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Hydro-power—extracting the coolth*

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SYNOPSIS

Hydro-power—the use of high-pressure water as an energy source—offers tremendous benefits for environmental control in deep, hot mines. The extent of these benefits depends on the mining method, the selection of equipment to be hydro-powered, and the efficiency with which the coolth is extracted from the water and into the working environment.

The engineering of hydro-power systems continues to receive much attention. However, this paper considers the environmental implications of using hydro-powered equipment, particularly with regard to positional efficiency. The integration of hydro-power with developments such as backfill, mechanization, and higher face-advance rates is discussed.

Layouts are proposed that attempt to minimize the quantity of water in circulation by extracting the maximum coolth from the water.

SAMEVATTING

Hidro-krag—die gebruik van hoëdrukwater as 'n bron van energie—bied geweldige voordele vir omgewingsbeheer in diep, warm myne. Die omvang van hierdie voordele hang af van die mynboumetode, die keuse van toerusting wat van hidro-krag voorsien moet word, en die doeltreffendheid van die onttrekking van die koelte uit die water in die werkomgewing in.

Die ingenieursaspekte van hidro-kragstelsels geniet steeds baie aandag. Hierdie referaat handel egter oor die omgewingsimplikasies van die gebruik van toerusting met hidro-krag veral wat betref posisionele rendement. Die integrasie van hidro-krag met ontsluitings soos terugvulling, meganisasie, en hoër frontvorderingstempo's word bespreek.

Daar word uitlegte voorgestel wat poog om die hoeveelheid water in omloop tot die minimum te beperk deur die maksimum koelte uit die water te onttrek.

Introduction

Hydro-power in the present context refers to a high-pressure water supply as an energy source in deep mines where the pressure is obtained from the static head of a column of water in a deep shaft and the water is used to power stoping equipment.

The increasing quantities of water required underground for cooling, especially water supplied from surface refrigeration plants, saw the introduction of energy-recovery devices—usually water turbines coupled to pumps or generators. Not only do they counter the high pumping costs, but the potential energy of the water is converted into useful power instead of unwanted heat (2,3°C per 1000 m). This improves the cooling efficiency of the system with obvious environmental benefits.

The productivity benefits of face cleaning with high-pressure water jets have already been proved with electric pumps, and the superiority of hydraulic drilling has been demonstrated with electro-hydraulic systems, which have passed the development phase and are now available as standard equipment.

Hydro-power offers all of the above advantages in a much simpler system. The turbines, generators, air compressors, and much of the electric cabling and compressed-air piping can be eliminated or reduced. The stoping equipment can be powered directly from the high-pressure water in a single pipe system.

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However, hydro-power cannot be discussed on its own: it is an integral part of a mining system. This is especially true in regard to the implications for mine ventilation and cooling strategies. Backfill, mechanization, recirculation, and face advance all have their implications, and these are discussed here mainly for hot mines over 1000 m deep.

A Typical Deep Mine

The following parameters relate to a typical deep gold mine on the West Witwatersrand.

Upper mining level	2000 m
Lower mining level	3500 m
Monthly reef tonnage	150 000 t
Virgin-rock temperature at 2750 m	46°C
Monthly face advance	7 m
Stoping width	1,3 m

A concept that I have found useful in planning the ventilation and cooling of a deep mine is to regard the mining and stoping operations below the reef horizon as being in a mine situated 2000 m below surface, and *not* in a mine with a mean mining depth of 2750 m. The upper portion of solid ground can then be considered as a 'transport zone' (Fig. 1).

Cooling Requirements

The stope heat load for such a mine is approximately 20 MW without backfill, and 12 MW with 75 per cent backfill 5 m from the face. If the face advance is increased to 10 m per month, the stope heat load becomes 17 MW and 10 MW respectively.

