The challenge of deep-level mining in South Africa
(Presidential Address)

by H. WAGNER*

SYNOPSIS
The discovery of the gold-rich Main Reef Group of reefs on the farm Langlaagte in 1886 marked the opening of the richest and most extensive goldfield in history. Mining of the narrow reefs progressed from the outcrops to more than 3.5 km, and has made South Africa the foremost mining country in the world.
Changes in the political and socio-economic climate create a new challenge to the gold-mining industry. The most significant of these is the emergence of Black trade unions, with their demands for higher wages, improved safety, job advancement, and abolition of discriminatory legislation. Industrial conflicts on gold mines have risen significantly in the past ten years, and are likely to continue in the future, although the causes of these conflicts may change. Events largely outside the control of the gold-mining industry, such as the improved dollar price for gold and the depreciation of the value of the rand relative to major currencies, have enabled the industry to meet the demands for higher wages and to narrow the wage gap. However, labour productivities have improved insignificantly and are a cause of major concern for the future development of the industry.
Continued pressure in the industrial-relations area, the inflation of working costs, and the extension of mining operations to greater depths and more difficult areas create major challenges to mine management and mining engineers. Significant improvements in mining technology, environmental control, and safety will have to be made to ensure the long-term survival of the industry. The unavoidable introduction in deep gold mines of mechanization on a larger scale to meet the requirements of higher labour productivities and a better and safer underground environment will have a major impact on the cost and management structure of these mines.
Engineering will assume a more important role on deep gold mines, and management styles and structures will have to be adapted to accommodate these changes. The supply of suitably qualified engineers, technicians, and artisans will be a crucial factor controlling the rate of technological change.
The industry is well-gearred through its Group system to meet these challenges, and to benefit from the experience gained in the operation of highly mechanized mines. However, changes take time to implement and there is very little time left.

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Die ontdekking van die goudryke Hoofrifgroep riewe op die plaas Langlaagte in 1886 het die ontsluiting van die rykte en omvangryke goudveld in die geskiedenis ingelui. Die ontginning van die smal riewe het gevorder van die dagtoome tot meer as 3.5 km en het Suid-Afrika die belangrikste mynbouland in die wêreld gemaak.
Veranderinge in die politieke en sosiaal-ekonomiese klimaat het 'n nuwe uitdaging vir die goudmynbetreders geskep. Die belangrikste van hierdie veranderinge is die opkom van Swart vakunies met hul eise om hoër lonne, groter veiligheid, vordering in die werk, en die afskaffing van diskriminerende wetgewing. Industriële botsings by die goudmyne het die afgelope tien jaar beduidend toegeneem en sal waarskynlik in die toekoms voortdure, hoewel die oorsake van hierdie botsings moontlik kan verander. Gebeurtenisse wat grotendeels buite die beheer van die goudmynbetreders, soos die hoër doelprys vir goud en die daling in die waarde van die rand teenoor die vernaamste geldeenhede, het die betred in staat gestel om aan die eise om hoër lone te voldoen en die loongaping te vernou. Daar was egter 'n onbeduidende verbetering in arbeidsproduktiwiteit wat groot kommer wek oor die toekomstige ontwikkeling van die betred.
Voortgesette druk op die gebied van arbeidsverhouding, die inflasie van bedryfekoste en die uitbreiding van mijnbedryvigheid na groter diepte en moeilikheid gebiede, skop 'n ernstige uitdaging vir mynbou en mynbouingenieurs. Daar sal groot verbeterings in mynoutomatisering, omgewingsbeheer en veiligheid aangebring moet word om te verseker dat die betred op die lange duur oorleef. Die onvoorspellike invoering van grootskale meganisasië in diep goudmyne om aan die vereistes vir hoër arbeidsproduktiwiteit en 'n beter en veiliger ondergrondse omgewing te voldoen, sal 'n belangrike uitwerking op die koste- en bestuurstuktuur van hierdie myne hê.
Ingenieurswese sal 'n belangrikker rol in diep goudmyne speel en bestuurstyl en -struktuur sal aangepas moet word om hierdie veranderinge te akommodeer. Die voorstiening van behoorlike gekwalifiseerde ingenieurs, tegnici en vakmanne sal 'n deurslaggewende faktor wees wat die tempo van tehnologiese verandering sal bepaal.
Die betred is deur sy groeptele onderskeen goed daarop ingestel om hierdie uitdaginge die hoof te bied en te baat by die ondervindings wat opgedoen is deur die betred van hoogse gemeganeerde myne. Dit neem egter tyd om veranderinge te implementeer, en ons het bitter min tyd.
**Introduction**

The discovery of the gold-rich Main Reef Group of reefs on the farm Langlaagte in 1886 marked the birth of what was to become the richest and most extensive goldfield in history. This discovery proved to be of great economic and political significance not only for the region but for Southern Africa as a whole.

As a mining engineer who is closely concerned with gold mining, I could not resist the temptation of taking the centenary of the proclamation of the Witwatersrand goldfields as the base on which to build my Presidential Address. However, I have resisted the temptation of giving a historic overview of the development of mining on the Witwatersrand. Furthermore, I have resisted the temptation of forecasting the future economic role of gold mining. Too often have such forecasts been proved wrong. Instead, I shall attempt to address certain aspects of the gold-mining industry that, in my opinion, are crucial for the future well-being of the industry and the country as a whole. In doing this, I shall confine myself, as far as possible, to areas in which I consider myself to be knowledgeable. Also, wherever appropriate, I shall draw from the wealth of experience that has accumulated over the past one-hundred years.

Traditionally, the President-elect is permitted to look into the future and speculate with a certain amount of impunity. In this respect, I propose to join the ranks of my distinguished predecessors. I hope that, in doing so, I shall provoke some debate with regard to the future of our mines and in this way make a positive contribution. There is no doubt in my mind that not all my ideas and thoughts will enjoy general acceptance.

