SAFETY IN MINES RESEARCH ADVISORY COMMITTEE

# SIMRAC

## Final Project Report

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| Title: | ASSESSMENT OF REFUGE BAY DESIGNS IN COLLIERIES |
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## EXECUTIVE SUMMARY

The original output of this project was directed at reassessing the survival strategy following colliery explosions and fires. With regard to explosions, problems were experienced with delivering the outputs with regard to strength requirements for refuge bay bulkheads. These problems were resolved during a special meeting held early during 1996 when the scope of the final output was redefined to focus on the characteristics of the explosions that refuge bays could be subjected to in the underground environment and how (it is anticipated) they would react to these explosive forces. By comparing present practice with these requirements, an indication of the present suitability of structure could be determined.

In assessing the characteristics of explosions use was made of experience at experimental mine and explosion gallery facilities throughout the world. To determine the effects explosions have on structures and human beings, use had to be made of experience gained in the fields of commercial and military usage. Information relating to the construction of refuge bays on mines was obtained from codes of practice and discussions with staff from the industry.

It was found that the most probable explosion forces that had to be catered for would lie in the order of 140 kPa pressure. It is, however, not anticipated that the refuge bay bulkhead would require this strength, at the practical distances it would be placed away from the face. By using the 140 kPa specification the possibility of a lower order coal explosion would also be catered for. If the strength requirements were increased above this specification of incidence of fatalities at these higher pressures would be so severe that very few or no survivors would be left to make use of the refuge bay.

The refuge bay designs on the mines are more than adequate in the event of fires occurring. It is, however, doubtful whether the strength of these structures, as evidenced by the codes of practice, would withstand an explosion. What is of greater importance, however, is that the distance allowed between the face and the refuge bay make the possibility of workers reaching the refuge bay in condition of low visibility almost non-existent. To establish refuge bays at the intervals required to cater for these conditions would place onerous requirements on the mines concerned. The need for a survival strategy that incorporates an intermediate place of safety is indicated.

From the findings of this report it is thus recommended that a strength requirement for designing refuge bay bulkheads of 140 kPa is used. To enable these bulkheads to be tested, it is further recommended that the establishment of a local test facility, where local designs can be tested, be investigated.

It is also recommended that the use of an intermediate safe haven be introduced as part of a revised rescue strategy.

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# 1 INTRODUCTION

This report, which deals with aspects of the design of refuge bays, is directed at members of the mining industry, as well as the members of the SIMRAC system. The purpose of the report is to give a rationale to determine the most probable forces that a refuge bay would be subjected to, and from this develop proposals which can be used in the design of these structures. By comparing the determined requirements with the specifications of refuge bays presently being used in underground mines, shortcomings in the system can be identified and possible solutions proposed. This report also addresses the construction of refuge bays, with specific reference to the construction method of bulkheads that are used to construct refuge bays.

Finally, further action, as well as work based on the identified shortcomings, is proposed. Although specific details, regarding the effects of explosions in the underground environment and the methods to cope with them (due to the uncertain manner in which they occur), cannot be given, the report, nevertheless, does address the issue to the extent that decisions can be made or further work formulated.

## 1.1 Scope of the Report

For various reasons the scope of this report was changed by the sub-committee controlling its progress (SIGEH).

The revised requirements for this project can be formulated as follows:

> *To investigate the characteristics of methane and coal dust explosions in underground coal mine workings.*
>
> *To review the effect of such explosions on typical underground structures.*
>
> *To list the existing practices being used by mines to construct refuge bays. Specific attention will be given to methods of construction, placement of bays and the type being used.*
>
> *To determine the ratio between the required thickness and the area of a bulkhead to cope with the explosion characteristics as determined in the first part of this study.*

These issues were addressed through relevant literature, as well as through consultation with the experts in the field and in-house experience in dealing with rescue and escape strategies. Although not contained in the scope, information in the literature that is useful in devising escape strategies is also included in this report.

## 1.2 Constraints

Though the scope of the project required the determination cf the effects of typical coal mine explosions on underground structures in order to quantify these issues to a high level of certainty, it was found to be impossible. It became evident that the nature of underground explosions is so diverse that is almost impossible to predict the circumstances under which they would occur, and, therefore, the effect of the explosion. In the light of the uncertainty about the actual explosion, coupled with the effects caused by the underground geometry, it becomes even more difficult to predict the forces that a structure will have to withstand.

Although investigated in theory, on the whole overseas testing of bulkheads has mainly consisted of using trial and error methods[19,37] where the bulkheads, that have been designed, have been tested using actual explosions in test mines or galleries. By nature these test explosions were a simulation of what could occur, but experience at these galleries found that actual explosions can often not conform to the predictions and have lesser or more severe effects than what was anticipated.

It was further indicated in the study that it is almost impossible to do a theoretical design of a bulkhead unless very complicated and expensive finite element simulations were conducted. The results of these tests, however, would always be constrained by the inability to describe the explosion in the required detail. Even after such analysis has been conducted, actual testing of the seal is then still required. In the light of the above, and to effect as large a contribution as possible, use has been made of case studies and empirical experience worldwide to illustrate principles.

Where possible, techniques to improve the design have been provided but the exact effect of these techniques on the bulkhead withstanding a specific explosion could not be quantified.

# 2 EXPLOSIONS IN COAL MINES

## 2.1 The Characteristics of Explosions

An explosion occurs as the result of three components acting together. These three components are a source of initiation, an oxidizing agent (usually the air), and, thirdly, fuel. In the case of coal mines, this fuel is either methane or methane combined with coal dust. As legislation in all coal mining countries requires the inertisation of this coal dust, it can be assumed that when a coal dust explosion occurs something in the precautionary measures went wrong.

To enable an understanding of explosions and their effects to be quantified, information regarding surface explosions, as well as explosions occurring in the underground environment will be used. In many cases this information can only be found in the literature relating to commercial or military explosives or even the effects of nuclear weapon blasts.

Explosions are usually high speed decompositions of solids or liquids into a gas (In the case of methane the gas is oxidised into other gases), with the space previously occupied by the explosive or fuel, i.e. after the explosion, filled by the resultant gaseous mixture which would be at a high pressure and temperature.

Principally two types of explosives will be considered.

The first type of explosives are high explosives which detonate rapidly after the chemical reaction has been triggered by a mechanical shock wave that travels through the explosive. A typical high explosive is TNT, one gram of which can release 1120 calories of blast energy and at the moment of detonation generates pressures of approximately 6,900 MPa within the initial gas generated(1). As the energy of these explosives is released so quickly and the pressures generated rise so quickly, high explosives possess a characteristic called brisance which is the ability to shatter.

Other types of explosives, like explosive gases, dusts or gunpowder, release their energy at a slower rate either by burning or deflagrating, and, therefore, do not usually posses the brisance characteristic. It should be noted that when these slower burning explosions detonate, brisance could occur, however, it can be assumed that explosions of methane/air/coal dust mixtures so seldomly go into a detonation phase that the occurrence of brisance can be discounted.

When an explosion occurs the high pressure that is generated is transmitted to the surrounding air and propagated as a shock wave that travels out radially from the point of ignition. The idealized shock wave created by an explosion is a steeply climbing pressure that rises to its maximum value after which it decays over a longer period to a minimum that is less than the previous ambient pressure. In Figures 1, 2, and 3 examples of such wave forms are presented.

In characterizing explosions the static pressure is almost always used as an indication of the strength of the explosion. It is usually measured with a transducer that does not disrupt the shock front or gas flow and the sensing surface is oriented at right angles to the direction of travel of the blast wave.

The peak pressure, duration of the initial positive pressure phase, as well as the velocity of the shock wave are all functions of the size of the explosion. The size of the explosion is in turn a function of the amount of explosive fuel available. The medium in which the explosion occurs[*1] also plays a role in the manner the shock wave is propagated, eg. in water a wave will travel significantly faster due

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[*1] Although the medium through which the explosion travels is always air in mines, the explosive energy attenuation in water is so much less, due to the incompressibility of water, that the lethal radius of an explosion is about three times larger in water than in air.

to the incompressibility of the medium. For the purposes of this study only effects in air will be considered.

The medium that the explosive wave has to travel through has an attenuation effect and, thus, the distance that the wave travels from the explosion also has significant effect on the forces encountered by any object(2). This pressure wave travels much faster than the actual flow of hot gases expanding away from the point of ignition, hence the pressure wave generated by an explosion invariably precedes the flame front.

## 2.2 The Characteristics of Explosions in Coal Mines

### 2.2.1 Types of explosions

Two aspects need to be considered in determining the type of explosion that could occur in a coal mine. The first aspect is the fuel involved with the explosion. The fuels usually involved with coal mine explosions are methane and coal dust. It should, however, be considered that although methane explosions cannot be fully countered, the occurrence of a coal dust explosion, in the light of the preventative measures prescribed and used, cannot be accepted as an acceptable norm on which design decisions should be based.

The second aspect to consider is the type of explosion or the explosive mechanism that has occurred.

The manner in which the fuel for the explosion occurs has a significant, if not overriding effect, on the resultant explosion. The volume of the fuel in the form of a gas-air body affects the static explosion pressure that develops. In the Lake Lynne experimental mine which is an experimental facility run by the Pittsburgh Research Centre (formerly part of the United States Bureau of Mines), tests have been conducted with 7,4 $m^3$, 36,8 $m^3$ and 53 $m^3$ volumes consisting of a 9,5 % mixture, with static pressures of 63,280 and 368 kPa, respectively, obtained at the face. The flame length was approximately five times the length of the original volume containing the methane -air mixture(3). In a coal mine section the most probable fuel for an explosion would be from an accumulation of methane, which, if ignited, causes an explosion which would grow outwards from the point of ignition until the side of the roadway is reached, after which the explosion progresses along the roadway. If the methane is the only fuel the explosion will increase until the fuel or oxygen is consumed after which it would die out.

In the event of a methane ignition or explosion igniting coal dust the whole picture is changed as the coal dust adds more fuel for the explosion and, instead of a decreasing explosion, the addition of coal dust could actually increase the intensity of the explosion as it progresses.

If the gases are subjected to turbulence or mixing during the explosion, the pressure achieved by the explosion is also increased. In tests conducted to assess the strength of seals, Weiss, Greninger and others(4 5 6) specify that to achieve the required 20 psig (140 kPa) pressure wave it was necessary to create turbulence in the methane-air chamber by the use of water filled barrels.