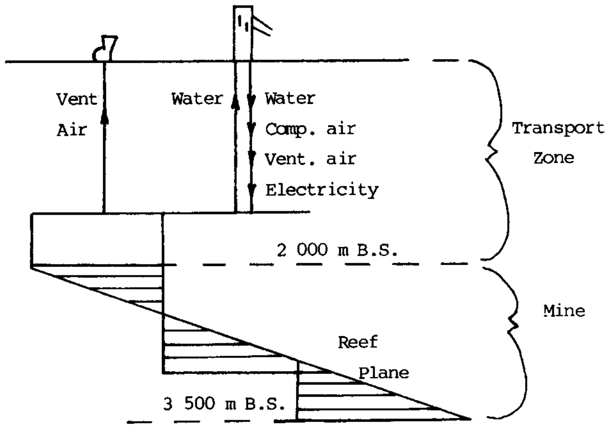

Fig. 1—The 'transport zone' in a mine
B.S. = Below surface

Below 2500 m, downcast air from the surface no longer provides any cooling and is, in fact, itself a heat load. At these depths, ventilation air is purely a medium for absorbing thermal energy and transporting coolth. This coolth can be supplied by bulk coolers on the surface or underground, from cooling arrangements throughout the mine, or any combination of these. It is assumed in this paper that the heat of auto-compression in the downcast air is removed before the air reaches the stopes.

The cooling required to counter the stope heat load is invariably provided by chilled water. This can be supplied directly into the stopes as service water and to in-stope coolers, or indirectly to spray chambers feeding additional cool air on the levels.

The minimum quantity of fresh ventilation air that a mine requires is determined by dust and gas dilution[1]. Recirculation does not affect this minimum quantity, but improves conditions by increasing velocities, and by providing more cooling for a given temperature range in the air circuit owing to the greater mass flow.

Backfill reduces the stope heat load but, unfortunately, narrows the size of the airway in the stopes and limits the air quantity. This can result in a more rapid rise in air temperatures. Fortunately, there is no real limit to the number of times that air can be thermally reconditioned.

Now what has all this to do with hydro-power? The answer is that all the above parameters are affected by the introduction of hydro-power, and all of them affect the efficiency of hydro-power.

Fundamentals of Hydro-power

The concept of hydro-power has received much publicity and is well documented in the literature[2-4]. It is particularly attractive if water is required underground for other purposes (e.g. cooling).

For efficient cooling, there is much benefit in making the water do useful work since it keeps the water cold. The potential energy of water is converted to a temperature that rises 2,33°C per 1000 m once the pressure has been relieved. This applies to cascade systems and pressure-reducing valve systems. (Cascade systems are subject to additional temperature rises owing to the regular contact of the water with the rock in the dams.) However, if energy-recovery and hydro-powered devices are used, the temperature increase is reduced in relation to the efficiency of the unit. At depth, keeping the water cold is as important, if not more so, than recovering the energy.

Instead of major energy-recovery installations at the bottoms of shafts—or at the bottom of the 'transport zone'—with turbines and generators feeding power to motors for compressors, etc., it is preferable for the high-pressure water to be taken directly to the devices requiring power (Fig. 2).

The 'break-even' depth for hydro-power, where the quantity of water required for cooling equals or exceeds that required for hydro-power, depends on several factors:

(i) the existing cooling arrangements,
(ii) whether the mine is new or has existing infrastructure (electricity and compressed air), and
(iii) the extent to which hydro-power is to be introduced.

However, the break-even depth is typically 1500 to 2000 m.

Efficiencies of Power Supplies

Compressed air is a safe but very inefficient power supply, with an overall efficiency of only 15 per cent (compressor 75 per cent, pipe-network leaks 50 per cent and drop in pressure 20 per cent, rockdrill 50 per cent). If water is required for cooling, hydro-power is a *free* source of energy. (Hydraulic tools are more efficient than pneumatic tools.) However, should the quantity of water exceed that required for cooling, consideration has to be given to the efficiencies of pumping the water to surface in the first place rather than to the use of hydro-power as an alternative to electric power. Electro-hydraulic power packs are another option, but they generally work with emulsions and not with mine service water.

Table I, which ranks power sources according to their efficiency regardless of cooling considerations, suggests that electric drives should be designed for all devices. However, safety considerations (e.g. fire hazards in the stopes) and the demands of emulsion systems impose additional constraints.

