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The effect of blasting on the rockmass for designing the most effective preconditioning blasts in deep-level gold mines

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The author's major contribution to the Rockburst Control Research Programme is based on the outcomes of the face-perpendicular preconditioning experiments, discussed in detail in Chapter 5.

Chapter 6 combines the research findings from the Rockburst Control and Rockmass Behaviour Research Programmes and tries to explain the most likely mechanism of preconditioning.

The key issues related to the implementation of preconditioning, such as the reasons for failure and the critical factors for successful implementation, are discussed in Chapter 7. In light of the findings, a structured implementation procedure is proposed in this chapter.

The results obtained from and the knowledge gained through this research programme are discussed in Chapter 8, and conclusions are drawn about the effectiveness preconditioning in terms of providing a safer mining environment.

Finally, some topics for further research are listed in Chapter 9.

2 LITERATURE REVIEW

2.1 Introduction

The purpose of this chapter is to provide a summary of the highlights of some of the publications related to rockbursts and attempts to minimise the damaging effects of rockbursts. An overview of the historical development of rockburst research in South Africa, the major findings of various research initiatives, some descriptions and classifications of rockbursts and suggested ways of controlling and minimising the damaging effects of these are given in relevant sections. Major emphasis is given to destressing / preconditioning techniques and several case examples from various parts of the world are discussed in detail.

2.2 Historical development

This section gives a brief overview of the evolution of rockburst research in South Africa during the first half of the 20th century. The information provided here is based mainly on a publication by Cook *et al.*, (1966). Since the amount of research work *on rockbursts and their alleviation has grown at an increasing rate* since this publication, these more recent research findings are reported under separate headings that follow.

At the end of the 19th century gold mining in South Africa had reached depths of a few hundred metres below surface, and took the form of extensive planar excavations supported mainly by small reef pillars. *Towards the end of the first* decade of the 20th century, earth tremors had become fairly common, and were associated with the concentrated mining activity.

In order to investigate and report on the origin of tremors and their effect on underground workings and on surface buildings, the Witwatersrand Earth Tremors Committee was appointed in 1915. The committee found that rockbursts

due to the sudden crushing of pillars were the major causes of tremors, but that some resulted from the fracturing or settling of overlying strata. Some of the tremors had resulted in extensive collapses at mine workings, even at relatively shallow depths of 600 m. Therefore, it was recommended that artificial support be used instead of reef pillars left behind.

In the years that followed, the practice of leaving support pillars virtually ceased. However, rockburst accidents in stopes continued to be a matter of serious concern and this resulted in the appointment of the Witwatersrand Rockburst Committee in 1924. Many specific techniques to reduce the hazard were recommended by this committee, such as leaving large protective pillars around vertical shafts and the over-stoping of inclined shafts. Rapid face advance in stopes and a selected direction of mining were also advocated when remnants were extracted. The need for artificial support and the avoidance of support pillars were re-endorsed. The importance of the overall layout of excavations was also recognised in the suggestion that the possibility of longwall mining should be considered.

As the mined-out areas became more extensive at greater depths, more efforts were made to combat rockbursts by the use of empirical methods. The mechanism of rockbursts and elaborate processes of strata movement were postulated, but no mining methods were developed that differed radically from those suggested in 1924. Owing to the shortcomings in the technology of the time, some difficulties were experienced in introducing stope support in the form of complete sand or waste fill at great depths. The result was that support methods tended towards the use of compressible timber chock packs and cribs. As early as 1944, caving of the hangingwall, in isolated instances, was claimed to reduce the stresses at the face.

From 1931 onwards, various hypotheses on rockburst causation and many descriptive papers on control measures were advanced by practical mining personnel but they were seldom based on reliable observations. Most of these papers are collected in a single volume that was published by the Transvaal Chamber of Mines for the Association of Mine Managers in 1933.

The adoption of longwall stoping layouts in the 1930s, where these were possible, was the major and most generally accepted change in mining method. The number of isolated blocks of ground was minimised and the incidence of rockbursts was initially reduced by this improvement in mining method. After an early successful introduction, longwalling became accepted as the standard method to be used wherever possible at great depths. In the early stages, it appeared to have solved the rockburst problem. Later, however, it was evident that serious rockbursts could still occur, particularly when adjacent longwalls approached each other, or geological features were encountered (Ortlepp, 1983).

Gane (1939) closely examined the association of tremors with mining activity and showed the distribution of the annual incidence of tremors since 1908. A closer examination of the time distribution of these tremors indicated a pronounced peak incidence during and just after blasting time and a significantly low incidence on Sundays.

Hill (1944) compared the incidence of rockbursts at small remnant abutments to that at large or "continent" abutments resulting from longwall mining. He also showed that the primary object of lessening the number of rockbursts had been achieved by longwall mining. Furthermore, it was shown that, as a remnant abutment size decreased below 3350 m^2, the rockburst incidence increased and this trend continued until an area of less than 1350 m^2 was reached. Thereafter, the incidence decreased.

During the first half of the century most of the attempts to reduce the rockburst hazard were based on practical experiences of the mining engineers who were closely involved with the problem (Cook *et al.*, 1966).

Towards the end of the first half of the 20th century it was apparent that these isolated and purely practical attempts to solve the rockburst problem were inadequate. These attempts were frequently based on a cause-effect relationship inferred from the observation of a statistically insufficient number of events. Therefore, in order to obtain a fundamental understanding of the rockburst problem, a properly designed scientific research initiative was necessary.

2.3 Early research initiatives

In 1948, formal research was initiated by the Central Mining-Rand Mines group, which commissioned the Council for Scientific and Industrial Research (CSIR) to take measurements and make observations underground and establish a bureau for collecting statistics on rockburst incidence.

In 1953, the Chamber of Mines of South Africa took over sponsorship of all rockburst investigations on behalf of the whole mining industry and embarked on a broadly defined scientific research programme. A statistical study of relationships or associations between mining variables and the rockburst incidences observed in the stopes was the basis of this first large formal project (Cook *et al.*, 1966).

Hill (1954) also showed that the incidence of rockbursts was considerably higher than the average during the mining of faces in a dyke.

