Considerations in the design of integrated systems for distributing refrigeration in deep mines*

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SYNOPSIS

Reference is made to the approach to mine cooling in which the service water is used as one of the means of distributing refrigeration, and attention is drawn to various engineering disciplines or functions necessary for effective distribution and reticulation of cold water from refrigeration plant. The demand for service water is intermittent, the peak flow-rates being typically two to three times the average flow-rate. The refrigeration plant, on the other hand, must preferably be operated steadily throughout the day and night, with the result that a large storage dam for cold water must be incorporated into each system in order to even out the surge in demand for water. These dams should be operated as constant-temperature, variable-volume reservoirs. The conventional cascade system involving dams on each level is not the best for sending water down mines, and schemes are described that avoid the need for such dams. Reference is made to various tests that were carried out, and to several large systems that were installed. Management and organizational problems that could arise as a result of new technological developments in mine cooling are referred to, and cost figures are quoted to indicate the large potential savings, in addition to the improved environmental conditions, that can be achieved through the use of integrated water systems.

SAMEVATTING

Daar word verwys na die benadering van mynverkoeling waarin die gebruikswater gebruik word as een van die maniere om verkoeling te versprei en die aandag word gevestig op verskillende ingenieursdissiplines of -funksies wat nodig is vir die doeltreffende verspreiding en retikulering van koue water vanaf die koelinstallasie. Die vraag na gebruikswater is onderbroke en dit is tipies dat die spitsvloeitempo's twee tot drie maal die gemiddelde vloeitempo is. Aan die ander kant moet die koelinstallasie liefs dag en nag gelykmatig werk met die gevolg dat daar 'n groot opgaardam vir koue water by elke stelsel ingesluit moet word om die opwelling in die vraag na water gelyk te maak. Hierdie damme moet as reservoirs met 'n konstante temperatuur en veranderlike volume werk. Die konvensionele kaskadestelsel met damme op elke vlak is nie die beste metode om water in myne af te stuur nie en daar word skemas beskryf wat die noodsaaklikheid van sulke damme uitskakel. Daar word verwys na verskillende toetse wat uitgevoer is en na verskillende groot stelsels wat geïnstalleer is. Daar word ook verwys na bestuurs- en organisasieprobleme wat as gevolg van nuwe tegnologiese ontwikkelings in mynverkoeling kan ontstaan en kostesyfers word aangehaal om die groot moontlike besparings wat benewens die verbeterde omgewingstoestande deur die gebruik van geïntegreerde waterstelsels bewerkstellig kan word, aan te dui.

Introduction

This paper discusses integrated water systems for the distribution of refrigeration in mines, and describes the experience gained and the conclusions drawn from cooling experiments conducted on several mines by the Environmental Engineering Laboratory of the Chamber of Mines. Many of the recommendations resulted from the need to solve actual problems that were encountered on these mines. The work is proceeding, and no doubt there will be further developments and improvements in the future.

Before consideration is given to the design of systems for the distribution of cold water in mines, it is necessary to review briefly several matters that play a part in determining how the refrigeration should be distributed.

Production of Heat, and Distribution of Cooling

Refrigeration in mines must be distributed in accordance with heat production. Methods are available[1, 2] for predicting the magnitudes of the main sources of heat in a mine, this information being required in the planning of both the long-term overall refrigeration requirements and the immediate requirements.

The main sources of heat that are relevant to the distribution of refrigeration in a mine fall into two distinct groups:

(1) heat that can be removed by the service water if the service water is cooled, and

(2) heat that cannot be removed by cooling of the service water, and hence heat that must be removed by cooling of the ventilation air.

The following sources of heat fall into Group (1):

(a) heat from the rock at stope faces where service water is normally used,

(b) heat from the faces of development ends, and

(c) heat from the service water itself, if this water on arriving in the section is hotter than the prevailing wet-bulb temperature.

Group (2) includes the following sources:

(i) heat arising at working faces in excess of the heat that can be removed by the service water,

(ii) heat arising from the rock in the worked-out areas of ventilated stopes, where no service water is used (this is one of the largest sources of heat),

(iii) heat from the rock surrounding haulages, cross-cuts, travellingways, and development on reef, which cannot be cooled by the service water,

(iv) heat arising from the rock surrounding the many excavations that are found in shaft pillars, such as ore passes, dams, pipe-ways,

(v) other heat such as that from electrically powered hoists, mining equipment, diesel engines, explosives, metabolic heat, and the energy released by mining,

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(vi) heat entering the ventilation air from water in open drains in the intake-airway system, and from water on the footwall in stopes,
(vii) heat arising from fissure water (this can have a dominating effect in some mines),
(viii) heat arising from oxidation of the exposed ore-body (this does not occur in South African gold mines),
(ix) the energy of autocompression arising from movement of the ventilation air downwards in the shaft systems,
(x) the potential energy of the broken rock that is carried down ore passes to the loading boxes at the bottom of the shaft.

In many cases, the introduction of chilled service water as one of the means of distributing refrigeration has alleviated the most difficult problem in the cooling of mines, which is that of the removal of the heat that arises in the working zones of stopes and development. Experience has shown that one of the far-reaching consequences of cooling the service water is that, provided the air control is good, wet-bulb temperatures at the face in working stopes are almost always lower than the reject wet-bulb temperature of the ventilation air[3]. This factor is of great significance as regards the exposure of workmen to heat in the hotter parts of a mine.

In planning a system for distributing refrigeration through any mine to the places where it is needed, it is necessary to know how much heat is produced on each level, where on each level the heat arises, and how much heat can be removed by the service water since heat that cannot be eliminated in this way must be removed by the ventilation air. This knowledge enables an assessment to be made for each level of the amount of refrigeration needed to cool the ventilation air, and the best location in the mine for the air-cooling facilities. The planning of the entire distribution system for water and refrigeration on the mine is then possible.

Mining is anything but static. The pattern of heat pick-up changes continually as production moves further out on each level, and eventually to new levels or new blocks of ground. The system of distributing refrigeration through the mine must therefore be planned to take care of these movements of the centres of production.

Although it is possible to predict with a reasonable degree of accuracy the rate of heat pick-up in mines, and hence the cooling rate that is required, the amount of refrigeration to be installed depends to a large extent on the efficiency of its distribution. This efficiency must include an allowance for unavoidable imperfections in the distribution of the ventilation air, and for leakage of air to the return-airway system.

In order to ensure optimum distribution of ventilation in relation to the needs for cooling, it is necessary to have a clear understanding of the amount, distribution, and nature of the heat production in each section of the mine. Also, an appreciation is necessary of the many practical considerations to be taken into account, such as the availability and location of airways, and the availability of ventilation air. It is important to distribute the ventilation air in any one section in accordance with the magnitude of heat production in that section, keeping in mind other constraints that may arise, for example if methane is a problem.

When cooling of the ventilation air is required, poor distribution of this cooled air or losses of air to the return-airway system can result in poor and inefficient distribution of the refrigeration, and hence extra care is needed in the control of the ventilation air.

A scarcity of air in an area having a high rate of heat production will naturally require pre-cooling of this air to lower temperatures, which can have several disadvantages. One disadvantage is the increased rate of heat pick-up by this air on its way to the workings. Another is that the consequent lower temperature of the cooling water returning to the refrigeration plant will require larger quantities of water to be circulated, and hence larger pipes and higher pumping costs.

The introduction of chilled service water as one of the means of distributing refrigeration can contribute greatly both to lower costs and to improved effectiveness in the distribution of refrigeration. Improved effectiveness here refers particularly to improved average conditions in working places, as well as to the elimination of so called 'hot spots', in which wet-bulb temperatures are significantly higher than average or higher than the air reject wet-bulb temperature.

In any section of a mine, the consumption of service water is roughly proportional to the rate of production, and the water is distributed mainly to those areas where mining takes place. As a consequence, the availability of cold service water results in a distribution of a portion of the refrigeration that is generally in accordance with the rock production, and hence the heat production, in a given section. Since the amount of water is usually determined by mining considerations, the only means of controlling the amount of refrigeration that can be distributed by the service water is adjustment of the temperature to which the service water is cooled.

Several experiments have indicated that service-water temperatures as low as 10 °C at the hosepipe connections leading to the stope faces are acceptable. Cooling of this water at the plant to about 4 °C will ensure that the maximum amount of refrigeration is distributed by the normal service water. The indications are that the temperature of the service water will rise from about 4 °C at the plant to above 10 °C at the stope faces, particularly if some of the pipes bringing the water to the faces are left uninsulated. The heat gain by the water on its way to the stopes is not a loss in the usual sense unless the pipelines are located in return air.

If water leaves the refrigeration plant at 4 °C and returns at 28 °C for re-cooling, 100 kW of cooling will be distributed for each litre of water being circulated per second. However, if the water is cooled to only 10 °C and returns at 22 °C, double the quantity of water would need to be circulated to achieve the same cooling rate.

Mine Cooling Using Refrigeration

Refrigeration becomes necessary in mines only when the required cooling cannot be achieved by ventilation air alone. In South African gold mines this generally occurs when the workings are below sea level. The manner in which the refrigeration is used or distributed depends on circumstances, but generally should be within the framework of three basic phases[2] as follows.

Phase 1: Cooling of service water

When refrigeration is needed because conventional means of controlling the face environment are inadequate, consideration should be given first to cooling of the service water. When cold service water is available, consideration can be given to altering the overall distribution of ventilation air through the mine. The design objective should be that the ventilation air together with the cold service water would ideally neither over-cool nor under-cool any working areas.