TABLE I
EFFICIENCY OF POWER SOURCES

Electric power	Efficient reticulation and highly efficient electric motors: > 90% overall efficiency
Electro-hydraulic	Reduced by the efficiencies of hydraulic pumps and devices, short hydraulic reticulation: 30 to 70%
Hydro-power	Limited to the efficiencies of water pumps and devices, long reticulation: 25 to 60%
Diesel	Low-efficiency engine, exhaust fumes: 30%
Compressed air	Low-efficiency compressors and pneumatic devices, bulky and leaking reticulation: 15%

Hydro-power Reticulation

There is a certain attraction in the prospect of providing cooling, service water, and a power source in the stopes from a single pipe system with quick-fit couplings for equipment.

Hydro-power reticulation consists of a continuous, closed, pressurized network of high-pressure pipes branching out on the levels and into the stopes with

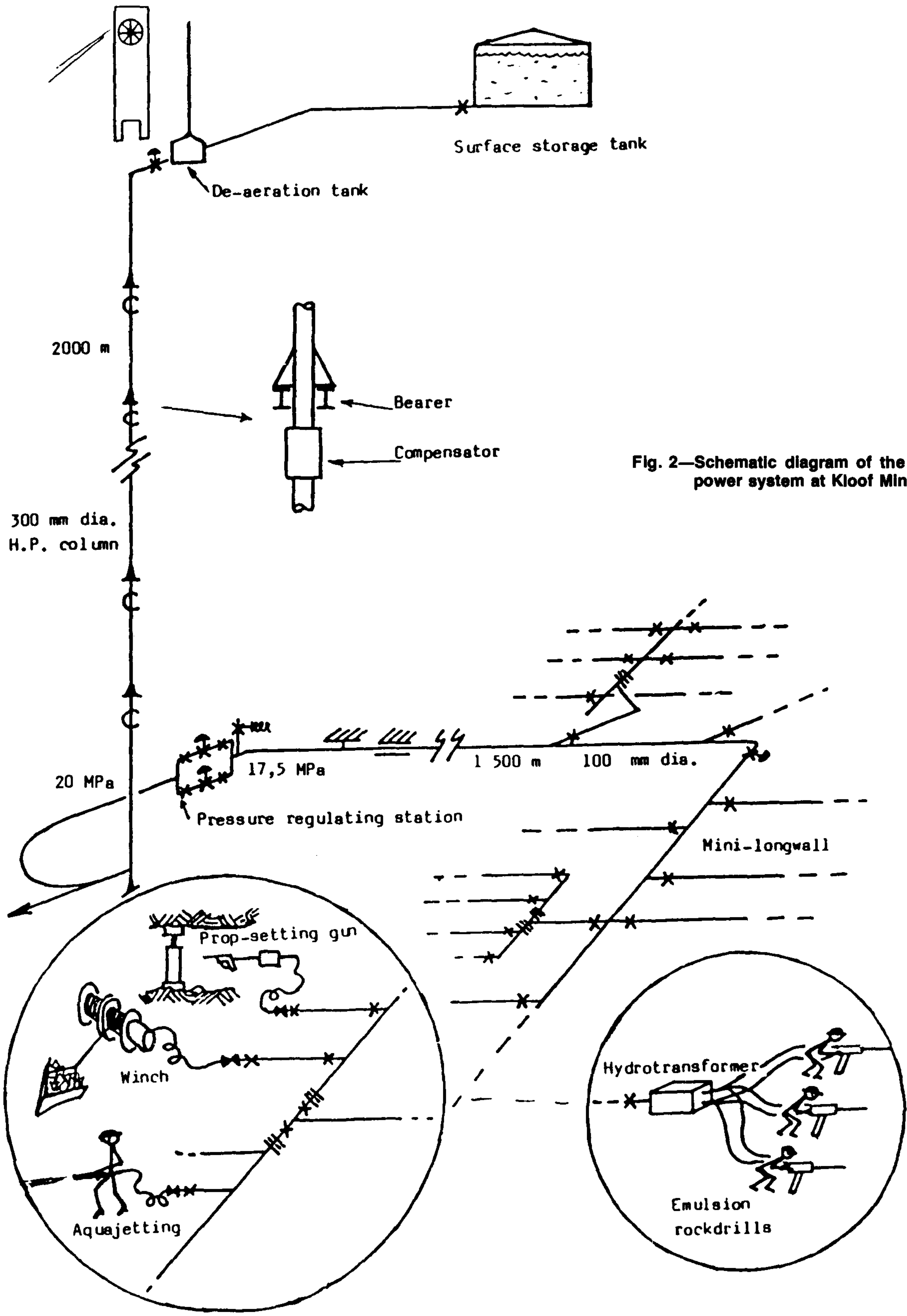

Fig. 2—Schematic diagram of the hydro-power system at Kloof Mine

isolating valves,
pressure-regulating valves,
flow-limiting devices,
fuses (to close when excess flow is detected), and
distribution manifolds in the stopes.

Hydro-powered Tools

The following sections describe the major users of hydro-power. It is worth noting that all the ancillary stoping equipment, including hole-flushers and winch signalling devices, can be hydro-powered. Prototypes for all these devices have been tested.

Aqua-jets

The benefits of high-pressure water jets during face cleaning have been proved using electric pumps drawing water from the low-pressure mains. The guns (as they are known) are used to assist the face scraper and to improve cleaning times by reducing the number of scraper-path moves. In steeper dips it is possible to clean the face using an aqua-jet on its own.

It is a simple matter to change from pumps to direct hydro-power.

Hydraulic Drills

Tests have been carried out by the Chamber of Mines in conjunction with Gold Fields of South Africa at West Driefontein using electro-hydraulic power packs and 98/2 emulsion (98 per cent water, 2 per cent lubricant). The power-packs are positioned in the cross-cuts, and two pipes are required for the supply and return lines up to the drills at the face. The drilling rates are double those of pneumatic machines, the net consumption of electric power is half, and the noise is appreciably less[5,6].