Ortlepp and Cook (1964) presented the results of extensive measurements of displacement in the rockmass around two South African gold mines. The authors showed that the measurements of strata-movement patterns in these rather different environments were similar and, in both cases, these patterns were in agreement with displacements calculated from elastic theory. The authors also showed that elastic theory was adequate to explain much of the behaviour of the rockmass beyond the immediate vicinity of the excavation.

In order to assess the rockburst potential of underground rock structures, various methods and techniques were developed and many of these were based on the *energy balance around the excavations*. Cook *et al.* (1966) proposed the well-known concept called Energy Release Rate (ERR). In the years since it was proposed, ERR has been widely used for the assessment of rockburst potential. *In order to determine the energy available for rockbursting*, the balance of the energy stored in the rockmass and the energy that can be dissipated when a geometrical and / or stress change occurs in the rockmass must be calculated. This energy balance is *usually calculated by assuming elastic behaviour of the* rockmass around the excavation.

Elastic theory was used as the basis of the early attempts at understanding the physical processes involved in rockburst mechanisms. Cook *et al.*, (1966) stated that the rockmass behaviour inferred from the empirical data acquired from statistical analyses, seismic observations, and rock property studies was not inconsistent with the assumption of elastic behaviour. The theory of elasticity indicates that a large change in the gravitational energy of the rockmass must take place as a result of mining. At least half of this energy change must be released in one form or another. The energy release must either be in the form of non-violent dissipation in the course of the crushing of rock or supports, or in the form of violent events. In the former case the released energy is transformed *mainly* into heat through friction and, in the latter case into kinetic energy. A portion of the violent event is manifested as rockbursts. The existence or otherwise of the rockburst hazard depends on whether the geometrical rate at *which energy must* be released is greater or smaller than the rate at which energy can be dissipated non-violently as the excavation is enlarged.

While the theory of elasticity gives a good approximation of the rate at which energy must be released, the rate at which energy can be consumed non-violently can only be estimated (Cook *et al.*, 1966). This rate depends on many *factors, such as rock properties, excavation size and shape, maximum possible* closure and depth below surface. The rate referred to here is the energy released or dissipated per unit area mined, and is based on the theory of elasticity, which is *independent of, and neglects, time effects. In every case where a fracture zone* exists ahead of a face, energy must be consumed in the transition from elastic rock to fractured rock. Since a rockburst is a manifestation of violent energy release it is obviously necessary to examine *the balance that must exist between* the energy supply, storage and dissipation.

Cook *et al.* (1966) demonstrated that the incidence of rockbursts is *virtually zero* for excavations below a critical size. At small spans the rate at which energy could be dissipated by crushing is greater than the rate at which energy is released. The span at which the two rates become equal can be interpreted as the critical excavation size. As the excavation is enlarged beyond this critical size, the amount of energy released per area mined increases rapidly with increasing span while the rate of dissipation remains almost constant. Hence, the incidence

of rockbursts rises rapidly. A decrease in the amount of maximum closure permitted reduces the amount of energy released per area mined, which results in a reduction in the rockburst hazard. Since the rate of energy release increases with depth, the rockburst hazard can be expected to be higher with increasing depth. If the excavation surrounds a small abutment the incidence of rockbursting can be very high. An increase of stoping width has also been shown to increase the rockburst incidence. In each of the above situations the incidence of rockbursts further increases with the proximity of dykes or faults.

With respect to mining layout and sequence, Cook *et al.* (1966) stated that the alternative methods of arriving at the identical configuration of mining result in very different rates of energy release. While the total released energy is determined solely by the final configuration of mining, the geometrical rate at which it is released is influenced by the manner in which this is approached.

Cook *et al.* (1966) explained that the rate at which energy is released can be minimised by keeping the total energy change as small as possible and by adopting a method of mining that ensures the most uniform rate of energy release. Since the total energy released increases as a function of the total volume of closure, its magnitude can be reduced by restricting the volume of closure. The total volume of closure can be reduced by keeping the stoping width as small as possible. There is, however, a practical limit below which the stoping width cannot be reduced. Further reduction can only be achieved by either waste filling or by leaving solid supporting pillars. In order to achieve the most uniform rate of energy release, irregular face shapes, small abutments and remnants should also be avoided.

Cook *et al.* (1966) also stated that the rockburst hazard can be reduced either by increasing the rate at which energy can be dissipated in a non-violent manner or by reducing the rate at which energy is released.

The study of rockbursts conducted by Cook *et al.* (1966) showed that the problem can be viewed in two parts: that concerned with the region of continuous rock (assuming no geological discontinuities) remote from the excavation, in which the behaviour is assumed to be elastic and predictable; and that concerning the

region between the elastic solid and the excavation, where the behaviour is non-elastic and inadequately formulated. The transition from the elastic to the non-elastic region involves fracturing and an associated release of energy.

Since the rockburst phenomenon has always been associated with rock fracture, it appeared necessary to examine more closely the mode of occurrence of fractures, the extent of the rockmass involved and the stress environment in which fracturing occurred. Simple visual examination and recording of underground manifestations of fracture commenced in 1953 (Cook *et al.*, 1966). Characteristic patterns of rock fracture around the main excavations were identified. It was found that the dip of fractures in the hangingwall was generally towards the face whereas the footwall fractures dipped away from the face. While clean, inter-crystalline fracture surfaces did occur, it was common to find evidence of powdering or slickensiding suggestive of considerable normal stresses acting during movement along the fracture plane. Many mine officials claimed that these fractures, which they termed "burst fractures", occurred some distance ahead of the stope face and were direct evidence of the violent fracturing that caused some particular rockburst some time before the fracture was revealed.

Cook *et al.* (1966) indicated that with increasing distance from the plane of the reef, the frequency of fracture planes diminished but that many were still clearly evident in post-developed footwall drives as much as 30 m below the stope. In the hangingwall, fractures were observed as high as 60 m above the stope. The width of the fractured zone ahead of the face was considered to influence the incidence of rockbursts markedly. However, due to the limited access available it was not possible to determine the distance ahead of the advancing face at which fracturing became evident, or to suggest a definite shape for the fractured zone in the stope hangingwall and footwall.

2.4 Rockbursts

Legge (1987) analysed the rockburst and rockfall accident data of the South African gold mining industry over the period 1926-1985 and summarised his findings in tabular form. The table is shown below.

