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The use of small cooling plants on a mine*

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SYNOPSIS

It has long been recognized that the provision of an acceptable thermal environment minimizes the danger and the adverse effect of heat stress, which is directly linked to decreased productivity, increased accident rates, and excessive physiological strain in workmen. Refrigeration in one form or another helps to provide this acceptable thermal environment.

This paper outlines the problems encountered in a working area, and the steps taken to alleviate environmental conditions in some stopes with the introduction of selective cooling employing small water-chilling units in conjunction with specially designed stope coolers. Performance figures are given for plant and stope coolers, and the effectiveness of the system is assessed from an evaluation of the improvement achieved in the environmental conditions.

SAMEVATTING

Dit word lank reeds erken dat die voorsiening van aanvaarbare hittetoestande die gevare en die ongunstige gevolge van hitte spanning, wat direk gekoppel word aan verlaagde produktiwiteit, verhoogde ongeluks syfers en abnormale fisiologiese spanning by werkers verminder. Aanvaarbare hitte toestande word geskep deur verkoeling in een of ander vorm.

Hierdie referaat skets die probleme wat in werksplekke ondervind word en die stappe wat gedoen word om omgewingstoestande in sommige afbouplekke te verlig deur die aanbring van selektiewe verkoeling deur gebruik te maak van klein waterverkoelingseenhede tesame met spesiale ontwerpte verkoelers vir afbouplekke. Die werkverrigtings syfers van verkoelers van masjienerie en afbouplekke word aangedui en die doeltreffendheid van die sisteem word getakseer deur die verbetering in omgewingstoestande wat bereik word te evalueer.

Introduction

At Durban Roodepoort Deep Ltd, the Far West Main Reef mining area is situated 1850 m west of the No. 6A sub-vertical shaft and extends from 35 level to 48 level, between the 1740 m and 2490 m horizons below surface. Main access to this area is from the sub-vertical shaft via haulages on 35, 40, 44, and 48 levels. The workings are served by two service ways: the West 32 service way extends from 35 to 40 level and serves the workings above 40 level, and the West 30 service way serves the workings between 40 and 48 levels (Fig. 1).

Mining had been abandoned in this area for many years in favour of the higher-grade and less arduous conditions of the shallower Kimberley Reef. With time, however, the grade in some of the Kimberley Reef workings deteriorated, and replacement workings in the Main Reef were again considered. As a result of this, it was decided that the Far West should be re-established as a mining area. Encouraging grade led to an extension of the mining programme to its present output of 30 kt per month.

The mining problems encountered in this area were those associated with severe geological faulting, which precluded the establishment of longwalls and often resulted in poor mining layouts. From an environmental point of view, the long distance travelled by the ventilation air from the downcast shaft, coupled with the presence of natural ground water, resulted in some 1100 kW of heat being added to the intake air, which contributed to the development of poor environmental conditions in the working areas. The lack of suitable return airways placed heavy reliance on a largely inaccessible reef horizon to handle the return air from this area. A two-fold ventilation-strategy programme was adopted to alleviate conditions. On the one hand, temperatures had to be reduced by the introduction of some form of cooling, while on the other adequate return-airway capacity had to be established to provide the outlets necessary for maintaining the design air volume through the section. The establishment of return airways was started and is ongoing, but, as it is beyond the scope of this paper, it is not dealt with further in any detail.

Ventilation

The No. 6 shaft system is ventilated by two fans operating in parallel on 30 level. The fans are situated between the No. 6 shaft vertical and subvertical banks, and produce 270 m^3/s of air at 7200 Pa. A volume of 100 m^3/s is split from out of the sub-vertical shaft and supplied to the Far West along 40, 44, and 48 haulages. The Far West is divided into two ventilation districts. One district comprises the workings below 40 level and is ventilated with air from 44 and 48 haulages, while the air from 40 haulage serves the stopes above 40 level. Poor environmental conditions had developed mainly in the workings above 40 level, where temperatures had risen to 33,0°C wet-bulb in places. Air control also presented a problem, which was created by the vast mined-out back areas through which leakage had to be controlled. A seal-