**Gold Mining in a Changing Political and Socio-economic Climate**

South Africa, unlike many other countries, has enjoyed a relatively stable political and economic climate since the Anglo-Boer war. As a result of this, the economy of the country expanded at an average rate of about 5 per cent per annum. This steady growth in economy, together with virtually no inflation, is reflected in Fig. 1, which, for the period 1902 to 1985, shows the tons of ore treated by South African gold mines, the average working costs per ton of ore treated, and the rand value per kilogram of fine gold. Several important observations can be made. Firstly, the tons of ore treated have gradually increased since the early days of gold mining. Secondly, for a period of nearly fifty years, 1902–1948, the working costs of gold mines remained virtually unchanged. From 1948 to 1971 working costs increased gradually, and from then on increased rapidly. Thirdly, since the demonetization of gold in 1971, the working costs have increased rapidly. Recently, the increase in the price of gold in rand terms was largely due to the drop in the rand-dollar exchange rate.

A close examination of the working costs on gold mines since 1972 shows that these costs have increased at a very much faster rate than, for example, the consumer price index (CPI). During the period 1972 to 1984, the increase in gold-mine working costs was more than 50 per cent higher than the increase in CPI (Fig. 2). As gold mining is a highly labour-intensive industry, labour being responsible for about half of the total working costs, it is very sensitive to wage increases. In the early 1970s the industry embarked on a programme of reform to substantially improve the conditions of employment of its Black workforce. The results of this policy are shown in Fig. 3.

The cost of Black labour has increased at a rate that is more than three times higher than that of the labour
index issued by SEIFSA (Steel Engineering Industries Federation of South Africa). However, this exceptional increase in the cost of labour was not matched by an increase in overall labour productivity. Labour productivity increased from 189 t of ore treated per man per year in 1970 to 222 t in 1984, or by 17.5 per cent.

The exceptional economic performance that the gold-mining industry has achieved since the early 1970s was made possible by a tenfold increase in the dollar price of gold. At the same time, high cost inflation and political pressure on South Africa resulted in a very marked depreciation in the value of the rand, which benefited the gold-mining industry.

The prosperity enjoyed by the industry in recent years is, therefore, largely due to external factors, rather than the result of improved technical and cost performance. However, continued economic strength can be maintained only if the industry frees itself of its almost complete dependence on external factors. This can be achieved only by a determined and sustained effort to control costs and to improve productivities. A prerequisite for this is stability in the work situation and industrial peace.

Since the early 1970s, significant changes have taken place in industrial relations. The most obvious indicator of these is the increase in industrial conflicts (Fig. 4). A breakdown of the conflicts into major causes highlights the complexity of industrial relations on gold mines (Fig. 5). Hostel conditions, which tended to be an important cause of industrial conflict in the 1970s, have accounted for relatively few incidents in recent years. Wages and bonuses, social conditions, and solidarity issues have become more frequent causes of conflict.

The high incidence in wage-related conflicts following the exceptional wage increases in the early 1970s is initially surprising, but can be explained by changes in the distribution of income among the different sections of the work force on the mines. This was aggravated by raised expectations of continued high increases after an initial increase of more than 60 per cent in 1973.

The emergence of Black trade unions and the recognition of some of these by industry are without doubt the most significant developments in the gold-mining industry in recent years. While the first few years of union development were characterized by their struggle for recognition by the mines and for support by the heterogeneous work force that exists on mines, it is predicted that this trend will change and that typical trade union issues will become more important.

Already there are certain patterns emerging in industrial relations, and it is reasonable to assume that questions concerning conditions of employment (including wages and bonuses), job advancement, and safety and environmental conditions on the mines will become major issues. In the longer term, this picture will become more complicated by the polarization of different unions representing White and Black members of the industry, and the increase in politicization of separate unions.

Industry will have to give much attention to these changes in industrial relations and to their impact on management and mining practice on the mines.

As a result of these changes, the gold-mining industry, to ensure its long-term well-being, will have to intensify its efforts to improve the productivity per capita, to further improve environmental conditions and safety in its mines, and to create opportunities for job advancement. In the short term, improvements can be achieved primarily through better mine management, supervision, and training. However, with the generally competent level of management already in existence on the mines, the scope for improvement is limited. In the longer term, real improvement can be brought about only by better mining methods and new technologies.

In my address I shall deal with these issues in some detail, and shall attempt to give some direction and to identify some of the areas that, in my opinion, require urgent attention. I shall do this under three main headings: mining, engineering, and human.

The Mining Challenge

Gold on the Witwatersrand occurs in generally narrow tabular reefs that extend over many kilometres on strike and dip. The reefs vary from near-horizontal to near-vertical, but the majority have an angle of dip ranging from 10 to 30 degrees. The depth at which these reefs
are being mined ranges from near-surface to well in excess of 3 km. The average rock-breaking depth has remained relatively constant at about 1600 m in recent years, but will increase in future when many of the low-grade areas on existing gold mines, which were previously unpayable, have been extracted (Fig. 6).

The tabular nature of the hard, abrasive gold-bearing reefs, the irregular distribution of gold in the reefs, and the great depth at which most of the reefs are situated affect mining in many ways. Firstly, the geometry of the reef bodies and their depth are very unfavourable from the point of view of rock stresses and heat flow. High stresses occur in the rock ahead of the working faces. These cause extensive rock fracturing, and result in difficult and hazardous mining conditions, and the need for elaborate support measures. The tabular shape of the orebody facilitates heat flow from the rock into the workings, thereby creating an unfavourable thermal environment and the need for extensive mine cooling. Secondly, the restricted mining height in the stopes, together with the hard and abrasive nature of the rock that has to be mined, and the hot and humid environmental conditions that exist in stopes, have prevented large-scale mechanization of stoping operations. Thirdly, the depth at which the reefs are situated and the irregular distribution of gold in the reefs make mine planning and grade control difficult and favour mining methods that have a high degree of flexibility. Fourthly, a concentration of mining operation is difficult to achieve in tabular deposits of variable ore grade. Fifthly, transport and communication lines increase with depth, resulting in high cost, loss of effective working time, and difficult control.

