Design of the world's largest bulk air cooler for the Enterprise mine in northern Australia

D. J. Brake
Mine Ventilation Australia, Brisbane, Queensland, Australia

ABSTRACT: The 3.5 million tones per annum Enterprise mine is the most recent underground copper mine at Mount Isa, located some 400 km inside the Tropics in northern Australia. At a depth of up to 2000 metres, it is the hottest and deepest mine in Australia. In-situ rock temperatures sometimes exceed 60°C requiring the installation of substantial amount of refrigeration to provide safe working conditions for mine workers. The latest refrigeration project at the mine, R67, required the design and installation of the world's largest bulk air cooler and Australia's largest chilled water plant. The plant is mounted on the surface and provides 25 MW of refrigeration to cool some 580 kg/sec of ambient (26^0 wet bulb) air to 14.6°C, equivalent to the production of 6300 tonnes (7100 refrigeration tons) of ice per day. The bulk air cooler has been designed for a capacity of 34 MW(R) [without any upgrading], which is the expected ultimate carrying capacity of the 7 m diameter vertical intake shaft. Being located in the tropics, technical issues such as control of thermal pull-down required special consideration. Also, the bulk air cooler had to be designed to handle whatever demand for fresh air was imposed by the mine below, with over 100% variations in airflow expected, and without loss of thermal efficiency. A substantial program of risk assessment and HAZOP studies was used to protect underground miners from leaks of ammonia into the air or water circuits, along with the risks from Legionella, fire and others. Fully automatic control systems result in a totally unmanned plant that is supervised remotely. To improve efficiency, the plant is controlled by the outlet wet bulb temperature from the bulk air cooler - the first in the world to be controlled in this fashion. Engineering solutions to address environmental considerations were incorporated at the design stage through features such as the use of ammonia (a greenhouse-friendly gas) as the refrigerant, zero atmospheric discharge and a wastewater collection and re-use system.

1 INTRODUCTION

1.1 *Background and the need for refrigeration*

Mount Isa hosts one of the world's most substantial deposits of silver, lead, zinc and copper. Initially discovered in 1923, the mining, concentrating and smelting operation continues to be one of the largest individual producers of these metals in the world and has contributed enormously to the economic development of Queensland and Australia over much of the twentieth century.

Faced in the early 1990s with declining production from its existing mines at Mount Isa, MIM gave approval for the development of an ambitious new mine, called the Enterprise mine, located underneath the existing operations. The overall ventilation and refrigeration design of the mine has been described elsewhere (Brake and Fulker, 2000).

With a production rate of 3.5 million tonnes per annum, the Enterprise mine is not only Australia's deepest and hottest mine, but also one of the world's largest underground producers of high-grade (>3.5% Cu) copper ore.

With a depth of up to 2000 m below surface, a near-surface rock temperature of 28^0 C and a geothermal gradient of 20^0 C per km, rock temperatures in the deeper regions of the Enterprise mine are in excess of 60^0C due to the constant flow of heat from the earth's core. In addition, "autocompression" – the heating of air as it drops down the intake shafts due to the conversion of its potential energy – results in a further increase of 10^0C dry bulb (DB) and about 4^0 C wet bulb (WB) per 1000 m of depth.

These technical issues, combined with the hot summer surface climate (+40^0C), result in conditions underground that are beyond the limits of human endurance for industrial workers. Without cooling of the air, this orebody would not be technically viable, resulting in major economic impacts and significant loss of employment in north Queensland.

The most difficult technical challenge for the Enterprise operation was therefore that of heat.

Heat stress is known to affect industrial workers in at least five different ways:

- *Health*: excessive heat stress leads to heat illness, typically characterised by extreme fatigue, headaches, nausea, vomiting, cramps and potentially even more serious symptoms such as syncope (fainting or collapse) and stroke.
- *Safety*: heat is known to affect concentration, hand-eye coordination, mental acuity, and other neurological functions and is therefore a known contributing factor to accidents.
- *Productivity*: physically demanding work in thermally stressful environments must be carried out at a slower pace to avoid overheating the body. Heat stress therefore results in reduced output, particularly for labour-intensive activities.
- *Morale*: where work must be conducted day after day under significant levels of thermal stress, morale falls. Among other concerns, this may result in an increase in absenteeism and turnover of staff, with its problems of loss of skills, lack of care, family conflict, etc. Workers are also less amenable to workplace change when they believe that one of the key issues in the workplace, the heat stress they are experiencing, is not being taken seriously by management. Therefore, chronic levels of heat stress frequently result in frustration and poor workforce attitudes.
- *Cost*: due to the lower productivity, safety, health and morale, operating costs increase where the workforce is under significant thermal stress.

