Problems of Mining at Great Depths*

By PROF. S. J. TRUSCOTT

THE heights of mountains and the depths of oceans are measured from sea-level; depths in mining are measured from the surface at the particular spot. The mineral won has to be raised to that surface; there is the cost of raising. The water met has generally a vertical distribution bearing some relation to that surface; there is the cost of pumping. The rock temperature increases with depth from the surface; there is the consequent cost of ventilation. Finally, the rock pressure increases with depth from the surface; there is the consequent cost of support.

Great depth in mining may nowadays be taken to be 6,000–8,000 ft. below the surface, depths which, being out of reach of a winding engine situated at the surface, require other winding engines underground. Outstanding cases of mining at great depths, and at the same time the deepest mines in the world to-day, are: the Morro Velho mine in Brazil, the lowest level of which is 8,040 ft. below the surface; the Robinson Deep mine in the Transvaal, the lowest level of which approaches 8,000 ft., while the lowest point reached is deeper; and the Champion Reef mine on the Kolar goldfield, Mysore, the lowest level of which, where development is proceeding, is 7,580 ft. All of these mines, which started thousands of feet above sea-level, are now working below sea-level.

It is of interest that all these mines are gold mines and all are situated in Archæan or pre-Cambrian country, that is, in rocks of very great age. Though they have that much in common, they work entirely different types of deposit. The Robinson Deep is one among many mines working a very extensive conglomerate bed moderately inclined. The Champion Reef is one of a small number of mines along a steeply-inclined quartz reef; while the Morro Velho is a lonely mine working a relatively short, heavily mineralised ore-shoot pitching at an angle of about 45° upon a plane roughly vertical. Of additional interest is the fact that, situated in such widely separated regions as they are, these mines are all British enterprises; this being also true of most other mines approaching their depth.

The problems to be reviewed are those arising in the technical operations of primarily the four which have been mentioned. Raising or winding is only possible by means of wire rope. The best wire ropes will, however, not serve with safety and economy for a greater depth than about 4,500 ft., the rope then becoming too heavy and the winding engine excessively large. Below that depth or even before it is reached, a second winding stage will be necessary or will have been judged desirable, this second stage, not generally so deep as the first, being equipped with shafts

and electric winders of its own. Again there may be a third stage. The Morro Velho has seven stages, each short, though greatly daring in view of the relatively small horizontal extent of the deposit. The Robinson Deep has a first vertical stage, a second main-incline stage, and a third sub-incline stage. The Champion Reef has a primary vertical, a secondary vertical, and then bottom inclines. Though such stage-winding with the unavoidable transfers from one shaft to the next is more expensive than winding at such depths as permit a single stage, it may be said that the problem of raising the mineral causes no more than ordinary concern. Greater mechanical efficiency has largely offset the greater number of units of work to be done.

Pumping is normally no problem at great depth. The water-table or ground-water level marks the upper limit of a zone saturated with water, but this saturation becomes less with increasing compactness of the rock beneath, and normally at no great depth a dry zone is entered. At Morro Velho there is little water below 2,500 ft. and none below 3,500 ft.; deeper than that, such water as is required for men and machines must be sent down. On the Witwatersrand, fissures reaching up to saturated ground above occasionally cause a troublesome amount of water to be met in depth, but speaking generally, the amount of water to be raised is relatively small. Pumping is done by electrically driven centrifugal pumps in stages each of about 2,500 ft. The Champion Reef and neighbouring mines are dry below about 1,000 ft. so that service water must be sent down. It is interesting here to recall that steam engines came into being to enable mining to be carried on below adit or drainage level; in those early days mine drainage was the major problem.

Ventilation, that is the coursing of air through the workings in manner suitable and in quantity sufficient to maintain it in good physiological condition, is one of the two main problems in mining at great depth, largely because of the increase of rock temperature with depth. The rate of this increase of temperature, known as the geothermal gradient, varies from region to region on the crustal sphere: it is lowest where the country has long been a land surface and long free from igneous intrusion. Of the three districts mentioned the Witwatersrand has the lowest gradient; namely, a rise of 1° F. for every 212 ft. or of 4·7° for every 1,000 ft.; starting from an average surface temperature of 60°, the rock temperature at the present lowest level of the Robinson Deep will be about 97°. The gradients in the other two districts are about 1° for every 150 ft. of depth or 6·6° per 1,000 ft. The recorded rock temperature at the 7,380 ft. level of the Champion Reef is 129°, the average surface temperature being about 75°. Starting from a somewhat lower surface

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temperature, the rock temperature at the present bottom of the Morro Velho is about 125°.