Period	All injuries*	Rock-related injuries* (% of total)	All fatalities*	Rock-related fatalities* (% of total)
1926-1935	36.7	8.9 (24.1%)	2.36	0.93 (39.5%)
1936-1945	50.9	10.9 (21.5%)	1.68	0.74 (44.1%)
1946-1955	58.3	12.1 (20.7%)	1.55	0.71 (45.9%)
1956-1965	61.3	14.0 (22.8%)	1.44	0.72 (50.1%)
1966-1975	59.1	14.7 (24.8%)	1.31	0.73 (55.7%)
1976-1985	37.4	9.7 (25.9%)	1.28	0.70 (54.7%)

*Rates are given per 1000 employees.

There were 34600 fatal accidents in the South African gold mining industry between 1926 and 1985, 16300 of which were related to rockbursts and rockfalls. Although the fatality rates (per 1000 employees) industry-wide were decreasing, rates attributable to rockbursts and rockfalls remained similar from 1936 onwards. Rock-related fatalities as a proportion of all fatalities increased steadily after 1926, and amounted to 55% of these in the period 1976-1985 (Legge, 1987).

2.4.1 Description and types of rockbursts

An excavation at depth is visualised as being surrounded by a zone of fractured ground, which in turn is surrounded by the solid rockmass (Roux *et al.*, 1957). Consequently, two types of rockbursts are visualised:

i. "Extradosal" bursts which are sudden failures of solid ground and result in an enlargement of the fractured zone.

ii. "Intradosal" bursts which are failures of the systems of equilibrium in the fractured zone.

Cook *et al.* (1966) defined the rockbursts as a damage to underground workings caused by the uncontrolled disruption of rock associated with a violent release of energy additional to that derived from falling rock fragments.

A dictionary of Mining, Mineral, and Related Terms, U.S. Bureau of Mines (1968), defined a burst as a phenomenon, which occurs when a volume of rock is strained beyond the elastic limit and the accompanying failure is of such a nature that accumulated energy is released instantaneously. In coal mines similar phenomena are called bumps or air blasts. Waddell (1970) described rockbursts as sudden, violent release of stored strain energy in rock by some mechanism of rock failure, generally accompanied by expulsion of rock with consequent damage to the mine.

Ortlepp (1983) described rockbursts as sudden and violent natural occurrences, accompanied by a shock or tremor, which cause damage to excavations and support. The damage results from disruption of the rock surrounding the excavation and / or massive inward displacement of the excavation walls. The basic cause of these bursts is believed to be a sudden slip along an existing discontinuity and / or the creation of fracture in previously solid rock.

Cook (1983) described rockbursts as violent rock failures that occur in proximity to underground excavations. In many respects rockbursts resemble earthquakes. Cook (1983) commented that rockbursts had long been recognised as a major hazard when mining hard rock at depth. One explanation for the origin of rockbursts was that they were unstable releases of some of the potential energy of the rock around the excavations. Another explanation was that the changes brought about by mining merely triggered latent seismic events that derived mainly from the strain energy produced by geological differences in the state of stress.

Cook (1983) attempted to marry the wealth of practical observations that had been made of the geometry of fractures in the vicinity of isolated stopes at depth in hard rock with theoretical and experimental work on the failure of rock as seemed applicable, in order to produce a model of the fracture zone. He then proposed a model for the formation of the fracture zone and of the mechanism of

rockbursts. The model was based on continuum or discrete behaviour of rock in the fracture zone. He described the model for the fracture zone in terms of three types of fractures, namely: inclined shear fractures, cleavage fractures, and vertical shear fractures that are the most likely candidates for the origin of rockbursts.

Brummer (1985), and many South African rock mechanics engineers, considered rockbursts to be of two major types:

i. "Volumetric failure (face crushing) events": These are relatively small events which result in very localised damage. These events show mainly contractional first motions, probably as a result of a pillar or the rockmass ahead of the face crushing in an unstable manner. Later, this type was termed "unstable fracture of intact rock" (Brummer, 1988).
ii. "Slip events on pre-existing or newly formed fault planes" These are larger events which result in widespread damage. These events, usually further away from the mining excavations, are of the fault plane type and almost certainly are the result of large-scale movement along pre-existing or newly formed faults.

The mechanisms thought to be responsible for major rockbursts, the techniques which can be used to control rockbursts, the engineering requirements of these techniques and the planned experimentation to evaluate these techniques were studied by Brummer (1988). He classified two types of seismic events that result in damage in South African gold mines, namely "fault slip events" and "unstable fracture of intact rock". Mining in regions that have been subject to considerable faulting results in the formation of remnants, mostly as fault losses. These are consequently subjected to increasing field stresses as the area around them is mined. Owing to the increased stresses on the fault surfaces, which are inherently weak in shear, the potential for unstable slip is enhanced and thus a "fault slip event" may be caused. On the other hand, events of the "unstable fracture of intact rock" type occur relatively near to the working faces under the high stresses induced by mining. As the mining face is advanced, the zone of fractured rock ahead of it also advances until the equilibrium fracture zone size is once again established. However, usually severe interlocking of the fractures near the mining face occurs and this interferes with the normal, stable growth of

the fracture zone beyond that "lock-up". As the mining face gets closer to the zone that is in a state of unstable equilibrium, sufficient energy is released for a moderate seismic event to occur near the stope face.

Most rockbursts that occur in South African deep-level gold mines can be divided into two groups, according to the mechanism of the source. The first group, referred to as crush-type rockbursts, are rockbursts, which occur as a result of violent failure of a critically stressed volume of rock in the vicinity of an excavation, usually an advancing stope face. The second group comprises rockbursts that occur as a result of shear movement along steeply dipping planar structures, such as faults (Rorke and Brummer, 1988).