1.2 *The project concept and timing*

The combined problems of heat and depth of operation also led to the development of new working-in-heat and egress and entrapment strategies for this deep and difficult to access mining operation (Brake, Donoghue and Bates, 1998; Brake and Bates, 1999; Brake, 1999)

Accordingly, MIM developed an overall concept for a new mine air cooling plant over the R67 shaft using South African and Australian mine ventilation consultants, and issued tender documents in mid-1999 for the design, supply, manufacture, installation and commissioning of a 25 MW(R) ammonia-chilled water refrigeration plant and associated bulk air cooler and water circulating systems.

The documents called for a guaranteed 22 MW(R) of cooling under the high surface wet bulb temperatures occurring in mid-summer (26^0 WB), and a nameplate capacity of 25 MW(R).

The contract was awarded in November 1999 to an Australian contractor and the plant was commissioned 12 months later in November 2000.

1.3 *Project scope*

The R67 Surface Refrigeration Plant Project includes the following:

- 25 MW(R) vapour-compression refrigeration plant (Figure 1) comprising two refrigeration machines each with two Howden ammonia compressors driven by 3.3 kV 1300 kW electric motors. Each of the two machines contains some 3.5 tonne of ammonia and is cooled by liquid refrigerant injection. Oil separators are provided to remove the lubricating oil entrained in the circulating ammonia refrigerant before the gas is discharged into the condensers.
- Associated plant building and pipe support structures 12 m high x 32 m long x 19 m wide, including an ammonia receival sump containing sufficient water to absorb and dilute the entire

Figure 1. R67 Refrigeration plantroom (left) and 4-cell condenser cooling tower (right). Sub-stations, electrical switchroom and control room in foreground of plantroom. Pipe bridge on left supports chilled water supply and return pipes to bulk air cooler. Waste water tank in foreground of cooling tower.

Figure 2. R67 Bulk Air Cooler (BAC). Water distribution level is about 2/3^{rds} of the way up the BAC. Top portion of BAC is the plenum where air changes direction 180^0 to enter the shaft. Mid portion of plenum contains the fill where the heat exchange occurs. Bottom portion (with louvres) is the rain zone. Below the rain zone are the basins. Air enters through the louvres. The four cells surround the 7 m diameter vertical shaft.

ammonia charge from one machine.

- Plate type (semi-welded, stainless steel) evaporators (622 plates) and condensers (724 plates).
- Interconnecting ammonia piping between compressors, evaporators and condensers.
- Associated compressor lubricating oil transfer/return and oil cooling systems.
- Two ammonia evaporator surge drums and condenser liquid receivers.
- Two operating (in parallel) and one spare chilled water pumps – 335 kW 260 l/s @ 113 m head each and associated recirculating water piping systems.
- Chilled water filtration to 1 mm particle size.
- Chilled water treatment/chemical dosing plant.
- Two operating (in parallel) and one spare cooling water pumps 375 kW 560 l/sec @ 50 m head each and associated recirculating water piping systems.
- Cooling water filtration to 1 mm particle size.
- Cooling water treatment/chemical dosing plant.
- Special provisions for the control of water hammer during start-up and shutdown of the chilled water and cooling water systems, including surge control valve and special surge control chambers and vacuum breakers.
- Wastewater control and discharge systems (discharging to the MIM process water system for subsequent re-use).
- Four-cell counter-current cooling tower (Figure 1) 40 m long by 10 m wide by 15 m high (each cell 9 m x 9 m plan, with 110 kW variable speed drive fan) cooling 1120 l/sec of water from the condensers from 35.2°C to 28.2°C. [Note: all temperatures are quoted at the nameplate capacity of 25 MW(R) and allow for heat losses in pumps, pipes and structures).
- Four-cell counter-current bulk air cooler building (Figure 2) 16 m wide x 24 m long x 22 m high delivering 580 kg/s of air at 14.6°C to the mine (handling 520 l/sec of water in at 6.5°C water out at 18.0°C). The bulk air cooler and chilled water systems have been designed to be able to be upgraded to 750 kg/s of air down the shaft without any further expenditure.
- Electrical switchroom, 15 m long x 8.3 m wide x 3m high, and control room. Total electrical load 5.8 MW at maximum refrigeration capacity.
- Plant Sequential Control and Data Acquisition System (SCADA) control system.
- Plant emergency warning systems connected to MIM internal communications network.

– Workshop.
– Compressed air system.
– Wastewater system.
– Site infrastructure, roads and security fencing.