An acceleration of the flame is brought about either by turbulence (from the walls of the structure or from obstacles to the free expansion of the gases, like equipment) or by pressure piling as the flame progresses down the tunnel. This acceleration could lead to more rapid combustion, leading to either a rise or maintenance of pressure(7).

Pressure piling is an additional increase of pressure in the main body of exploding gases brought about by the accelaration of gases from the back and the constraining of the gases at the front caused by the tunnel walls as well as a reluctance of the gases in front of the pressure wave to move due to resistance from the sidewalls or other obstructions.

The explosion type

In assessing work done at the USBM, Maser *et al*(8) classified explosions that could happen in the underground coal mine environment into three groupings.

1 Simple deflagrations wherein the reaction zone travels away from the ignition zone at constant velocity (significantly less than the speed of sound, e.g. at about 1-2 m/sec).

2 Accelerating deflagrations where the reaction zone accelerates through the unburnt gas. As this causes a distortion of the flame front the process is self accelerating. The zone of acceleration creates pressure pulses which travel at the speed of sound in ambient air. The feature of the shock wave is the increase in speed and almost instantaneous rise-time. The pressure peak or maximum pressure is greater than that of the simple deflagration.

3 Detonations occur when the shock wave and reaction wave move together. This explosion is characterized by a high pressure (1 MPa) and a very short duration, as the shock wave travels at a speed greater than the speed of sound in the ambient air. Detonations could occur in very long (>60 roadway diameters) or confined gas zones. It is, however, felt that these are unlikely to occur in the underground environment. If, however, a gas is pressurized to a high level, as could be the case in ideal wave reflection conditions, a detonation in the gaseous explosion could occur. Under these conditions it has been found(9) that the speed of the explosion could rise to between 2100-2400 m/s with respective pressure increase of between 0,5 and 90 MPa.

Cybulski[10], in a similar fashion, classifies explosions into the categories presented in Table 1.

Table 1 TYPES OF EXPLOSIONS CONNECTED WITH CHEMICAL REACTIONS

| Name of the process | Velocity | Mechanism of the heat transfer |
|---|---|---|
| Thermic | Very slow | Conductivity, convention. |
| Deflagration | From low to high | Conductivity, convention, radiation |
| Detonation | Very high (>1000 m/s) | Hydrodynamic |

In Figure 1 the relationship of pressure and time for the three types of explosions are presented in idealized form, and in Figure 2 the progression of an explosion in the Buxton tunnel is presented. Figure 3 shows an example of the progression of an methane explosion in the GP Badenhorst Tunnel, while Figure 4 shows how all of the characteristics of the explosion are changed when coal dust is part of the fuel.

In Figure 3 points $a_1$ and $b_1$ show the pressure of the wave as it travels along the tunnel. In the 200 m length there is no real change. In Figure 4 it is evident how the initial pressure ($a_2$ ) caused by the methane is much lower than that caused by the coal dust igniting ($b_2$). When the flame has progressed down the tunnel only then is the maximum pressure obtained ($c_2$).

## 2.3 Aspects Influencing the Force of Explosion

The prime characteristic of an explosion is the speed at which the reaction occurs. In a coal mine, the explosion can also be characterized by the speed of the expanding burning gases, the speed at which the pressure pulse travels down the roadways, the increase in static pressure and the temperature that the gases reach.

Although the severity of an explosion is traditionally described by the results or damage caused, it has been proposed that severity can also be indicated by a combination of the pressure and the time of the explosion. If the explosion is represented as a Displaced Cosine Pressure - time graph, the severity can be indicated by the area falling under the graph[11].