Owing to the great depths of mining, the rock ahead of the face becomes very highly stressed. As a result, intense mining-induced fractures, which are sub-parallel to the stope face, develop in this region. This zone consists of many interlocking solid blocks of rock in a state of limiting equilibrium with the surrounding rockmass. The zone of fractured rock does not "grow" instantaneously to its full extent when the face is blasted, but steadily increases in size for some time after a blast, due to the time-dependent nature of the rock failure within the fracture zone. The fracture zone usually forms stably and advances with the stope face. Occasionally it does not "grow" to its equilibrium size, but becomes "locked up" due to asperities, undulations in or the disappearance of parting planes or the presence of small faults that cause steps across parting planes. These factors inhibit the shear movements ahead of the stope face, thus providing a clamping effect which increases confinement, prevents rock fracture and causes strain energy accumulation ahead of the face. When this occurs, the fracture zone is in a state of unstable equilibrium, and violent rock failure (i.e. facebursts) can occur and these are often accompanied by major damage to the workings (Rorke and Brummer, 1988).

The cause of face bursting may be the build-up of stresses ahead of the mining face. Such high stresses may occur as a result of locking up of existing fractures and a lack of development of new fractures ahead of the face to maintain a fractured zone proportional to the stoping width and the mining span when the ground becomes loaded by further mining. When the stresses reach high enough

levels, the rock fails catastrophically, causing severe damage to the face area, where the workforce is concentrated (Adams *et al.*, 1993).

Comeau *et al.* (1999) described the rockburst phenomenon simply as "a seismic event ... caused by a sudden release of potential or strain energy stored in highly stressed rockmasses". On the basis of the previous research, they listed four types of rockbursts:

i. "Strain bursts": due to high stress concentrations at the edges of mine openings,
ii. "Pillar bursts": sudden violent collapse of single stiff pillars,
iii. "Crush bursts": equivalent to a sudden multiple pillar collapse,
iv. "Fault-slip bursts": due to sudden slippage along a geological feature.

Then, the authors broadly grouped these four types into two, which are either "strain bursts" or "fault-slip bursts", depending on their mechanisms.

Brummer and Andrieux (2002) listed three conditions for violent rock failure to occur:

i. high stress levels, in order to drive the failure mechanism in particular, there needs to be a stress path to failure whereby the major principal stress increases while confinement remains high;
ii. a stiff, strong and brittle rockmass, in order to rapidly accumulate large amounts of energy and release it suddenly at failure; and
iii. a soft loading system, in order to provide excess energy at failure, and "fuel" a violent rupture of the rockmass.

2.4.2 Control of rockbursts

Given the state-of-the-art at the close of the 1960s, the mine operator had three choices to follow in controlling rockbursts (Waddell, 1970). He could:

i. design a mining system that prevents development of critically high stressed zones around the active mining area; or
ii. induce bursting at the time of the excavation blasting cycle; or

iii. destress by fracturing the ground with explosives immediate to, and in advance of, the opening.

The problem of rockburst control resolves into two types of considerations: those involving factors that affect the incidence of seismic activity, and those concerned with factors that reduce the effects of the damaging seismic events (Ortlepp, 1983). The reduction of volumetric convergence offers the best possibility for control of seismic activity through a reduction of the total potential energy available. The total energy change can be reduced in three ways: by reducing the stoping width, by waste filling, or by resorting to a system of partial extraction.

Steps taken to minimise the mining-induced energy changes may be sufficient to reduce the incidence of rockbursts to an acceptably low level. These steps may involve merely the geometrical preplanning of stope layout and extraction sequence to avoid the formation of high-stress areas, particularly remnants (Ortlepp, 1983). The density and the type of support are important in limiting the damage that results from the majority of seismic events.

Salamon (1983) stated that the alleviation of the risks associated with rockbursts may be achieved by seeking:

i. a reduction in the number of seismic events;
ii. a lessening of the kinetic energy content of seismic events;
iii. a decrease in the proportion of seismic events which manifest themselves as rockbursts; and
iv. minimising the damaging effects of rockbursts.

Salamon (1983) listed the strategic control measures as follows:

i. planning of the layout and the sequence of mining;
ii. reduction in stoping width;
iii. backfilling; and
iv. partial extraction.

Ryder *et al.* (1987) described four strategies for the control of rockburst hazards. These are:

ii. the support of mining excavations;

iii. the layout design of mining excavations;
iv. employment of seismic monitoring (early-warning) systems; and
v. triggering of seismic events through preconditioning of the rock to be mined.

Oliver *et al.* (1987) discussed various rockburst control measures implemented at INCO's Creighton mine. They reported that the improvements in mine planning, methods, support systems and developments in destressing had alleviated the rockburst problem to a certain degree. In order to help further reduce rockburst hazards, these researchers made use of stress measurements, numerical modelling and microseismic source-location technology.

Jianyun and Jiayou (1988) classified the measures for rockburst control into two types. The first one is an overall and fundamental measure that involves making efforts to eliminate the occurrence of rockbursts. This type of measure includes controlling the stresses within acceptable levels, and using reasonable mining layout and sequences. The other type of measure, which has local and temporary effects, relates to the application of destressing in the rockburst-prone region.

Brummer (1988) listed the most widespread of the measures employed to minimise rockburst incidences and the damage caused by them. He mentioned major advances in the design of mine layouts, which minimise the Energy Release Rate (ERR) and thereby decrease the number of damaging rockbursts that occur. For the reduction of rockburst damage, he emphasised the use of support systems such as rapid yielding hydraulic props and backfill systems designed specifically for use in areas prone to rockbursts.

Durrheim *et al.* (1997) conducted detailed investigations into 21 rockbursts that caused damage to excavations in deep South African gold mines. The objective of these researchers was to determine the principal factors controlling the severity and distribution of damage. They found that the source mechanism is often controlled by the mine layout, and regional structures such as faults and dykes; while local conditions and support systems strongly influence the location and severity of damage.

2.5 Destressing / preconditioning

Hill and Plewman (1957) listed the important problems facing mine management, once a destressing programme was to be implemented on a substantial scale. These are:

i. deciding on a destressing technique;
ii. deciding where to destress;
iii. gaining the co-operation of the mining (production) personnel; and
iv. organising destressing in such a way that it was done regularly and systematically.

Destressing or preconditioning of the vein rock prior to mining was shown to be an effective means of controlling rockbursts (Corp, 1980). Drilling and blasting a radial pattern of long-holes before stoping starts preconditions or softens the vein material to the extent that seismic energy released during mining is reduced and no bursting occurs. Increased burst and seismic activity while mining above the preconditioned zone points out the need to precondition an entire stope block before mining (Corp, 1980).