2 DESCRIPTION OF FACILITIES

2.1 *General*

The plant has been proven to deal with the maximum expected cooling loads and the SCADA control systems automatically adjust the number of compressors in operation and the compressor cooling rates to match the varying cooling loads throughout each operating day.

The plant uses ammonia gas as the refrigerant, and in order to reduce the likelihood of the leakage of gas into the mine, the refrigeration plant has been located some 300 metres from, and downwind of, the R67 mine ventilation intake shaft.

2.2 *Refrigeration plant*

2.2.1 *Compressors, evaporators and condensers*

The refrigeration plant comprised two refrigeration machines, each with two Howden compressors driven by 1300 kW, 3.3 kV direct drive electric motors. Each machine has a plate heat exchanger evaporator and condenser. Each machine is also provided with an evaporator surge drum and a liquid receiver capable of containing the entire ammonia charge of the machine.

As oil is used to lubricate and cool the compressors, a five-stage oil separator vessel is provided on each compressor to ensure that oil is not carried forward with the compressed gas to the condenser plate heat exchangers. Separation stages are: impingement, centrifugal action, reduction in velocity, filtration and coalescing. The oil separators handle some 11 kg/sec of a 50:50 mixture of oil and ammonia and separate this so that only a maximum of 5 ppm of lubricating oil remains in the ammonia gas discharge to the condensers. Lubricating oil pumps and oil coolers are also provided.

2.2.2 *Ancillary equipment*

As the heat losses from the drive motors are discharged into the plantroom, four roof-mounted ventilation fans are provided to draw sufficient air through wall-mounted filters to maintain the temperature inside the building to within 5^{o}C of the ambient temperature.

The plant building also contains the air compressors, instrument air dryers and air receivers, which supply instrument air to operate automatic valves within the plant, and provide compressed air to operate air tools during maintenance operations.

A 10 tonne safe working load electric maintenance crane with auxiliary hoist is provided within the plantroom building.

2.2.3 *Plantroom building*

The plantroom building comprises a steel-framed and steel-sheeted structure supporting the crane. Full plantroom length ventilation louvres allow air ingress. Dust filters are fitted to the louvres to reduce the dust entering the plant room from nearby mining operations.

2.2.4 *Switchroom and control room*

An air conditioned steel framed and elevated switchroom contains all the electrical switchgear associated with the refrigeration plant, cooling water pumps and cooling tower fans.

Adjacent to the switchroom, an air-conditioned control room is provided, with a viewing window into the plantroom. This room contains personal computers connected to the plant SCADA system.

2.2.5 *Transformers and cabling*

The plant 11 kV to 3.3 kV and 3.3 kV to 440 V transformers are located adjacent to the refrigeration plant switchroom.

2.3 *Cooling water system*

2.3.1 *General*

The cooling water system discharges the waste heat from the refrigeration plant condensers to the atmosphere. The system comprises a cooling tower, pumps and a piping system connecting the tower and pumps to the refrigeration plant condensers.

2.3.2 *Cooling tower*

The cooling tower is a proprietary design supplied by Hamon Australia. It is a four-cell unit mounted over a basin 40 m long x 10 m wide, containing a reserve capacity of 800 m^3 of water. The structure of the tower is treated timber and the overall height is 22 m. Each cell measures 9 m x 9 m in plan.

The tower is clad in fibreglass (FRP) sheeting. Each cell is fitted with a 110 kW variable speed drive fan. The tower packing is a type of splash fill, being a proprietary design by Hamon. The tower has the capacity to cool 1120 l/sec of water from 35.2^{o}C to 28.2^{o}C, a heat rejection load of 33.0 MW(R).

2.3.3 *Cooling water pumps*

Two operating and one standby cooling water pumps are provided. The pumps are of the horizontal split case design and each will deliver 560 l/sec at a discharge head of 50 m. Each pump is fitted with a 375 kW 3.3kV direct drive electric motor.

2.3.4 *Water hammer provisions*

The system is fitted with a special control valve and start-up orifice plate and a number of air cushion pots fitted with special air release valves, to reduce any surge effects caused by the purging of air at start-up. The cooling water pumps deliver in excess of one tonne of water per second and the starting and stopping of the pumps could otherwise cause separation of the flow stream. If flow separation occurs, a vacuum is produced within the piping systems. The plate heat exchangers and other components would suffer damage if subjected to this vacuum.

2.4 *Chilled water system*

2.4.1 *General*

The chilled water system is the means by which heat is removed from the ambient air. Approximately half a tonne per second of chilled water enters the bulk air cooler at 6.5°C and contacts 580 kg/s of air entering the mine shaft. During the contact, the air temperature is reduced from 26°C WB to 14.6°C WB, and the water temperature is raised to 18.0°C. The water is then returned to the refrigeration plant evaporators and is re-chilled to 6.5°C.