Hydraulic drills powered by service water are not yet available, although they are being developed. In the interim, a hydraulic stope transformer has been developed that powers a secondary emulsion circuit from a hydro-power supply. This offers most of the benefits of the hydraulic drills, but is complicated by the necessary transformer. During this interim phase, because the transformer is away from the face, the water is not discharged at the face.

Winch Motors

Hydro-powered winch motors comprising Pelton-wheel turbines are currently being tested. One mining house has considered hydro-power for winch motors just to remove the use of electricity from the stopes. However, from an efficiency point of view, hydro-power can be considered as a replacement for electricity only if there is a demand for the amount of cooling that the water can provide.

A further consideration is the positional efficiency of the cooling. The number of face scrapers required may be reduced with improvements in aqua-jetting, especially in steeper stopes (more than 40 degrees). Gully winches can be 100 m away from the face. Some provision has to be made to get the cold water up to the face. Schemes to optimize the cooling are discussed below.

Mechanization may see the demise of gully winches except for a few major slusher gullies. These will be few in number and remote from the face, and will probably remain electrically driven.

Fans

Very few fans are found close to the face, and it is unlikely that those remote from the face will be hydro-powered. Again, as for winches, the positional efficiency is poor. However, in one of the strategies considered below, there may be a demand for hydro-powered fans in airways created within backfill.

Air Coolers

Two types of hydro-powered air coolers are required.

(1) *In-line type.* Hydro-powered machines help to keep the water cool by doing useful work, instead of the pressure being converted to heat. Most machines discharge the water onto the footwall, and it may not be possible to extract all the coolth before the water enters the gully and then the box-hole. Even with the current use of low-pressure chilled water, temperatures in the low 20's are often measured in the cross-cut drains. Because there is a need to remove the coolth before the water is put to use, this is discussed more fully below. The need for high pressure, in-line heat-exchangers may incorporate a hydro-powered fan to force air over the coils.

(2) *Spray type.* It is likely that stope cooling will be required in excess of that provided by the quantity of hydro-power water used. This will require a self-powered device that consumes water while trying to extract the maximum amount of coolth. The Chamber of Mines has tested a few devices, and more are being developed.