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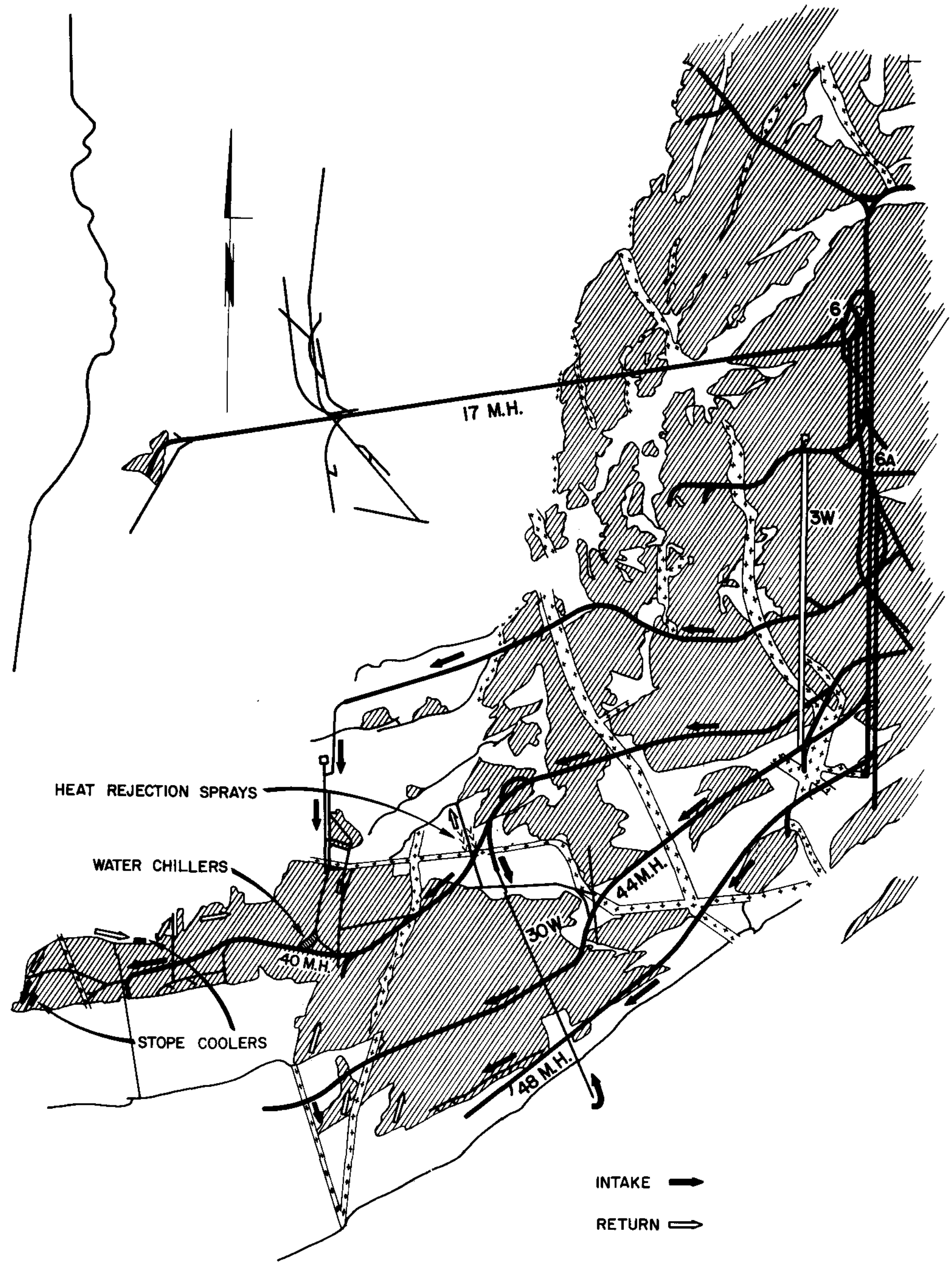

Fig. 1—The mining area on the Far West Main Reef at Durban Roodepoort Deep Mine

ing programme was embarked upon to isolate the mined-out areas from the working faces by the installation of dip walls from level to level. Strike control is maintained by seals installed from the dip wall to the face, thus providing the seal continuity that is so essential for effective air control. Although simple in concept, the system has made slow progress because of the practical difficulties encountered.