The water is continually recycled. In addition, there is some condensation of the water vapour in the air being cooled. This water is used to provide some of the makeup water required in the cooling water system.

2.4.2 *Bulk air cooler*

The bulk air cooler is a four-cell concrete structure 16 m wide x 24 m long x 22 m high (equivalent to a 7-storey high building). The structure is mounted directly above the R67 mine ventilation intake shaft and contains the system reserve water capacity of 500 m^3 in concrete basins. The cells are filled with a proprietary design non-fouling, non-corroding splash packing. Each pair of bulk air cooler cells is designed to be individually isolated, so as to enable cleaning of the cell water basins or maintenance of the packing or other components.

2.4.3 *Chilled water pumps*

Two operating and one standby chilled water pumps are provided. The pumps are of the horizontal split case design and each will deliver 260 l/sec at a discharge head of 113 m. Each pump is fitted with a 335 kW 3.3 kV direct drive electric motor.

2.4.4 *Water hammer provisions*

The system is fitted with a special control valve and start-up orifice plate and a number of air cushion pots fitted with special air release valves to reduce any surge effects caused by the purging of air at start up.

The chilled water pumps deliver half a ton of water each second, and with over 140 tonnes of water in motion at any point in time, the starting and stopping of the pumps could otherwise cause separation of the flow stream, generating water hammer with consequent damage to the system, particularly to the plate heat exchanger components. These provisions have successfully protected the system against such damage.

2.5 *Wastewater system*

2.5.1 *General*

Water conservation is essential at Mount Isa due to the arid nature of the surrounding country. The plant is therefore equipped with a wastewater collection system to ensure that any water discharged from the plant for process reasons, is collected and recycled within the mine site.

2.5.2 *Backwashing of heat exchangers*

Atmospheric dust is washed by the recirculating water from the airstreams in the cooling towers and the bulk air cooler. This dust, together with the solids dissolved in the recirculating water, can be deposited on the internal surfaces of the heat exchanger plates. It is therefore necessary to backwash the water side of the condensers and evaporators regularly in order to maintain peak heat transfer efficiency.

The backwash process for the water side of both the evaporators and condensers requires in excess of 500 l/sec for some five minutes and the resulting water quantities are captured in the plant wastewater tank. A wastewater discharge pump transfers this water to the mine process water system for re-use in the mine's ore processing facilities.

2.5.3 *Drainage of water basins*

In addition to the backwashing requirement, the wastewater system collects any water discharged from the plant as a result of periodic drainage of the cooling tower and bulk air cooler basins for Legionella and other biological control. The wastewater pump also transfers this water to the mine process water system for re-use.

2.6 *Compressed air system*

The plant is located at some distance from the nearest source of compressed air. The plant has therefore been equipped with an independent air compressor set, receiver and air dryer. Compressed air is available for the use of portable tools during maintenance operations. Dried air is available for powering plant instruments and controls.

3 INNOVATIVE ASPECTS OF THE DESIGN

There are a number of aspects of this plant that are original or innovative, as well as areas of technical complexity. These are discussed under separate headings below.

3.1 *Differences between South African and Australian mine refrigeration requirements*

The range of strategies and general engineering considerations for the various configurations of refrigeration plant in mining applications has been described elsewhere (Howes, 1983; Howes, 1990; Brake, 2001a, Brake, 2001b).

While there have probably been in excess of 200 mine refrigeration plants built around the world over the past 50 years, the majority of these are in South Africa, generally in the deep underground gold and platinum mines of the Witswatersrand area, a region located within about a 300 km radius of Johannesburg. In Australia, outside of Mount Isa, only two surface refrigeration plants have been built at mines and one of these has now been decommissioned. Other projects are, however, currently underway.

One of the reasons for the relatively few refrigeration plants in Australia is the difference in allowable working temperatures in Australia compared to the Northern Hemisphere. Australian mining is regulated at the State, not Federal level. Most states have recently abandoned prescriptive upper limits on working temperatures, preferring a risk based and "Duty of Care" approach, although new regulations in Queensland restrict metal mining to 34^0 WB and coal mining to 29.4^0 ET(basic). South African mines tend to work to a limit of 32.5^0 WB with an allowance up to 34^0 WB under certain circumstances. German coal mines, however, bring in a shortened shift once either the DB exceeds 28^0 C or the ET exceeds 25^0 C ET and no work is allowable at all, even under shortened shifts, when the DB exceeds 32^0 C. Mount Isa regularly has temperatures exceeding 40^0 C on the surface in summer, with one recent summer having over seven consecutive weeks where the surface temperature exceeded 40^0 C every day! UK coal mines have no limit but tend to work to a limit of 28^0 ET and 28^0 DB, whichever is exceeded first.