Backfill

Backfill and hydro-power are mutually supportive. Backfill limits the quantity of air up the face, and hydro-power provides the regular thermal reconditioning that is then necessary.

Optimum backfill is carried close to the face, but this creates a narrow airway with a high resistance. The air velocity should be limited to about 2 m/s to control the pick-up of dust, and the net result is a generally lower air quantity with reduced cooling power in the stopes.

Although backfill reduces the heat load in the stopes by reducing the heat flow from the back areas, the lower amount of air available requires more frequent thermal reconditioning. There are indications that this lower amount of air may even be below the minimum required for the dilution of dust and gas, and that additional airways will have to be created in the backfill parallel to the face. These airways may provide practical positions for stope coolers.

It has been shown[2] that, at depths of less than 1500 to 2000 m, the quantity of water required for hydro-power is less than that required for cooling. This suggests that stope coolers are still needed, albeit fewer of them. This depends very much on the efficient thermal utilization of the hydro-power water. A few layouts are suggested later in this paper.

Recirculation

As already stated, a minimum quantity of fresh air is needed to ventilate a mine. This quantity is not affected by recirculation schemes[1], but recirculation considerations are greatly affected by backfill. The following two examples illustrate this.

(1) Recirculation can be used to improve stope velocities, but it is likely that backfill has already pushed these velocities to the limit in the stopes.

(2) Recirculation can also be used to increase the mass of air in circulation, thus extending the intervals between thermal reconditioning. However, if this strategy requires additional airways in the fill, it is unlikely to be feasible.

Hydro-power serves to extend the intervals between thermal reconditioning in that the air is cooled regularly through the stopes—a benefit that also affects recirculation considerations.

Mechanization

A clear distinction must be made between true mechanization with stoping machines such as impact rippers, and trackless mining with rubber-tyred vehicles operating in the gullies and connecting roadways.

Mechanization offers great improvements in rock and material handling, but introduces undesirable aspects such as maintenance and trailing cables and, particularly on the ventilation side, exhaust gases and heat.

Stoping Machines

It should be possible to hydro-power stoping machines as they are likely to be slow moving and operate in a confined area. The impact ripper on trial at Doornfontein Gold Mine is an example of this. Again, the difficulty lies in extracting the maximum amount of coolth from the water.

Trackless Machines

It is not likely that trackless machines will be hydro-powered. They are generally high powered—up to 350 kW—with a range of a few hundred metres. They would require long, sophisticated high-pressure hoses. These machines do pose a thermal problem, which is further aggravated if diesel power is chosen in place of electric.

These machines do little 'useful work' in the true Newtonian sense. Rocks are moved sideways, and the machines park back where they came from. Most of the input power is eventually liberated as heat, e.g. in the hydraulics and wheel bearings. An electric motor is over 90 per cent efficient, and the cooling requirements are approximately equal to the input power. A diesel engine is only 30 per cent efficient and requires three times the cooling. A typical figure for the air requirements over a diesel machine are 0,1 m^3/s per kilowatt (actual duty). This air must absorb 3 kW of heat, which causes a 6°C rise in the wet-bulb temperature and an even greater rise in the dry-bulb temperature.

Furthermore, a vehicle often 'plugs' the airway in which it operates, reducing the airflow and causing even greater increases in temperature.

Efficient Extraction of Coolth

Hydro-power brings chilled water from a main surface storage dam, through a simple pipe network with a short retention time, directly to the stopes. The simple law concerning the conservation of energy confirms that the potential energy of the water at the top of a shaft has been converted to pressure and that the water is still cold. The Joule–Thompson effect (the conversion of pressure energy to heat) is realized only when pressure is relieved without work being done.

The theoretical temperature rise at this stage is due to friction in the pipes and pressure-reducing valves, and heat conduction through the insulation. Once a system is fully operational and reasonable flowrates have been achieved, the temperature rises should be about 2 to 5°C, and stope-water temperatures of 7 to 10°C are possible.