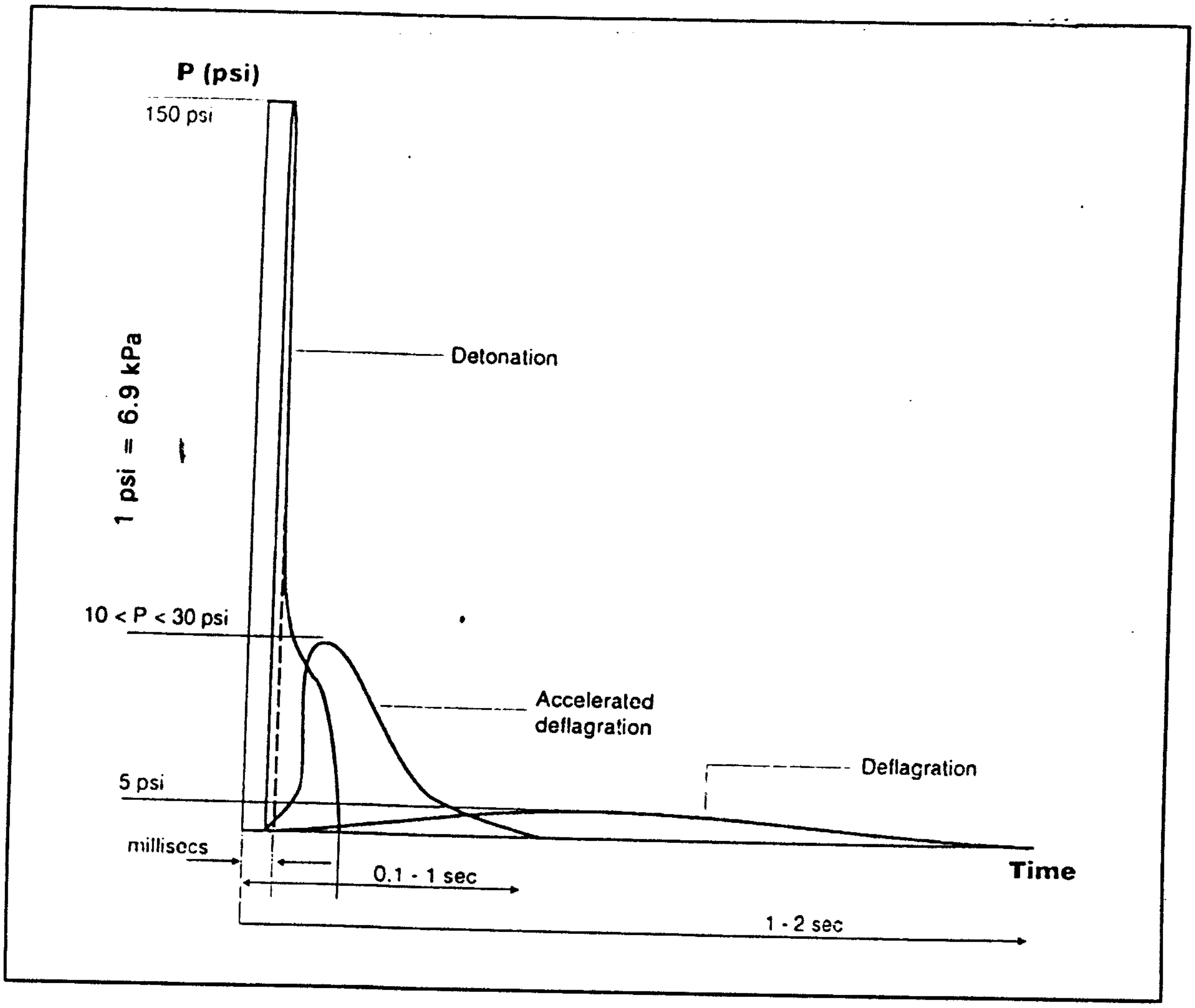

Figure 1 TIME-PRESSURE GRAPHS FOR DIFFERENT TYPES OF EXPLOSIONS

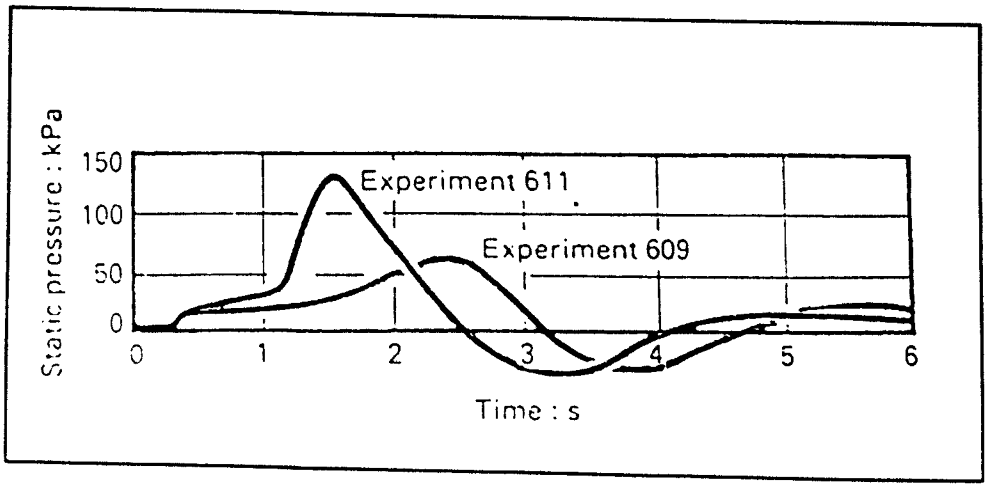

Figure 2 TIME-PRESSURE GRAPH FOR A TYPICAL EXPLOSION IN THE BUXTON FACILITY

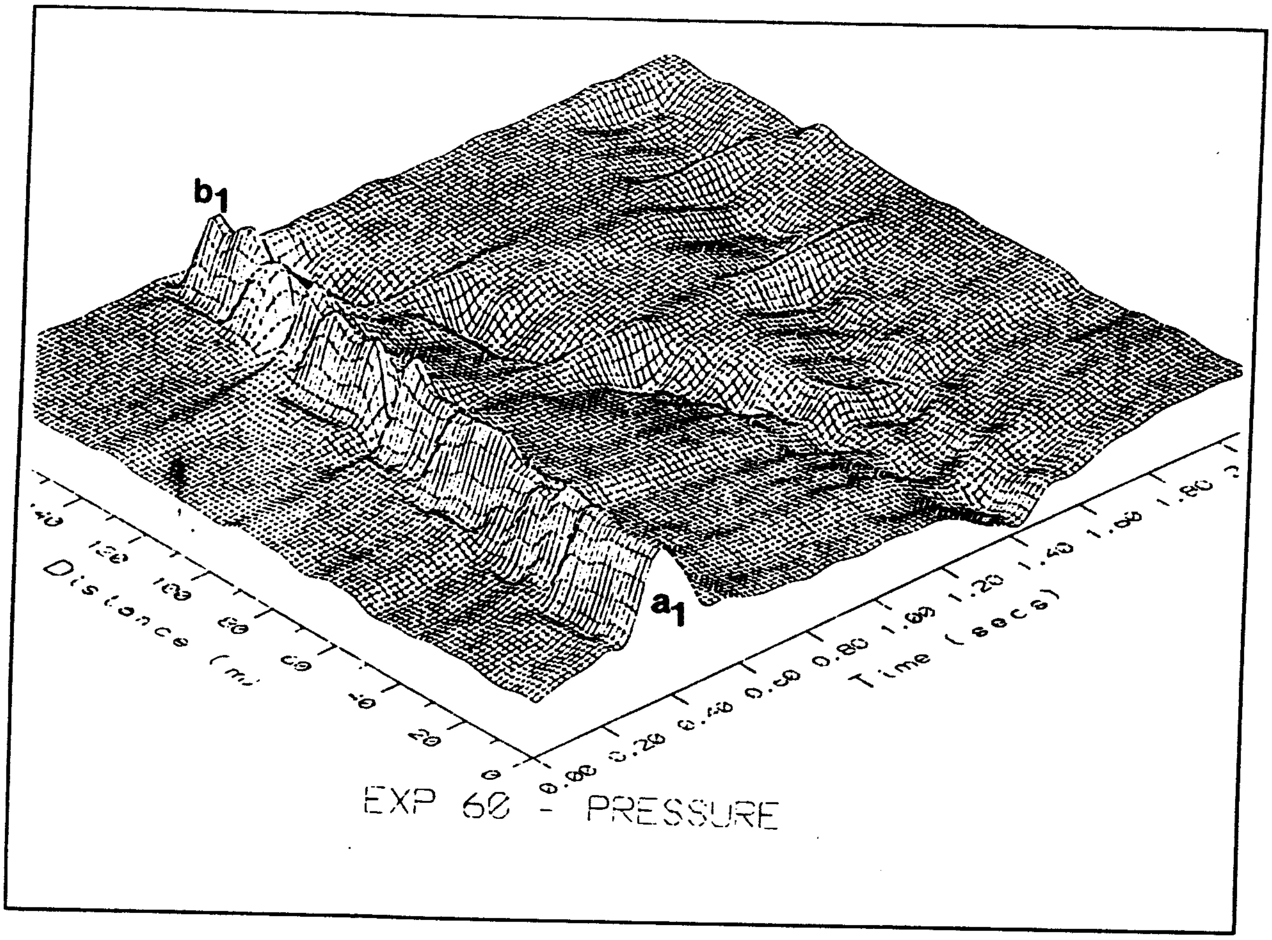

Figure 3 TIME-PRESSURE-DISTANCE GRAPH OF A METHANE EXPLOSION
(Results obtained at the Kloppersbos Test Gallery)

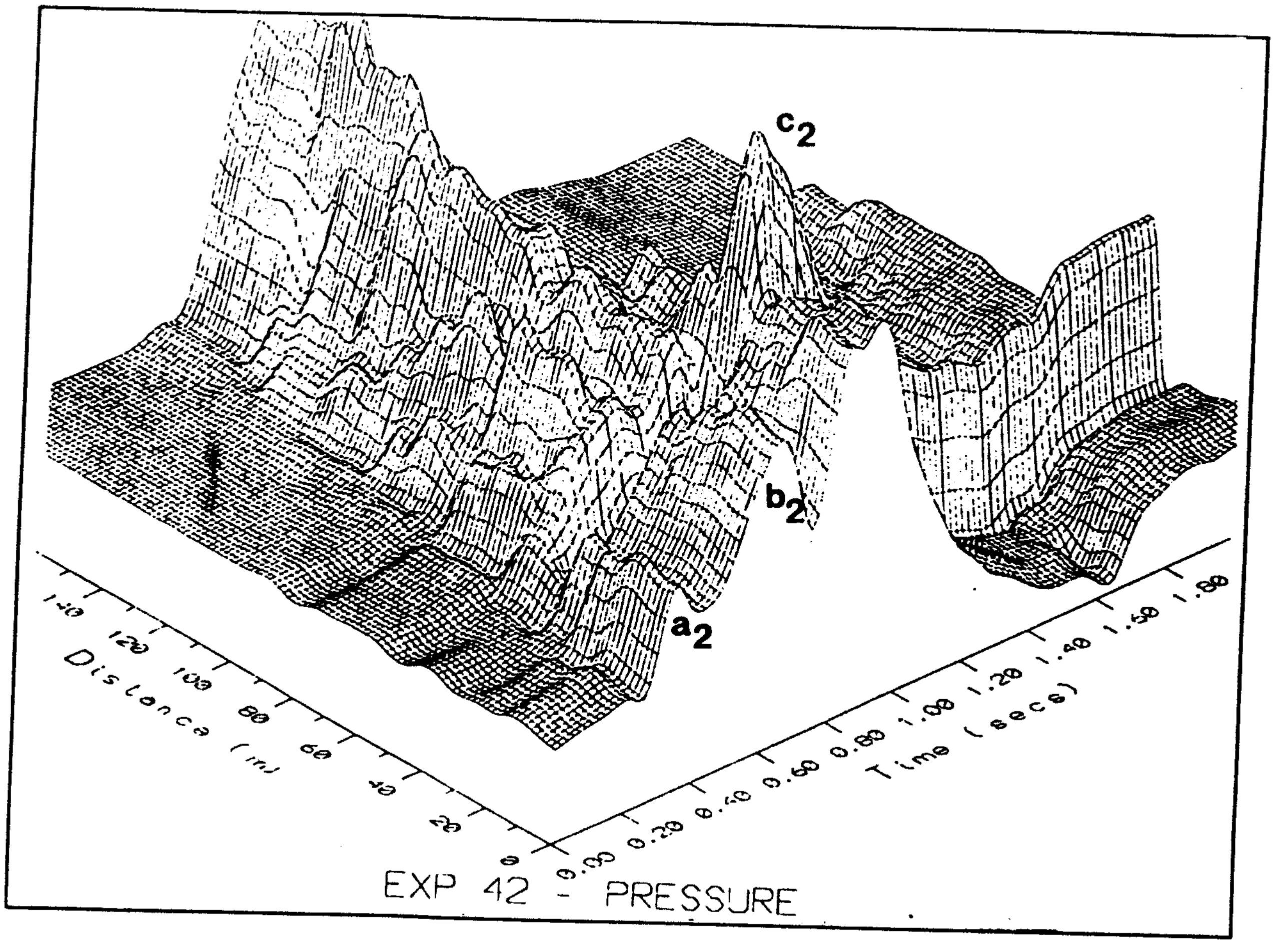

Figure 4 TIME-PRESSURE-DISTANCE GRAPH OF A COAL DUST EXPLOSION INITIATED BY A METHANE EXPLOSION
(Results obtained at the Kloppersbos Test Gallery)

### 2.3.1 Amount of explosive fuel

In air the peak pressure reached by the explosive products is proportional to the cube root of the charge mass(12) of the explosive.

Work done by Nagy(17) indicated an increase in the explosion intensity as the volume of methane increased. Figure 5 compares methane explosions where doubling the amount of explosive (methane gas) lead to an increase of almost two and a half times the pressure. Apart from the increase in pressure the speed of the explosion increased.

The experiments were conducted in a gallery where the cross-section was constant and the contained volume of gas/air mixture was thus proportional to the length of the chamber of gas. The amount of fuel was proportional to both the concentration of methane and the volume of the gas/air mixture.

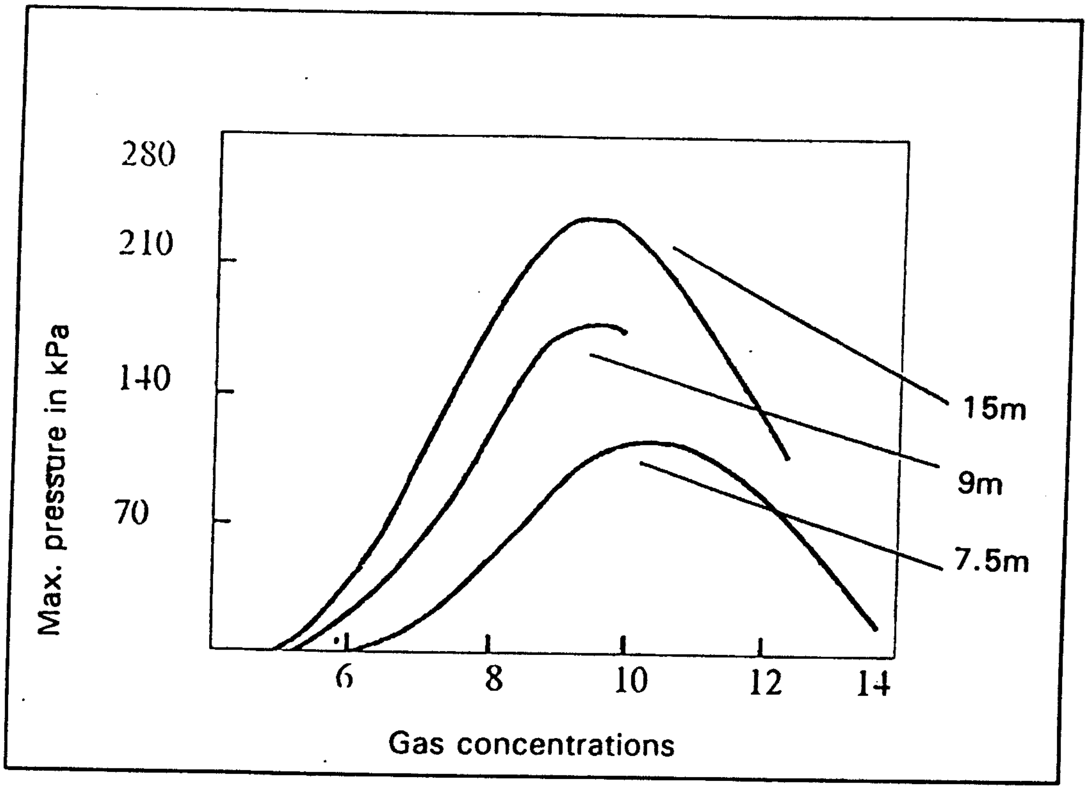

Figure 5 EXPLOSION PRESSURE 15 m FROM FACE PRODUCED BY IGNITION OF GAS-AIR MIXTURES IN 7, 5, 9 AND 15 m ZONES

### 2.3.2 Containment

Uncontained the pressure of a gas, or diffuse reactant, will not exceed 16 psi (112 kPa). The reason for this is that the speed of the reaction will not exceed the speed of sound which means that the positive wave cannot exceed the absolute negative pressure (an Absolute Vacuum which is 16,7 psi (116,9 kPa) at sea level(13)).

