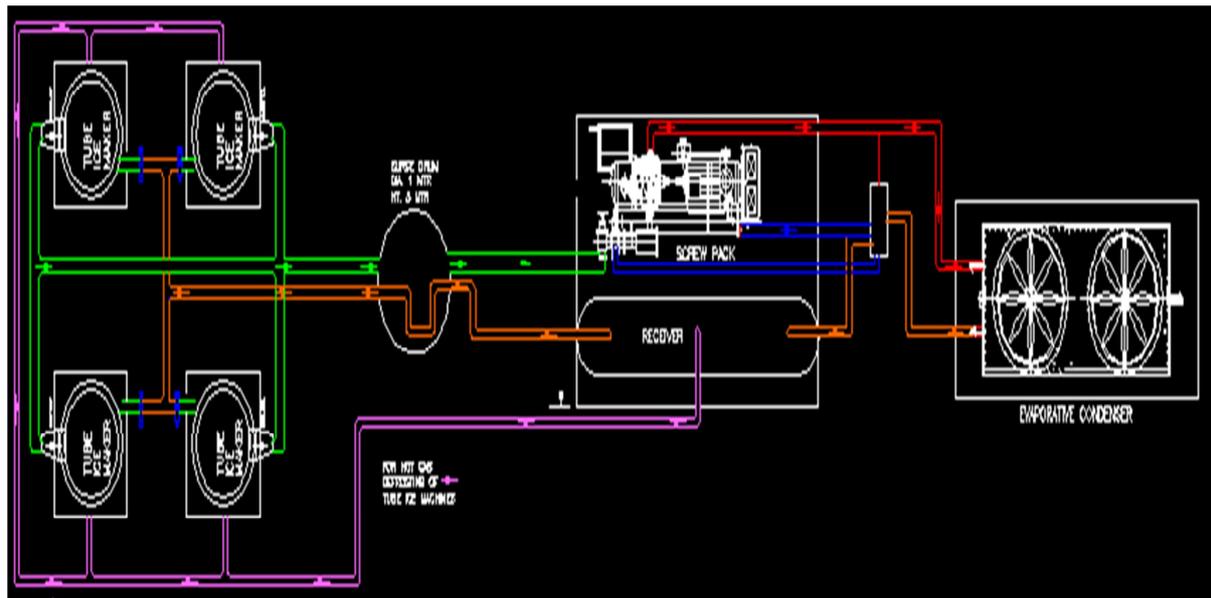
Phakisa installed an Icelings Tube Ice plant on surface. The plant mainly consists of ten individual plants operating each with one compressor unit with a 550kW electrical motor and four evaporators (ice makers). The units are fed with potable water from the local water supplier.

The work of de Leeuw (2011) described the basic process flow of the Icelings ice plant as follows:

- A compressor compresses medium temperature, low pressure ammonia vapor from the ice maker and discharges high temperature, high pressure vapor to a condenser.
- The condenser is a shell-and-tube type heat exchanger with ammonia in the tube and water in the shell. Ammonia vapor is condensed by water circulated in the shell of the condenser. Condensed ammonia vapor becomes low temperature liquid ammonia, and is collected in the receiver. A cooling tower cools the condensing water and recirculates the same.
- Low temperature low pressure ammonia liquid, from the receiver, is fed to the evaporator (ice maker) via an expansion valve.
- The expansion valve reduces the temperature and pressure of the ammonia and injects the vaporized ammonia into the ice maker (evaporator).
- The evaporator (tube ice maker) is similar to the shell-and-tube type condenser. With the water on the inside of the tubes and refrigerant (ammonia) filling the areas between the tubes on the outside.
- Low temperature, low pressure vaporized ammonia absorbs the heat from the water running in the tubes. Ice forms inside the evaporator tubes.
- Medium temperature, low pressure ammonia vapor exits the evaporator and the same is fed to the compressor.
- The cycle is repeated.
- Freezing cycle time of the ice maker is about 16 minutes where after hot gas (top of the receiver) is introduced into the ice maker to defrost the ice from the tubes of the evaporator.
- Ice is harvested by a mechanical cutter located at the lower end of the ice maker.
- The ice is delivered onto a conveyor belt which transfers it to a transfer chute that feeds a series of screw conveyors, which delivers the ice to the 300mm ice column down Phakisa shaft to the ice dam on 55 level.