Hydro-power achieves the goal of bringing more chilled water to the stopes, providing cooling *where* it is required and *while* people are working. To make the system efficient with good air and rock cooling, the water should leave the stopes at as high a temperature as possible, thus minimizing the quantity required.

In the simplest system (Fig. 3), chilled water from hydro-powered devices discharges directly onto the footwall. The air has minimal contact time with the water, and relies on a cold footwall for most of its cooling. There is little control over the contact time between the water and the footwall and broken rock before the water runs into the gully. Temperatures below 20°C have been recorded for water leaving the footwall and rock. This is obviously inefficient and wasteful of the water's cooling potential.

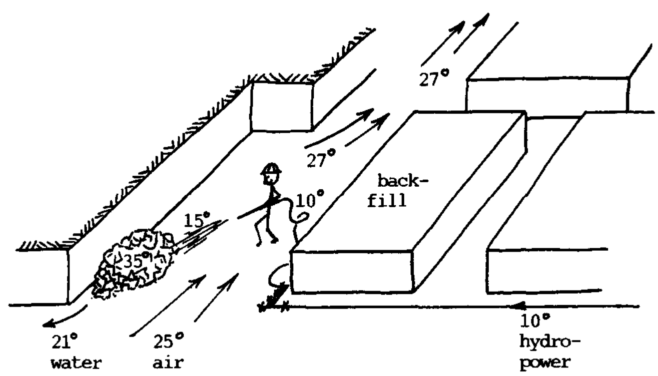

Fig. 3—Simple application of hydro-power

In theory, the rock itself does not need cooling. The *air* needs to be cooled to counter the heat flow from the rock and to maintain air temperatures suitable for men to work. Cooling the footwall will reduce the heat flow into the air, but is likely to over-cool the rock, unnecessarily increasing the overall heat load in the stope by inducing heat flow from the earth to the cold footwall.

This can be regarded as parallel-flow cooling, where the hot and cold elements mix towards a weighted-average temperature. Counterflow cooling, on the other hand, where the coolant travels from the coolest to the hottest elements, makes efficient use of the coolant. This suggests that the water should first cool the air, then provide hydro-power, and finally cool the rock (Fig. 4). Even if water leaves a hydro-powered device at 25°C, it can still do useful cooling on the hot footwall, and it may be possible for the water to leave the stopes at temperatures close to the ambient wet-bulb temperature. The operators of hand-held hydro-powered devices also benefit from this arrangement in that warm water (20°C) passes through their machines. Imagine holding a rock-drill at 10°C!

Positioning of Coolers

Again, backfill, recirculation, face advance, and mechanization all affect the decisions concerning the positioning of coolers. As discussed above, there are two types of cooler—in-line and open spray.