When the explosion is contained it results in raising the effective pressures and prolonging the effect of the explosion. The maximum pressure that can be attained with the optimum concentration of any gas or dust completely filling any closed space (with complete combustion within the space) is about 700 kPa. Changing the room size would only effect the time the perimeter of the exploding gases take to reach the walls of the space. Smaller contained volumes would reach this maximum level quickly whereas larger volumes would take longer to reach the peak pressure(7).

The issue of containment is important in the design of bulkheads for refuge bays, as well as for the construction of seals. When a seal is erected to close off an old area, it contains the old area. In the event of an explosion occurring behind the seal, the pressure generated will, ultimately, be determined by the amount of fuel behind the seal and the volume to which the explosion expands. If the volume behind the seal and that of the explosion is similar, then the explosion will become contained, with a significant expected increase in pressure on the seals.

A bulkhead for a refuge bay is not subject to the same conditions as it is not in a contained condition (except if the explosion starts in the bay itself, the probability of which is neglectably small).

As the chances of an explosion originating at the face is greater than at the bulkhead, the bulkhead would be subjected to a explosive wave and overpressure that has already diminished significantly.

Thus care has to be taken not to accept the same strength requirements for bulkheads as demanded for mine seals, as they have been designed for significantly more adverse conditions.

The maximum pressure developed by a dust explosion can best be measured in a 1 $m^3$ vessel. Although it has been found that the pressure developed is not a strong function of vessel size, the pressure developed in the Hartmann vessel is in the order of two to three times lower than in a 1 $m^3$ vessel. As the dust concentration is seldom optimum in practice, the 1 $m^3$ vessel usually gives enough of a margin of safety so as to give representative values for contained explosions(18). It has been found that by using this technique, pressures, ranging from 500-600 kPa for carbonaceous dusts and up to 1,3 MPa for aluminium dusts, could be generated. Using the same method methane had a maximum pressure of 750 kPa.

### 2.3.3 Size of the initiating energy for the explosion

The influence of the size of initiating energy on the progression has been indicated by both local and overseas research. In the event of a larger initiating energy source the explosion progresses at a faster rate.

Cybulski[10] noted that an increase in power of the initiating explosion from 200J to 1000J causes the static pressure to increase from 45kPa to 70kPa. In latterday tests in the 20m tunnel at Kloppersbos[48] it was found that there was almost no increase when the detonators strength was increased. This could possibly be due to the relatively small amount of methane in the tunnel volume or the unconfined nature of the explosion.

In the underground environment the probability of a frictional ignition is higher than other sources, e.g. electrical sparking or the misuse of explosives. When an ignition is caused by the friction between the cutting picks and rock then such an initiating event can be considered to be of low energy, which means that explosions resulting from this would have a lower severity than those created in test facilities where chemical or electrical igniters are used.

However when such a methane explosion involves a large amount of methane and is allowed to expand, it can serve to create enough of an initiating event to ignite coal dust even when the amount of inert material is relatively high. (Cybulski refers to an explosion that devastated a mine even when the amount of inert material exceeded 80 %.)

### 2.3.4 Presence of suppressants

The presence of suppressants can reduce the effect of an explosion. Cursory work done in the USA(17) has indicated that the effects of even a methane explosion can be reduced significantly by the presence of stone dust.

The presence of stone dust, at the legal requirements, stops a methane explosion from progressing to being a significantly more severe coal dust explosion.

According to Cybulski[10] and confirmed by Du Plessis[49] the stone dust has the following functional action.

It acts as a heat sink
It screens the radiation from combustion processes between coal particles.
The stone dust particles obstruct the diffusion of oxygen and combustible gases.

Although not implemented in South African mines as yet, the use of an active suppression system would reduce the effects of a methane ignition even if it does not manage to douse such an ignition completely.

### 2.3.5 Release of pressure - distance from the source

The highest static pressure is obtained at the face of the entry, and the maximum pressure decreases as the distance of the gas body from the face increases. No matter where the body of gas was located the highest pressure recorded is at the face, and this pressure is usually two to four times higher than the pressure 150 m from the face(3).

Cook(1) gives the peak pressure at any distance as a function of the initial charge mass and the distance from the explosion. The following formula describes this:

$$\text{Peak pressure} = A/z + B/z^2 + C/z^3$$

where spread of the explosion, z, is equal to

$$z = R(\text{distance})/Q^{1/3}$$

and Q is the charge mass of the explosive.

It has been found that for an explosion in the air, the last term of the equation ($C/z^3$) is dominant very close to the explosion (<10 charge radii), with the peak pressure varying as the inverse of the distance cubed. At further distances the first term starts to dominate with the peak pressure now varying as the inverse of the distance from the explosion.

In practice this means that close to the explosion there is a significant drop in pressure, while further out from the explosion there is a lower rate of pressure drop.

This is borne out by the damage caused to structures and humans close to the explosion, whereas only a relatively small distance away, very little or no damage occurs.

Referring to work done by Maser(8) the effects of intersections and turns were also determined. It has been found that the shock wave is attenuated by a factor 0,80 for every intersection passed. Thus, if three intersections have been passed then the peak pressure of the wave would have been halved. This aspect will result in lower pressure being experienced a distance away by bord and pillar sections than in the case of long walls, where the entries are long and straight.

This is of great relevance to the present study since these results were obtained as part of a study to determine the optimum design of seals in underground roadways.

From Figure 6 it is evident that there is almost a halving of the pressure over a distance of a bord of 150 m. This decrease is more noticeable in the higher volume explosion and higher initial pressures: When the initial pressure is lower there is less of a pressure reduction. From this graph it is also evident why it was difficult to obtain high pressures to test seals at distances greater than 100 m. This is of great significance for determining strength requirements as the graph would tend to indicate that only massive methane explosions would be able to reach pressures in excess of 140 kPa at distances greater than 150 m from the face.

In Appendix G a summary is presented showing further ranges of explosion characteristics as used for testing seals.

In assessing the pressure reading from various sources it was observed that the maximum pressure peak obtained by controlled methane air explosions was 30 psig (210 kPa). It was also noted that the duration of the pressure pulse was in the order of approximately 0,25 of a second.

This aspect is borne out and reported by Nagy(3) in work which determines the way the maximum pressure is reduced by the distance travelled away from the point of explosion. In Figure 6 this relationship has been presented.

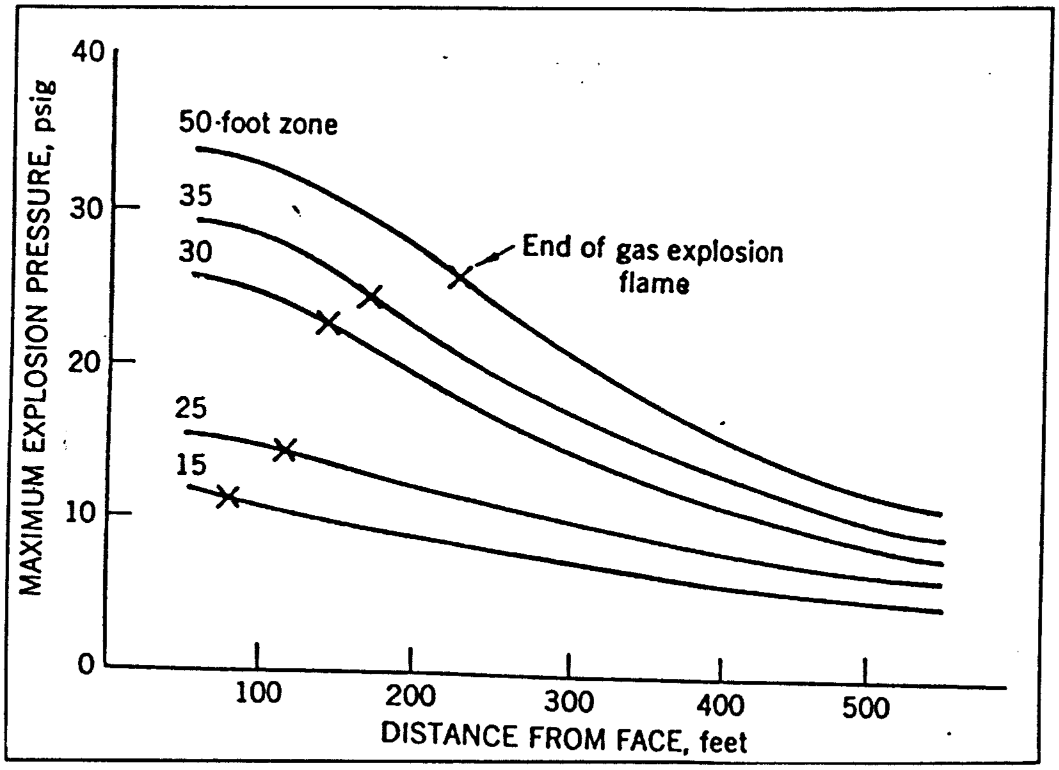

Figure 6 DISTANCE-PRESSURE GRAPH SHOWING THE PRESSURE DECAY OVER DISTANCE

### 2.3.6 Effects of an explosion in a coal mine

In the underground environment explosions are more complex than those measured in test situations using commercial explosions or a controlled environment. Firstly, although the charge mass is small because of the density of methane, its physical size is usually fairly large and its volume increases significantly during and before the final completion of the explosion. Secondly the explosion is contained within the tunnels, thereby causing a "gunbarrel" effect where the still igniting gases are pushed down the tunnel caused by the effect of the pressure wave being reflected from the walls.

The matter is exacerbated when an coal dust explosion occurs. Firstly the charge mass is now increased due to the coal dust acting as fuel, and, secondly, the explosive is actually caused by the action of the mechanical action of the gases (the coal dust is being physically lifted into the air). Instead of the explosive being depleted during the chemical reaction, it is being supplemented all the time as the explosion progresses, which leads to the phenomena of the peak pressure actually increasing with the distance that the explosion travels (see Figure 4.) This will continue until the fuel or oxygen is depleted, after which the explosion will reduce.