While there may be situations in which cooling of the ventilation air without cooling of the service water would appear to be more cost-effective, it is the firm conviction of the authors that this practice is not advisable unless the natural temperature of the service water reaching the working faces is lower than about 20 °C. In the South African gold-mining industry, the combination of depths and virgin-rock temperatures are such that refrigeration for Phase 1 cooling becomes necessary when rock temperatures exceed about 35 °C. This applies where it is desired to keep average stope wet-bulb temperatures below 28 °C.

Phase 2: Cooling of air on main intake levels

When it appears that cooling of the ventilation air with the aid of refrigeration will be required in addition to the cooling of the service water, provision should be made to install primary bulk-air coolers underground on the main intake levels, or even on surface, before consideration is given to the provision of any facilities for cooling the air in the production areas or stopes. It is important that the distribution of this conditioned ventilation air should be based on the amount of heat to be removed by this conditioned air. Furthermore, it is essential that hot drain water in the intake airways should be carried back to the shaft in pipes. This applies to any situation in which the temperature of the drain water is higher than the wet-bulb temperature of the intake air.

The primary bulk-air coolers on the intake levels may be located in the shaft pillar, but it is obviously better for them to be located as near as possible to the production areas. These coolers would normally remain in one position for many years, and hence their cost would be amortized over a relatively long period. Recommendations on the design of spray chambers for the bulk cooling of intake air have been given elsewhere[4].

Phase 3: Cooling of air on or near stopes

The third phase (involving the cooling or re-cooling of air in or near the stopes) becomes necessary when the thermal capacity of the ventilation air (that is, the quantity of air) is inadequate for all the cooling to be done at the Phase 2 bulk-air coolers, or when poor distribution of the cooled air (relative to the needs for the cooling of particular production sections) is unavoidable. This phase of cooling involves the installation of secondary semi-bulk coolers in the production area close to the stopes, or tertiary coolers in the stopes themselves, for periodic recooling of the ventilation air.

Every effort must be made to avoid the introduction of Phase 3 cooling, not only because of its considerable cost, but also because such cooling is highly labour-intensive and it is almost impossible to keep these systems properly up to date when the rate of face advance is high. In many mines it is the perpetual difficulty of keeping these systems fully operational that results in refrigeration plant standing idle at times when cooling is desperately needed.

Engineering Disciplines and Functions

The achievement of good environmental conditions in deep mines requires mining practices that minimize the heat problem, and close co-ordination of the several disciplines or functions that are involved in mine cooling: ventilation, refrigeration, and distribution of the refrigeration.

Ventilation

For several reasons, a further dimension is added to ventilation when refrigeration is introduced. One reason is that the need for high air velocities (above about 2 m/s) in stopes is no longer a primary consideration in the overall layout of the ventilation system. Another is that the ventilation engineer needs to pay careful attention to the selection of the design face wet-bulb temperatures. There is often no need to utilize large quantities of used air having high wet-bulb temperatures to achieve high face velocities and so compensate for high wet-bulb temperatures. The various ventilation options that are open in such cases can be investigated with the aid of a computer[2].

It must be emphasized that, when refrigeration is introduced, it becomes even more important that the control of ventilation be maintained at the highest possible quality. Air must not be wasted merely because the face conditions seem cool.

Refrigeration

The refrigeration installation forms a vital and integral part of the mine cooling system. The design of the installation, where it is located in the mine, how it is operated, and what factors are incorporated in its automatic control, all have an influence on the size of the refrigeration installation that is required, and on the total amount of cooling that can be achieved with the installation. These factors become of even greater significance when the service water is cooled, partly because of the intermittent demand for service water. The design and control of the refrigeration installation are specialized engineering functions on their own, and are the subject of a separate study.

*Water distribution and reticulation**

The cooling of service water has potential in reducing significantly the cost of distributing refrigeration through a mine. Relatively large savings can be achieved if the system for the distribution of service water is integrated

**Distribution* refers to the distribution of service water to the working places of a mine. *Reticulation* refers to the circulation of cold water through a mine for the purpose of cooling the air.

with the system for the reticulation* of the cold water that is used in various places in the mine for cooling the ventilation air. Extreme flexibility is a primary requirement of systems for distributing refrigeration so that the systems can be adapted to suit virtually any new production or ventilation situation that may arise. The possible need for water to fight fires must also be kept in mind[5].

It is because of unforeseen requirements and because production is always advancing into new ground that mine cooling, refrigeration, and in particular the distribution of refrigeration are dynamic engineering functions. Continual review is necessary if the changing needs of mining are to be met.

Management Considerations

When consideration is given to the amount of capital that could be involved in mine cooling, and to the need to ensure full and effective utilization of the equipment in which this capital is invested while at all times maintaining maximum productivity of the mine, it becomes apparent that careful attention is needed in the co-ordination of the various disciplines involved in cooling. The status of mine cooling should be defined clearly in terms of its importance to production and rock breaking, and this status must determine the nature and structure of the team responsible for achieving and maintaining satisfactory conditions. The leader of the team cannot be expected to bear the responsibility for achieving the targets if he is not granted adequate directive authority.

Integrated Systems for the Distribution of Refrigeration

The purpose of integrating the water distribution and reticulation systems is primarily to reduce the costs and to improve the efficiency of the distribution of refrigeration.

The first benefit arises from improved utilization of refrigeration plant. Generally speaking, the system should be designed to give first priority to the cooling of the service water, and then to the cooling of the ventilation air. Any change in the demand for refrigeration to cool the service water as a result of the hour-by-hour changes in the consumption of service water can be accommodated partly by transferring the load automatically from air coolers. The size and location of the dams play an important part in meeting the varying demands of the mine for cold water.

The second benefit is the saving in cost that arises because the refrigeration can be distributed with fewer pipes. The number of pipes that are required in the shaft to supply cold service water and cold water for cooling the air can be reduced from the conventional four to two, or even one, depending on which basic system is preferred. The number of pipes on each level supplying water can be reduced from the present two to one. As a result of the reduced need for air cooling, the cost of the pipes required for returning water to the refrigeration plant can be reduced to some extent. A further benefit arises in situations in which the installation of secondary and tertiary air cooling can be delayed, particularly during the early stages of mining, so that the provision of a return pipe to the refrigeration plant can also be delayed.

A further objective in integrated systems is to provide a flexible system that can be adapted easily as production changes from one area to another or as weather conditions change with the season. Although each system should be treated on its merits, there are a number of basic principles, which are discussed here before practical examples are given.

Systems Without Shaft Cascade Dams

An idealized system without shaft cascade dams, which explains the basic principles of integrated systems, is illustrated in Figs. 1 and 2. The system shown in Fig. 1 is suitable where levels are less than approximately 60 m apart, while the system shown in Fig. 2 is preferred where levels are more than 60 m apart. The only difference lies in the location of the pressure-reducing valves on each level. In the systems illustrated, because the static head in the pipes will always be less than 180 m, low-pressure piping can be used everywhere.

In both systems, the warm make-up water passes from the small 'hot' dam on 0 level through the evaporators (E) and back up the shaft into the large cold dam. The temperature-control valve (TCV) serves to regulate the temperature of the water leaving the evaporators so that it will not exceed the preset temperature of, say, 4 °C. This control is achieved through the bypassing of water back into the evaporators, and it functions automatically regardless of the number of evaporators that may be in operation. Provision is usually made for the over-riding of this temperature-control valve if the water in the cold dam falls below a predetermined low-level point.

In the system shown in Fig. 1, water is fed down the shaft from the large cold dam, which is situated on 0 level. On 2 level, water is tapped from the shaft pipe for service water. At this point the pressure in the pipe is equivalent to a head of 2 levels, since the diameter of the pipe is sufficient to produce a negligible friction loss even during periods of peak water demand. Further down the shaft on 3 level, a pressure-reducing valve (PR) reduces the pressure (which is now equivalent to 3 levels) to a head of 2 levels or whatever is required for that level. This reducing operation is repeated on each level down the shaft to regulate the pressure of the water to the next level.

On 4 level are the additional piping and control valves that are needed when the incoming ventilation air is to be cooled. The system illustrated involves a primary bulk-air cooler in the vicinity of the shaft. Two possibilities are illustrated, one involving the use of cooling coils (CC) and the other of an open spray chamber (SP). Water is taken from the pipe feeding the level through either a pressure-sustaining valve (PS) or pressure-reducing and pressure-sustaining valve (PRS), which supplies cold water to the bulk-cooling-coil installation or the bulk-spray chamber, respectively. A pump then returns the water to the refrigeration plant. The design of open spray chambers is discussed elsewhere[4].

A restricting orifice (RO) is located between the pressure-reducing and pressure-sustaining valves. The purpose of the restricting orifice is to give full control over the water that is supplied to 4 level. The pressure-reducing valve (PR) maintains a fixed pressure on the upstream side of the restricting orifice (RO) while the pressure-sustaining (PS) or pressure-reducing and pressure-sustaining valve (PRS) limits the minimum pressure of the water on the downstream side of the orifice (RO), provided that the total consumption of water on 4 level does not exceed the maximum amount of water that has been allocated to that level. When the consumption of service water increases, the pressure on the downstream side of the restricting orifice drops until the pressure reaches the setting on the pressure-sustaining valve (PS) or pressure-reducing and pressure-sustaining valve (PRS). At that pressure, the pressure-sustaining valve starts to close in order to sustain a constant pressure on the downstream side of the restricting orifice (RO) while starving the air coolers. The fact that the pressure drop across the restricting orifice is limited, or even fixed, means that a maximum or fixed quantity of water (refrigeration) has been allocated to 4 level. The maximum amount of refrigeration that 4 level could receive at any time can thus be controlled by setting the various pressure control valves. A further objective with the restricting orifice (RO) is to limit the loss of water in the event of a broken or burst pipe in the section. An example of how to select such an orifice, together with the equation used in the calculation, is given later in this paper.