If the discharge water from all the hydro-powered

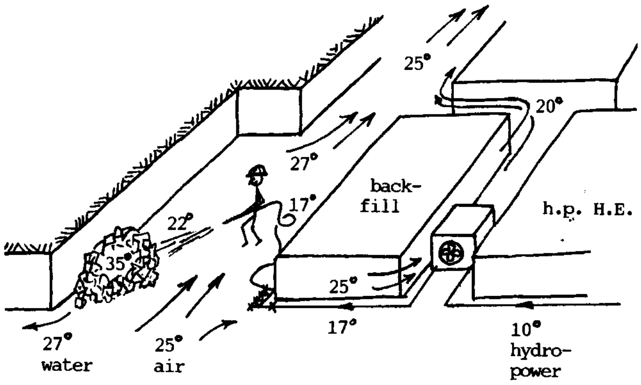

Fig. 4—High-pressure heat-exchanger (h.p.H.E.) before the manifold

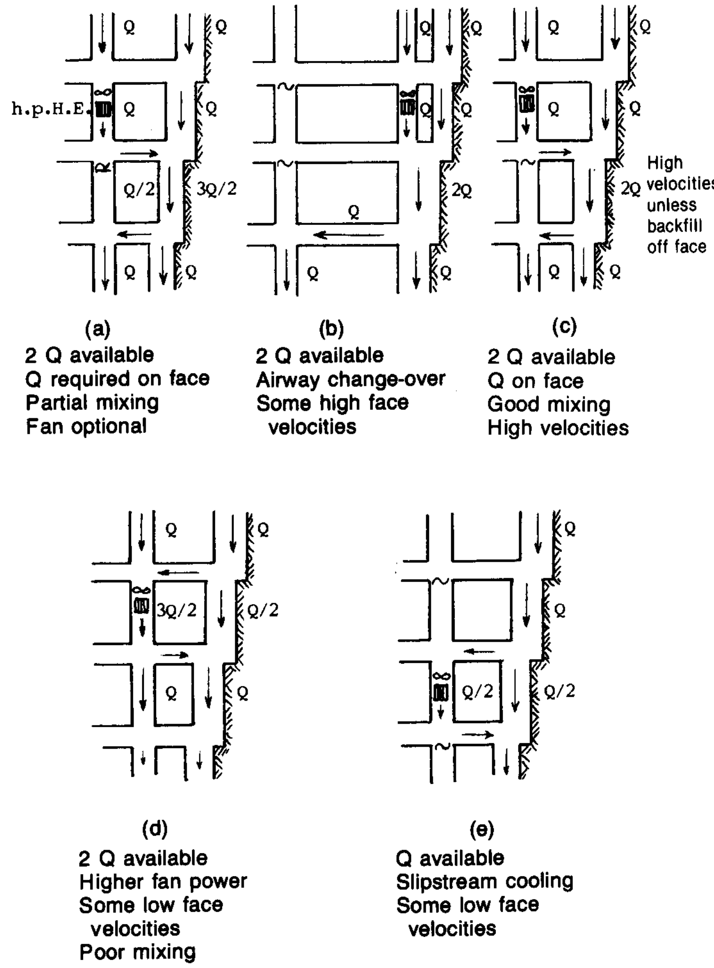

Fig. 5—Air flow and cooler layouts with airways in the backfill (h.p.H.E. = high-pressure heat-exchanger)

devices in a stope could be conveniently collected, it could be sprayed through conventional low-pressure coolers. However, water from hand-held devices will be contaminated and difficult to collect, and the water will also have already been heated by the inefficiency of the device. Ideally therefore, hand-held devices require the coolth to be extracted from the water prior to its use. This requires in-line high-pressure heat-exchangers before the distribution manifold.

Stationary hydro-powered equipment away from the face, such as winches, may require additional piping to and from the heat-exchangers. This type of heat-exchanger is likely to be heavy and bulky, and needs to be installed in a position protected from the blast. The problem is to get the air to and from the cooler.

If backfill is in use, and this is more likely than not, airways can be constructed in the fill parallel to the face (Fig. 4), and the air can be cooled on a slipstream basis. However, if the quantity of air necessitates parallel airways along the entire face, there is the problem of interchanging the two air streams. Some alternatives are suggested in Fig. 5. These airways in the fill, together with the heat-exchangers, are likely to have a high resistance and require fans (possibly hydro-powered). Prototypes of these are under development.

Another alternative is for winches and stationary machines to use water motors—especially those remote from the stope face, i.e. for motors to have a residual outlet pressure sufficient to pump the water to conventional low-pressure stope coolers. These coolers can be positioned in the stopes or in airways in the backfill (Fig. 6).

If additional cooling is still required in the stopes, then water-consuming coolers operating off hydro-power are needed (Fig. 7). The Chamber of Mines is currently designing and testing units that can be positioned on the face or in the fill as necessary.

Conclusion

Hydro-power offers enormous benefits for energy and cooling efficiencies. It must be repeated that water is not introduced for the sake of hydro-power alone, although in some cases this can be justified. Where water is required for cooling underground, hydro-power attempts to extract the maximum energy from the water and thus increase its cooling power. Hydro-power requires a simple piping network, with minimal retention time from surface to underground, and provides chilled water in the stopes, still under pressure. Some of the coolth can be extracted before the pressure is relieved, without the associated thermal penalties. Hydro-power may increase water usage in the stopes, but the bulk air-cooling requirements should be reduced in relation. Cooling is provided in the stopes where and when the men are working, and only the *useful* air is cooled.