Cooling System

Apart from the programme of air control within the stope, refrigeration was also required. The installation of cooling plants of conventional size was impossible at the time because of the lack of the return-airway facilities necessary for heat rejection, and because the existing refrigeration plants were located too far away to provide even partial cooling to this area. However, a year before, two water chillers of 350 kW capacity had been purchased to cool two multi-blast development haulages, but the units had never been installed because the project had been temporarily shelved. It was felt that these chillers could be used to provide some of the much-needed cooling in the hotter stopes, where relief was most needed. Heat rejection on this moderate scale could be accommodated with a few minor alterations to the ventilation system.

A schematic layout of the cooling system is shown in Fig. 2. The system is based on the two water-chilling refrigeration units installed in a chamber excavated off 40 haulage in close proximity to a chair lift that provided direct access to the levels above at the time. The chamber is situated approximately equidistant between the heat-rejection site and the two air-cooling sites. Each refrigeration plant serves its own air cooler with chilled

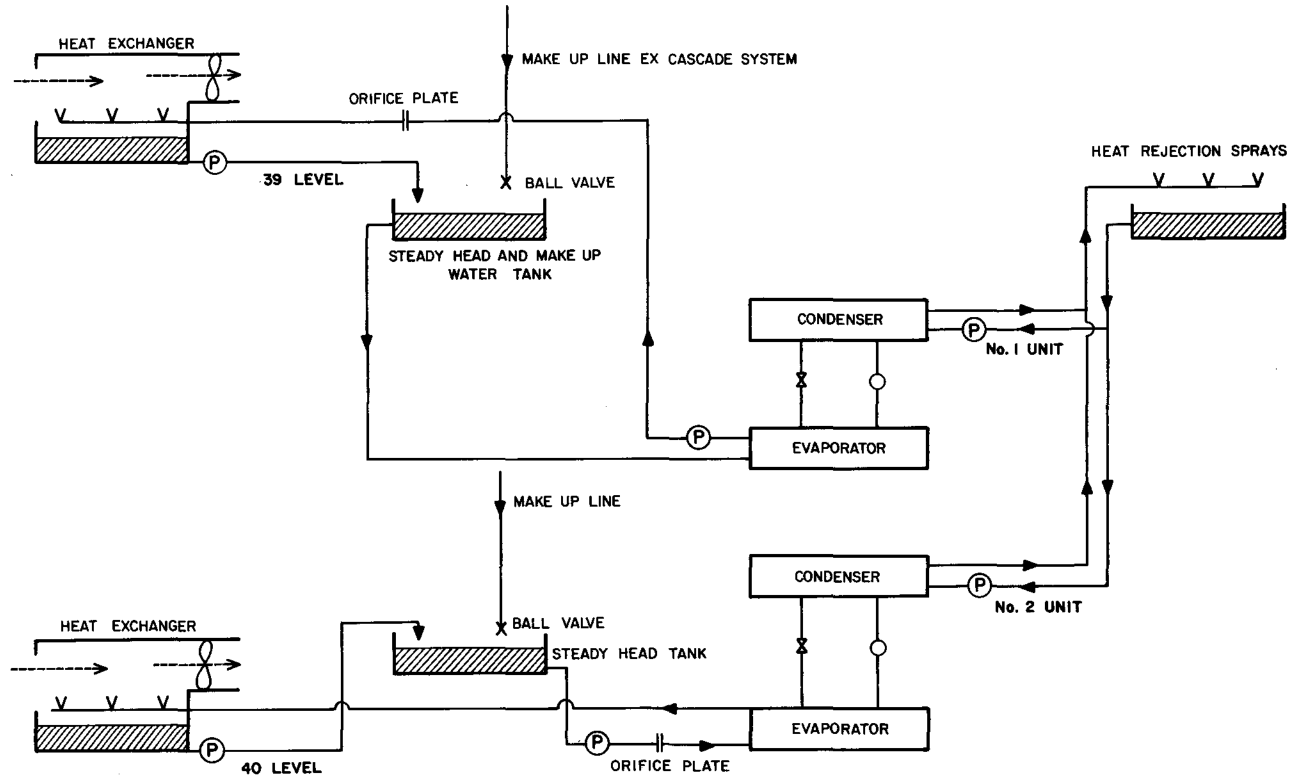

Fig. 2—A schematic diagram showing the cooling system

water through independent reticulation systems. The air coolers are novel direct-contact units in which the chilled water is sprayed into the warm air stream. The water is then collected in a sump below the sprays, from where it is pumped back to a steady-head tank and then gravity-fed to the evaporator. The condenser heat-rejection system makes use of a single spray chamber located a level above the chillers. Although each refrigeration unit has its own condenser water pump, there is a common supply and return piping system serving the heat-rejection spray chamber.