Against this background it is not surprising that deep level gold mining uses a relatively low level of mechanization, a low degree of face utilization, and very labour-intensive methods.

In my opinion, these are the features that have to be changed if the gold-mining industry is to meet the challenges resulting from the changing socio-economic and political environment. After having said this, I must point out that there is no doubt in my mind whatsoever that, as far as the mining of deep tabular hard-rock orebodies
is concerned, the South African gold-mining industry is the leader in the field, and can justifiably look with pride on its achievements. However, there is no time for complacency, and the industry must make serious attempts to change the level of its technology. In this regard, I have to record that the need for significant improvements in mining technology was recognized by leaders in the industry as long ago as 1974, when the industry embarked on a long-term research-and-development programme. Details of this programme were presented to this Institute by Professor M.D.G. Salomon in his Presidential Address in 1976. Progress in most of the areas addressed by him has been satisfactory, but the changes that have taken place since then have emphasized the need for the industry to introduce the developments that have already been made and to increase its efforts to accelerate progress in the other areas.

Productivity

The key to many of the problems in deep-level gold mining is productivity. In this context, I define productivity as the output obtained from a production resource, be it a mine worker, a production machine, or a portion of a working face. Since the various production resources are interdependent, it follows that an assessment of productivity has to take all factors into account. Ultimately, the most productive system is one that optimizes profits; that is, one that allows for costs as well as revenue.

Labour productivity is seen by many as the key to cost control in deep-level gold mining. As pointed out earlier, there are a number of factors that support this view: first, nearly 50 per cent of working costs are labour-related; second, demands for higher wages can be met in the long term only by a higher output per worker; thirdly, as indicated by historical evidence, the social and economic improvements for the work force that are needed to ensure long-term industrial peace can be realized only if the output per worker is increased.

Historical evidence in the gold-mining industry shows a steady increase in overall labour productivity, expressed in tons of ore treated per employee per year, since the turn of the century (Fig. 7). Three periods of significant improvements in labour productivities can be identified. The first of these is the period 1905 to 1915, which coincides with the introduction of the light reciprocating rock drills that replaced the earlier hammer drills. The second period of marked improvement in labour productivities, namely the period 1930 to 1940, is linked to the introduction of scrapers in stopes and stope gullies. The third period started in the early 1960s and coincided with the introduction of sequential firing of shot-holes in goldmine stopes, which made the concentration of stope operations possible. Since then various other developments have been introduced, including improved methods of transporting materials into stopes, better support of underground workings, and mechanized methods of developing raises and boxholes. The combined effect of these has been a general increase in productivity in recent years.

The significant feature of this historical evaluation is that, in each case, a marked improvement in labour productivity was brought about by a change in mining technology. From this point of view, gold mining does not differ from other mining industries. However, this situation does not imply that the industry should not continue with its efforts to improve productivity through better management, organization, planning, training, and motivation. Important benefits could be derived in the short term from attention to these aspects.

Stopping has been identified as the most obvious area for improvement. Nearly half of the total underground labour force is employed in stopping, the level of mechanization in stopes is very low, and the most significant change took place more than fifty years ago when face scrapers were introduced to replace lashing.

A convenient measure of assessing the level of mechanization in tabular deposits is the output per unit length of face per year. Fig. 8 shows the total length of stope face mined annually and the annual production per metre of stope face for the gold-mining industry for the period 1972 to 1984. During this period, which was marked by the demonetization of gold, the total length of face decreased from more than 400 km in 1972 to about 280 km in 1984, while the tons produced per metre of face per year increased from about 170 t in 1972 to nearly 400 t in 1984. Much of this improvement in face production was due to an increase in the number of stope workers per metre of stope face, rather than to an increase in stope labour productivity (Fig. 9).

A comparison of stope-face productivities with typical coal-face productivities is given in Table I.
of the annual production per metre of stope face shows that the output from 1 m of coal face is between 5 and 15 times more than from 1 m of gold-mine stope. Stope labour productivities on coal mines are 7 to 30 times higher, depending on the level of mechanization, than those achieved in gold mines. Interestingly, the differences in stope labour density, expressed in the number of stope workers per metre of stope face, are small. However, as expected, there are significant differences in terms of the cost of stopping equipment per metre of stope face. In the case of gold-mine stopes, the cost of scrapers, scraper winches, pneumatic rock drills, and hydraulic props per metre of stope face is about R3000. The cost of equipment per metre of production face in coal mines varies between about R17 000 and R100 000, depending on the degree of face mechanization. Finally, the revenue per metre of production face on coal mines varies from about 0.5 to 2 times that earned by 1 m of gold-mine stope face.
Fig. 9—Stopeworkers per metre of stope face, and stope labour productivity, on South African mines

![Graph showing stopeworkers per metre of stope face and stope labour productivity](image)