On levels where secondary or tertiary air cooling is required in or near the stopes, a design that is based on the principles shown for 5 level can be considered. Here the pressure-sustaining valve (PS) is situated in the return pipe from the cooling coils (or spray chambers), while still controlling the pressure on the downstream side of the restricting orifice (RO).

The system illustrated in Fig. 2 is recommended where levels are more than 60 m apart in order to avoid unduly high pressures in the standard-grade piping that is used throughout. The pressure-reducing valve (PR) that controls the pressure on the upstream side of the restricting

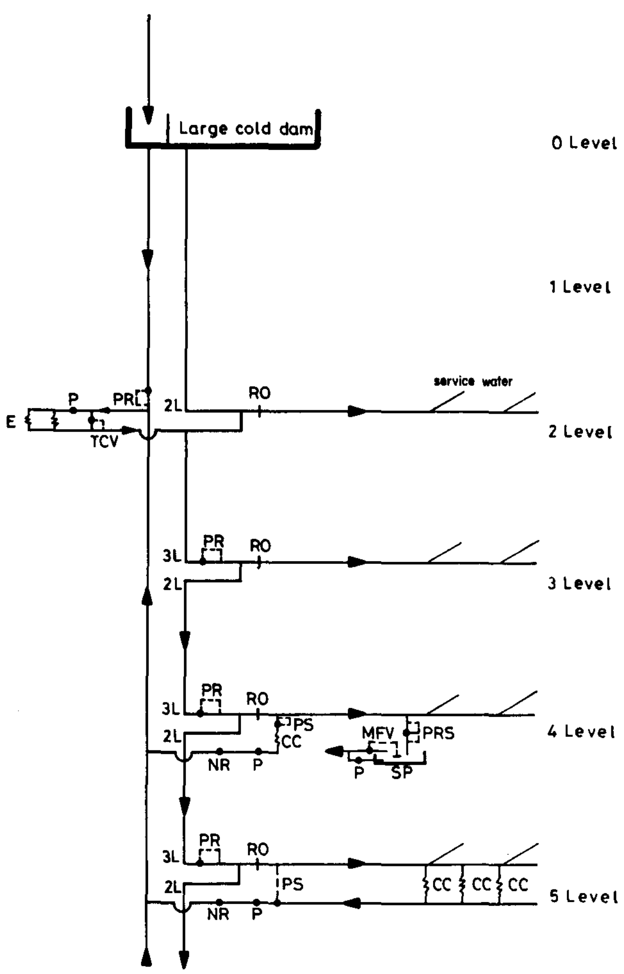

Fig. 1—Idealized water distribution and reticulation system without shaft dams for levels less than 60 m apart

PR Pressure-reducing valve
PS Pressure-sustaining valve
PRS Pressure-reducing and -sustaining valve
MFV Modulating float valve
NR Non-return valve
TCV Temperature-control valve
RO Restricting orifice
CC Cooling coil
SP Spray chamber
P Pump
E Evaporators
L Level head

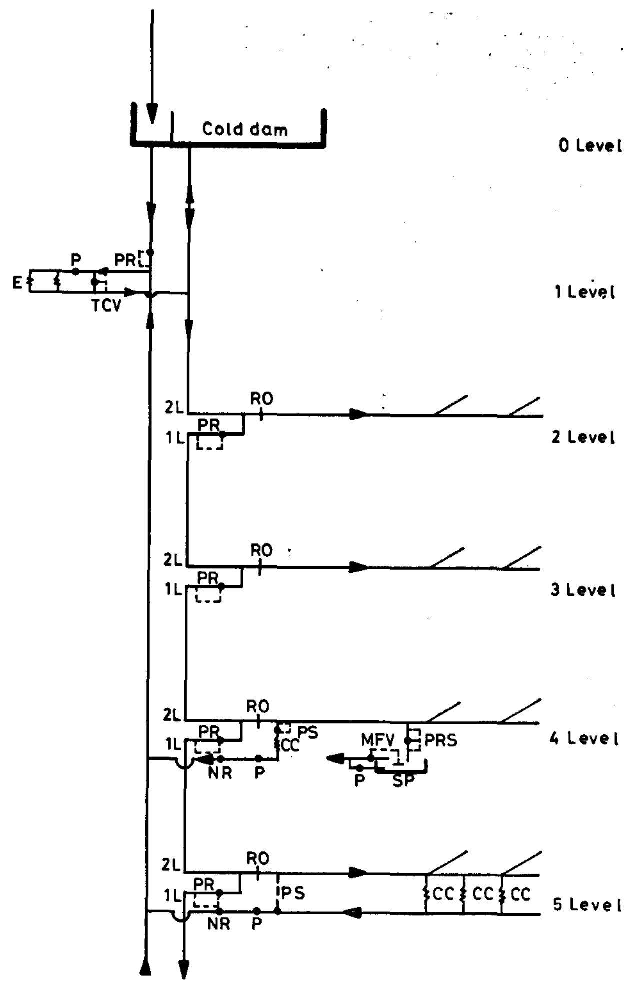

Fig. 2—Idealized water distribution and reticulation system without shaft dams for levels more than 60 m apart

PR Pressure-reducing valve
PS Pressure-sustaining valve
PRS Pressure-reducing and -sustaining valve
MFV Modulating float valve
NR Non-return valve
TCV Temperature-control valve
RO Restricting orifice
CC Cooling coil
SP Spray chamber
P Pump
E Evaporators
L Level head

orifice (RO) is located at the level above. This ensures that the normal maximum pressure in the system is approximately 2 levels head. In all other respects, the system is identical to that illustrated in Fig. 1.

Although the systems illustrated do not require shaft dams on the various mining levels, one large-volume storage dam above the stoping horizon is essential. The system is ideally suited to situations in which refrigeration plants are located on surface, or where refrigeration plants are less than three levels below the large cold dam. The large-volume storage is required as part of the design and control of service-water refrigeration installations and not because of the elimination of shaft dams.

Water supply systems without cascade dams have a number of important advantages.

(1) When new shafts on mines are developed, the excavation of shaft dams could increase the sinking time, which could be significant in terms of profit and cash flow. The elimination of shaft dams could therefore bring production forward by several months.

(2) Because the design relies on the use of pressure-reducing valves (PR), the shaft head can be utilized to full advantage. This feature can be of great importance when existing pipes supplying the section with water are under-capacity and a higher pressure is required to supply sufficient service water. It would also be of great value if there were a need to fight fires in the section.

(3) Probably the greatest advantage is that the system gives full control over the water distribution and reticulation requirements and, therefore, also over the distribution of refrigeration.

(4) On a two-pipe system that incorporates air cooling, the system gives first priority to the cooling of service water and its distribution.

(5) The system is less expensive than a shaft-dam system, and it is simple and easy to install and maintain.

(6) The system requires only one insulated pipe in the shaft for supplying the service water and the water for air cooling.

(7) Only low-pressure pipes are required except, obviously, for the pump return column in the shaft.

(8) The refrigeration plants can be loaded more evenly, particularly when there are large hour-by-hour fluctuations in the demand for service water.

(9) A further advantage is that the service water is exposed at fewer places to bacteriological and other forms of contamination.

The integrated system without cascade dams has several disadvantages.

(a) Perhaps the greatest disadvantage of the system is that it is unconventional, and that it therefore requires trained and experienced staff for its design and maintenance.

(b) The return water from the cooling coils must be pumped back to the plant.

(c) If there were to be a simultaneous failure of more than two pressure-reducing valves in series, high pressures could develop in the system.

Feasibility Tests on Systems Without Shaft Cascade Dams

Numerous tests on mines have established that integrated systems without shaft cascade dams are indeed feasible.

Pressure-reducing valves

Nine pressure-reducing valves (PR) were installed during the period November 1975 to December 1976. Five were at No. 4 Shaft and one at No. 7 Shaft, Hartebeestfontein gold mine. Two were at the Orangia Shaft and one at the Southern Shaft, Buffelsfontein gold mine. The upstream pressures on these valves were at times as high as 3,5 MPa (350 m head). On both mines, these valves proved to be extremely versatile and reliable, and additional valves have been ordered by the mines for their own use.

Pressure-sustaining valves

Two pressure-sustaining valves (PS) are in use. At No. 4 Shaft of Hartebeestfontein gold mine, one has been in use since November 1975. Another has been in operation since May 1976 at the Orangia Shaft of Buffelsfontein gold mine. The latter forms part of a system as shown for 5 level in Fig. 1, which includes a pressure-reducing valve (PR), a restricting orifice (RO), and a remotely sensed pressure-sustaining valve (PS), together with a pump return for getting the water back to the refrigeration plant.

Pumped return system

The system shown for 4 level in Fig. 1, which incorporates the necessary pressure-control valves and a pump for returning water from a 1500 kW bulk-spray chamber, has been in operation at the Hartebeestfontein gold mine No. 4 Shaft since December 1976. The system has proved to be very flexible, particularly in controlling the amount of refrigeration used in the spray chamber, and in regulating the temperature of the air leaving the spray chamber[4]. As a result of the success of this arrangement, two more 1500 kW spray chambers were constructed at the mine to do all the air cooling until the entire section of the mine that is served by the No. 4A Sub-shaft has been worked out, which will be towards the end of this century. One of these additional spray chambers came into operation during February 1978, and the other was commissioned in July 1978.