These characteristics of explosions in coal mines could have led Cybulski(10) to note that even though much is known about explosions in coal mines, it is almost impossible to predict their intensity and scope from the fuel and situation geometry.

To give an indication of the severity and extent of explosions, as influenced by the determining factors, Table 2 presents results obtained from major test centres in the world.

Information on the effects of coal mine explosions on humans and structures are usually in a less scientific form and difficult to use. The main reason for this is that when an explosion occurs it is difficult to quantify the strength of the explosion except through its results. As the situation just before the explosion took place also has to be determined, real quantification of a cause and effect relationship has little value. To obtain usable information, a comparison will have to be drawn from commercial or military explosion experience, where significant amounts of research have been done.

Table 2 PRESSURES OBTAINED WITH VARIOUS CONDITIONS IN VARIOUS ESTABLISHMENTS

| Test Institution/ (source*) | Test Conditions and Type of Explosion | Static Over-pressure in kPa | Distance from Source |
|---|---|---|---|
| Tremonia(14) | Tests with a coal dust zone 50 % of length containing 80 % inert materials. | 25.8<br>17.1 | At source<br>200 m |
|  | Tests with a coal dust zone 50 % of length containing 80 % inert materials. | 28.8<br>17.2 | At source<br>200 m |
| Buxton(15) | Coal dust explosions, dust on floor containing 50 % inert materials | 49.4 | 94 m |
|  | Coal dust explosion with dust on floor containing 10 % inert materials. | 132.6 | 94 m |
|  | Coal dust explosion with dust on floor and shelves containing 50 % inert mats. | 184.5 | 94 |
| GP Badenhorst (16) | 24 $m^3$ methane | 56 | - |
|  | 36 $m^3$ methane | 64 | - |
|  | 40 $m^3$ methane | 72 | - |
|  | 36 $m^3$ methane and 20 m coal dust | 100 |  |
|  | 36 $m^3$ methane and 30 m coal dust | 150 |  |
|  | 36 $m^3$ methane and 50 m coal dust | 210 |  |

Table 2 (Continued)

| Test Institution/ (source*) | Test Conditions and Type of Explosion | Static Over-pressure in kPa | Distance from Source |
|---|---|---|---|
| Lake Lynne(3) | 50 m$^3$ Methane @ 9,5 % | 238 | 15 m |
| | 43 m$^3$ Methane @ 9,5 % | 168 | 15 m |
| | 35 m$^3$ Methane @ 10,5 % | 112 | 15 m |
| Lake Lynne(17) | Weak explosion with coal dust | 35 | - |
| | Moderate explosion with coal dust | 105 | - |
| | Violent explosion with coal dust | 288 | - |
| | Coal dust/methane detonation piling | >700 | - |
| Lake Lynne(19) | Normally expected explosions without excessive build-up of coal dust*2 | 140 | 60 m |
| Barbara(10) | Violent explosion weak initiator-similar to what could happen in coal mine. | 57<br>130<br>287 | 200 m<br>160 m<br>source |
| | Steady propagation of coal dust in road | 200 | 200 m |

*2 Standard test conditions used for testing explosion proof bulkhead constructions.

## 3 THE EFFECT OF EXPLOSIONS IN THE UNDERGROUND ENVIRONMENT

In assessing the impact of explosions in the underground environment only two aspects will be considered, the effect on humans and structures.

Although this study was involved with the design requirements of refuge bays and refuge bay bulkheads, it is also necessary to determine the effects on human beings. It would be senseless to erect structures underground which could withstand the effects of high intensity explosions when these same explosions would already have caused the death of all those that the structure was intended to protect. In determining the upper range of forces that humans can withstand, a good idea of the practical strength requirement for refuge bay structures is obtained.

### 3.1 The Effect on Human Beings

Lees(20) identifies the following factors that cause injuries and fatalities in people subjected to the effects of an explosion.

1) Heat radiation or direct burns.
2) Blast effects.
3) Combustion products.

The heat radiation threshold is set(21) at 4,7 kW/m$^2$ for a period of no more than 30 seconds as burn injuries could occur above these levels of heat and time of exposure.

The biological effects of blast are customarily dived into:

1 Primary - due to variation in local pressure.

Typically the damage caused by blasts is in the form of lesions at or near the interface between tissues of different densities. Air-containing organs are especially affected .

The largest number of injuries or fatalities from blast effects are caused either by the direct blast or the complex secondary waveforms causing accelerations on organ walls in the thoracic region. The lungs are the most susceptible to such damage(22).

2 Secondary - Associated with the impact of debris energized by blast, shock, overpressure, blast winds and gravity.

Secondary missiles can cause a variety of injuries to the body including lacerations, contusions, penetrating wounds and fractures. These injuries depend on the mass, profile velocity and areas of the body, as well as the objects involved.

3 Tertiary- comprising injuries from gross body displacement (translation)

This is mainly due to the body being moved through space and the resultant decelerations encountered when impacting with another body or object.

4 Miscellaneous or indirect examples.

Thermal injuries resulting from fires initiated by hot gases or damage to structures and material.

In the chemical industry gas explosions very similar to methane explosions can occur. The exception being that they are mainly unconfined, so that the main cause of death, when a vapour cloud explodes, is mainly due to the effects of flame inhalation(23).

The extent of the flame radius is similar to the 70 kPa overpressure radius (around the source of the explosion). As the probability of surviving the flame is much lower than the blast effects, the danger threshold is taken to be 70 kPa, rather than the higher values that would be obtained if just the blast and direct heat effects were considered.

The results for blast effects as determined by Williams[42] is presented in the following table.

Table 3 TENTATIVE CRITERIA FOR PRIMARY BLAST EFFECTS

| Critical Event[42] | Related Max Pressure psi (kPa) |
|---|---|
| Felt as a sudden blow | 2 (14) |
| Eardrum failure | 5 (35) |
| Person knocked off feet | 6 (42) |
| Lung damage threshold | 15 (105) |
| Lethality: | |
| threshold | 30-42 (210-294) |
| 50 % | 42-57 (294-399) |
| 95-100 | 50-90 (350-630) |

In quoting Glasstone[24] Lees sets out the following relationships between the explosion characteristics and the probability of injury.

Table 4 LETHAL POTENTIAL OF A RELATIVELY FAST EXPLOSION WITH A POSITIVE PHASE OF DURATION 400 ms

| Probability of Fatality in % | Peak Overpressure in kPa |
|---|---|
| 1 (Threshold) | 245-315 |
| 50 | 315-385 |
| 99 | 385-455 |

Table 5 RANGE FOR FASTER EXPLOSIONS 1-20 ms POSITIVE PHASE DURATION

| Probability of Fatality in % | Peak Overpressure in kPa |
|---|---|
| 1 (Threshold) | 100 |
| 10 | 120 |
| 50 | 140 |
| 90 | 175 |
| 99 | 200 |

Table 6 PROBABILITY FOR THE EARDRUM RUPTURE, THE MAIN NON-LETHAL INJURY FROM DIRECT BLAST EFFECTS

| Probability of Eardrum Rupture in % | Peak Overpressure in kPa |
|---|---|
| 1 (Threshold) | 16,5 |
| 10 | 19,3 |
| 50 | 43,5 |
| 90 | 84,0 |

Table 7 PROBABILITIES FOR INJURY FROM A STANDARD MISSILE PROJECTED BY THE BLAST. (10 gm missile with a density of 2,65 gm/cm$^3$, glass.)

| Injury | Peak Overpressure in kPa | Impact Velocity in m/s |
|---|---|---|
| Skin laceration: | | |
| Threshold | 7-14 | 15 |
| Serious wound: | | |
| Threshold | 14-21 | 30 |
| 50 % Prob | 28-35 | 55 |
| 100 % Prob | 49-56 | 90 |

In assessing the effects on tunnel occupants, Considine(25) puts the lethality range of people being killed by blast damage between 100 kPa (1 % of fatality) and 200 kPa (almost 100 % of fatality).

The longer the period of the pressure the greater the possibility of damage. A pressure of 800 kPa acting for 5 m/s would have the same effect on a human as a pressure of 425 kPa for a period of 20 m/s.

Table 8 TENTATIVE CRITERIA FOR TERTIARY BLAST EFFECTS ON IMPACT AGAINST A HARD FLAT SURFACE(26)

| Effect | Impact Velocity m/s |
|---|---|
| **Body** | |
| Mostly safe | 3,0 |
| Lethality threshold | 6,0 |
| Lethality 50 % | 7,8 |
| Lethality near 100 % | 9,0 |
| **Skull fracture** | |
| Mostly safe | 3,0 |
| Threshold | 3,9 |
| Lethality 50 % | 5,4 |
| Lethality near 100 % | 6,9 |

The above table assumes a travel of approximately 3 m. A longer duration blast, however, can accelerate a body for significantly further distances. Stapczynski(27) calculated that for a typical adult weighting 75 kg a peak pressure of 105 kPa from an explosion can produce an instantaneous acceleration of about 135 $m/s^2$ or approximately 14 gravities. Whilst in the case of short duration blast the accelerations might only last milliseconds, and, therefore, the ultimate velocity reached by a victim might be very low, longer duration blasts of lower pressure could impart greater movement to a body.

## 3.2 The Effect on Structures

The majority of work on the effects of explosions on structure was done by the military. In determining the effect, the wave is characterized by the overpressure. The effects on civilian type structures are given below. Very little information with regard to mine structures, except for the testing of seals, could be found.

Table 9 EFFECTS OF PRESSURE ON COMMON STRUCTURES(28)

| Pressure kPa | (PSI) | Effects |
|---|---|---|
| 0,14 | (0,02) | Loud Noise (137dB) |
| 0,21 | (0,03) | Occasional Glass Breakage |
| 0,28 | (0,04) | Loud Noise (143 dB) |
| 0,85 | (0,15) | Typical Glass failure |
| 7,0 | (1,00) | Partial demolition of house |
| 14,0 | (2,00) | Partial collapse of walls of |
| 21,0 | (3,00) | house |
| 35,0 | (5,00) | Concrete block walls shatter |
| | | Utility poles snap |
| 70,0 | (10,0) | Eardrums rupture rarely |
| 85,0 | (15,0) | Building totally destroyed |
| 2100 | (300) | Fifty percent eardrum rupture |
| >2100 | (>300) | Crater formation |
| | | Destruction of human body |

Structures subjected to the explosions will react differently to the blast of an gaseous explosion than when subjected to effects of High Explosives. The reason being the absence of the stress wave caused by the High Explosive. Elasto-Plastic deformation of the structure will be caused by the "secondary effect" of blast pressure, which has a lower level than that of High Explosions, but is much longer in duration than the stress waves(29).