### TABLE I
**Comparison of Typical Stopping Figures for Coal and Gold Mines in South Africa**

<table>
<thead>
<tr>
<th>Type of mining</th>
<th>Output per metre of face t/a</th>
<th>Output per man t/a</th>
<th>No. of men per metre of face</th>
<th>Equipment cost* per metre of face R</th>
<th>Revenue† per metre of face R/a</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Witwatersrand gold-mine stoping‡</strong></td>
<td>350-400</td>
<td>700</td>
<td>0,5</td>
<td>1500-3000</td>
<td>50 000</td>
</tr>
<tr>
<td><strong>Coal mines</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional board and pillar</td>
<td>3 800</td>
<td>8 500</td>
<td>0,4-0,5</td>
<td>17 000</td>
<td>76 000</td>
</tr>
<tr>
<td>Conventional pillar extraction</td>
<td>2 300</td>
<td>4 500</td>
<td>0,5</td>
<td>17 000</td>
<td>46 000</td>
</tr>
<tr>
<td>Continuous miner—bord and pillar</td>
<td>3 300</td>
<td>14 000</td>
<td>0,25</td>
<td>22 000</td>
<td>66 000</td>
</tr>
<tr>
<td>Continuous miner—pillar extraction</td>
<td>3 100</td>
<td>7 500</td>
<td>0,4</td>
<td>22 000</td>
<td>62 000</td>
</tr>
<tr>
<td>Continuous miner—rib pillar extraction</td>
<td>3 300</td>
<td>9 500</td>
<td>0,3-0,4</td>
<td>18 500</td>
<td>66 000</td>
</tr>
<tr>
<td>Longwall mining—narrow seam (1 m)</td>
<td>1 150</td>
<td>4 500</td>
<td>0,25-0,5</td>
<td>40 000</td>
<td>23 000</td>
</tr>
<tr>
<td>Longwall mining—wide seam (3 m)</td>
<td>4 500-6 000</td>
<td>10 000-20 000</td>
<td>0,3-0,4</td>
<td>100 000</td>
<td>90 000-120 000</td>
</tr>
</tbody>
</table>

* 1985 rands  † Calculated on basis of 1 kg of gold = R20 000 and 1 t of coal = R20  ‡ Industry average

It follows from this comparison that the three main differences between the production faces in coal and gold mines are the tons produced per metre of stope face, the amount of capital equipment installed per metre of stope face, and the tons produced per face worker. Any discussion of gold-mining stope productivities must address these aspects. A first estimate of the amount of capital that can be spent in stope mechanization can be obtained from formula (1), which is based on a comparison of stopping costs before and after mechanization and takes into account all cost changes resulting from the introduction of mechanization. The comparison is based on the assumption that the tonnage mined, the gold grade, and the gold price remain unchanged. The equipment cost per metre of stope face per month, $k$, is given by the following equation:

$$ k = \frac{v \cdot W_o \cdot \Delta P}{P_o + \Delta P} + l_o \cdot \frac{\Delta v}{v_o} - v \left( \frac{\Delta F}{A} - \Delta b \right) - r, \ldots (1) $$

where

- $v$ is the rate of face advance per month (m),
- $\Delta v$ is the change in rate of face advance (m),
- $W_o$ is the stope labour cost prior to mechanization (R/m$^3$),
- $l_o$ is the cost per metre of face per month prior to mechanization (R),
- $P_o$ is the stope labour productivity per man per month prior to mechanization (m$^3$),
- $\Delta P$ is the change in stope labour productivity per man per month (m$^3$),
- $\Delta F$ is the change in fixed cost per month (R),
- $\Delta b$ is the change in other stoping costs (R/m$^3$), and
- $r$ is the monthly cost of maintenance (R/m).

Based on the 1986 stoping costs of R300 per square metre and allowing 15 per cent per annum for capital charges, the maximum permissible investment per metre of stope face can be determined from the nomogram.
shown in Fig. 10. The results obtained from this model indicate that, provided the current productivity of the face labour can be increased, significant investments per metre of stope face can be made in gold-mine stopes, even at relatively modest improvements in the rate of face advance. The incentive for the mechanization of Stoping operations in gold mines is even more obvious if the existing trend of labour costs, i.e. a faster rate of increase than that of other costs, continues.

It should be noted that these conclusions are not new, but are an amplification of observations made by Professor Salamon in his Presidential Address to this Institute in 1976. What is new, however, is the rapid change in the political and socio-economic field that has taken place since then. The need to press ahead with a determined effort to mechanize the central activity of gold mining—stopping—is greater now than ever before.

In the light of these findings, the question arises as to why the gold-mining industry has not succeeded in introducing highly mechanized methods of stopping. Many arguments have been put forward to explain this.

One argument maintains that great lengths of face have to be available at any moment to ensure consistent production and grade of ore mined. However, this argument is correct only if tonnage and grade are the main control parameters. Furthermore, if total revenue and total working costs are considered, the logic of the argument falls away. For example, the cost of refrigeration, ventilation, and maintenance is closely linked to the length of stop face that has to be maintained to ensure a certain level of production.

Another argument is based on the claim that labour-intensive methods of mining are required to solve the massive unemployment problem. It is my contention that, in the present socio-economic climate, this approach would be correct only if labour costs were a small proportion of total costs. Once labour costs become the major cost component, the economic viability of mines becomes highly dependent on wages, and wage demands and working places may indeed be lost as a result of such demands.

Yet another argument is based on the belief that mechanized methods are uneconomic because of the high cost of the equipment and the high cost of running and maintaining it. However, the economics of a mining system cannot be judged solely on the capital, running, and maintenance costs of equipment. Instead, the cost of mechanization has to be judged against the output achieved and the resultant savings in other cost areas.

It is sometimes argued that mechanization requires a more highly skilled labour force, but highly mechanized methods of mining have been introduced successfully in local underground coal and base-metal mines, where the levels of skills are not significantly higher than in gold mining. The essential factor for the successful introduction of these methods is rather that they should have a high production output.

A factual argument against mechanized stopping in deep hard-rock mines is that the harsh environmental conditions are not conducive to mechanized methods. In particular, the introduction of mechanization is adversely affected by the corrosion resulting from the hot, humid environment and the high proportion of dissolved solids in the mine water, the abrasion caused by the hardness of the rocks, the rock-breaking difficulties arising from the great strength of the rocks being mined, and the rockfalls and rockbursts caused by the high rock pressures that exist in deep mines.