To understand some of the design challenges in the R67 plant in such a hot climate, it is informative to list the differences between the Witswatersrand and the Mount Isa regions and in particular, the different refrigeration needs of South African mines compared to a deep mine in Australia (in this case, the Enterprise mine at Mount Isa). These differences are summarised in Table 1.

The main points to note from Table 1 are:

South African mines have a surface elevation much higher than Australia, and even higher than Denver, Colorado. The surface DB and WB temperatures are much lower in the main South African mining centres compared to Australia due to the elevation.

The increase in virgin rock (strata) temperature with depth is much lower in these South African mines than in typical mines in Australia.

The South African mines are much deeper and the workings are more spread out. This results in much lengthier intakes and a long transit time for the intake air to a South African mine, compared to an Australian mine. This means that South African intake air generally picks up much more heat than Australian intake air.

This is aggravated by the fact that South African mines are generally very wet, particularly in and near the production areas, whereas Australian mines, which use massive mining techniques, are generally much drier. It is widely recognised that open drains and (hot) wet footwalls, typical of South African conditions, result in chilled air picking up large amounts of heat before reaching the workers.

Table 1: Differences between Witswatersrand and Mount Isa.

	Witswatersrand	**Mount Isa**
Surface elevation (m above sea level)	1700 m	300 m
Average yearly surface ambient temperature	18^0C	28^0C
Average summer surface WB temperature	18^0C	22^0C
Peak summer surface WB temperature	22^0C	26^0C
Average surface rock temperature	18^0C	28^0C
Geothermal gradient	10^0C per km	20^0C per km
Average virgin rock temperature at 2 km depth	36^0C	68^0C
Style of mineralisation	Flat, tabular	Massive
Mining method	Reef mining	Open-stoping, panel stoping
Mechanisation of mining activities	Low	High
Wetness of mine	High	Low
Diesel plant usage underground	Little/none	Extensive
Physical human effort involved in production	High	Low
Use of air-conditioned cabins in mobile plant	Nil	Extensive
Cost of electrical power	Low (typically US$0.02/kW.h)	High (typically US$0.04/kW.h)
Intake air transit time to workplaces	Lengthy	Short
Thermal flywheel (damping) effect in intake airways	High	Low
Exogenous to endogenous heat loads (climatic to other heat loads)	Low	High
Summer to winter refrigeration turndown ratio	Low	High

Moreover, mechanisation in Australia has been achieved largely by putting workers inside productive mobile plant. Over the past 15 years, almost all trucks and LHDs in Australia are now air-conditioned, and the majority of development and production drilling machines now also have air-conditioned cabins. This "microclimate" cooling has removed the many workers from the heat exposure.

Those workers that are not in air-conditioned cabins are no longer working as physically hard as they did 15 years ago. This has been prompted largely by the epidemic of acute and chronic injuries related to manual handling. Devices such as rod-handling equipment are now the "norm" on all drilling equipment, including raise-borers, production and development jumbos and diamond drill rigs. Almost all workplaces underground are now serviced by large 4WD forklifts, purpose-designed flattop trucks (often with integral hydraulic lifting jibs), multi-purpose tool carriers and other specialised devices for activities such as hanging auxiliary fans.

The high "exogenous" (external or climatic) heat loads in Australia compared to South Africa mean that the refrigeration requirement in Australia is low or nil in "mid-season" and winter, and high in summer, i.e. a high turndown ratio. Therefore the capital cost of the plant is more critical in Australia compared to South Africa.

The much higher power costs in Australia (typically double those of South Africa) mean that refrigeration systems in Australia need to be designed to achieve high efficiencies.

South African mines are labour-intensive and make extensive use of hand-held rock drills, which use copious quantities of (chilled) water to cool the drill bits and for dust suppression. Australian mines are heavily mechanised and use more "massive" mining methods. It is rare to find any hand-held mining today in Australian mines, and some long-held practices (such as hand-held raise mining) are in the process of being banned by legislation.

The net result is that most of the heat load in a South African mine occurs within the mine itself (endogenous or internal), due to the very long intake air transit times. Cooling of the air on the surface of a South African mine is therefore relatively inefficient due to the low climatic heat load, and due to the fact that the colder the air is sent underground, the more strata heat it will absorb from the long intake airways prior to arriving at the workplace.

Therefore, South African mines tend to make extensive use of localised underground air cooling close to the workplaces, and also make extensive use of chilled service water to the extensive network of hand-held drilling machines, as this has been found to be very effective in providing refrigeration directly to the workplaces.