Willan *et al.* (1985) identified 30 destressing case studies and collected detailed data on the actual design layout used in eachof these. They then classified these cases into four groups, according to type of related mining activity, i.e. development headings, shafts and raises, pillars and stopes. The survey reflected the sparse availability of detailed data on both the practice of destressing and the degree of success. It was apparent that practice varied and tended to be based more upon subjectivity than scientific evaluation. Destress blast design was concluded to be more an art than a science, requiring further refinement and deliberate study.

Brummer (1985) stated that preconditioning appears to be a viable technique for combating the "crush" type rockbursts and has been shown to be successful worldwide, in hard rock and coal mines. Practical difficulties and the cost are probably the main reasons that preconditioning is not used extensively in South Africa.

Destressing involves the use of explosives to fracture potential rockbursting zones, in order either to reduce the build-up of stress concentrations and the potential for rockbursting, or to trigger seismic events while men and equipment are away from such zones. Preconditioning is essentially a form of destressing, undertaken in advance of mining, with the intention of reducing rockmass stiffness to prevent the subsequent build-up of excessive stress concentrations. In terms of mine planning, destressing is a tactical method of rockburst prevention, whereas preconditioning is strategic, being planned well in advance of mining (Willan *et al.*, 1985)

Ryder *et al.* (1987) listed preconditioning as one of the major strategies for dealing with the rockburst hazard and they described it as an active engineering measure to modify or control the dynamic behaviour of the rock.

On the basis of studies conducted at the Campbell Red Lake Mine, Scoble *et al.* (1987) stated that the area affected by a destress blast does not extend far beyond the immediate vicinity of the blasted holes. Fractures beyond the immediate vicinity of the destress blastholes appear to be created predominantly along pre-existing discontinuities.

Brummer (1988) described two types of seismic events that result in rockburst damage in South African gold mines, namely: "fault slip events" and "unstable fracture of intact rock". Similarly, rockburst control measures can be considered under two broad categories; these are the triggering of seismic events on known faults or geological structures and the preconditioning of the rockmass ahead of mining. In situations where rockbursts occur at mining faces, the preconditioning technique could be employed to prevent the build-up of a potentially dangerous state of unstable equilibrium in the rock ahead of the face, and reduce the number of rockbursts.

Mitri *et al.* (1988) used a numerical analysis technique based on a two-dimensional and linear-elastic finite-element method to model rockmass response to destress blasting. Simulations of blast-design options revealed that the location of the blast was more critical than the actual volume of rock fractured.

Rorke and Brummer (1988) explored the feasibility of using explosives from both a technical and a practical point of view, and examined the conceptual models for the mechanisms of preconditioning and destressing, using explosives. They stated that the partitioning of explosive energy into gas and shock energy affects the mechanism of preconditioning or destressing.

Momoh *et al.* (1996) described a numerical modelling technique that can be used to model destress blasting in sequential mining operations at depth. Stresses and mining-induced strain energy densities were computed at the end of each mining step. Destress blasting was simulated by a modification of the deformation properties of the rockmass in the destressed zone. The results indicated that large reductions in strain energy densities and stresses were attainable in the fractured zone of a destress blast, thereby supporting the hypothesis that destress blasting can be used to alleviate the hazards of rockbursts of the strain type.

Simon *et al.* (1999) presented the results of a numerical and experimental investigation of the effect of destress blasting on the rockburst potential of a horizontal pillar located below a stope in a hard rock mine. In order to determine the effects of the blast, a methodology based on the evaluation and comparison of the relative stiffness of the failed rock and the surrounding rockmass was used. It was shown that the destress blast investigated would have reduced the amount of available energy for violent failure, but it would not have eliminated the rockburst potential.

Comeau *et al.* (1999) recently reported on various destressing applications used in different hard rock mining environments in the world. Although they stated that their worldwide survey on the subject was ongoing, the preliminary results from a number of case examples were as follows:

i. Preconditioning or destressing achieves its ultimate goal;
ii. It is potentially beneficial and a useful tool that has gained worldwide recognition;
iii. The destressing mechanism is still unclear;
iv. It does not generate new fracturing in the hangingwall (Toper, *et al.*, 1998);

v. The effect of preconditioning or destressing is localised;

vi. In order to assess the effect of preconditioning or destressing, the most useful tools are found to be microseismic monitoring and convergence measurements; and

vii. The most successful results so far have been obtained from applying preconditioning on boundary pillars.

Grummer and Andrieux (2002) compiled the results of various destressing case studies from South Africa, USA, Canada and Sweden and presented them in the form of a design chart that compares the explosive energy input to the target mass of the rock intended to be destressed. They deduced the appropriate (required) level of explosive energy from the reported success of the various case studies. From their deductions they proposed a methodology for the design of large-scale destress blasts based on theoretical considerations, practical limitations and the reported case studies. They recommended that large-scale destress blasts be designed for an explosive energy factor of between 200 and 500 *kcal/tonne*.

2.5.1 The principle and objectives

The idea of artificially destressing slope faces evolved early in 1953 when *investigators felt sufficiently confident to suggest it to the committee* that was, at that time, steering the rockburst investigation (Roux *et al.*, 1957). The evidence and considerations which led to this are briefly summarised below.

i. According *to the experience of mining men, a working stope face which is* "hard" and "solid" and which has a "shiny", "glassy" appearance is more likely to burst than one which has a fractured appearance and may easily be barred down. *It seems reasonable, therefore, that to fracture a working* face would relieve it of the stress conditions likely to lead to facebursts.

ii. Experience on the Witwatersrand goldfields shows that rockbursts very seldom occur at working faces in *overmined or undermined ground. Since* such ground is usually fractured as a result of the previous mining operations above or below it, the implication again is that rockbursts of the

extradosal type at any rate are seldom, if ever, experienced in fractured ground.

iii. According to an analysis conducted by Hill (1944) on rockbursts involving 36 remnants, the frequency of bursts is greatest when the remnant size is 1350 m^2, decreasing suddenly when the size becomes less than 670 m^2. The remnants which were smaller than 670 m^2 in size were observed to be almost completely fractured.