The system shown on 5 level in Fig. 1 is in operation at the Orangia Shaft of the Buffelsfontein gold mine. The air-cooling coils are located in the stoping area several kilometres away from the shaft. The system had the great advantage that service water could be drawn from the cold-water column once the system had been converted and there was consequently no need to insulate the existing long service-water pipes that ran parallel to the existing cold-water pipes.

A number of minor problems arose with these valves.

(i) Entrained air in the service water initially caused air locks in the pilot system of the valves at the Hartebeestfontein gold mine; consequently, these valves occasionally started to hunt and eventually closed. This problem was rectified by a slight modification in design that permitted a steady bleed-off of the air to the downstream side of the valve.

(ii) At the Orangia Shaft, scaling occurred on one occasion on the unprotected cast-iron part of the valve plunger. This was due apparently to excessive treatment of the water with lime. Scale formation of this type could hinder the movement of the valve plunger, but proper and regular maintenance at about three-monthly intervals will avoid operational difficulties from this cause.

(iii) Stones in an unflushed pipe once gave rise to problems during the commissioning of a valve; these stones were removed after the top cover of the valve had been taken off.

(iv) The pressure-sustaining valve at the Orangia Shaft was initially somewhat oversized, which resulted in unstable control. When the design of the seat was changed so that restricting orifices were incorporated in the seat, the difficulty was solved.

The experience gained so far has indicated that an integrated system without shaft dams has great potential and is feasible providing the system is correctly designed and regularly maintained. Control valves must be selected so that the nominal water velocity is between 5 and 6 m/s during periods of peak flow.

Systems With Shaft Cascade Dams

In a recently published paper dealing with gravity-fed water systems in mines[6], attention was drawn to the following main problems that often arise in existing water-supply systems in mine shafts.

(1) The size of the pipe leading out of the dam walls is too small for the available head of water in the dams to be able to accelerate the water to the required velocity.

(2) For the quantities of water that are required, the elevation of the shaft dams above the footwall is insufficient to overcome the frictional losses in the pipe leading from the dam to the shaft.

(3) Alternatively, the size of the pipe leading from the dam to the shaft is far too small to supply enough water to the pipe in the shaft, particularly when the pipe in the shaft is permanently open at the bottom, and hence the pipe must operate at terminal velocity if the flow is to be stable.

(4) The inlet to the discharge pipe leading from the dam to the shaft is badly designed, as is the transitional pipe section that connects the pipe on the horizontal to the vertical pipe in the shaft.

These deficiencies usually cause air to be drawn into the pipe, or cavitation and surging. The end result is severe water hammer, excessive erosion and corrosion of the pipes, and shortages of water during the main shift and during fire-fighting operations.

It is not intended in this paper to discuss remedies for these deficiencies, since these can be found elsewhere[5, 6]. However, since many mines may prefer a system that incorporates shaft cascade dams simply because such a system is conventional and better understood, a system is proposed in Fig. 3 that incorporates most of the novel features of the system shown in Fig. 1, while retaining shaft cascade dams. One feature of the system shown in Fig. 3 is that fewer pipes are needed than in conventional dam systems. Water is fed from the cold dam on 0 level down the shaft to 2 level. The shaft pipe, particularly the section in the shaft that connects the shaft dams, must be of such a size that the friction loss is negligible at peak water demand. (Suggested pipe sizes for different flow-rates are given later.) The section of the shaft pipe immediately before the restricting orifice (RO) could be of the same diameter as the pipe on the horizontal feeding water into the section.

The restricting orifices (RO) on each level are particularly important in that they serve to regulate the distribution of water. They are of such a size that sufficient head is always available at the level above the restricting orifice (RO) to supply water to the dam above and hence to all other levels below, particularly under broken pipe conditions. (An equation for the sizing of the restricting orifice (RO), together with a worked example, is given later in this paper.)

The dam on each level is filled directly from the pipe feeding the level below. At that point, the piping arrangement is such that the modulating float valve

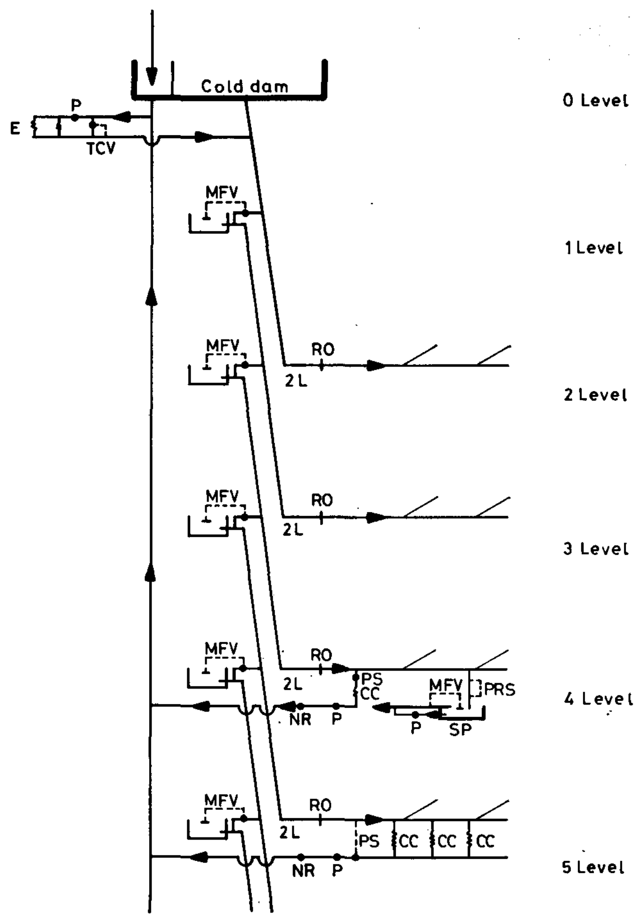

Fig. 3—An integrated water distribution and reticulation system with shaft dams

PR	Pressure-reducing valve	RO	Restricting orifice
PS	Pressure-sustaining valve	CC	Cooling coil
PRS	Pressure-reducing and -sustaining valve	SP	Spray chamber
MFV	Modulating float valve	P	Pump
NR	Non-return valve	E	Evaporators
TCV	Temperature-control valve	L	Level head

(MFV) and the entire section of pipe that connects the two shaft pipes are very close to the shaft. This naturally reduces the number of bends and the length of pipe at each station. Since the shaft dams in this system serve to provide an open end and to serve as a sensing point for the modulating float valve (MFV), and since the piping arrangement is such that the water by-passes the dams almost entirely, there is less need for large elevated shaft dams on each level. The adoption of this type of arrangement for the bypassing of the dams on each level is perhaps the simplest way of overcoming some of the major water-flow problems in existing shafts.

On 4 and 5 levels in Fig. 3, arrangements for the introduction of primary bulk-air cooling and of secondary and tertiary air cooling are illustrated. The design of these portions of the system is exactly the same as that for the system without shaft dams.

Several of the valuable features of the system without shaft dams (Fig. 1) are absent from a system that incorporates shaft dams (Fig. 3). These are as follows.

The water pressure on each level is limited to that corresponding to the dam position. The full shaft head cannot be utilized and, consequently, some of the control over the distribution of water and refrigeration is lost. A system with shaft dams often requires pipes of larger diameter than those in a system without shaft dams.

Since the modulating float valve is essentially the same as the pressure-reducing valve except for the pilot system, the problem of inadvertent pressurizing of the system when valves in series fail to close is exchanged for one where shaft dams can be flooded. Admittedly, the latter is probably the lesser of the two problems.

Feasibility Tests on Systems With Shaft Cascade Dams

Prior to eliminating the shaft dams at the Orangia Shaft of the Buffelsfontein gold mine, the system as shown on 5 level in Fig. 3 was introduced, and was kept in operation for some months. However, because of the limited shaft head (2 levels), there were times when the pressures were insufficient for both service water and air cooling. Accordingly, the system was subsequently converted to one without shaft dams.

The experience with modulating float valves was limited to eight valves. Four of these are at Hartebeestfontein gold mine, where they form part of the control of the bulk-air spray chambers. Tests with a fifth valve at Scott Shaft of Stilfontein gold mine in the mode shown for the shaft dams in Fig. 3 showed that the valve operated satisfactorily provided there was no entrained air in the system. Two more valves are operating at the surface cooling installation at the Southern Shaft of Buffelsfontein gold mine. The sixth valve was that at the Orangia Shaft, Buffelsfontein gold mine. All these valves proved to be entirely satisfactory.

System Without Shaft Dams, Hartebeestfontein

The water-distribution and reticulation system for the No. 4A Sub-shaft of the Hartebeestfontein gold mine is shown in Fig. 4. It is believed to be the first of its kind in the South African gold-mining industry, the main features of the system being as follows.

(a) There are no shaft dams.
(b) A single cold-water pipe serves all levels down the shaft.
(c) The system relies entirely on pressure-reducing valves (PR) to break the pressure at each level.
(b) The system incorporates primary bulk-spray coolers to cool the incoming ventilation air.

Since a large water-storage dam was already available on 32 level, the available static head on 33 level is only one level (41 m). Hence, it was necessary to incorporate a pump (P) and pressure-reducing valve (PR) on 32 level to provide the necessary head of two levels on 33 level, as shown in Fig. 4. Unlike the system illustrated in Fig. 1, water is drawn on each level from a common 250 mm high-pressure pipe in the shaft. The maximum head at the bottom of the pipe in the shaft is 230 mm head, which is still well within the range of a standard 'class 250' pressure-reducing valve.