The two stopes selected for cooling were 40W34 and 39W32. The selection was based on the poor environmental conditions that prevailed in these stopes and the fact that both sites were easily accessible from the plant room along recognized travelling routes, which facilitated the installation of the stope air coolers and water columns. Polyethylene piping was used throughout the chilled-water reticulation system mainly because of ease of installation, and also because of the partial insulating properties of this type of material. No external insulation was applied to any chilled-water piping. All the steel piping in the condenser reticulation system installed in intake airways was insulated. The stope coolers were placed as near to the working face as was practically possible so that maximum benefit could be obtained from the available cooling. A further feature of the system is the cooling imparted to the intake air through the chilled-water piping. This cooling serves a useful purpose and is regarded as an integral part of the cooling system.

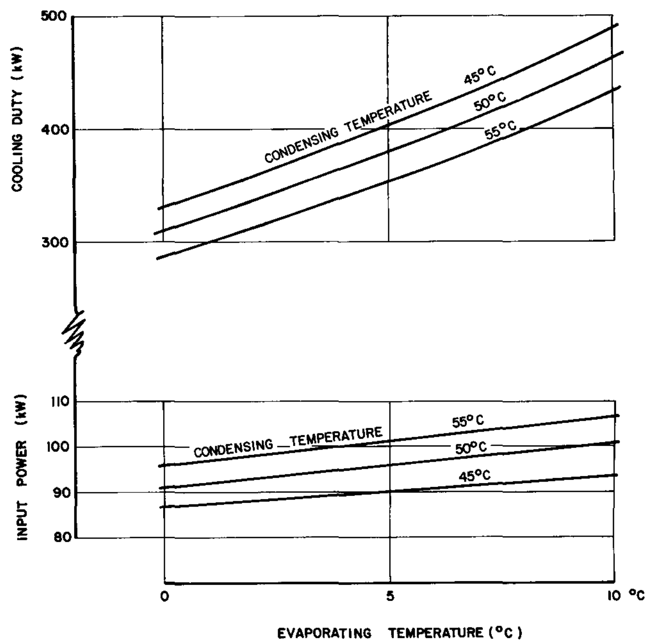

Fig. 3—The expected performance of the refrigeration unit

Water-chilling Refrigeration Units

Each refrigeration unit makes use of a reciprocating compressor directly coupled to a four-pole induction motor. The actual water chiller is a tube-and-shell heat exchanger in which the refrigerant (R22) evaporates inside the tubes and the water flows on the outside. The condenser is also a tube-and-shell heat exchanger (condensation occurring on the outside of the tubes), with removable end-covers for tube cleaning. These items, together with the electrical panels and switching equipment and the other refrigeration accessories, are all integrally mounted as a package on a common base. The overall length of the unit is 3,5 m, and it stands 1,8 m high and 1,4 m wide.