From these observations Roux *et al.* (1957) concluded that the incidence and / or severity of rockbursts might be reduced by ensuring the presence of an adequate depth of fracture zone at the face of a working stope. If holes were to be drilled at right angles to the face and blasted they might have the effect of increasing the width of the fracture zone at the face and of shifting the zone of the high-stress peak further away from the face into the solid. If the magnitude of the stress peak happens to be high enough and sudden failure occurs in the highly stressed zone, no serious damage would result because of the cushion effect of the *fracture zone at* the face.

Roux *et al.* (1957) considered that if this purpose could be achieved, the *incidence of extradosal bursts and, particularly,* severe ones, which cause fatalities among underground workers and serious damage to stopes, could be reduced if not altogether eliminated. There seem to be indications that the *application of the destressing principle might* also assist in reducing intradosal bursts. This conclusion is based on the fact that destressing results in better support at the abutment for the intradosal ground because of the enlargement of the *fracture zone ahead of the face and better hangingwall conditions.*

Brummer (1985) explained the rationale behind destressing and the major components of the process. *Mining activity redistributes the virgin stresses* around the mining excavations. Certain local regions of the rockmass that may contain low strength discontinuities are subjected to a changed stress state. Under this changed stress state *the region in question can deform in a stable* manner or in an unstable manner, possibly causing damage. The term "destressing" is thus seen to refer to two distinct activities (Brummer, 1985). One of these activities involves reducing the rockmass strength so that a drop from

peak to residual strength (i.e. a rockburst) never occurs. This is also called preconditioning. Preconditioning "... is to pre-fracture ...a stope or zone of solid rock prior to mining so that the high stresses that usually result from mining are relieved by the yielding of the preconditioned zone." (Blake, 1982). The second activity involves altering the stresses at a particular time so that the drop from peak to residual strength occurs at a predictable time under controlled circumstances. This activity is also called "triggering".

Brummer (1985) also indicated that a good mine layout design is essential in order to prevent the development of high-stress areas or to minimise ERR. This will be practised in any case and destressing must, therefore, be done in conjunction with good mine design; it is not intended to replace sound mine layout practice.

The objective of the preconditioning exercise is thus to reduce the stress that the rock immediately ahead of the mining face carries, and to maintain the fracture zone in a state of stable equilibrium (Brummer, 1988). The most appropriate way of achieving this objective appears to be to ensure that the rock ahead of the face is heavily fractured. This can be achieved by means of explosives. Blasting the rock ahead of the face will have several results. These are listed below.

i. The rockmass strength will be reduced, and consequently the rock near the face will be unable to carry high stresses.
ii. The rock within the fracture zone will be shaken and loosened by the deep blast, resulting in a more stable condition.
iii. The fracture zone will be artificially advanced ahead of the face and, consequently, the potential for sudden changes in fracture zone size will be reduced.
iv. Less strain energy will be stored in the rock near the mining face, and less will, therefore, be available for unstable release near the working face.

Following their worldwide survey, Comeau, *et al.* (1999) have concluded that there is uncertainty with respect to the preconditioning or destressing mechanism. They have stated that it is still not clear whether the stress waves or the gas penetration generated by blasting is mainly responsible for destressing.

They have also stressed the necessity of understanding the effects of blasting in highly stressed and confined rock.

Brummer and Andrieux (2002) described realistically achievable goals of destress blasting as:

i. to increase the degree of inhomogenity in the rockmass through promotion of microfracturing; and
ii. to promote increased shearing deformation on existing fracture surfaces.

2.5.2 Field Trials

South African field trials

East Rand Proprietary Mines (ERPM) experiment

Hill and Plewman (1957) stated that the practice of destressing was in fact already being tried out on Rose Deep Ltd. before the destressing efforts were made in a remnant abutment at East Rand Proprietary Mines (ERPM). However, these early efforts did not seem to be very successful; the results were difficult to interpret and were inconclusive. Since the need for alleviating the rockburst problem was pressing and it was believed that the theory underlying the case for destressing was sound, the ERPM management team decided to experiment with destressing on a wider scale.

From March 1954, a standard destressing practice was applied to over 30 stopes at ERPM, with not more than 25 stopes being subjected to this practice at the same time (Roux *et al.*, 1957). The procedure was as follows. The destressing holes were drilled into the face at right angles and blasted approximately once a week. The production holes were not drilled on the same day. The destressing holes were drilled 1.5 m apart in reef and 0.9 m apart in dyke faces. The holes were 3 m long and the charge length was 1.5 m. On the assumption that a normal working face advanced at the rate of 0.9 to 1.2 m per week, this ensured that a cushion of rock at least 0.9 to 1.5 m thick always existed at the face.

The histories of all the destressing stopes were carefully recorded. It was found that the conditions for equal periods before and after the commencement of destressing could be considered as reasonably comparable in only 17 stopes. The effect of destressing on production, the incidence and severity of rockbursts, production delays and casualties caused by rockbursts were tabulated and compared for the 17 stopes under consideration. The time periods before and after destressing was started were equal (Roux *et al.*, 1957). The conclusions drawn from this analysis are listed below.

i. The total number of rockbursts dropped from 48 to 32 and the number of rockbursts per thousand square metres mined declined from 0.76 to 0.50, which represents a 35 percent decrease.

ii. Some of the rockbursts that happened during the destressing period occurred after periods of regular weekly destressing. They occurred mainly at blasting time when only a portion of the face had been destressed.

iii. The total number of severe rockbursts dropped from 22 to 6 and the number of severe rockbursts per thousand square metres mined from 0.41 to 0.09, which represents a 78 percent decrease.

iv. The total number of rockbursts occurring on the day shift reduced from 13 (27 % of total) to 1 (3 % of total) and the total number of casualties (injuries and fatalities) decreased from 44 (38 fatalities + 6 injured) to only 1 (injured).

v. Owing to the introduction of the destressing practice at ERPM, one production shift per week was lost. Therefore, one-sixth or a 17 percent reduction in area mined might have been expected, assuming that destressing has no effect on ore breaking. However, during the destressing period a slightly greater area was mined than during the pre-destressing period. This does not give an immediate indication that production improved during the destressing period, but does indicate that destressing resulted in no sudden decrease in area mined immediately after its introduction. It is possible that a further improvement might be obtained if mining practice can be organised in such a way that no shifts are lost due to destressing. Under these conditions the additional costs involved in employing special destressing teams would have to be offset

against the increase in production and saving resulting from decrease in damage as a result of rockbursts.