The effects presented in Table 10 have been noted by researchers(30) studying the effects of military explosives on animals and structures.

Table 10 EFFECTS OF MILITARY EXPLOSION BLAST WAVES

| Peak Over Pressure level (kPa) | Effects |
|---|---|
| 20-40 | TOL*. Small animals in the open |
| >55 | TOL. 50 -pound animal in the open |
| 190 | TOL. Small animals in burrows |
| 320 | TOL. Larger animals in burrows |
| 45 | Lung damage to small animals in burrows |
| 85 | Lung damage to large animals in burrows |
| 20-35 | Ear damage to animals in the open |

| Peak Over Pressure level (kPa) | Effects |
|---|---|
| 35-70 | Injury to birds in flight |
| 35-70 | Toppling of small leaved trees |
| 20 | Damage to tree branches |
| 7 | Damage to building walls/roofs |
| 3,5 | Skin penetration from broken windows |
| 1,4 | Flight hazard to light aircraft |
| 0,20 | Window breakage at low incidence |
| 0,20 | Impulsive noise limit 140 dB |
| 2 | Tinnitus or ringing of ears |

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* Threshold of lethality (TOL).

# 4 REFUGE BAYS IN SOUTH AFRICAN COLLIERIES

## 4.1 Requirements of Refuge Bays

The establishment, maintenance and function of refuge bays are defined in the Minerals Act and Regulations:

"refuge bay shall mean a place in the underground workings which is inaccessible to air containing noxious smoke, fumes or gases and which shall be having regard to the maximum number of persons likely to be present in the area served by the refuge bay-

(i) Equipped with means for the supply of respirable air unless conditions are such that this is not required,

(ii) equipped with a sufficient supply of potable water,

(iii) equipped with first aid equipment,

(iv) of sufficient size to accommodate that number of persons,

(v) equipped with a means of communicating verbally to surface,

(vi) situated where possible in an area free of combustible material."

From the above it can be seen that the main purpose of the refuge bay is to keep workers safe from the effects of poisonous gases and fumes, while the structural requirements of the refuge bay are, thus, that it should be able to stop any ingress of such gases and fumes into bay after an explosion. Although not defined as such in the act it can be assumed that damage to the structure should be contained to the limit that there should not be leaks of sufficient size and number that would allow an inflow of gases into the refuge chamber itself. It, therefore, stands to reason that the construction should also be such that the support systems like water, air and communications should still be available and working after the explosion.

While the refuge bay is not intended to protect workers from the actual explosion, if the refuge bay does not function after the explosion it cannot protect the workers Thus, the question that really needs to be answered is how strong should the design of a refuge bay be in order to ensure the protection of workers in the aftermath of an explosion The stronger the explosion, the higher the strength requirements, but lesser the chance that a worker would be alive to use the bay. Therefore, the practical strength requirements for a refuge bay should not be significantly higher than the pressure at which the probability of workers surviving the explosion and using the bay is minimal The criteria that is used by the majority of countries is the static overpressure generated by the explosive blast

There is, however, another use of the refuge bay that is not influenced by the effect of an explosion, that as gathering place for workers that have been trapped for other reasons. Although the law has not identified this use, the refuge bay should also be seen as a place where the workers can gather in safety until they can be rescued. In this case the whole issue of life sustaining and communication systems becomes more important than the isolation from poisonous gases. Provision for a place of refuge in the case of flooding has not been made for in the law. This might be a shortcoming that needs to be addressed.

## 4.2 Methods Presently used in Collieries

Information, with regard to refuge bays in collieries, was obtained from the codes of practice as kept in the regional directors offices. These could be considered as the specifications to which mines would erect their refuge bays. Further information was gained from discussions with relevant staff, as well as other parties involved with the rescue of workers in the aftermath of a fire or explosion.

Appendix A presents a table containing a summary description of the construction types, siting, signalling and ventilation requirements for the majority of larger collieries.

### Siting of refuge bays

The majority of mines specify the proximity of the refuge bay to be in the order of a kilometre from the working face, with some mines reducing this limit to 700 m and other extending this up to over two kilometres. This would mean that in those circumstance where the furthest permissible distance is used, there is a very low probability that workers would reach safety. Although some of the mines specify times within which the refuge bay should be reached (less than 30 minutes), the distances specified are not compatible with the specified maximum distances, if conditions after an explosion are considered.

### Construction of refuge bays

Refuge bays are constructed by two major methods. Firstly a bay or cubby is cut into a pillar forming a blind road. This could be between pillars, or into a pillar itself. The second method is to build two stoppings, or bulkheads, between pillars to form a chamber.

Only one mine specified the thickness of the wall. Apart from this there is no indication of how the mines define the strength requirements.

On the whole, specifications for the finishing of the walls, sealing the bulkhead and safeguarding the pillar walls against spalling, are extensive and deemed to be sufficient.

### Supplying of air

The majority of mines provide fresh air to the refuge bay by forcing air down a borehole by means of a fan or blower on surface. It appears that no provision has been made in case of the possibility of an pressure wave moving up the borehole and destroying the fan's operation. The fans are usually not coupled to the boreholes until an incident necessitates it.

There is a discernable trend in the codes of practice that the more detailed the design of the air supply, the longer the distance between the refuge bays.

Although one mine has made provision for routing air between seams, the possibility of multi-seam workings might pose a problem in the supply of air when surface boreholes are being used. This is also borne out by Durant(45).

### Design advantages

A large amount of attention has been given to the design of the surface installation to supply air.

In one of the codes, use was made of mesh suspended across the roadway to direct workers to the refuge bay. This is a good concept as such a system would not only have a high probability of withstanding the force of an explosion, but would, in circumstance of low visibility, stop workers from going past the refuge bay.

### Identified shortcomings

On the whole no attention is given to ensuring that the placement of signs, lights or directing structures is done in such a manner that they could survive the force of an explosion. These signs, while enabling the worker to become familiar with the placement of the refuge bay under normal conditions, would not assist him in finding the bay, if destroyed or moved by the force of an explosion.

Very little evidence is found in the codes of how the bulkheads, walls or doors are to be designed. It is only pointed out that they should be robust or able to withstand an explosion. Nowhere are actual design requirements laid down, and only in isolated cases are specified thicknesses presented.

It is evident from discussions held with various industry members that keeping fully equipped refuge bays at the required intervals is becoming a problem. The main problem is the access and work on surface in providing the boreholes to supply the fresh air.

Nowhere in the codes of practice is mention made of the overlapping of refuge bays or the procedure of moving refuge bays.

In the majority of cases use is made of methods employing vision to direct or identify the location of the refuge bay. Work done by Van Rensburg(34), as well as post explosion experience, has highlighted the lack of visibility even in the case of fires. This would mean that these signs, although well placed and installed, would have very little effect in getting the worker to the refuge bay.

It is the author's opinion that all the refuge bays detailed in the Codes of Practice studied would be more than adequate to cope with the results, or the aftermath, of an non explosive event that has led to the creation of poisonous fumes and gases. However, when bad visibility and the effects of an explosion have to be coped with, it is doubtful if the specifications will guarantee worker safety.

## 5 ASPECTS IN THE DESIGN OF REFUGE BAYS

In designing the refuge bay the first consideration must be that the design conform to the requirements of the law.

The second consideration is that it should have a high probability of fulfilling the function it was intended for, in conjunction with self rescuers, as part of the rescue strategy. It should be reachable during the period after an incident occurs and while the worker is dependant on a self rescuer to sustain life. The refuge bay should further be in such a condition that when a worker reaches the bay, after an incident, it should afford the worker the protection it was intended to give.

Another use of the refuge bay is that it can become a place where the workers can be kept safe for longer periods in the events other than fires or explosions. In the case of serious roof falls, for example, it might take longer for the mine to rescue the workers from the underground environment.

Another aspect to consider, regarding refuge bay requirements and the rescue strategy as a whole, is the possibility of second explosions. At present the whole Queensland(31) rescue strategy is being reviewed to take account of the possibility of a second explosion after the first has occurred. This has led to the decision that rescue brigadesmen will only enter the mine after confirmation that a second explosion cannot occur. This implies that rescuers will not always be able to reach the refuge bay in the period that is presently given, extending the time period for help reaching a refuge bay to more than a day. In such an event it would be necessary to have a refuge bay that ensures a longer term air supply. However the possibility of a second explosion is regarded as highly unlikely in South Africa(32) and longer term usage of a refuge bay would be more dependant on accessibility factors than the unwillingness of management or the DME to allow the rescue brigadesmen underground. In any case the use of a large-diameter surface borehole would be considered under these circumstances.

McCracken(35) quotes the possibility of explosions being caused by the products of fires in the underground environment. This is usually prevented by the ventilation sweeping these gaseous products beyond the fire and the other products of the fire creating a barrier between the fire and the explosive mixtures. In the event of the ventilation stopping, or surges in airflow being experienced, the probability of an explosion could increase significantly. This might affect the presently held attitude of sending brigades men into a coal mine after an initial explosion or underground fire.

## 5.1 Placement of Refuge Bays

During an exercise to determine the distances that could be travelled by workers in the aftermath of an explosion, Van Rensburg, JP *et al*(34) found that due to problems with low/zero visibility the refuge bay should be placed within 500 m from the work areas. The exact distance requirements will, however, be influenced by the method used to assist workers to find the refuge bay.

It was recommended that less formal bays be considered, thereby allowing the escape distances to be shortened. These bays should, however, be accurately pinpointed on mine plans so that the surviving miners can be reached by boreholes.

Travelling roads should be regarded as the preferred escape routes and guidance should be provided right up to the door of the refuge bay, with unused entrances barricaded or guidance system provided to prevent accidental entry during escape conditions.

These local findings are well supported by the distance specifications as determined by Maser *et al*(8) who gives the following figures for placing the refuge bay.

> For a sixty minute movement period, the distance that can be travelled by workers has been identified to be:
>
> - below 0,76 m height the distance to shelter should be no more than 457 m
> - below 1,07 m height the distance to shelter should be no more than 760 m
> - below 1,52 m height the distance to shelter should be no more than 915 m
> - above 1,52 m height the distance to shelter should be no more than 1 220 m

Since initially following an incident there is a period of time required to think and orientate oneself and these figures have been based on a sixty minute self-rescuer, the distances can be more than halved to obtain the required distances for local self-rescuers, with a duration of thirty minutes.