At the manufacturer's performance specification, the duty of each water chiller would be 350 kW, cooling 10,5 l/s from 18 to 10°C, while each of the condensers would require 21,5 l/s to be heated from 35 to 40°C. The electric motors would draw just less than 100 kW each.

The performance of a refrigeration plant is improved if the condensing temperature is lowered (rejection of cooler heat) or if the evaporating temperature is raised. Fig. 3 shows the expected performance for these particular coolers. It should be noted that, although the input power increases as the evaporating temperature rises, the refrigeration duty also increases, resulting in an improved coefficient of performance (ratio of cooling duty to input power).

Heat-rejection Facility

At the design condition, the heat-rejection facility is required to reject 450 kW of heat for each unit. A regulated volume of 22 m³/s of return air at 29°C wet-bulb provides the cooling medium for this purpose. This heat transfer is achieved in a standard single-stage crossflow[1] spray chamber using eighty-two nozzles to spray the warm water vertically upwards in a horizontal airway. The water is distributed through a manifold into three columns of 100 mm diameter installed in parallel along the length of the airway base. The nozzles are positioned at regular intervals along the columns and spray water at right-angles to the airflow. They cause the water to spray at an angle of 65° in a flat V-shaped profile, resulting in the full cross-section of the airway being filled with spray. The cooled water is gravity-fed back to the condensers.

Stope Air-cooling Units

Each air cooler is dedicated to one of the refrigeration units and must obviously have characteristics matching those of the chiller. Since the refrigeration units had been purchased at an earlier date, the design and selection of the air coolers were largely dictated by the characteristics of the water chiller.

It was expected that the warm inlet air to the coolers would have a temperature of approximately 32°C wet-bulb. The stope air coolers would therefore be required to operate with a water efficiency* of about 36 per cent. Even if the cooling effect of the pipe system is ignored, this is not a particularly difficult duty to attain and indicated a relatively simple solution. Generally, the more sophisticated the cooler, the less air flow is required to satisfy a given duty. It should be noted that, the less the rate of air flow, the greater the change in temperature of the air stream, even though the overall cooling duty (measured in kilowatts) remains the same. The cooling duty is calculated from the following equation:

$$\text{Cooling duty} = M_a \times Ca'' \times \Delta t_{wb},$$

where M_a is the mass flowrate of air,
Ca'' is an equivalent specific-heat term, and
Δt_{wb} is the change in wet-bulb temperature.

Thus, the less the air flow, the lower the temperature of the air leaving the cooler if the overall cooling effect remains unchanged. Fig. 4 shows a plot of the required rate of air flow, for different design configurations, that would satisfy the required water efficiency of 36 per cent.