vi. There was some indication that destressing caused the shear failure planes in the hangingwall to dip at a slightly steeper angle. Before the commencement of destressing the condition of the hangingwall was described as poor but, shortly after destressing started, the conditions improved very markedly and at the end of the period reviewed the condition of the hangingwall was described as moderately good. However, it was difficult at that stage to explain why destressing should necessarily improve hangingwall conditions.

vii. It was found that destressing tended to shift the time of bursting from the period when men were in the stope towards the off-shift periods. This might partly explain the improvement in the casualty figures. It was certainly a desirable trend from the point of view of the morale of the workers. It was eventually found that it was impossible to eliminate the occurrence of rockbursts completely, but the ability of gaining some control on the time of the day when they occur was an important development.

viii. It was reported on several occasions that small bursts occurred at the time of the destressing blast. This immediately raised the question as to whether slight, harmless bursts could not be induced at every destressing blast and so prevent the build up of conditions causing the sudden, violent type of burst. This would present an important step in the direction of controlling the occurrence of rockbursts, if their complete elimination were found to be impossible.

ix. Out of 32 rockbursts that occurred during the destressing period 14 were associated with either dykes, faults, raises or remnants. This showed that the particular destressing practice used, although having resulted in a marked improvement, had not prevented bursts not associated with such circumstances altogether. It was, therefore, concluded that further improvements in the destressing procedure were necessary if these bursts were to be avoided.

x. Reports from the mine officials directly associated with destressing emphasised the improved morale of all workers in burst-prone areas

where destressing procedures had been applied (Hill and Plewman, 1957).

Hill and Plewman (1957) evaluated the efficacy of the destressing practice at ERPM and concluded that it was beyond reasonable doubt that destressing was successful. They cited the improvement of 35 percent in incidence of rockbursts, the improvement of 77 percent in incidence of severe rockbursts, and the improvement of 92 percent in dayshift rockbursts. In the case of remnant abutments and dykes the applied destressing procedure did not seem to be wholly successful; variations of the technique should therefore be tried out to meet these special cases. The net cost of the practice was small. Because of the indicated improvement of 98 percent in casualty rate and the apparently beneficial effect on general morale, the introduction of the destressing technique seemed justified on humanitarian grounds alone. The technique of destressing could probably be applied with success to any mine which suffers from rockbursts. Hill and Plewman (1957) described the destressing technique used at ERPM as a successful and proven technique, and stated that if it was further developed and perfected, it would play an increasingly important part in making conditions at great depths safer and more tolerable.

Nine years later, Cook *et al.* (1966) re-evaluated the destressing practice at ERPM from the point of view of radiated energy by destressing blasts. They stated that seismic records of rockbursts showed that two-thirds of the energy released was radiated in the form of vertically polarised shear waves. The results of the detailed seismic studies of destressing blasts at ERPM indicated that almost all of the seismic energy radiated by these shots was in the form of radial compressive waves, as would be expected from a simple explosion, and that negligible energy was radiated in the form of vertically polarised shear waves, which would be expected if a significant reduction in the vertical stress ahead of a face had taken place. Furthermore, the magnitude of the energy release was about 0.5 percent of the chemical energy of the blast, which suggested that no energy other than that derived from the explosive was released by the destressing blasts.

Much later, Hill (1982) stated that the destressing exercise at ERPM was statistically a success, and Ortlepp (1982) agreed that the destressing was a success, but added that the real reason why destressing was not carried out at greater depths was difficulties experienced with drilling. He added that there was probably merit in drilling long holes from some sheltered environment into known "hot spots" and either blasting or hydrofracturing. Tyser (1982) explained the reason for the termination of the ERPM destressing experiment as the impossibility of charging up the stress-deformed holes in the deeper areas.

The reason given by Cook *et al.* (1966) for the rejection of the benefit of destressing was that seismograms resulting from destressing blasts showed none of the characteristics of seismic events (Brummer, 1985). This reasoning was probably fallacious, as it seemed certain that the destressing as used at ERPM did not trigger seismic events, but did precondition the rockmass. In the technique of preconditioning, it was not necessary to cause events to occur; the benefit of the method lay in its reducing the rockmass strength. Triggering, however, caused more energy to be emitted than was actually put in to the rockmass by the triggering stimulus.

The results of the reef destressing (preconditioning) experiments carried out at ERPM were inconclusive and were the subject of debate. The holes were difficult to drill, and at that stage the seismic coverage of the site was not as comprehensive as that possible today; doubt existed, therefore, as to the actual effects of the destressing (Brummer, 1988).

Despite very encouraging results and the apparent benefits reported by Roux *et al.* (1957) and Hill and Plewman (1957), because of the debate on the whole experiment, preconditioning was not generally accepted by mines as a viable and safe technique. In order to address this problem, the Chamber of Mines Research Organisation (COMRO) initiated a research programme to re-investigate preconditioning as a viable and safe technique in the mid-1980s.

Most recent experiments

In the mid-1980s, the Chamber of Mines Research Organisation (COMRO) initiated a research programme to investigate active rockburst control techniques, such as the triggering of slip along major faults and the preconditioning of the rockmass ahead of mining faces, and to assess the potential of these techniques for use in deep gold mines (Brummer, 1988).

COMRO's involvement in preconditioning began in 1987 with experimentation at West Driefontein Gold Mine, where the 32-12W stope was being mined into a large remnant along the Western Deep Levels (WDL) boundary (Rorke *et al.*, 1989). The technique being implemented made use of long, face-parallel holes drilled along the length of the 30 m panels. The 76 mm diameter holes were positioned between 2.5 m and 3.5 m ahead of the face and drilled within a shift. The panels were mined beyond the line of the previous preconditioning holes and, hence, the spacing between preconditioning holes averaged about 8 m.

Following a trial period of five months of test drilling, preconditioning was implemented in two panels. Once the technique had been optimised, all five panels within the stope were preconditioned. A total of 18 preconditioning blasts were carried out in the 11-month period of the project. Convergence of 5 mm to 40 mm associated with a preconditioning blast, face scaling of up to 300 mm, and a lack of damage at the face following large seismic events were reported. An observed reduction in shallow-dipping fracturing compared to non-preconditioned panels resulted in improved hangingwall stability, which may partly account for the lack of seismic damage. However, the project was terminated when the technique could not be integrated into the new layout that was required, as the stope was approaching a seismically hazardous structure.