It follows from the above that there are no factors other than the environmental conditions in deep-level stopes to prevent the use of mechanization in stopping operations. However, there are a number of areas that would have to be addressed. The first of these concerns the development of mining equipment for use under the specific conditions in gold mines; the second concerns the man-power and management infrastructures on the mines; and the third concerns the cost infrastructure on the mines. In the course of my address, I shall return to these points.

Environment

Any real progress in the productivity of gold-mining operations will depend not only on mechanization but on
improvements in the underground environment in which miners and equipment will have to operate. I have deliberately added the term mining equipment since environmental engineering on gold mines is traditionally concerned with the physiological aspects of the underground environment. As I pointed out earlier, one of the motivations for mechanization is the creation of more skilled jobs in the mining industry so as to provide a basis for the establishment of a more stable professional workforce. It stands to reason that, as the level of skills required to perform a certain task increases, so will the demands for an improved working environment. Furthermore, reliable operation of even custom-designed mining equipment will depend to some extent on the environmental conditions. Another important factor in mechanized mining is that uncontrolled changes in excavation geometry due to rockbursts or rockfalls have a far greater impact on mining performance than in conventional mining. Consequently, the demands for improved strata control will increase in the future.

By far the most important environmental problem facing deep-level gold mines is that resulting from heat flow into the workings. Fig. 6 shows the increase in the average rock-breaking depth and virgin rock temperature for the period 1962 to 1985. In an examination of this trend, it should be remembered that, with the demonetization of gold in the early 1970s, many low-grade reserves on existing gold mines became payable, and consequently the rate of increase in mining depths and rock temperatures flattened considerably in the 1970s. However, this is only a temporary phenomenon, and once these reserves have been exploited, the rate of increase in rock-breaking depths and virgin rock temperature will again steepen. Fig. 11 gives a summary of the installed and predicted rated refrigeration capacity on South African gold mines. The rapid increase in refrigeration capacity since 1976 is an indication of the industry’s commitment to solving the heat problem.

The long-term strategy is to ensure a wet-bulb temperature below 28°C in all working places so as to eliminate the need for heat acclimatization. Fig. 12 gives an estimate of the refrigeration requirements for the achievement of this goal in deeper mines. These requirements are based on current mining practice and rates of face advance, and have been calculated for a rock production of 1000 kt per month. From this information, it is obvious that the approach to the cooling of very deep mines will have to be examined critically.

It is of particular significance that the thermal problem in deep mines is closely related to the total length of working faces and to the heat flow that is allowed from the worked-out areas. An effective means of controlling the thermal environment in deep mines is to reduce the total length of face worked and to minimize the heat flow from worked-out areas by the filling in of these areas. The latter not only helps to improve the thermal environment but, even more important, has far-reaching consequences in terms of improving strata control. The benefits that are likely to result from high rates of face advance and backfilling are very substantial, as shown in Fig. 13. A 50% reduction in heat per ton per month appears to be quite feasible in the case of deeper mines as a result of an increase in the average monthly rate of face advance from 5 to 20 m and of the introduction of backfill.

In the case of mines in which the rates of face advance are already high, the only means of reducing heat loads in deep stopes is through the backfilling of mined-out areas.

An important conclusion that follows from this example is that the objectives of face mechanization and environmental control are complementary. A further conclusion is that the solution to the thermal problem in deep-level gold mines lies in overall mine design and mining method, and not through the provision of additional refrigeration capacity. This aspect was ignored in the past and requires much attention.

Mechanization of any kind requires that optimal conditions for the operation of the equipment should be established and maintained. Strata control and stopewidow control are therefore essential prerequisites for successful stope-face mechanization. Indeed, many attempts to mechanize face operations have failed because of poor strata control. Production delays due to rockfalls and damage to mining equipment due to rockbursts assume far more serious proportions in highly mechanized stopes than in conventional stopes. Consequently, there is an urgent need for radical improvement in strata control in deep-level gold mines. A first step in this direction was the introduction of rapid-yielding hydraulic props in goldmine stopes in the 1970s. Several hundred thousand of these props have now been purchased by the industry (Fig. 14), but even this large number is insufficient to
equip all of the 280 km of stope face. Again, the low level of face utilization as characterized by the low production per metre of stope face is the major stumbling block for significant progress in this area.

Where there is large-scale mechanization, rapid-yielding hydraulic props on their own are insufficient to provide the degree of strata control required. Of all the methods of strata control available at present, backfill appears to be most suitable since it not only provides regional support but also improves local strata control in the face area. In this connection, it should be pointed out that successful mechanization of deep-level stoping operations is possible only if the rockburst problem is eliminated. This statement is based on two observations. First, most rockbursts occur within a few hours of the blast; that is, when the mine has been evacuated. Second, as shown in Table I, virtually none of the equipment installed in stopes can be damaged as a result of rockbursts. In highly mechanized stope faces, mining is likely to take place around the clock, particularly if non-explosive methods of mining are employed. Consequently, every rockburst that occurs constitutes a danger to life and limb. Furthermore, the cost of the equipment installed in stope faces is many times greater than that used in conventional stoping. Effective rockburst control is therefore a prerequisite for successful and meaningful stope-face mechanization.

Only two known methods have shown promise in achieving effective rockburst control: the use of stabilizing pillars, and the use of backfill. Of these methods, stabilizing pillars are more easily introduced but suffer from the disadvantage that valuable ore reserves are lost in the pillars and that local strata-control problems are created in areas where the pillars form tight corners with the stope faces. From these points of view, backfill is more attractive since it does not suffer from these disadvantages. However, backfill of the highest quality and installed close to the stope face is required to ensure effective rockburst control. Backfill, because of its excellent local support characteristics and its environmental ad-

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**Fig. 12**—Effect of depth of mining on total refrigeration requirements to ensure an average stope wet-bulb temperature of 28°C (monthly rock production 1000 kt)

![Graph showing the effect of depth of mining on total refrigeration requirements](image1)

**Fig. 13**—Effect of backfill and rate of face advance on heat production in stopes

![Graph showing the effect of backfill and rate of face advance on heat production in stopes](image2)
vantages, is the obvious preference when mechanized mining is practised.