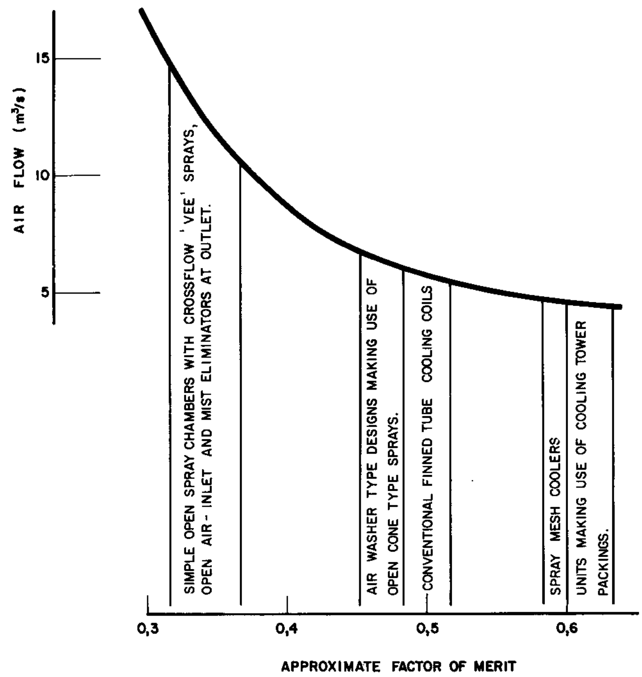

Fig. 4—Required flowrate of air through air coolers of different designs

The problem involved the selection of the best design configuration and the optimum operating conditions in view of the possibility that the refrigeration machines could be operated at an off-design condition if this should be expedient. An overall cost analysis was carried out for varying operating parameters and different types of cooling unit so that the most cost-effective installation could be obtained. This analysis considered the capital cost of the units, the overall cooling duty, the costs of fans and pumping power, and the consumption of refrigerant compressor power. The cost analysis indicated that a small simple cross-flow spray chamber should be used, that the rate of air flow should be about 10 to 11 m³/s (indicating a factor-of-merit[2] of 0,34), and that there is no benefit to be obtained from significant variations in the flowrate of water from the chiller specification value of 10,5 l/s. Fig. 5 shows the expected thermal performance of the air cooler at the underground conditions. It should be noted that this is a good example of the fact that the unit with the highest factor-of-merit is not always the best when the overall system is considered[3].

Two research-and-development aspects of this air-cooler design are of interest. Firstly, in the interests of

* Water efficiency[2] is the ratio of the actual change in water temperature to the maximum possible change that occurs when the temperature of the exit water is equal to the wet-bulb temperature of the inlet air; thus, if the heat pick-up in the piping system is ignored, the water efficiency is given by $(18-10)/(32-10) = 0,36$.

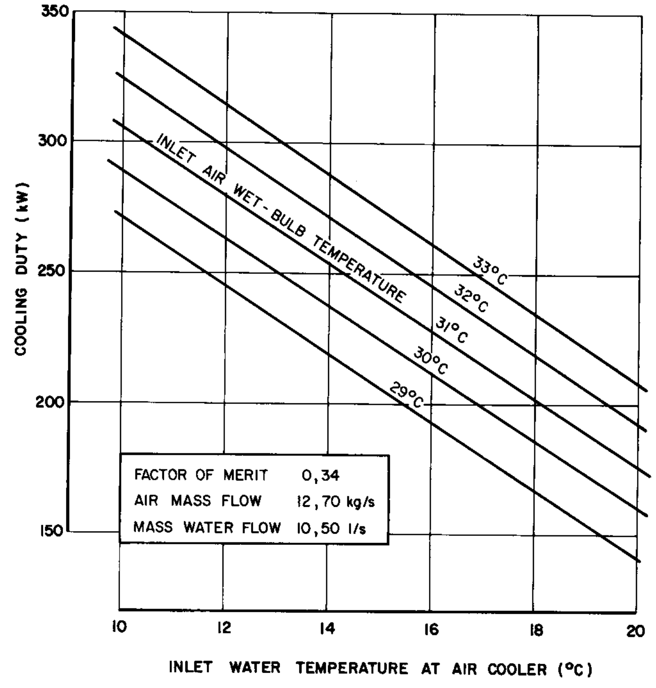

Fig. 5—The expected performance of the air cooler under underground conditions

making the unit as small as possible, it was to be operated at air velocities higher than those used in the past, and some novel mist eliminators had to be tested. Secondly (as discussed below), it was decided that the use of small water turbines to drive the fan and return-water pump should be investigated.