## 5.2 Discussion of the Strength Requirements

The majority of work throughout the world into the strength characteristics of bulkheads has been in terms of seals. Although the forces that will ultimately impact on a seal might be different to that of a refuge bay bulkhead, and the severity might be higher, the method in which these seals were tested provides information of great value.

In both Europe and the UK, bulkheads are required to withstand pressures of up to 500 kPa, which is seen to be the upper limit of static pressure reached by an explosion of moderate strength(8,10).

The negative pressure that a wall would experience is determined to be in the order of less than 7 kPa. However work done by Westinghouse(8), and Nagy(17) indicates that provision should be made for the wall to withstand a negative static pressure of 35 kPa.

To destroy a structure it is necessary for the pressure not only to reach or exceed that which would be necessary to bring about static failure, but also for it to do it for long enough to carry the element forward sufficiently to obtain the critical deformation(40). With a gaseous explosion the time of the pressure wave is usually longer than with high explosives and, therefore, this critical displacement is usually achieved if the pressure is sufficient to enable failure.

Structures should thus be built strong enough to withstand the static loading or be physically of such size that displacement of the elements during the overpressure period does not cause critical failure of the structure. Efforts directed at restricting movement of the elements will also assist in maintaining the integrity of the structure.

Work to determine the strengths of buildings to withstand the effects of internal gas explosions(41), found that because walls have a natural frequency less than that of the rapidly changing pressure of the wave front, these changes would be almost completely absorbed by the mass inertia of the wall. To refer back to the conventional static basis, a formula was derived to give a uniform static loading on the wall.

Explosion load $P = 3 + P_v$ kN/m$^2$

Where $P_v$ is the recorded static pressure of the explosion (at the wall).

In the tests done at the Lake Lynne facility of the USBM in the USA evaluating various types of seals, Weiss, Greninger and others(4,5,6) specify the pressure that seals have to withstand, both for purposes of formulating revised regulations[7] and for the test purposes, as 20 pound per square inch (140 kPa). In testing these seals they were so constructed that they were placed in a cross-cut which means that the pressure pulse was obtained side-on to the main pressure wave. This meant that the seal was not subjected to the dynamic force of the explosion, but only to a standardized rise in static pressure which was presented head on to the seal. The pressure wave was obtained through the ignition of a 14 m long, 2 m high and 5,8 m wide volume of 10 % methane air mixture. To obtain increased pressures (25, 30 and + 35 psi or 180, 215 and +250 kPa), use was made of coal dust placed on shelves close to the roof.

This would lead to the conclusion that in the case of a methane explosion in a heading, without coal dust taking part, it would be highly improbable for pressures a distance away from the heading to exceed 140 kPa (20 psi).

Although local pressure increases can be expected due to reflection of waves off solid objects, there could also be a significant reduction due to the attenuation of the waves going around corners or through intersections.

It should be noted that to enable testing at even higher pressures the explosion wave had to be generated through the use of blasting powder.

In trying to determine what pressures should be accounted for when designing bulkheads, Maser(8), in determining the strength characteristics for reusable bulkheads, found that the only two sources for experimental data are the US Bureau of Mines and the European Community for Coal and Steel.

In quantifying the resistance of bulkheads to explosion forces Mitchell(42) notes that it is impossible to foretell what forces could be expected in the case of coal dust explosions. He notes that work done in the USBM's experimental mine have produced pressures ranging from 1 to 127 psig, and, in some cases, pressure piling caused even higher, but unrecordable pressures. In considering the pressures that bulkheads are subjected to, it must also be assumed that the area is stonedusted according to the requirements of the law. This would lead to a reduction of the wave, through attenuation, when the wave travels through the inertised area. This is what could have led him to conclude that at distances of greater than 200 feet (60 m) from the origin, and where the coal dust accumulations are not excessive and the incombustible contents within the legal requirements, the pressure will very seldom exceed 20 psig (140 kPa).

Other investigators(8) have found that for a side-on exposure a value of 20 psi (140 kPa) overpressure should be used, but for a head-on close or direct explosion, this value could be insufficient as pressure of up to 30 psi (210 kPa) have been measured.

The duration of the pulse of the wave is in the order of seconds or fractions of a second. As this duration is much longer than the response time of the structure, the structure will respond to the pressure pulse as if it were a step loading.

It is then further stated that research in the United States and in other countries indicate that bulkheads designed to withstand a given static load will have a considerable margin of safety should it be subjected to a greater dynamic load, for example, in a test conducted in the experimental mine a bulkhead designed to cater for a static load of 14 psig (100 kPa) withstood 27 explosions developing from 5 up to 50 psig (3,5 to 35 kPa).

Work done recently in Australia(35) to determine seal strength also confirm these previous findings.

Table 11 STRENGTH REQUIREMENTS FOR SEAL IN OTHER COUNTRIES AS SUMMARIZED BY MCCRACKEN[35]

| Country | To Withstand a Overpressure of: |
|---|---|
| Germany | 525 kPa |
| United Kingdom | 350 kPa |
| United States | 140 kPa (60 m stonedust inbye) |
| Australia (proposed) | |
| Normal conditions | 140 kPa (100 m stonedust inbye) |
| Extreme conditions* | 345 kPa(36) |

* These extreme conditions are specified to be "When persons are to remain underground whilst an explosive atmosphere exists in a sealed area and the possibility of spontaneous combustion, incendive spark or some other ignition source could exist". This means that there is a high potential for a contained explosion to occur behind the seal.

Latterday work in Australia into the design of normal seals favour the standard adopted by the United States, but have, added a precaution of heavy stonedusting for at least 100 m inbye from the seal. The purpose of this is to ensure that there are sufficient suppressants to prevent any coal dust explosion and to dampen the methane explosion.

## 5.3 Proposed Strength Requirements

In proposing a strength requirement for a refuge bay bulkhead the following factors were assumed or taken into account.

1) The refuge bay would not be built closer than 100 m to the face.

2) As the most severe pressures are experienced at the face, any other point of ignition would lead to lower or equivalent pressures at the refuge bay.

3) In the light of legislation and industry awareness the probability of a coal dust explosion is now very low. Provision is made for the more likely occurrence of a methane explosion.

4) There is little purpose in designing a refuge bay if the explosion has been so violent that there is an insignificant chance of survivors. In bord and pillar workings a gas explosion is virtually uncontained. Since the maximum pressure that can be reached in a totally uncontained gas explosion is 112 kPa, a good estimate of the maximum pressure in bord and pillar workings would be 140 kPa.

5) At 140 kPa overpressure the effects on people working in the section would be:

   (i) for very fast explosions about a 50 % fatality rate, while for slower explosions this could fall to less than 1 %
   (ii) almost certain probability of eardrum rupture
   (iii) some workers would have suffered lung damage
   (iv) probability that some workers would have been struck by missiles.

   However, there is a strong probability that up to 50 % of the workforce would still be alive following the explosion.

6) At overpressures of 140 kPa most normal building walls and stoppings would have been destroyed and concrete walls or brick walls less than 300 mm in thickness would be seriously damaged.

It is therefore proposed that the strength requirements that a refuge bay bulkhead should withstand is an overpressure of 140 kPa (1 Bar) and a pulse period of 0,25 ms. By using these specifications to design the refuge bay, the following criteria or implications can be accepted.

- The requirements will be equivalent to requirements for structures in the USA and Australia.

- Designs for seals and bulkheads produced by the USBM can be used with safety.

- A deflagration type of methane explosion will be adequately catered for.

- The bulkhead would be capable of withstanding pressure from a methane explosion in an open volume.

- The bulkhead would not cope with a contained methane explosion, methane detonation, or a violent coal dust explosion.

- It would cope with a moderate explosion, with some participation from coal dust.

Thickness of the bulkhead

Initial work (1930) done by the USBM(8) using 350 kPa pressures (obtained through the use blasting powder) indicated the following relationship between thickness and width, if the bulkhead is to survive.

Thickness(T) >= Width/10

Rib Recess(R) >=Width/10

For soft coals this relationship was changed to:

Thickness(T) >= Width/8

Rib Recess(R) >=Width/5

In all cases the bulkhead thickness had to exceed 300 mm.

In later work (1970-1973)(37) tests were also conducted to an upper pressure limit of 350 kPa from which the following specifications were derived. These are presented in Table 12.

Table 12 USBM RECOMMENDED STANDARDS FOR ACCEPTABLE BULKHEADS FOR NORMAL MINING SITUATIONS

| Type | Minimum Thickness |
|---|---|
| Concrete | t/4 |
| Concrete reinforced | t/10 |
| Concrete block | 400 mm |
| Fly ash | t/4 |
| Gypsum | t/4 |
| Rock, grouted | W+H/2 |
| Rock, packed | 2t |
| Sands bags | WH/3 |

Where t = W or H, whichever is the greatest.
W = Average width of the passageway, and
H = Average height of roadway, plus the depth of recess for concrete block and reinforced -concrete bulkheads.

In the above table the following principles have been used.

- Sandbags are usually jute bags filled with loose sand and stacked in the roadway.

- Concrete, both reinforced and plain, consisting of sand, cement and gravel, with a compressive strength of approximately 21 MPa and tensile strength of 2,45 MPa.
- Concrete blocks are prefabricated blocks that have been used with cement mortar to build either a single or triple layer (course) wall.
- Fly-ash and gypsum are mixtures with flexural strength varying from 0,7 to 4,2 MPa.

Holding(38) in setting out means to design mine seals to withstand the effects of coal dust explosions uses the following formula to determine the thickness of the seal:

$$\text{Thickness} = \frac{P_o \times A_m}{2(w + h) \times f_s}$$

Where $P_o$ = maximum explosion pressure in MPa
$A_m$ = cross sectional area of stopping in m$^2$
$w$ = width of stopping
$h$ = height of stopping
$f_s$ = shear strength of concrete or coal, whichever is the lesser.
$f_s$ for concrete is taken to be 15 to 25 MPa
$f_s$ for coal is taken to be 5 MPa

It is calculated that to withstand a coal dust explosion with a pressure of 700 kPa and using a safety factor of 3, the resultant seal thickness in a roadway with dimensions 6 m x 3 m would be a 9,6 m long plug of concrete. Such constructions would by their very nature be impractical for a refuge bay bulkhead.