In practice, this means South African refrigeration plants, even when located on the surface, generate most of their refrigeration output as very cold water (typically 0.5^0C to 1.0^0C) to be sent underground as chilled service water. The water is generated as cold as possible so as to carry the greatest amount of cooling effect underground in the least amount of water, as pumping costs back to the surface are very expensive in these very deep mines.

Where surface bulk air cooling is installed, it is usually in association with such chilled service water, and South African surface bulk air coolers are therefore designed for inlet water temperatures of 0.5^0C to 1.0^0C. Due to the relatively low surface ambient WB temperatures, the "return" water from such a bulk air cooler to the refrigeration plant is also relatively cool (the return water temperature must always be lower than the ambient WB temperature).

In contrast, at Mount Isa, most of the heat load is due to the extreme surface summer climate. This, combined with the very rapid intake transit times, makes surface bulk chilling of the air technically more effective and attractive. In addition, it is cheaper to install and operate refrigeration on the surface, and much easier to maintain a surface plant than an underground plant.

Furthermore, because the Enterprise mine is highly mechanised, the refrigeration of the service water does not significantly improve conditions where manual work is being carried out. This is because such work typically does not use large volume flows of service water, and where service water is used, it is used for only relatively short periods of time.

Therefore, the Mount Isa plant, as one of only a handful in the world located in the tropics, is rare in consisting *solely* of a surface bulk air cooler. This presents both opportunities and technical challenges. The opportunity is that to obtain the most efficient plant possible, the chilled water is cooled *only* to the extent necessary to chill the surface air to the desired temperature. This significantly improves the coefficient of performance (COP) of the plant, but when combined with the high ambient WB temperatures at Mount Isa, results in return water temperatures from the bulk air cooler to the refrigeration plant that are much higher than in South Africa. This creates significant problems in controlling the evaporating temperatures (and hence evaporating and suction pressures) within the compressors. Excessive suction pressures result in premature thrust bearing failure.

3.2 *No control over mine load*

The volume of air being drawn through the bulk air cooler at R67 is not controlled by the plant. It is a function of some eight major (1 to 2 MW each) surface intake and exhaust fans, and about 200 underground circuit fans (total another 8 MW), which force ventilate the Enterprise mine in a "push-pull" system.

The airflow through the bulk air cooler must therefore cope with extremes from 250 m^3/s to 700 m^3/s (over various stages of mine life), without damage to the bulk air cooler itself or its packing, and whilst maintaining an efficient heat transfer process at the air/water interface.

In addition, the potential heat load imposed at the bulk air cooler can exceed the plant's capacity, particularly if one or more compressors are not available, and will certainly exceed the plant's capacity during a "hot start". These starts occur during summer when both the initial circulating water temperature is high and the ambient WB temperature is high.

3.3 *No recognised safety code for mine refrigeration plants*

While there is an Australian standard for industrial refrigeration systems, this code is not designed to cope with the situation where several hundred workers could be inside the "cold room" (the mine) with no practical means of escape should refrigerant leak into it.

There are no recognised statutory codes anywhere in the world for mine refrigeration plants, although South Africa does have a code that is voluntarily accepted by the larger mining companies.

The lack of any statutory codes, combined with the recently introduced Queensland mining legislation with its "Duty of Care" and ALARA ("as low as reasonably achievable") concept of risk management, put significant onus on both MIM and the contractor (Simon Engineering Australia) to adopt a very formal and rigorous approach to risk assessments and HAZOP studies.

Even after adopting the South African mine refrigeration code, the main HAZOP study led to 255 items being listed for further investigations. Numerous levels of risk assessment were conducted at the conceptual and detailed design stages in areas such as fire risks and loss of refrigerant containment.

3.4 *Longevity of plant and criticality to production*

During hot summer periods, if the R67 plant goes off-line for more than about 60 minutes, much of the mine will need to be evacuated, as temperatures will rapidly increase to the point where escape will be physiologically compromised. Therefore, high uptime and flexibility of operation and maintenance are important.

The plant has been designed for a 20-year life, and in particular, has been designed so that, as the mine becomes deeper and more spread out and the refrigeration requirement increases to perhaps as much as 34 MW(R), the plant can be upgraded with only some simple piping tie-ins. There will be no requirement to upgrade the BAC or the main chilled water lines or pumps.

3.5 *Plate heat exchangers*

The plant uses plate-type heat exchangers (PHEs). These result in a very volumetrically-compact heat exchanger for the duty, allowing a physically smaller plant building, and, very importantly, a much reduced refrigerant charge. The small refrigerant charge results in a safer plant than shell-and-tube heat exchangers, especially in the unlikely event of a loss of refrigerant containment.