From this discussion of the environmental aspects of deep-level mining, three important conclusions emerge: firstly, high rates of face advance result in a more favourable thermal environment and should be aimed for; secondly, backfill should be seriously considered as a method of supporting deep-level stopes since not only does it provide good regional and local support but it greatly facilitates the cooling of deep mines; and thirdly, the environmental requirements of mechanization should lead to a very much safer mining environment.

Safety
Much has been said in recent years about safety on South African mines in general and deep-level gold mines in particular. The mining industry has been accused by unions of a lack of concern for the safety of its workers. In turn, the industry has pointed out the steady improvement in safety records over the years, and this is borne out by statistics (Fig. 15). Much of this improvement has been due to managerial attention to safety matters and a concerted drive to increase general safety awareness on the mines. The introduction of a loss control programme and an international safety-rating scheme in the late 1970s have contributed much to the improved safety situation in recent years. However, there is no doubt that much more will have to be done in the progress along the path towards safer deep-level mining.

Safety, particularly in mining, is a complex problem that has many facets. First and foremost is the human aspect, constituting an area in which much benefit can be gained from closer contact between management and workers. Clearly, both parties have the same overall objective, namely the elimination of accidents on the mines. There is a need to create a forum where worker and management can meet to address safety matters. Second, there is the management aspect of safety. Much progress has been made in this area in recent years, and many of the safety achievements can be attributed to better management. However, it should be realized that even the best management cannot compensate for an unsafe environment. Thirdly, there is the aspect of safety engineering. In essence, safety engineering aims at the achievement of a safer environment. Fourthly, there is the aspect of protection of workers, which should not be seen as a primary safety strategy but as an additional safety measure.

In this address, I shall concentrate on the aspect of safety engineering, which I regard as the most powerful approach to improved safety on deep-level mines. For example, the approach adopted by the industry before 1960 to protect workers against the effects of heat was heat acclimatization and the identification of heat-intolerant workers. The success of this approach is evident from Fig. 16, which shows the annual fatalities due to heat stroke for the period 1930 to 1985, together with the population at risk as a result of increases in labour force and in the average depth of mining. During this period, the incidence of fatalities due to heat stroke declined considerably, despite an equally significant increase in the labour force. However, there is a limit to this approach and, as the depth of mining increases, the only feasible means of protection is extensive mine cooling. The extent to which this approach is followed by the industry is apparent from Fig. 12. The benefits to be gained from mine cooling are shown in Fig. 17, which gives the predicted incidence of heat-stroke fatalities as a function of wet-bulb temperature. According to this relationship, the problem of heat stroke can be eliminated for all practical purposes if the wet-bulb temperature in all working places is reduced to about 28°C. Ways in which this objective can best be achieved in deep-level gold mines have been outlined.

The most serious safety hazard in deep-level mining is that related to rock pressure. According to the most recent safety statistics, falls of ground and rockbursts accounted for 53 per cent of all fatalities and 27 per cent of all injuries on gold mines. Furthermore, in relative terms accidents caused by rockbursts and rockfalls have increased in recent years, indicating that the rate of progress made
in the reduction of safety hazards related to rockfalls and rockbursts was slower than that in other areas. There are four main reasons for this: firstly, despite the general and significant improvement in the understanding of the rock-pressure problem in deep-level gold mines, there are still several open questions concerning rockbursts; secondly, regional stabilization measures take considerable time before they become fully effective; thirdly, whereas the average depth of mining has not increased in recent years, the extent has. In addition, previously unpayable remnants of reef that are highly stressed have been extracted as a result of the improved price of gold; and fourthly, the length of stope face that has to be supported, although significantly reduced over the past decade, is still excessively long.

Significant improvements in accidents related to rock pressure can be made only if the question of regional stabilization measures is rigorously addressed and if the length of working places that have to be supported and made safe on a daily basis are reduced. At present, more than 1.5 km² of hangingwall have to be made safe daily in stopes alone if it is considered that all stoping activities take place within 6 m of the stope face. A doubling of the rate of face advance would reduce the working area to half this figure. At the same time, the density of face support in the form of hydraulic props would double, and hence the quality of face support would improve significantly. This is illustrated by Fig. 18, which shows the effect of rapid-yielding hydraulic props on safety.

While there is room for improvement in the rate of face advance through better organization and management, I believe that, in the long term, substantial increases in the rate of face advance will result only from changes in mining technology. In this connection, I refer to experiences in the British coal-mining industry (Fig. 19). In 1955 more than 140 persons were killed by falls of ground at the coal face in British collieries. This was at a time when face operations were largely labour-intensive hand-filling systems and strata control was achieved by handset steel props and bars, and by hand-erected pack-and-waste systems. The introduction of hydraulic props, hydraulic chocks, and ultimately fully mechanized self-advancing hydraulic support systems reduced this number to 3 in 1983. At the same time, significant improvements in productivity were brought about by the changed mining technology. In his Presidential Address to the North Staffordshire Branch of the Institute of Mining Engineers, W.L. Pugh concluded: 'the man-power-intensive mining systems which remained largely unchanged from the 1920’s to the early 1940’s also sustained an annual fatality level of the order of 1000 deaths per year. The technical stagnation of the industry during this period was, in my opinion, the main inhibiting factor mitigating against any real improvement in safety'. I can only concur with this conclusion.

The major challenges of deep-level mining—to achieve high labour productivities, to establish a better and healthier environment, and to improve safety on our mines—can be met only by improved mining technology, particularly stoping technology, and by increased output per metre of stope face. Any development that is aimed purely at better labour productivity without an accom-
Fig. 19—Fatal accidents due to falls of ground at the face compared with face labour productivity (O.M.S.) in British collieries from 1955 to 1984 (after Pugh).}

panying improvement in production per unit length of face will fall short of achieving the goals of the industry.