Differing as they do in respect to temperature gradient and to surface air temperature, there is one essential factor practically constant for all regions: namely, the rise in temperature of the air due to the heat expressed from it by the compression it experiences as it passes from surface into depth, this rise being about 5.5° F. per 1,000 ft. On the Witwatersrand the resultant air temperature at the present lowest level of the Robinson Deep would be 104°, that is, 7° higher than rock temperature. At the 7,380 ft. level of the Champion Reef it would be about 115°, and at the bottom of the Morro Velho about 110°, these two being lower than the respective rock temperatures.

Fortunately, air temperature is not the index to the physiological condition of the air. The position with respect to temperature underground is not dissimilar to that at surface in some tropical regions; indeed in going underground we pass from a relatively cool climate to a hot one. Take for illustration the air condition at the military station of Quetta, the Aldershot of India; in the dry summer season the temperature in the sun is well above 150° and for periods shade temperatures of 100° and more are registered, yet military exercises are carried out without interruption in the open. This activity is possible because the air is dry, the relative humidity being 10–20 per cent, equivalent to a wet-bulb temperature of, say, 70°. Wet-bulb temperature is the most ready index to the condition of the air. The body is in effect much like a wet-bulb thermometer in that at high air temperatures it is cooled by evaporation, and evaporation is always possible so long as the air is not saturated with moisture. There is this difference, however, that the body generates heat which the wet-bulb thermometer does not. To keep the body temperature from rising above normal, that is, 98.4°, the wet-bulb temperature must be below body temperature, and all the more so when the wet-bulb approaches the air temperature.

The measures taken for mine ventilation start by conducting the surface air as directly as possible to distributing stations at depth by downcast shafts kept so free as possible from water or moist surface. By so doing, the air arrives at a temperature determined by auto-compression and little affected by that of the rock. It also arrives drier than at the surface, since though the wet-bulb temperature rises, it does so at a substantially lower rate than the air temperature. Indeed even at such depths as 8,000 ft. the air can arrive in good condition. From the distributing stations the air passes along horizontal roads where, though there will no longer be any heating by auto-compression, there will be heating from the rock if the temperature of the rock be higher than that of the air, or if there be water present; in the first case both air and wet-bulb temperature rise; in the second the wet-bulb temperature will

rise while the air temperature may or may not.

At normal air velocities, the condition in respect to cooling can still be fair even at considerable distances from the downcast. Then the air begins its upward movement through the working places where the air velocity is lower, the contact with freshly exposed rock is greater, oxidation in one form or another generates heat, air pressure drops, humidity rises. Here are the severest conditions; it is here that the ventilating system is tested. Critical working conditions are reached in dry mines such as Morro Velho and Champion Reef when the wet-bulb temperature approaches 95°, and in saturated air as at the Robinson Deep when that temperature is above 90°; before then, working efficiency will have fallen off. Fatal heat stroke has occurred and does occasionally occur on all these mines. Finally, the air moves upward out of the working places into definite and well-maintained upcast shafts or airways and eventually passes out of the mine saturated at a temperature well above that at which it entered.

Taking average temperatures, the greater weight of the downcast air column over that of the upcast column would maintain natural ventilation, particularly when after the lapse of time the downcast had cooled off and the upcast had warmed up; but such a ventilation would be too precarious, and in summer might even stop. It is obvious that where normal working conditions may quickly change for the worse, the ventilation must be under such mechanical control as fan ventilation only can give. Technical control likewise must be in the hands of a responsible official, who, on the Witwatersrand, is actually designated the 'ventilation officer'. In this control, temperature readings, humidity calculations, velocity and volume measurements, pressure surveys, and dust counts where necessary, become routine work.

The management of the Robinson Deep considers that the present ventilating procedure on the Witwatersrand, which takes winter and summer air as it comes and accepts the poorer ventilation which summer brings, will suffice not only for sinking but also for mining down to a depth of 8,500 ft., and on that field that mine will be the first to put the matter to the test. Other engineers there consider that mining at such a depth will not be possible unless the air be re-conditioned by artificial cooling, at least during the summer months.

Some artificial cooling is achieved in ordinary working by the exhaust from rock drills or auxiliary hoists using compressed air, and this is particularly useful in cooling development ends. Sometimes underground pumps have been worked by compressed air with the same intention, and even main underground hoists. But if cooling of the main stream is to be an essential part of the ventilating scheme, it must be by means of special cooling plants.