Two bulk-spray chambers for cooling the incoming ventilation air are located on 32 and 33 levels, which are the primary intake levels for the ventilation air. Each spray chamber has a maximum capacity of 2500 kWR*, and will enable incoming ventilation air to be cooled to

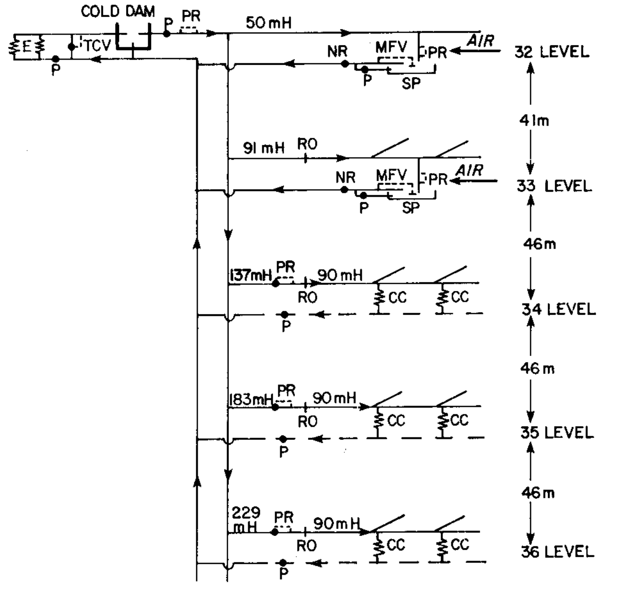

Fig. 4—The water distribution and reticulation system (without shaft dams) at 4A Shaft of the Hartebeestfontein gold mine

Note: (1) 32 and 33 are the main supply airways for the 4A Shaft mining area; each primary bulk-spray chamber (SP) has a maximum capacity of 2500 kWR

(2) The service-water supply consists of a single insulated column, installed on double hanger brackets, which facilitates the quick installation of a second pipe column (return shown by broken lines) if secondary and tertiary air cooling (CC) become necessary

PR Pressure-reducing valve
MFV Modulating float valve
NR Non-return valve
TCV Temperature-control valve
RO Restricting orifice
CC Cooling coils
SP Spray chambers
P Pump
mH Metre head
Isolating valves not shown

*kilowatts refrigeration

a wet-bulb temperature of 20 °C even during the hottest days of summer.

The main production levels for the shaft are on 34, 35, and 36 levels. The rock temperature is about 47 °C at 36 level, which is about 2220 m below surface. On each of the production levels, the pressure of the service water is reduced to 90 m head or whatever pressures may be required. The columns for the service-water supply on these levels consist of a single insulated pipe, installed on double hanger brackets that facilitate the quick installation of a second pipe column (return pipe) if secondary and tertiary air cooling become necessary.

The pressure-reducing valves (PR) on 34, 35, and 36 levels are standard 100 mm 'class 250' pressure-reducing valves, which are able to handle water at a normal maximum flow-rate of 50 l/s. A parallel standby valve is installed on each level. Each valve has either a restricting orifice (RO) on the discharge side of the valve, or a reduced seat, to limit the flow in the event of a pipe breaking or bursting. This avoids starvation of water to other levels in the event of excessive water flow on any one level.

System With Shaft Dams, Buffelsfontein

At the Southern Shaft of Buffelsfontein gold mine, all the service water is sent underground from surface and none of the service water is recirculated. The basic system for the distribution and reticulation of water that was in use before any modifications were made and before a system for chilled service water was introduced is shown in Fig. 5.

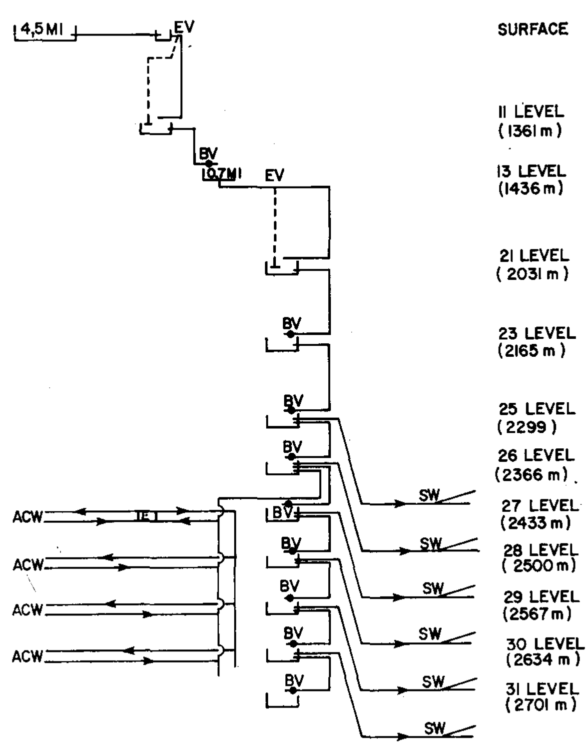

Fig. 5—The water reticulation and distribution system at the Southern Shaft of Buffelsfontein gold mine before the system was modified

Note: The service-water column runs parallel to the air-cooling-water column on the various levels; they are not separated as the diagram may suggest

EV Electrically actuated valve ACW Air-cooling-water column
BV Ball valve
SW Service-water column E Evaporators

Supply of water from surface

Two 150 mm pipes take water from surface down to the dam on 11 level, from which a 200 mm pipe in the shaft feeds water to the dam on 13 level. The pipe from 13 level to 21 level and all the other pipes in the shaft that connect the various dams *in seriatim* are all 200 mm in diameter. The service-water pipes that supply water to the various levels from the shaft dams on 25 to 30 levels are all of 150 mm diameter. The chilled-water columns in the shaft below 27 level (where the 20 000 kW underground refrigeration plant is located) are high-pressure pipes of 300 mm diameter. The diameter of the various pipes feeding chilled water to the air-cooling coils on 27, 28, 29, and 30 levels vary from 250 mm to 100 mm, depending on the distance and the amount of water that is required.

The levels of water in the dams on 11 level and 21 level are controlled by electrodes in these dams that signal the valves located on surface and on 13 level, respectively, to open or to close them*. All the water levels in the remaining dams are controlled by ball valves.

An investigation that was conducted after complaints had been received of water shortages on 21 level revealed the following.

(i) There was insufficient head (water pressure) on surface at the water tank near the shaft to overcome the acceleration and inlet losses to the vertical pipes (two 150 mm) in the shaft, resulting in cavitation and surging that could be cured only by the fitting of a breather pipe so that air could be drawn into the pipes. The maximum amount of water that could be sent down the shaft through these two pipes was 117 l/s.
(ii) The same problem, but to a lesser extent, existed at the dam on 11 level.
(iii) The elevation of the dam on 13 level was insufficient, particularly when the dam was low, to overcome the frictional losses in the 250 mm horizontal pipe on 13 level. This resulted in shortages of water at the dam on 21 level and ultimately all the way down the shaft.

In order to overcome the water-shortage problem and also to increase the amount of water that could be sent down the shaft to meet the needs of increased production, several modifications were introduced, as illustrated in Fig. 6. At the same time, alterations were made to the chilled-water reticulation system serving the underground refrigeration plant.

On surface, the 350 mm pipe that fed water from the main water reservoir on surface (4,5 Ml) to the tank at the shaft head was extended to bypass the tank and was taken 10 m down the shaft, where a 'smooth' transitional pipe section connected the 350 mm pipe to only one of the two 150 mm columns in the shaft. On 11 level, the 150 mm pipe in the shaft was modified to bypass the

*These controls would not necessarily be suitable if a pelton wheel were used to recover the potential energy of the water coming down the shaft.

dam on 11 level, and was extended to connect directly into the discharge pipe from the dam on 13 level, leading to the dam on 21 level. The latter modification was essential to avoid the entrance losses that would have occurred at the inlet to the discharge pipe at the dam on 13 level.

The horizontal pipe on 13 level leading from the dam on 13 level to the sub-shaft was replaced with a 400 mm column that was extended to 10 m below the collar of the sub-vertical shaft. At that point, a smooth transitional pipe section connected the 400 mm pipe to the 200 mm pipe down the shaft to the dam on 21 level.

In order to avoid similar 'inlet discharge' problems on the other levels, all the pipes feeding water to the dams were connected directly into the discharge pipes leading from the dams. Modulating float valves replaced all the ball valves. The modulating float valves were such that the system could supply 250 l/s from the dam on 21 level to any level down the shaft before having to draw water from any of the dams on 23 to 30 levels.

The system as modified has a number of important features.

(1) The single 150 mm column down the primary shaft, operating at terminal velocity, handles a measured flow-rate of 225 l/s, which is much greater than the flow of only 117 l/s that had been obtained previously through the two 150 mm columns.