Plate 2 – Unique operation of four ice makers with one compressor (de Leeuw, 2011)



8. PROJECT MILESTONES: ICE PLANT PROJECT

During 2006, tubular ice plants were proposed in formal project documentation. The table below lists some of the project milestones as the project progressed:

Table 2 – Comparison: ice versus water as cooling media (de Leeuw, 2011)

Date	Milestone
2006, November	Business case approved
2007, May	Gate 1: Technical case approved
2007, June	Gate 2: Commercial case approved
2007, July	Gate 3: Final approval
2007, November	Capital approval
2007, November	Final design approval
2010, March	First ice production
2010, November	Final commissioning of ice plant

9. POST-COMMISSIONING PERFORMANCE OF THE ICE PLANTS

The ice plants at Phakisa have been in operation since 2010. Upon commissioning some design shortcomings were identified which are described in the following paragraphs.

9.1 Refrigerant overflow

The newly installed ice machines averaged 82% of its designed ice making capacity. Investigations revealed that a large amount of refrigerant overflows from the ice maker to a surge drum after the thawing cycle. This problem originated due to the system design of four ice makers operating with



one compressor as well as control valves not operating at design pressures. Ramden (2011) recommended the installation of non-return valves in the liquid drain line to prevent liquid from bypassing the accumulator and collecting in the surge drum as well as to install a return line from the surge drum with a non-return valve to the ice makers to allow any liquid refrigerant to be returned from surge drum to the ice maker. The design alternation implemented by the mine resolved the refrigerant overflow.

9.2 Ice column blockage in the shaft

Ice is transported down the shaft in an uPVC pipe with a column vertical length of 1623m which then angles at 34° for 67m into the ice dam on 55 level. When the ice plants were installed a safety trip arrangement was incorporated to protect the ice column in the event of a blockage. Ice flow, however, is difficult to measure. A load cell was designed and installed to initiate a trip as soon as it reads ice mass in the column in excess of the set control limits. This trip did not operate reliably and during January 2011 the ice pipe blocked, resulting in the failure of 50 pipe sections of the shaft ice column. The mine subsequently incorporated three independent safety devices to initiate a safety trip on: mass changes, vibration changes and temperature changes. The additions have resulted in reliable safety trip-outs to prevent damage and associated down time.

9.3 Screw conveyor

Ice is transported from the ice plants to the shaft by a series of screw conveyors. Sheer bolts coupling the screw spirals to the drive shafts were under designed and led to multiple breakdowns and associated plant down time. The bolts were replaced with bolts of a higher tensile grading and this alleviated the problem. The series of screw conveyors, however, still require excessive maintenance. The mine has planned to replace the screw conveyor with a conveyor belt in future.

9.4 Ice dam ice-up

The dam to which the ice is delivered is a 5m diameter vertical raise bore hole. Although hot return water is re-circulated back into the ice dam, the mine has encountered situations where ice formed a cone on top of a frozen layer on the dam surface. The cone builds until it blocks the delivery-end of the ice pipe. The mine has since implemented various methods of dispersing the hot water and the ice and combined it with safety trips on the dam level to prevent a reoccurrence.

10. OPERATING EXPEDITURE

The three main operational costs are:

- Electrical power consumption.



- Working costs.
- Potable water cost.

The largest contributor to operational cost is electrical power consumption. Working costs are largely spread into 3 categories namely: 55% to labour, 40% to stores and 5% to outside contractors. Although labour is a high percentage of the working cost the plant operates with minimum complement of only 18 permanent staff.

11. CONCLUSION

Harmony opted for high mass fraction tubular ice as part of the cooling solution for its Phakisa mine.

This paper probed into the hypothesis that high mass fraction tubular ice is the optimum solution for the specific cooling application at Phakisa.

The mine design and logistical constraints imply that ventilation and cooling solutions are highly complex. The combined effect of the latent heat thermodynamic advantage of ice, the optimisation of pumping costs, limited capacity for underground heat rejection and the time and cost associated with developing underground chambers to house alternatives, presents a strong case that ice is the correct solution for the mine.

The Phakisa ice plant has been the primary cooling system at the mine for 4 years and proved to be effective. The remaining criticism is that the designed parameter (volume of ice) has not yet been consistently achieved. Albeit close to design, this resulted in a cooling-gap which has to be delivered by the other refrigeration installations at the mine.



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