The PHEs use some of the largest plates in the world and the largest plate heat exchanger frames manufactured.

In addition, all mine refrigeration plants built to date have used Alfa Laval PHEs. These are fabricated from a minimum 0.8 mm stainless steel. This is the first mine refrigeration plant to be built using a new range of APV PHE fabricated from only 0.6 mm plate.

Further, previous PHEs used in mining applications have had a 6 mm space between the plates on the water side. The R67 plates are the first to be used in a mining application with only a 3 mm gap on the water side. This provides a much cheaper and more compact PHE with better thermal characteristics, but puts the plates at more risk of implosion or explosion due to water hammer or vacuum, and also at more risk of fouling due to contaminants in the water.

Finally, these very large PHEs with high water flows are subject to high-pressure losses in the PHE inlets and the main distribution headers within the PHE pack themselves. This could result in an inefficient heat transfer process if some of the plates were receiving insufficient water flow. To ensure this did not occur, all the PHEs were double-ported on the water inlets.

Moreover, as the liquid refrigerant boils in the evaporator PHE, the volume flow of refrigerant (as a gas) increases greatly compared to its volume flow as a liquid. To avoid excessive pressure losses in the return gas lines from the evaporator to the surge drum, the refrigerant outlets on the evaporators were also double-ported. Such double-porting in PHEs of this size is very unusual.

3.6 *Water hammer*

The size of the plant, the difference in elevation between the BAC and the chilled water plant, and the use of newly developed plates (thinner and more compact) in the PHEs create the potential for both significant water hammer and for full vacuums to be developed within the system, with potentially disastrous results on the most expensive mechanical items in the plant: the PHEs.

This has been addressed by a comprehensive approach to preventing water hammer and any sub-atmospheric pressures occurring in the system, particularly at the PHEs. Because of the differences in levels between water system components, during start-up and shutdown the system can be subject to pressure fluctuations due to flow separation. This means that system pressures in the chilled water circuit can be significantly below atmospheric pressure (potentially up to a full vacuum) during these system transients. Special provisions have been included in the design to prevent separation of the water columns and thus avoid damaging negative pressures within the sensitive plate heat exchangers.

3.7 *Water strainers*

The much closer tolerance on the PHEs (3 mm rather than 6 mm on the water side) required the water strainers to remove particles above 1 mm, rather than the 2 mm strainers used previously on mine refrigeration plants. This required careful consideration of the impact of the high insect loads experienced in the tropical wet season at Mount Isa.

3.8 *Liquid refrigerant injection*

Several methods exist to cool the compressors in a refrigeration plant. However, with the need for high plant availability and long service periods between PHE overhauls, it is critical to keep the compressor discharge (compressed refrigerant gas) temperatures safely within the temperature tolerance of the gaskets in the condenser PHEs. Even the modern elastomers used in condenser PHEs deteriorate with age, and particularly with temperature.

The only practical method of keeping discharge temperatures to the desired maximum of 50^0C was to use liquid refrigerant injection (LRI). This is a process in which liquid refrigerant (typically at about 30^0C) is drawn from the liquid receiver and injected into the compressor inlet. The amount of refrigerant injection is controlled by the compressor discharge temperature.

Liquid refrigerant injection allows the discharge temperature to be kept within a very tight tolerance of the nominated target value (in this case, 50^0C). However, successful liquid refrigerant injection requires condensing temperatures to not fall below the point at which the saturated ammonia pressure in the condenser would be insufficient to force the liquid refrigerant into the compressor inlet (there is no pump in the liquid refrigerant injection system).

Offsetting this, the overall plant efficiency improves substantially if condensing temperatures are kept as low as possible. Therefore, control of condensing temperatures (not too high and not too low) is critical with liquid refrigerant injection.

3.9 *Condenser cooling tower water temperature control*

Variable speed fans have been installed on each of the four cells within the condenser cooling tower (CCT) water temperature control. Rain gutters located in the rain zone (between the bottom of the packing and the basin) continuously sample a portion of the water falling through the rain zone. Dual RTDs located at the outlet of each gutter, logically connected to the variable speed fans at the top of each cell, allow the return water temperature to be controlled within 0.5^0C.

Such precise temperature control in the return water is unusual for a condenser cooling tower, but is important in maintaining stable liquid refrigerant injection and high COPs in the plant.

3.10 *Oil separators*

At normal operating condition, each compressor discharges approximately 5.5 l/sec of compressed ammonia gas along with 5.5 l/sec of hot oil mist into the oil separator. From this vessel, the compressed gas exits with an oil content not exceeding five parts per million.