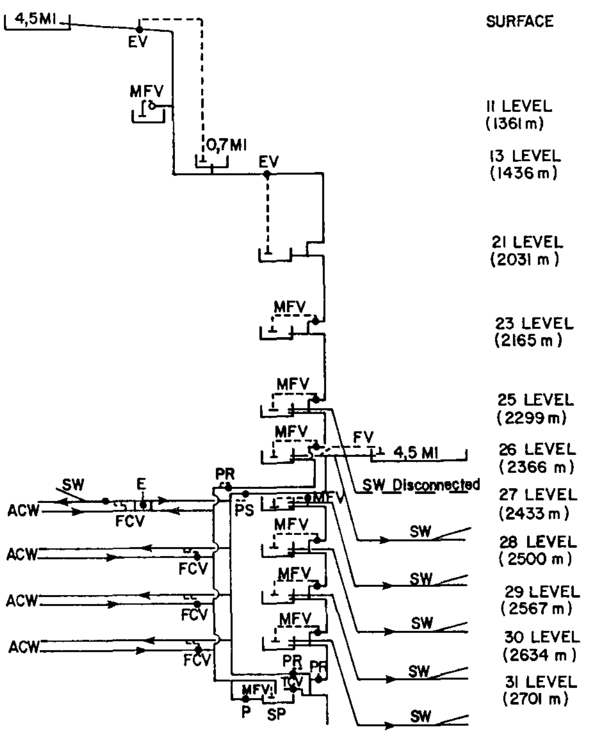

Fig. 6—The water distribution and reticulation system at the Southern Shaft of Buffelsfontein gold mine after the introduction of chilled service water and bulk cooling

EV	**Electrically actuated valve**	**FV**	**Float valve (low level)**
BV	**Ball valve**	**PR**	**Pressure-reducing valve**
SW	**Service-water column**	**PS**	**Pressure-sustaining valve**
ACW	**Air-cooling-water column**		
E	**Evaporator**	**P**	**Pump**
MFV	**Modulating float valve**	**SP**	**Spray chamber**
FCV	**Flow-control valves**	**TCV**	**Temperature-control valve**

(2) Similarly, the 200 mm column down the secondary shaft could handle 460 l/s at its terminal velocity, although it is not possible to feed water into this pipe on 13 level at this flow-rate. (Unfortunately, this 200 mm pipe column is too large, and hence it will be necessary to allow air into the pipe on 13 level to avoid cavitation and surge problems.)

(3) Except for the first 10 m from the collar down the shaft, no other shaft work was required for these modifications.

Integration of chilled-water and service-water systems

The next stage was to integrate the chilled-water reticulation system with the service-water distribution system. Since the refrigeration plant produces cold water at a constant rate but the service-water demand is intermittent, it was necessary to provide storage to meet peak water demands. Because of various mining and other considerations, the best location for such a storage dam was on 26 level, located 67 m above the refrigeration plant on 27 level shown in Fig. 6. The piping arrangement on 26 level was modified so that the pipe from the dam on 25 level feeds into the discharge from the normal shaft dam on 26 level, which in turn supplies water to the refrigeration installation on 27 level through a pressure-reducing valve (PR). Thus, water arriving from surface proceeds directly through the refrigeration plant on 27 level.

The cold water leaving the refrigeration plant passes through a pressure-sustaining valve (PS) on 27 level into the 200 mm pipe that normally supplies the dam on 27 level with water. The latter is connected into the new 4,5 Ml storage dam on 26 level. A low-level float valve (FV) on 26 level isolates the standard 'hot'-water dam from the 'cold'-water storage dam. Should the cold storage dam become empty, the float valve (FV) will open at a low level in the cold storage dam and feed the normal uncooled water on down the shaft. Hence, regardless of the state of the refrigeration plant, there will never be a shortage of water for drilling purposes.

The amount of service water that is required on 27 level is small enough to be tapped directly from the chilled-water columns, which run parallel to the service-water pipe on this level. This eliminates the need for the service-water pipe on 27 level to be insulated.

On the lower levels (28, 29, and 30) it is not possible to tap service water directly from the cold-water columns because there is no surge capacity available as part of the chilled-water reticulation system, and also because the pipe columns are too small to be able to supply both the water for the cooling coils and the service water. Consequently, there is no alternative but to use a three-pipe system on 28, 29, and 30 levels.

It is expected that, as production moves further away from the shaft, the service-water columns on 29 and 30 levels will become inadequate to supply the necessary service water. The only alternative, other than replacing the service-water columns, would then be to eliminate the shaft dams on 27 and 28 levels and to convert the modulating float valves (MFV) to pressure-reducing valves (PR) on these levels. This will increase the available head on 29 level to between 2 and 3 levels, and on 30 level to between 2 and 4 levels, thus enabling the high friction losses in these long pipes to be overcome without any need to increase the size of the pipes on the levels.

Balancing of flow through the cooling coils

One of the major problems with the chilled-water distribution system on 27, 28, 29, and 30 levels was that of balancing the flow of water through the various cooling coils. The system incorporated 89 cooling-coil installations. Adjustment of the flow through any one of the cooling coils influenced the flow-rate through all the others. Consequently, it was never possible to properly control the distribution of refrigeration between the levels, nor the distribution between the individual coils. The best that can be done in these circumstances is to allocate a specified maximum water flow-rate to each level, using flow-control valves (FCV) on each level.

The flow-control valves (FCV) shown on 27, 28, 29, and 30 levels (Fig. 6) are situated in the return chilled-water column on each of these levels and close to the station. The flow-control valves sense and control the flow of water in the intake column to each level. The main object of this arrangement is to ensure sufficient pressure in the event of the need to draw service water from the chilled-water column. This modification serves a similar purpose to that of the system on 4 and 5 levels shown in Figs. 1, 2, and 3 for transferring load automatically to and from cooling coils when the quantities of service water fluctuate.

The system is not ideal in terms of the integrated system, which should automatically give first priority to the provision of cold service water. In fact, the settings on the pressure-reducing valve (PR) and pressure-sustaining valve (PS) on 27 level determine the pressure drop across the cooling coils, and hence the water flow-rate and, to a certain extent, the distribution of refrigeration. Only the balance of the water will flow through the pressure-sustaining valve (PS) and will be available as service water. It will therefore be necessary to control the setting on the pressure-sustaining valve either manually or automatically so as to give first priority to the provision of sufficient cold service water.

Tertiary shaft below 31 level

At this shaft, 31 level is the connection between the secondary and tertiary shafts, the latter having only three levels below 31 level. For mining below 31 level, the new approach to mine cooling will be followed using the system illustrated in Fig. 6 on 31 level. This system gives first preference to the provision of service water, and then to bulk cooling of the air. There are several options for the supply of service water and refrigeration down the tertiary shaft. The service water and water for the spray chamber on 31 level will eventually exceed the capacity of the 200 mm pipe feeding the dams down the shaft. It will therefore be necessary to draw some water from the main chilled-water column that serves the air-cooling coils on levels above 31. This amount of water will gradually increase as production moves from the upper levels to the lower levels.

Three spray chambers similar to that shown for 31 level are now in operation on 30 level. These were installed primarily because the existing pipes that supply chilled water to the cooling coils are inadequate to fully load the refrigeration plants on 27 level, and to deliver the required amount of cooling to the workings.

Hydraulic Design of Water-piping Systems

The selection of sizes for pipes, flow-measuring orifices, and flow-restricting orifices is important in the design of water-distribution systems for mines. Other important considerations in the design of gravity-fed water systems on mines such as the piping at dam walls are outlined elsewhere[6].

Water flow-rates in pipes

The friction head loss for water flowing in 'used' pipes can be calculated from equation (1), which was developed by a manufacturer of steel pipes. Several tests on pipes of various sizes have indicated that the difference between actual and predicted flow-rates are insignificant for a given friction head loss. The equation does not allow for losses resulting from bends, valves, and other restrictions.

$$\triangle h/L = 5 \times 10^6\ (Q^{1,92}/D^{5,13}), \quad (1)$$

where

$\triangle h$ is head loss in metres of water (mH)
L is length of pipe (m)
D is true inside diameter of pipe (mm)
Q is flow in litres per second (l/s).

When applied to pipes in vertical shafts, the term $\triangle h/L$ represents the proportion of the available shaft head that will be lost in friction for a given flow-rate, Q.

Pipe sizes for service water

For the supply of service water to work places on the various levels, the suggested maximum head loss in the pipes is 2,5 per cent at peak flow-rates. This means that, where the station pressure is a head of 2 levels (less the negligible friction loss in the shaft pipe) and a minimum head equivalent to 1 level is required in the cross-cut to the most distant stopes, the total length of pipe from the shaft to the stope with an equivalent diameter to the shaft pipe must be less than 40 times the vertical distance between levels. The sizing of these pipes along the various levels is therefore very critical where stopes are likely to be located several kilometres away from the shaft.

When water is fed from dam to dam or from surface to an underground dam, pipes can run at virtually 100 per cent head loss, or terminal velocity. Table I gives flow-rates for pipes of various sizes at 2,5 and 100 per cent head loss.

TABLE I

TERMINAL AND DESIGN FLOW-RATES FOR SERVICE-WATER SUPPLY

Pipe diameter		Flow-rates (l/s)	
Nominal mm (in)	Inside mm	2,5 per cent head loss	100 per cent head loss
100 (4)	104,8	12	80
150 (6)	155,6	34	230
200 (8)	206,4	73	480
250 (10)	257,2	131	890
300 (12)	308,8	213	1450
350 (14)	360,0	321	2190
400 (16)	410,0	454	3100

Sizing of orifices for measuring flow

From the British Standard (B.S. 1042 : Part 1 : 1964), the equation for flow-measuring orifices with D and $D/2$ tappings can be derived as follows:

$$\triangle h = 8{,}266\times10^{-8}[(m^{-4}-1)/C_d^2]Q^2/D^4 \quad . \; . \; . \; . \; . \quad (2)$$

where

$\triangle h$ is head difference in metres of water between the upstream D tapping and the downstream $D/2$ tapping (mH)

d is diameter of orifice in metres (m)

D is inside diameter of pipe in metres (m)

$m = d/D$

Q is flow-rate in litres per second (l/s)

C_d is 0,607 for $0{,}45 < m < 0{,}80$

C_d is 0,640 for $0{,}80 < m < 0{,}90$.

A suggested standard for flow-measuring orifices that is convenient in mining is given in Table II. The full-scale flow-rate corresponds to a head difference between the D and $D/2$ tappings of 2,54 mH (100 in), which is the full-scale deflection on many standard flow-meters.