The Engineering Challenge

In discussing the mining challenges to the industry, I have mentioned some of the factors that have prevented the large-scale mechanization of gold-mining operations. Among these, the most important are the strength, hardness, and abrasivity of the quartzites and reef conglomerates. Next come the constraints imposed on mining equipment by the narrow channel width of most reefs and by the absence of well-developed continuous parting planes that could be utilized to form smooth hangingwalls and footwalls in the stopes. The similarity in strength of the reef body and the surrounding strata is another factor that makes face mechanization difficult if blasting is employed as a method of rock breaking. Finally, the hot, humid environment and the high acidity of the mine water create an environment for corrosion that is far worse even than a marine environment.

The lack of success in the mechanization of stoping operations using traditional engineering approaches highlights the need for the development of new technology.

Materials

Corrosion and abrasion are the major factors limiting the life of mining equipment in deep-level gold mines. For example, the wearing parts of face conveyors employed on longwall faces in coal mines are designed to have a life of 1,5 to 2 Mt of coal before they have to be replaced. Similar conveyors used in gold mines wear out after only a few thousand tons of reef have been moved from the face.

Two approaches to overcome the materials problem are being followed by the Research Organization of the Chamber of Mines: to reduce the aggressiveness of the environment by treating the mine water, and to develop materials that are both corrosion-resistant and abrasion-resistant. The use of 8 to 12 per cent chromium steels with microstructures designed to provide hardness, toughness, and strength shows good promise in this regard. For special applications where extreme hardness and resistance to flow erosion are required, engineering ceramics have been identified as a possible solution.

Power

The provision of power in a suitable form is one of the greatest obstacles to the development of equipment for use in narrow stoping excavations. The great strength of the rock that is being mined requires stoping machines that can generate large forces and torques in a confined space.

Traditionally, compressed air and electricity have been used to power stoping equipment. Compressed air has the advantage that it can be used readily in stopes without the need for skilled labour, and it also provides a small degree of cooling. However, because of the generally low air pressures, large forces cannot be generated in the limited space available. Furthermore, compressed air is an inefficient and very costly form of power. Electricity is generally accepted as an excellent form of power for use in mines. It can be readily distributed but requires extensive safety precautions and controls, which can make the overall system expensive. Apart from safety considerations, the single largest factor mitigating against the use of electrical power in stopes is that it is totally unsuitable for generating high forces. Further disadvantages are the need for skilled labour and the fact that all the electrical energy used is converted into heat, thereby adding to the environmental problem in deep mines.

Hydraulic power has the major advantage in that large forces and torques can be generated by compact linear and rotary actuators. It is therefore ideally suited for use in compact equipment. However, hydraulic power is not free of problems. The most serious of these is caused by the loss of hydraulic fluid through leakages. If oil is used as the fluid, these leakages are not only very costly but also result in pollution of the environment. Because of difficulties in preventing leakages in the rigorous mining environment, the industry worldwide has been working on the development of equipment that uses oil-in-water emulsions. Following the successful introduction of this technology, the next obvious step is the development of hydraulic equipment that can operate on water alone. In deep-level mining, this approach is particularly attractive since the hydraulic head of chilled water brought into mines for cooling purposes is sufficiently high to power hydraulic stoping equipment. The attractions of a combined cooling and powering system are so great that the industry, through its Research Organization, has embarked on the development of the hydropower system. Already there is one section of a mine making use of the hydropower concept to cool stope faces and to operate water-jetting equipment. Also a hydraulically powered scraper winch has been built and operated successfully, and hydraulic transformers to power emulsion hydraulic rockdrills using the hydropower concept have been developed and tested.

Availability

System availability is the key issue to successful mechanization. To achieve high levels of availability, it
is essential that mechanized mining systems should have as few components as possible and that the equipment itself should be as simple as possible. It is in this regard that hydropower is most attractive. Operating experiences at Kloof Gold Mine have been impressive, with virtually no breakdown of the hydropower system over a period of one year. This has resulted in the total acceptance of water-jetting as a means of stope cleaning. On the contrary, despite many attempts, the introduction of water-jet stope cleaning on other mines not using hydropower has not been successful because of the unreliability of the pumps required to supply water in sufficient quantities at the right pressure.

A further factor governing the availability of mechanized mining systems is the provision of an adequate engineering infrastructure on mines. This applies underground as well as on surface. Artisans and artisan aids will have to be provided in sufficient numbers, and planned maintenance schemes will have to be introduced for underground equipment. Furthermore, the role of the miner will have to change, emphasis being placed on the operation and maintenance of equipment, rather than on mining aspects. In this regard, I should like to mention that, in highly mechanized coal mines, the traditional miner has been replaced by a miner–fitter. Similar developments will have to take place locally if mechanization is to succeed.

The Human Challenge
There can be no doubt that the introduction of new technology in deep-level gold mines will have far-reaching consequences in the human area. New technology requires new skills. This observation relates not only to the worker but also to management. Communication of the changes will have to be carefully planned to avoid otherwise inevitable industrial conflicts. The need for more highly skilled workers can be met only by a change from a migratory to a permanent work force. This, in turn, may require changes in housing policies and can lead to friction between permanent and rural workers. In particular, the latter may feel deprived of certain rights and privileges, which may have to be given to permanent workers, who will tend to live with their families on the mine property. Careful considerations will have to be given to all these questions so that the fruits of new technology can be reaped to the full.