As a result of tests on surface at the heat-exchanger test centre of the Chamber of Mines Research Organization, the initial design was modified slightly. The water eliminators were tested at average velocities of up to 8 m/s without any carry-over of water. The final configuration of the unit is shown in Fig. 6. The chilled water from the refrigeration machines is pumped to a set of nozzles mounted horizontally at the base of the air cooler. The water is sprayed vertically upwards in the form of flat V spray patterns, and the stream of air is drawn horizontally through the unit by a fan situated on the air-outlet side. The chilled air passes through elimination plates, which drops out excess water from the air, before being discharged towards the working face. The water is collected in the sump below the sprays, from where it is pumped back to the chillers for recooling. One of the attractive features of this type of unit is that it can be cons^tructed in a mine workshop.

Use of Turbines with Stope Air Coolers

Because the water chillers had originally been purchased for a different application, the chilled-water pumps had been designed to produce a higher pressure than that required for this particular application. It was estimated that the supply pressure at the air coolers would be as high as 720 kPa (the required nozzle pressure being only 50 kPa), which indicated that there would be sufficient energy in the water stream to drive the fan and the return pump through a small Francis water turbine. This meant that no electrical supply to the air coolers would be necessary.

The concept required some investigation on surface before it could be considered for implementation underground. Both units were designed so that turbines could be fitted once the system had been commissioned, and one of the units was fitted with a turbine and tested on surface prior to being installed underground. The tests impressively demonstrated that these small turbines could be used for this sort of application in place of electric motors. However, there is a stringent prerequisite that the supply pressure should be maintained at or above the design value—synonomous with electric-motor voltage.

Underground Testing

Both air coolers were installed underground with electric motors driving the fans and return pumps. It was decided that the turbines would be used only at some