TABLE II

SUGGESTED SIZES FOR FLOW-MEASURING ORIFICES

Pipe diameter		Orifice plate			Flow at full scale
Nominal mm (in)	Inside mm	Inside dia., mm	Outside dia.*, mm	Thickness mm	l/s
100 (4)	104,8	78,4	160	5	25
150 (6)	155,6	112,5	217	5	50
200 (8)	206,4	156,1	271	8	100
250 (10)	257,2	192,3	332	8	150
300 (12)	308,8	224,5	379	10	200
350 (14)	360,0	253,9	442	10	250
400 (16)	410,0	280,6	493	12	300

*All orifice plates should be suitable for use with British Standard flanges, Tables C, D, and E. This outside diameter would enable the orifice plates to fit within the circle of flange-bolts.

Sizing of orifices for restricting flow

When orifices are to be installed in piping circuits so as to limit the flow-rate to acceptable values when pipelines are broken, there is a choice between conventional square-edged orifices and orifices that have a 45° bevel at both the upstream and dowstream edges. The latter are preferred because the sharp edges of square-edged orifices tend to become damaged and to wear away.

For orifices that have a 2 mm 45° bevel at both the upstream and downstream edges, the head loss for design purposes can be taken to be 1,5 times the nominal velocity head. Thus,

$$\triangle h = 1{,}5(V^2/2g), \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (3)$$

where V is the nominal velocity of the water through the orifice without allowance for any vena-contracta effects.

For square-edged orifices, a factor of 2,5 should be used rather than 1,5. Alternatively, equation (2) could be used together with a recovery factor of $(1-1{,}1\ m^2)$ to allow for partial recovery of some of the kinetic energy in the water after passing through the orifice.

As an illustration of the use of equation (3), suppose that, on any level at the 4A Shaft of Hartebeestfontein gold mine (see Fig. 4), the normal peak demand for service water never exceeds 25 l/s. At that flow-rate, an acceptable head loss across the orifice would be, say, 25 mH. The size of restricting orifice (RO in Fig. 4) can be calculated from equation (3):

$\triangle h = 25\ \text{m} = 1{,}5\ (V^2/2g)$

$V^2/2g = 16{,}67$ m

$V = 18{,}07$ m/s

Area of orifice $= Q/V$

$= 0{,}025/18{,}07$

$= 0{,}001383\ \text{m}^2$

$\therefore$ Diameter of orifice = 42 mm.

(For a square-edged orifice, the calculated diameter is 48 mm.)

With reference again to Fig. 4, it will be recalled that the design objective was to set each pressure-reducing valve (which must be located on the upstream side of the restricting orifice) so as to maintain a minimum head of 90 m in the service-water pipes at each station. The valve would hence be set so as to maintain a head on the downstream side of the valve of 90+25=115 m. This would ensure a head of 90 m on the downstream side of the restricting orifice at a flow-rate of 25 l/s.

In the event of the pipe bursting immediately downstream of the restricting orifice (the worst possible position), the orifice would limit the flow through the burst pipe to a velocity such that

$\triangle h = 115 = 1{,}5\ (V^2/2g)$

or $V = 38{,}8$ m/s.

The corresponding flow-rate through the orifice would be 53,6 l/s. Naturally, if the burst occurred further out into the workings, the flow-rate would be much less because of the additional friction loss in the pipeline between the orifice and the location of the burst.

When additional water is needed, such as for fighting fires, the setting of the pressure-reducing valve can be increased so as to utilize more of the head that is available down the shaft. It would be unwise to remove the restricting orifice in such cases. However, the 42 mm orifice could be replaced with one of say 50 mm if necessary for the duration of the fire-fighting operation.

The principle in the selection of a restricting orifice to prevent excessive loss of water when pipes break or burst is to exploit the square-law friction loss when water flows in pipes.

Closed-circuit water reticulation in a three-pipe system (using separate pipes for the cooling-coil water supply)

One of the more serious problems currently experienced with closed-circuit water reticulation systems in South African gold mines is the need to balance or control water flow-rates through the individual cooling coils. This is because of the relatively low pressure drop across the individual cooling coils compared with the pressure drop across the system as a whole. To ensure full control over the distribution of chilled water for cooling coils, it is essential that the pressure drop across the cooling coils should be much higher than the friction loss in the pipes. Alternatively, and perhaps the safest approach to overcome the problem in new installations, is to use pipes of larger diameter than have been used in the past. Naturally, each situation will need to be optimized, taking into account in the normal way matters such as pumping costs, pipe and insulation costs, availability of space in the pipeways, and possible future expansion of the system.

For closed-circuit reticulation of cold water to cooling coils, suggested design flow-rates for various sizes of pipes are given in Table III. Designs based on these flows are unlikely to give rise to problems of balancing water flows. The table is based on a friction head loss of about 5 m per 1000 m of single pipe line.

TABLE III

SUGGESTED DESIGN FLOW-RATES FOR COLD-WATER RETICULATION TO STOPE COOLING COILS

Pipe m	Flow l/s	Approximate velocity m/s	Cooling distributed, kW, assuming a 12° change in water temperature
100	5	0,6	250
150	15	0,75	750
200	31	0,9	1 550
250	57	1,07	2 850
300	92	1,24	4 600
350	139	1,4	7 000
400	196	1,6	10 000

Cost of Distributing Refrigeration

In many South African gold mines, the cost of distributing refrigeration exceeds by far the cost of the entire plant-room installation. With a given mining layout, there are many factors that determine the cost of distributing refrigeration, the most important being the technique adopted, that is, whether the service water is used as one of the means of distributing the refrigeration.

The next most important factor is the degree of utilization of capital equipment and of pipes. The important factor here is the amount of refrigeration that is distributed. While the amount of refrigeration does not change the general philosophy on mine cooling, it has an influence on whether it is worth considering the next phase of mine cooling or whether higher wet-bulb temperatures should instead be accepted or not. There are also other factors that play an important part, such as the layout of the mine and the thermal capacity* of the ventilation air, i.e. the amount of air being circulated. To a large extent the latter determines whether secondary or tertiary air cooling will be required. In order to avoid secondary and tertiary air cooling, it may be worth considering an increase in the thermal capacity of the ventilation air, either by increasing the quantity of air or by recirculating air.

The method of mining and the layout of the mine are important factors. In addition to the position of the shafts and plants and the number of levels being worked at any one time, a significant parameter of the mine layout is the ratio of centares mined per metre developed. All these parameters have an influence on the amount of capital that has to be invested in chilled-water pipes etc.

In order to obtain information on the cost of the three phases of mine cooling, three situations were investigated in detail: E.R.P.M. (K Shaft), Hartebeestfontein (4A Shaft), and Buffelsfontein (Southern Shaft).

All the costings were based on the actual cost structures for these mines. Although some of the excavations for large-volume storage dams and bulk-air coolers already existed, these costs were included in the costings as though it would have been necessary to obtain these excavations. For this reason, the costs of the first two phases of mine cooling are somewhat higher than the actual costs to these mines.

*Thermal capacity refers to the amount of heat that can be carried away by the ventilation air for a given change in wet-bulb temperature. It depends primarily on the mass flow-rate of the air.

Cost of Service-water Cooling

There is no doubt that refrigeration that is distributed through the service water incurs lower costs than refrigeration that is distributed through stope cooling coils, particularly when the efficiency or effectiveness of the cooling is taken into account. The cost of distributing refrigeration through existing service-water pipes is made up essentially of the initial capital and running costs for the insulation of existing and future extensions of the service-water pipes, as well as the initial capital cost of providing a large-volume storage dam. It may be argued that such a dam is required in any event, and that its cost is offset by the savings resulting from the provision of smaller shaft dams or even from the elimination of shaft dams. The latter does not apply to existing shafts where shaft dams are already in use. It is therefore necessary to include the cost of large-volume storage dams.

The capital that has to be invested in the insulation of existing service-water pipes and the provision of a large-volume storage dam can be very high. Consequently, if the period over which these costs have to be discounted (the remaining life of the shaft) is short, it may not be worth considering a centralized service-water cooling system as a means of distributing refrigeration. An alternative would then be to cool the service water locally at each crosscut, using water-to-water heat exchangers in the chilled-water circuit, such as is being done at the L Shaft, E.R.P.M.

The costs in Table IV suggest that the annual cost of

TABLE IV

ANNUAL COST OF DISTRIBUTING REFRIGERATION IN EARLY 1977 (IN RANDS PER ANNUM PER KILOWATT OF REFRIGERATION)

	Service water	Bulk-air cooling	Stope cooling coils	
			3 pipe	2 pipe
E.R.P.M. K Shaft				
Initial	13,91	12,83	13,72	
Running	6,06	13,35	33,36	
Total	19,97	26,17 (coils)	47,08	36,17
Hartebeestfontein, 4A Shaft				
Initial	3,45	6,75	13,85	
Running	14,96	4,47	58,56	
Total	18,41	11,22 (sprays)	72,41	35,95
Buffelsfontein, Southern Shaft				
Initial	3,86	4,29	15,60	
Running	8,43	12,00	33,48	
Total	12,29	16,29 (sprays)	49,08	27,91
Average	17	18	57	33

the initial investment in the use of chilled service water as a means of distributing refrigeration on mines such as E.R.P.M. (K Shaft), Hartebeestfontein (4A Shaft), and Buffelsfontein (Southern Shaft) is R13,91, R3,45, and R3,86 per annum per kilowatt of refrigeration, respectively. This excludes the cost of the refrigeration plant and plant room.

The running and maintenance costs for the distribution of refrigeration through chilled service water are not necessarily lower than for other methods of distributing refrigeration, as the example for Hartebeestfontein indicates. These costs for E.R.P.M. (K Shaft), Hartebeestefontein (4A Shaft), and Buffelsfontein (Southern Shaft) are R6,06, R14,96, and R8,43 per annum per kilowatt of refrigeration, respectively.