Staff
As I have already pointed out, major changes have taken place in the industry during the past fifteen years. Considerable benefits can be gained from a closer examination of some of these changes. When discussing the need to improve the environment, I showed that, during the past fifteen years, the industry increased the installed refrigeration capacity on its deep-level mines from less than 200 MW to more than 1000 MW. Over the same period, the amount of air that is pumped into the mines to ventilate working faces and to distribute cooling increased from about 24,000 to 36,000 m³/s. However, the number of qualified environmental staff on the mines increased from 312 in 1970 to 380 in 1985 (Fig. 20). Over this period the installed refrigeration capacity per environmental officer increased from less than 0.5 MW to more than 3 MW, while the quantity of downcast air per environmental officer increased from 78.5 m³/s to about 100 m³/s. These figures suggest that the capital investment by the industry to improve environmental control has not been matched by a comparable increase in environmental staff. Similarly, the consumption of electricity in the gold-mining industry has risen at a faster rate than the number of electricians employed in the industry, as indicated by the number of kilowatt-hours per year that are supported by an electrician (Fig. 21). This increased from 43 million kilowatt-hours in 1970 to 55 million in 1985, or by more than 27 per cent.

In contrast to these trends, the number of managerial staff on the mines has increased in direct proportion to the ore production (Fig. 22). It is noteworthy that the tons produced and the number of underground workers per member of managerial staff remained virtually unchanged over the period.

These trends indicate that the mining industry has remained largely production-oriented, and that the staffing of some of the essential service functions has fallen somewhat behind. This trend will have to be reversed if the industry is to succeed in implementing new technology.
A determined effort is required to attract artisans and specialist staff to the mines to ensure that maximum benefit is obtained from major capital investments, and that a solid basis is created for the introduction of new technology.

**Management**

In the management area, I foresee a need for a change from the existing hierarchical system to a fully integrated system that promotes participation in the decision-making process by all the disciplines involved in the operation of a mine. New management structures will have to be introduced to ensure that the full benefits are being obtained from new technology. For example, I foresee difficulties if the management of a hydropower system is based on the same principles as that of the compressed-air and refrigeration systems, where two, and sometimes even three, different departments are responsible for certain aspects of the system. As the level of mechanization of mining operations increases, the contribution that the services, particularly the engineering department, can make to the performance of a mine will increase. This change in emphasis will have to be addressed by mine management, who will need to have much greater experience in the engineering aspects of mine operations than exists at present. In order to attract the best engineers to the mines, engineering must be seen as one of the routes to top management.
Similarly, the role of mining engineering will have to increase to ensure that mine designs take into account all the implications of new technology. Highly mechanized mining operations tend to be less flexible, and therefore require more planning and management attention, than labour-intensive methods of mining.

Costs
Closely linked to the management system on many mines is the cost control system. Traditionally, cost accounting and control are done on a responsibility basis, each mining official being responsible for the costs of labour and stores. Capital costs are usually written off, rather than being amortized over the lifetime of the equipment. The costs of the infrastructure for services such as compressed air, ventilation, refrigeration, and water handling are generally not allocated at the level at which they occur, but at a higher level. Consequently, it is difficult, if not impossible, to establish true production costs. A responsibility costing system has many advantages in situations where there are no changes (or only minor changes) in technology. However, the traditional responsibility, accounting, and costing systems are totally unsuited to the assessment of the costs involved in new technology. These can be assessed only by a truly functional costing system that accounts for all changes.

I am of the opinion that mines should give serious consideration to supplementing the traditional responsibility costing system with a functional costing system, and so provide a basis for the assessment of the economic performance of new technology.

Conclusions
I have attempted to analyse the effects of a changing socio-economic and political climate on deep-level mining operations. While many of my observations are specific to deep-level mining, some also apply to mining in general. I have come to the following conclusions.

(i) The continuing pressure for higher wages and improved conditions of employment on the mines can be met in the longer term only by an increase in labour productivities. The substantial improvements in wages paid to the largely unskilled work force on the gold mines was made possible only by the increase in the price of gold in rand terms, and were not the result of improved labour productivity.

(ii) Safety and environmental conditions on deep-level mines can be improved in the longer term only if the production per metre of stope face, that is the rate of face advance, is increased.

(iii) Improvements in labour productivity and in the rate of face advance are restricted largely by the technology employed in deep-level stopes. Significant improvements in deep-level mining efficiencies can result only from the mechanization of stoping operations.

(iv) The harsh environmental conditions in deep-level gold mines and the confined working space in stopes severely restrict the application of mining technology developed elsewhere, and require the development of special stoping equipment to suit local conditions.

(v) The successful introduction of new technology in deep-level mines will depend largely on the availability of skilled workers. The shortage of artisans and other skilled workers in the gold-mining industry is of great concern. Novel ways of solving this pressing problem will have to be investigated.

(vi) The role of the engineering and service departments on deep-level mines will increase as a result of the change from labour-intensive to more capital-intensive methods of mining. Due consideration will have to be given to this shift in emphasis to ensure the full participation of these departments in management decisions.

(vii) The cost thinking as it exists at present on most deep-level mines will have to change to account for the envisaged change from labour-intensive methods of mining.

(viii) The introduction of higher-level mining technology in deep-level mines has the potential for considerable job advancement and improved conditions of employment for all workers.

The South African Institute of Mining and Metallurgy has an important role to play in advancing science and technology in the minerals industry. This is achieved by the publication of a monthly journal and technical books, the organization of symposia and colloquia, and the holding of schools and workshops. In addition, the Institute promotes the formation of working-interest groups in areas of importance to the industry. I foresee that the role of the Institute in this area will have to increase to meet the requirements of the industry.

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In preparing this address, I drew freely on ideas (sometimes written, sometimes expressed verbally) of my colleagues in the industry and in the Chamber's Research Organization. I wish to thank them for the many fruitful and inspiring discussions. I gratefully acknowledge the assistance given to me by many units of the Research Organization and Head Office of the Chamber of Mines in collecting the data on which this address is based.

Finally, the foresight and courage of the leaders of the mining industry to embark on a structured long-term programme of research and development to change deep-level mining technology have to be applauded.

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