A further preconditioning experiment was initiated on Blyvooruitzicht Gold Mine (BGM) in the 18-13W stope, an up-dip panel along a protection pillar adjacent to a seismically active fault (Rorke *et al.*, 1990). A series of 30 m long, 76 mm diameter holes fanned out from the dip gullies was planned to be drilled into the entire pillar, with the intention of "preconditioning" the pillar with one blast. Eventually, only the holes on the edge of the pillar could be drilled to nearly their

full length. The other holes were drilled to only 10 m. Difficulties experienced with drilling into the core of the pillar provided some insight regarding the condition of the pillar. Despite the seismicity from the adjacent fault, the pillar was eventually mined out without incident by fanning the preconditioning holes drilled from the up-dip gullies at five different face positions. Improved hangingwall stability was reported to be due to steeper extension fractures following the introduction of preconditioning.

Extraction of a dip pillar with preconditioning at BGM began in mid-1990 (Lightfoot *et al.*, 1996). The 30-24W stope is situated at the southern extent of BGM near the boundary pillar to Western Deep Levels (WDL). This dip pillar was 40 m wide and 150 m long with the top of the pillar terminating on a stabilising pillar. Initially, the pillar was conventionally mined but, after problems with consistently poor ground and several large seismic events, the mine decided to implement their own preconditioning project in mid-1990. They requested COMRO to monitor this project. The method of preconditioning was similar to that used at the 18-13W stope: 10 m long holes fanned out from the dip gullies. Difficulties with drilling and frequent damage to support and the collar area of the holes all resulted in production delays.

Problems also arose due to the mining by WDL of two large longwalls just to the south of the boundary pillar. The stress changes induced in the preconditioning stope resulted in a significant increase in seismicity levels. A large rockburst in October 1991 resulted in several fatalities. This prompted a change in the preconditioning layout to face-parallel drilling. However, before any progress could be made with this technique, the stope had to be abandoned in early 1992, because of increasing seismicity levels.

Work on 17-24W stability pillar site at BGM began in April 1990, using preconditioning holes that were fanned out sub-perpendicular to the stope face. The intention was to extract a long strike pillar, using preconditioning to reduce the risk of rockbursts at the face. Initially, the mining was in an up-dip direction. However, in an attempt to improve the effectiveness of preconditioning, the panels were changed to breast in September 1992. This new layout allowed for the drilling of face-parallel preconditioning holes. On the whole, this mining

geometry proved to be more successful for preconditioning (Kullmann, *et al.* 1996).

In late 1994, it was recognised that, although face-parallel preconditioning appeared to be well suited to the mining of long and narrow strike pillars, it would be difficult to implement in a normal deep-level longwall production environment without imposing considerable delays in the mining cycle. For this reason, a new experimental site was opened on a deep-level longwall on WDL South Mine. Experiments were undertaken at this site, which involved drilling short face-perpendicular preconditioning holes as a standard addition to every production blast. The experiments indicated that it was possible to implement this method in a deep-level longwall mining environment without significant disruption to the mining cycle (Lightfoot *et al.*, 1996).

Adams and Geyser (1999) reported a successful preconditioning experiment carried out in a development end at Kloof gold mine No. 4 shaft where a high speed tramming haulage experienced instability and strain bursting. The problem was associated with the tunnel obliquely intersecting a dyke that was weaker than the surrounding lava, in an elevated stress field. A pattern of preconditioning blast holes was designed and following 14 preconditioning blasts and a similar number of conventional development blasts, the tunnel was safely driven through the dyke. The preconditioning technique in this site was found to be very successful in minimising the strain bursting and eliminating the injuries to personnel.

Non South African field trials

Metal Mines

Dickhout (1962) mentioned a successful destressing experiment at INCO's Creighton mine. The experiments were carried out in development headings. *Initially, one hole, approximately 60 mm in diameter, was drilled to a depth of* about 14 m. The hole was loaded with ANFO-type explosive, collar primed and fired. Immediate benefits derived from the destressing technique were: a marked reduction in overbreak *resulting in more stable shaped openings;* and a large

decrease in "working ground" and spalling. Later, the use of destressing was made standard in all headings in the deep-level development programme.

The use of a destressing technique as applied to the hangingwall of a cut-and-fill stope at Falconbridge Mine was described by Monzi and Pasieka (1984). In order to determine the effectiveness of the experiment, closure measurements and fracture and photoelastic strain analyses were conducted on drill-core samples taken from and around the destress holes. After thorough analyses, it was concluded that destressing failed to accomplish the purpose for which it was designed but did, however, act as a trigger for two large rockbursts.

Blake (1972a, 1972b & 1982) for several years advocated the practice of preconditioning highly stressed remnants or pillars by means of drill-and-blast methods and he cited examples of large-scale rockmass preconditioning in U.S. metal mines. Preconditioning was carried out by blasting in 100 mm diameter boreholes, with the holes charged to 7.0 kg of explosive per metre and stemmed using water or clay and sand. Microseismic monitoring at Hecla's Star mine in the Coeur d'Alene mining district showed a reduced seismic energy release per m^3 of mined ore and preconditioning was very effective in eliminating rockbursting.

Blake (1972a) described a destressing experiment done at the Wallace Galena mine (Idaho, USA). Here a near-vertical pillar about 1100 m below surface was destressed by long-hole blasting. A finite element analysis was done, which suggested that the destressing would be beneficial and this was borne out by the actual field experiment. The rationale for Blake's experiment was "... to prevent *bursting, the pillar must be sufficiently fractured* such that it will yield; hence it will fail slowly and non-violently".

Kaniowski et al. (1979) and Corp (1980) reported on the destressing activities at Hecla's Star mine in the Coeur d'Alene mining district. Destress blasting was used extensively to fracture the pillar, thereby reducing its structural stiffness and *allowing it to undergo stable yield. However, Corp (1980) questioned the* effectiveness of this type of destressing, although many rockbursts were triggered with the destress round when miners were not present. According to *Corp (1980)* another *rockburst control technique shown to be highly effective is*