It is interesting to note that the total annual cost of distributing refrigeration through chilled service water, representing the sum of the above two amounts, is between R12 and R20 per annum per kilowatt of refrigeration in these examples (Table IV). In both the E.R.P.M. and Hartebeestfontein examples, the actual costs are somewhat lower since the excavation for the large-volume storage dams already existed.

Cost of Bulk-spray Cooling

In South African gold mines, conditions are generally very favourable for bulk-spray cooling of the ventilation air, since a fairly large amount of air cooling is required, and the thermal capacity of the ventilation air is such that large bulk-spray coolers can be justified on technical grounds. For this reason, the utilization of bulk-spray coolers from the point of view of the total cooling achieved per unit cost of the facility is good, and as a consequence the total cost of distributing refrigeration in this way is often less than that of any other method of distributing refrigeration. Unfortunately, it is also the least efficient way of distributing refrigeration, not only because of increased heat flow in the intake-airway system but also because of leakage of cooled air. Its cost, however, is so much lower than that of distributing refrigeration through stope coils that in many cases a distribution efficiency of as low as one-third will still justify bulk-spray cooling of the air on economic grounds, as shown for Hartebeestfontein and Buffelsfontein.

The costs in Table IV indicate that the initial capital costs for bulk-spray coolers are higher than the initial cost of service-water cooling. For E.R.P.M. (K Shaft), Hartebeestfontein (4A Shaft), and Buffelsfontein (Southern Shaft), the annual cost of the initial investment in bulk-air coolers is R12,82, R6,75, and R4,29 per annum per kilowatt of refrigeration, respectively. For E.R.P.M., the costs are for a bulk cooling-coil installation that is significantly more expensive than a bulk-spray cooler.

The power and maintenance costs (running costs) for these examples are R13,35, R4,47, and R12,00 per annum per kilowatt of refrigeration, respectively.

With regard to running costs, the most important factor is the cost of the electric power required to return the spray water to the refrigeration plant. It is for this reason that the power and maintenance costs for Buffelsfontein are somewhat higher than for Hartebeestfontein. At Buffelsfontein, the water from the spray chambers has to be pumped against a head of approximately 300 m, whereas for Hartebeestfontein the head is only 45 m. At E.R.P.M. the total power required is increased further by the fan that is required for the coil installation. It is interesting to note that the total cost of distributing refrigeration through bulk-spray coolers for Hartebeestfontein and Buffelsfontein is significantly lower than when bulk coils are used, as at E.R.P.M.

Cost of Stope Air-cooling Coil Systems

The previous two types of refrigeration distribution are relatively easy to cost. However, the costing of the conventional method of distributing refrigeration by the use of stope cooling coils, particularly for a two-pipe system, is rather complex. Not only is it difficult to obtain the various cost figures, but it is more difficult to evaluate the relevant and marginal cost items. Great care must therefore be taken in evaluating the economics of these secondary and tertiary forms of air cooling. Fortunately, these costings involve a number of parameters that are of approximately equal importance, so that minor errors in these parameters will not influence the final evaluation significantly.

The degree of utilization of heat-transfer equipment and, in particular, of pipes is the most important factor influencing the costs of secondary and tertiary air cooling. There is, however, a limit to the extent to which pipes and other equipment can be utilized. Although it may appear that the frictional losses in chilled-water pipes are quite reasonable and acceptable, the amount of water circulated is limited to the quantities that will allow a reasonable degree of control over the distribution of chilled water. The cost of secondary and tertiary air cooling is also sensitive to the layout of the mine, although not nearly as sensitive as to the utilization of pipes and equipment.

The examples for the three mines in question indicate clearly that the initial capital cost of distributing refrigeration in the conventional way is higher than that of any other form of distributing refrigeration, except perhaps for E.R.P.M. The only factor that could change the picture is the remaining life of a working area, as has already been pointed out. The annual costs of the initial investment for E.R.P.M. (K Shaft), Hartebeestfontein (4A Shaft), and Buffelsfontein (Southern Shaft) are R13,72, R13,85, and R15,60 per annum per kilowatt of refrigeration, respectively (Table IV). The major initial capital item is the cost of the cooling coils, fans, cowls, cars, and all the fittings that are associated with cooling coils. The initial length of the pipes appears to be less significant.

The power, maintenance, and repositioning costs are of the same order as, if not higher than, the total cost of using service water or bulk-spray coolers as a means of distributing refrigeration. These costs for the three examples are R21,70, R21,59, and R20,94 per annum per kilowatt of refrigeration, respectively. These figures do not take into account the annual cost of extending the chilled-water columns, which, when included, bring the total running and maintenance costs to R33,36, R58,56, and R33,48 per annum per kilowatt of refrigeration, respectively, for the three examples.

The total annual cost for the three examples appears to be somewhere between R45 and R75 per kilowatt of refrigeration per annum. The important aspect at E.R.P.M. and Buffelsfontein is that the systems are highly utilized and consequently difficult to control. Therefore, the total cost figures for these two mines of R47,08 and R49,08 per annum per kilowatt of refrigeration are relatively low. An annual cost of R55 to R60 would seem to be more realistic.

Potential Cost Savings

In attempting to assess the cost savings that will result from the adoption of these new concepts in mine cooling, it must be mentioned that the actual savings would not necessarily be reflected in the balance sheets of these mines. This is because it would be impossible with the conventional cooling-coil method to distribute all the additional refrigeration that is contemplated, because of costs and technological limitations. All too often the cause of these difficulties is an unforeseen large increase in production to far above that intended originally when the ventilation and cooling systems were planned. In all three mines, there would have been some duplication of the existing conventional distribution facilities. For E.R.P.M., the cost of distributing refrigeration is reduced to approximately 80 per cent of the cost of distributing refrigeration in the conventional manner, which means a saving of approximately R50 000 per annum for the shaft.

The annual savings for Hartebeestfontein (4A Shaft) and Buffelsfontein (Southern Shaft) are about 80 per cent and 40 per cent, respectively. For Hartebeestfontein, the saving is very impressive, mainly because it is possible to distribute the necessary refrigeration without having to consider secondary and tertiary air cooling. The estimated saving of R300 000 per annum is considered to be realistic, and much of this will be reflected in the balance sheet of the mine.

At the Buffelsfontein gold mine (Southern Shaft), the saving is fairly significant and amounts to approximately R500 000 per annum because there is now no need to duplicate the distribution facilities serving the cooling coils.

Cost of Three-pipe Versus Two-pipe Systems

It is difficult to compare the costs of a three-pipe and a two-pipe system. It should be borne in mind that, although there is a saving because of the reduced number of pipes, it may be necessary to increase the size of the chilled-water column that carries the water in on each level.

A comparison of two-pipe systems that were superimposed on the three mines and the usual three-pipe systems revealed that there is a potential saving of between 25 and 50 per cent on pipes, or between 10 and 30 per cent of the total cost of distributing water for service water and for secondary and tertiary air-cooling coils. See Table IV. Perhaps more realistic would be a saving of 25 per cent on water pipes, and 10 to 15 per cent on the cost of distributing refrigeration through service water and secondary and tertiary cooling coils, since these savings are based on E.R.P.M. and Buffelsfontein, which both require secondary and tertiary air cooling.

The upper limit of these ranges is relatively high because it was assumed in the calculation that the service-water pipes in a three-pipe system are not reclaimed while some of the chilled-water pipes in a two-pipe system are reclaimed. For this reason the savings with a two-pipe system could be very high. The important conclusion to be drawn is that the cost of a two-pipe system could be higher than that of a three-pipe system if for some reason the chilled-water columns could not be reclaimed.

Such a comparison is possible for Buffelsfontein, particularly if a two-pipe system was considered originally. On this mine it would have meant an additional saving of R100 000 per annum or a further saving of 15 per cent.

Influence of the Distribution Efficiency

One of the unknowns in mine cooling is the efficiency of distributing refrigeration. The estimates given here were based on the amount of refrigeration that can be distributed from the plant without any allowance for distribution efficiency.

The efficiency of service water as a means of distributing refrigeration depends to a large extent on what portion of the service water is used in the working areas.

On the other hand, the efficiency of bulk-air cooling depends on whether the ventilation air is distributed in accordance with the heat production in the mine, and whether cooling of the drain water on the footwall is taking place. The former factor is dependent also on the extent to which cooled air is lost without ever reaching the working places.

It is generally accepted that the positional efficiency of secondary and tertiary air cooling is better than that of primary bulk-air cooling. However, the efficiency of secondary and tertiary air cooling can be affected adversely by the following:

(a) the inability to control the water flow through individual air-cooling installations so that the refrigeration distribution can be controlled in accordance with the heat production, and
(b) the difficulty in re-positioning secondary and tertiary air-cooling installations so as to keep them up-to-date.

Factor (b) is perhaps the main reason that the efficiency of secondary and tertiary air cooling is generally poor.

It will be appreciated that, with such unknown efficiencies, the cost of distributing refrigeration can best be based on the actual amount of refrigeration that can be distributed from the plant (i.e., the actual running capacity of the refrigeration installation averaged over 24 hours), and not on the rated capacity.

Conclusion

Sufficient experience has been obtained on the practicability of the concepts set out in this paper to warrant the recommendation that mines should seriously consider their adoption. It should be emphasized that the benefits are considerable, even where only a portion of the total refrigeration requirements can be distributed through the service water. The potential cost saving amounts to hundreds of thousands of rands per annum for each shaft on which these concepts are implemented.

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