Most mining methods affect hydro-power considerations, and it is not possible to specify a general system. However, it would appear that backfill and hydro-power are mutually compatible. Backfill restricts the stope airways and hence limits the air quantities, thus requiring more frequent cooling, which hydro-power can provide. Higher face advances would improve the utilization of equipment and reduce capital costs.

The efficiency with which the coolth is extracted can be increased by the creation of a counterflow system. The water, ideally, should first cool the air in a high-pressure heat-exchanger, then provide hydro-power, and finally be discharged onto the footwall to cool the rock. Thus, the air is cooled with the coldest water possible. It should be possible for water to leave the stopes at a temperature close to the ambient wet-bulb temperature. The operators of hydro-powered devices should also be relieved to have 'warmer' water in their machines.

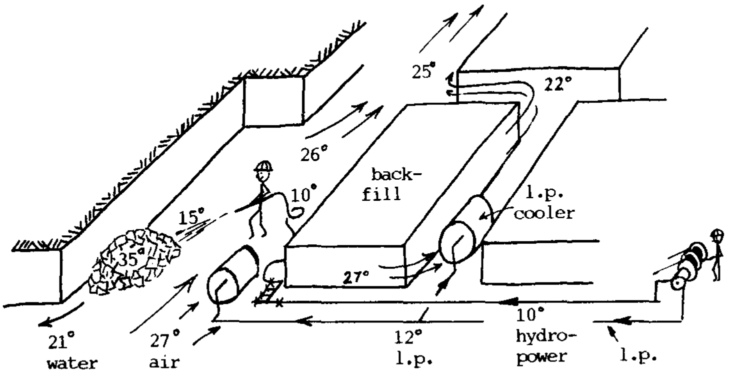

Fig. 6—Low-pressure coolers (l.p.) using residual pressure after the winch

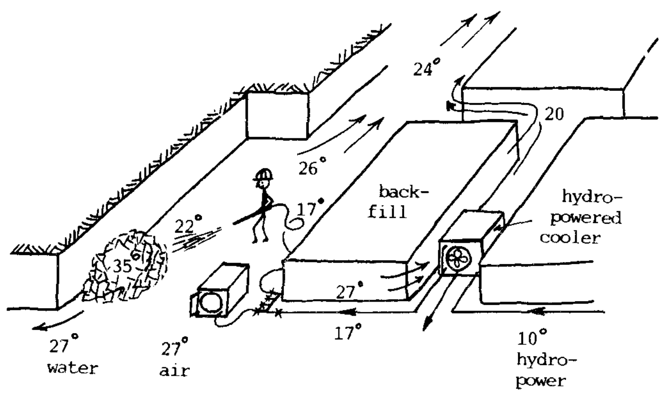

Fig. 7—Hydro-powered coolers—hydro-powered open-spray cooler on the left and hydro-powered in-line cooler on the right

The positioning of coolers must be carefully chosen with regard to both the water and the air circuits. The confined conditions make it difficult to route the cooled air back to the face.

Acknowledgement

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- *Atlas of the surface heat balance of the continents,* by Dieter Henning. Stuttgart, Gebrüder Borntraeger, 1989. (Available from E. Schweizerbart'sche Verlagsbuchhandlung, Johanesstrasse 3A, D-7000 Stuttgart 1, West Germany.) 402 pp. with 327 continent maps. DM178.
  This atlas presents detailed analyses of mean annual, semi-annual, seasonal, and monthly values of the following fluxes and parameters derived from the long-term monthly averages of routine meteorological data: net all-wave radiation, net long-wave radiation, actual evapotranspiration, the flux of sensible heat, the parameterized surface albedo, total cloudiness, the modified Bowen-ratio (the ratio of the heat needed for actual evapotranspiration to the total energy available), the radiational index of dryness (Budykarotio), and total runoff. In 26 maps, the months—i.e. their regional variability—are shown in which net radiation, actual evapotranspiration, the flux of sensible heat, and the modified Bowen-ratio are at their maximum. The last set of maps is methodological in character: these maps are devoted to the differences in quantity estimates resulting from the use of different methods.