Any oil carryover exceeding this level can pass through to the evaporator PHEs, where it will lodge, resulting in a rapid loss of efficiency. The size of the vessels and their achieved efficiency (less than 5 ppm or 0.000005% carryover) is unusual.

3.11 *Oil return system*

Even at less than 5 ppm oil carryover, some oil will end up in the surge drums. An innovative oil return system has been installed to return the oil to the separator.

3.12 *Control of plant*

All other mine refrigeration plants are controlled off the “leaving water temperature”, i.e. the temperature of water leaving the last evaporator PHE. Where it is desired to produce water at a fixed temperature (eg 1^0C), this is appropriate. However, it would result in significant over-cooling of the air at the Enterprise mine as neither the airflow down the shaft nor the ambient WB temperature is constant.

R67 therefore uses a unique system in which the evaporator PHE leaving water temperature is “cascaded” from the actual mixed air WB temperature at the top of the shaft. This has resulted in fine (within 0.5^0C WB) temperature control of the air entering the shaft, which has led to substantial cost savings to MIM, compared to the alterative of controlling off the leaving water temperature only.

3.13 *Physical size and configuration of plant*

The physical size of the R67 plant is unique. The configuration of the plant with two evaporators of this size in series is also unknown elsewhere. This series configuration, which allows two-stage cooling of the water, results in a much more efficient plant (higher coefficient of performance) than single-stage (evaporators in parallel) cooling.

The use of two compressors sharing a single liquid receiver and a single surge drum in a plant of this size is also very unusual for a plant of this size.

4 ENVIRONMENTAL FEATURES

The R67 Refrigeration Plant incorporates a number of environmental measures that are discussed below.

4.1 *Water conservation*

Owing to the relative scarcity of water in the Mount Isa area, and also to avoid environmental issues associated with the discharge of chemically treated water into the environment, it was considered necessary to design the plant to conserve water. Water is conserved in the following ways:

4.1.1 *Water conservation during PHE backwashes*

More than 500 l/sec is discharged for five minutes for each of the four backwash operations, typically producing about 250 kl of water per backwash. Operating experience to date indicates that each of the four heat exchangers will need to be backwashed at least once every three months in order to remove dust and mud deposits built up on the heat exchanger plates. This water is collected in a wastewater tank and then discharged to the mine's process water system for re-use in the ore treatment facilities.

4.1.2 *Water conservation in the bulk air cooler*

In normal operation, the ambient air is cooled below its dew point in the bulk air cooler. This will result in condensation of a portion of the water vapour in the inlet air stream. This condensed water (which can be up to 10 m^3/hr) is not wasted, but is piped to the condenser cooling tower to partly replace water drift losses discharged with the airstream, and losses resulting from the bleed stream.

4.1.3 *Cooling tower bleed*

The water in the cooling water circuit is concentrated by evaporation in the condenser cooling tower. In order to control the concentrations of minerals in the circuit, water is continuously bled from the circuit, at a typical rate of 30 m^3/hr. This water is also piped to the wastewater system and then discharged to the plant process water system for re-use.

4.2 *No loss (aqueous or gaseous) design*

4.2.1 *Ammonia*

Owing to the location of the plant within a mining site, special consideration has been given in the design to the trapping of gaseous ammonia emissions.

Ammonia safety valve and piping and vessel drains do not vent to the atmosphere, but instead are connected to a special ammonia collection system and then piped to an ammonia sump containing sufficient water to absorb the entire charge from one of the refrigeration machines. These provisions have been made to prevent the release of any gaseous ammonia onto the mine site during normal operation or maintenance activities.

4.2.2 *Oil retention*

There are substantial quantities of lubricating oil associated with the refrigeration compressors. The design of the refrigeration plantroom has included an oil catch sump to ensure that any oil spilt or leaking from the equipment will remain on the site and can be dealt with in a controlled fashion.

Similarly all of the oil filled transformers in the plant are mounted over oil catchpits to permit collection of any spilt or leaking transformer oil.

5 SUMMARY

The 25 MW(R) R67 refrigeration plant at Mount Isa is the world's largest bulk air cooler and one of the largest chilled water plants. Due to Mount Isa's climate, the plant had a number of technical challenges to be overcome. A number of innovations in mine refrigeration plant design resulted from these challenges. The plant was commissioned 12 months after award of a design and construct contract, was within budget, has been performance-tested to in excess of 25 MW(R), and has won the prestigious "Engineering Excellence" award for Queensland in the Resource Development category for 2001.

ACKNOWLEDGEMENT

The author would like to thank Mount Isa Mines Limited for permission to publish this paper.

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