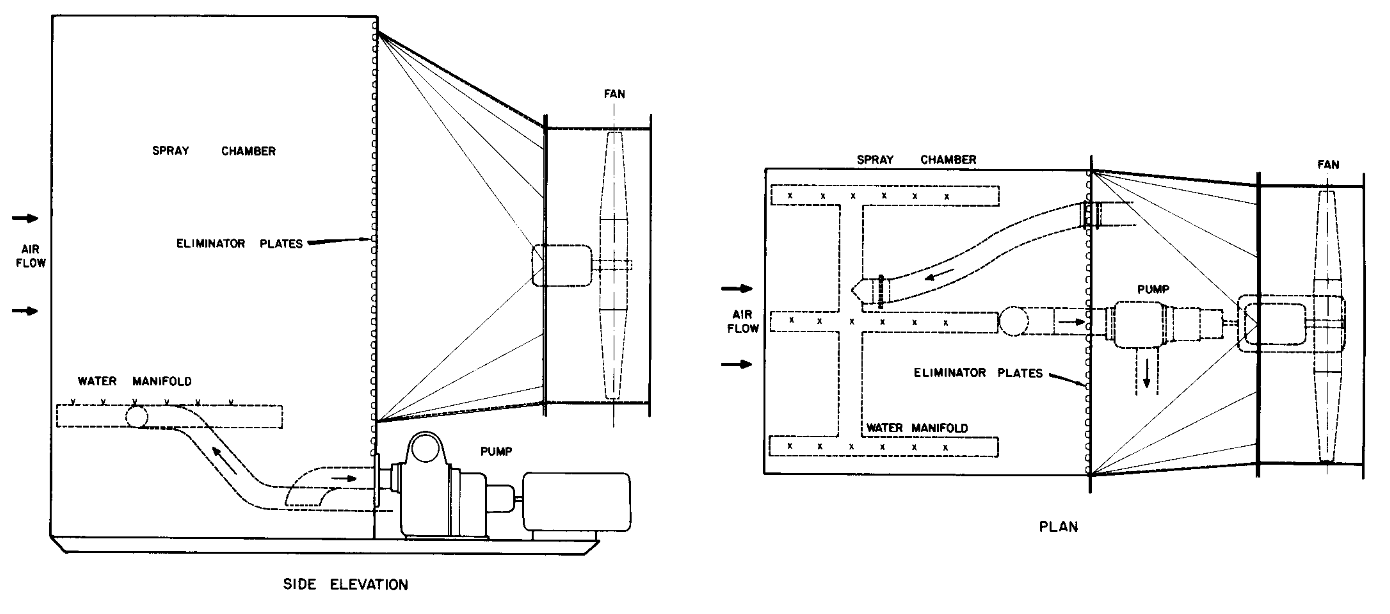

Fig. 6—The final design of the cross-flow air cooler

TABLE I

PERFORMANCE MEASUREMENTS ON COOLING SYSTEMS

Parameter	Plant 1 Air cooler on 39 level		Plant 2 Air cooler on 40 level	
	Test 1	Test 2	Test 1	Test 2
Flowrate of water (l/s)	9,7	8,9	6,2	9,6
Temperature of water into evaporator (°C)	24,6	24,6	24,7	21,0
Temperature of water out of evaporator (°C)	17,4	17,4	18,7	14,8
Water-cooling duty of refrigeration unit (kW)	292	268	156	249
Temperature of water into air cooler (°C)	19,0	19,2	20,4	16,5
Temperature of water out of air cooler (°C)	23,8	23,6	23,6	19,7
Air-cooling duty of spray heat exchanger (kW)	195	164	83	129
Air-cooling duty through supply pipe (kW)	65	67	44	68
Air-cooling duty through return pipe (kW)	32	37	29	52
Air flow through air cooler (m^3/s)	10,1	8,4	8,8	9,1
Wet-bulb temperature of air into cooler (°C)	31,2	31,4	28,6	27,8
Wet-bulb temperature of air out of cooler (°C)	27,5	27,8	26,8	25,0
Water efficiency	39%	36%	39%	28%
Factor-of-merit	±0,35	±0,35	±0,33	±0,29

Note: The actual measurements were adjusted slightly to create an energy balance throughout the system. However, the input power from the individual pumps (about 10 kW) and each fan (about 5 kW) was ignored.

future stage when the stope coolers would be served by chilled water with a constant static-pressure head, rather than by pumps to provide the pressure.

The measured performances of each of the refrigeration units and their associated air coolers are given in Table I. At the present time, some technical problems are being experienced with the refrigeration plants, resulting in the plants operating below specification. The relatively poor performance of the No. 2 plant was due to a faulty expansion valve. It is only a matter of time before these problems are resolved and the plants operate at full capacity. At no stage was the shortfall in plant duty due to inadequate loading on the air-cooling side.

The magnitude of the heat flow through the pipe walls was anticipated and, as can be seen from Table I, is not insignificant. It should be noted that this heat flow leads to further air cooling, and, although this cooling is not achieved as close to the working faces as that through the air coolers, it is still effective. The use of polyethylene piping minimized this heat flow, and there was certainly no justification for insulating these particular pipes.

Irrespective of the slight shortfall in refrigeration performance, the effectiveness of the cooling scheme depends ultimately on the improvement of conditions in the stopes. It has been found that, since the commissioning of these plants, the average face temperature in the two stopes involved dropped from 32,3 to 28,8°C wet-bulb. As was explained earlier, there has also been an ongoing programme to minimize air leakages and improve face ventilation control. The average face velocities have improved from 0,30 to 0,81 m/s. In an evaluation of the overall environment, the effects of the cooling and the effects of the air control cannot be separated. However, it is clear that the net result has been a remarkable improvement in stope environmental conditions, as reflected in Table II.

TABLE II

AVERAGE ENVIRONMENTAL CONDITIONS EXISTING IN STOPES BEFORE AND AFTER MODIFICATIONS

Average	Before modifications	After modifications
40 West 34 stope		
Velocity (m/s)	0,25	0,72
Temperature (°C)	31,7/33,5	27,8/28,1
Kata mcals (cm^2/s)	5,5	11,3
39 West 32 stope		
Velocity (m/s)	0,35	0,90
Temperature (°C)	32,9/33,1	29,8/30,7
Kata mcals (cm^2/s)	4,8	10,5

Acknowledgement

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