Some special cooling of the air along a main level by a cold water circuit has been attempted

at a German colliery, but the Morro Velho is the only mine which has fully adopted cooling of the main stream. There an ammonia refrigerating plant on the surface, commissioned in 1920, reduces the average air temperature entering the mine from 73° and 65 per cent humidity to 42° and saturation, the air being de-humidified in the process. With continued advance into depth, and because of the indirect course of the downcast through the several winding stages, an underground cooling plant became necessary and was put into commission in 1930. This plant, situated about three parts of the way down, uses ethyl dichloride as refrigerant since this liquid, while non-poisonous and non-inflammable, requires low and even negative pressures in the operation. By it the air temperature at that depth is reduced from 100° to 75° and the wet-bulb temperature from 75° to 64°, the heat being abstracted by water which is pumped to the upcast to be cooled by evaporation for re-use.

Reviewing the three ventilating procedures, the Robinson Deep, in common with all mines on the Witwatersrand, uses water to lay the dust and a moist atmosphere to keep it laid; in consequence, cooling in the working places must depend mostly upon air movement, large volumes roughly equivalent to five tons of air per ton of ore being required. The Morro Velho relies upon cooling the air to de-humidify it to such an extent that it remains sufficiently dry right through the working places, the volume of air being relatively small. The Champion Reef relies upon a direct downcast kept dry, so that the air remains dry throughout the workings; ventilation in depth is also promoted by shutting off the bottom part of the mine from the upper part, except for the air ways.

The second main problem in depth is that of support. In the undisturbed crust there is equilibrium; the weight of the superincumbent ground is borne by reaction from the rock beneath, that rock resisting further compression. If an excavation be made, that is, if a portion of the rock be removed, then the load which it originally supported is diverted to the sides, to become an additional load upon them. Moreover, free faces having been made, there is a tendency for the rock, since it is elastic, to close in upon the excavation; a pressure arch is formed in the rock above, a pressure invert in that beneath, and lateral arches at the side. At shallow depth the tendency of the back of the excavation to scale or flake and to assume an arched shape is common to see; the pressure invert underfoot, however, is obscured, and the lateral arches remain undeveloped. But in mining at great depth, which it may be said is only possible in hard, strong rock, the tremendous pressure of the superincumbent ground reveals much in the nature of fluid pressure; the tendency for the rock at the sides to close in upon the excavation becomes noticeable, as also does that of the floor to lift. The rock which thus moves into the excavation

is that which, being released from compression, shears itself from the solid.

A road left untimbered at such depths, unless it collapses entirely, will gradually assume a round or oval shape as equilibrium by arching becomes established. What takes place in respect to a road develops to a larger extent around the working places; the arching noticed in roads becomes doming in respect to working places. Doming follows the settlement or collapse of the roof and the upward shearing of the floor, or, as the case may be, the sag or collapse of the hanging wall and the inward shear of the footwall. At great depths the necessity of controlling these inward movements is as great with steep deposits as with flat deposits. No large span can be left open or there will be abrupt failure such as will close the working place. Routine support must see to that, and this support must be sufficiently yielding that it be not destroyed by the pressures which it cannot wholly resist but can at best only control. On the moderately inclined Witwatersrand, this support is by waste broken with the ore; on the steep Champion Reef it is by dry walls of granite bricks; at Morro Velho it is by waste filling.

As the excavation gets larger, doming will reach farther from the excavation, in roof, in floor, or in wall, by gradual settlement mostly, but sometimes by sudden failure of particular thicknesses. These sudden failures, though the actual movement be small, send a concussion wave through the country; this occurrence, when noticeable and causing falls of ground and damage, being termed a 'rock burst'.

Equally and almost as unavoidably, when one excavation approaches another and the mineral pillar between them becomes smaller, this remnant pillar will eventually yield under the pressure accumulating upon it, and a 'rock' burst will occur again, though careful and cautious work may minimise its effects. Domes which had their abutment upon this pillar will then become merged in a wider doming extending farther from the excavation, further tremors continuing until doming is complete.

As already explained, doming involves both hanging wall and footwall, or roof and floor, as the case may be; consequently it involves any roads existing within the distance to which it extends. Thus shafts and roads put in the footwall or floor for safety's sake, but not far enough away, will suffer.

Accidents set down to falls of ground are much more frequent than those ascribed to any other single cause. It is, however, an interesting fact that, on the Witwatersrand, sudden uplift of the footwall is considered to be the cause of the majority of fatal spinal injuries that occur in the working places. Support also costs more than ventilation. Greater accident rate and greater cost may be reasons for considering that mining in still greater depth will be limited by the problem of support rather than by that of ventilation.