The formula can, however, be transposed to give the relationship between the thickness of the seal and the area of the seal as follows:

$$\text{Thickness} = A_m \left( \frac{P_o}{2(w + h) \times f_s} \right)$$

## 5.4 Design Aspects to Increase the Strength of Refuge Bay Bulkheads

As it has been noted that there are high local reflected pressures at short distances down the cross-cut, it would be desirable to build a bulkhead flush against the crosscut to prevent these reflections from occurring.

In studying the response of structures subjected to severe dynamic loads it was found that materials with fibres imbedded reacted much better to withstanding the effects of pressure pulses.

Based on work done to develop explosion proof structures(39) the following principles have been identified to be used in increasing the strength of bulkhead walls.

Energy Absorption

When using this principle the wall or bulkhead absorbs the shock/overpressure or temperature, but has enough strength to maintain its integrity and stability, as well as the ability to seal out the atmosphere. This can be achieved through various methods.

Energy Dissipation

To dissipate the energy a sacrificial wall element may be employed to absorb energy and, in so doing, dissipate the energy before reaching the refuge-bay wall. Loose rock or debris may be placed in a gabion type structure in front of the wall to dissipate energy.

Energy Deflection

Provide a sacrificial chamber or structure to channel the shockwave away from the refuge-bay structure.

The walls can be made more ductile by affixing reinforcing bars on the inside and spraycoating them to the walls with a joining and covering medium(44).

There are distinct advantages in increasing the tensile strength of concrete, either cast or sprayed, by the addition of fibres. The fibres, which can consist of materials ranging from polyethylene, Kevlar, glass, carbon, etc substantially increases the tensile strength of the material without the use of reinforcing steel(43). Research currently being conducted at the Lake Lynne facility by the Australian company, Tecrete, makes use of these principles.

## 5.5 Practical Considerations with regard to the Establishment of Refuge Bays

### 5.5.1 Practical considerations in the placement of refuge bays

In deciding the placement of the refuge bay the first criteria is that it should be within reach of the workers it serves. From local and overseas work this distance lies in the order of less than six hundred metres.

To comply with these requirements it would be necessary for the mine to erect a refuge bay at time intervals ranging between 36 shifts for a very low seam (0,75 m) to about 185 shifts for a high seam (5,0 m). The time to erect such a refuge bay would also be commensurate with the height of the seam being mined due to the increased thickness requirements of the bulkheads for higher seams. (Figure 7 represents a schematic graph indicating times between the completion of a refuge bay for different seam heights.)

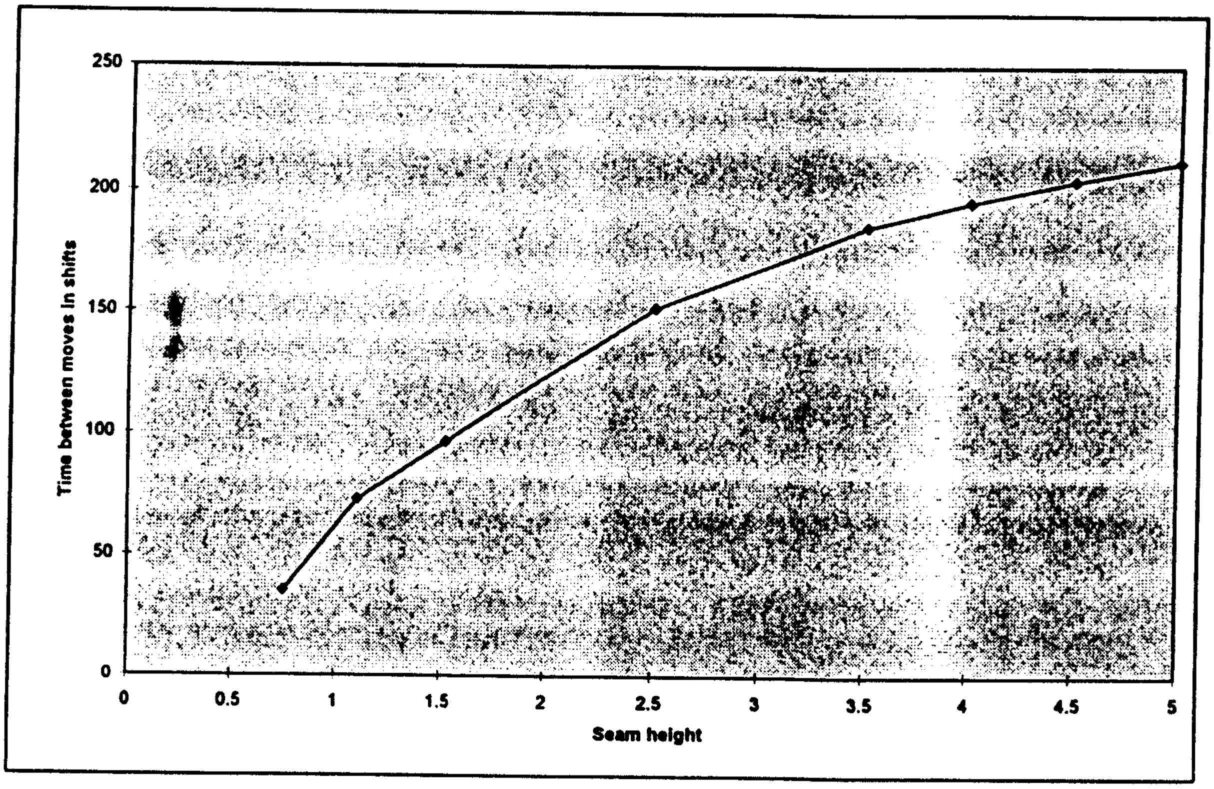

Figure 7 TIMES BETWEEN ERECTION OF REFUGE BAYS, MAINTAINING THE REQUIRED DISTANCE, FOR DIFFERING SEAM HEIGHTS

To comply with the above, and considering the number of sections in collieries, it can safely be assumed that mines would require a full-time team busy building bays.

Ventilation requirements further exacerbate the matter. A borehole from the surface to supply air over the longer term to trapped workers means that for every advance of 600 m a hole will have to be drilled from surface, as well moving the surface installation to the new position. If the property belongs to the mine the effects of such work on surface might not cause problems. However, if the surface belongs to a private owner problems could occur if these types of activity are conducted.

It should also be remembered that when these holes have completed their function they will need to be sealed off.

All in all it would seem that compliance with the distance requirement would be onerous and costly for the mines.

The solution, as indicated by these practical considerations, is therefore an alternative arrangement.

### 5.5.2 Practical consideration with regard to strength and design of refuge bays

If the shelter is chosen to be close to the working place then economics will dictate that it be of a lightweight, portable and reusable nature. If these shelters are to be a permanent structure in or around the main haulage routes, then it might be more economical to use monolithoic structures[(8)].

The building of the bulkhead at speed, as in the case of building seals to confine a fire, need not be considered.

Use must be made of the coal surroundings, as it would have a comparable or higher strength than concrete and exists in bulk. The coal need also not be sealed.

Where cubbies or chambers are cut into coal the effect of a pressure differential over walls between mine passage ways are also excluded.

Durant[(45)] notes the following aspects with regard to supply of air to refuge bays.

- Accepted practice for ventilation is by boreholes from surface or by piped compressed air from surface.
- Found that this process is difficult in deeper lying seams such as the mountainous areas of Natal.
- Proposes the use of compressed air cylinders. Provision is made for a maximum of 9 hours.

Work done by Kielblock *et al*[(46)] has shown that without ventilation the CO levels in a refuge bay, due to contamination from door openings and leaking to the inside of the bay, could reach the TLV within 8,5 hours. This is when there is no supply of air to the bay and the outside level is in the order of 1,5 % carbon monoxide. In the event of this level dropping to 0,25 %, the time required to reach the TLV is extended to 72 hours. A conservative estimate of life support in a refuge bay without air is taken to be in the order of 5-8 hours. Compare this to the Gloria fire experience where no explosive forces were present and the time required to reach the miners with a rescue drill was about 21 hours and to get them out about 46 hours[(47)].

This means that for bays where workers are to stay for longer periods there must be a method to flush out the air or create a positive pressure inside the bay. The use of oxygen might not be sufficient to ensure that the level of CO and $CO_2$ caused by exhaled breath does not reach dangerous limits.

This also emphasizes the importance of sealing the door to ensure that no poisonous gases enter the bay during, or shortly after the incident, or when there are workers inside after the incident.

# 6 CONCLUSIONS

## 6.1 Characteristics of Explosions

From the literature and worldwide experience it is evident that there is not such a thing as a typical explosion as the pressure rise, duration and other characteristics can be influenced by many factors.

Using the standards as adopted by the United States as well as Australia, i.e. an explosion with an overpressure of 140 kPa, the strength requirements of the refuge bay bulkhead can be specified and these would cater for a very large proportion of the possible incidences.

This level of strength is deemed to be sufficient to cater for explosions that could still occur even if the preventative steps to prevent coal dust explosions are fully operational. To ensure that there is no risk of a coal dust explosion effects close to the bays, stonedust should be kept to the 80 % level of inert materials for a perimeter of at least two pillars around the bulkhead (based on US and Australian criteria.).

## 6.2 Design Criteria for Bulkheads

There are no universal methods that can be readily applied to the design of bulkheads without testing them in a facility where the explosive forces can be simulated.

Use of the standards as proposed for the USA, and as contained in the appendices of this report, will, however, form a good basis on which mines and structural designers can produce designs specific to their local conditions of seam height, roadway widths, etc.

Acceptance of this overpressure standard will allow the use of overseas technology to design bulkheads without the industry incurring the costs of testing them.

It is doubtful if mines will be able to construct refuge bays much closer than a hundred metres from the face which means that when the explosion is only an ignition of methane the pressure levels should not exceed 140 kPa.

Designs for local conditions should be directed at achieving the required strength while using readily available and cost effective building materials and techniques.

## 6.3 Present Practice with Regard to the Construction of Refuge Bays

The present practice of constructing refuge bays conform to the law. It is however evident that the practice does not yet encompass the practicalities of reaching the refuge bays in the available time. On the whole the distance between the working face and the refuge bay would not be travelled in the event of bad visibility or disorientation of the workers.

On the whole the infrastructure of the bays, as presented in the codes of practice is more than adequate.

The use of current methods to supply air by replacing the oxygen in the air without causing a positive pressure or diluting the CO and $CO_2$ in the chamber might lead to dangerous poisonous gas levels in the bay, as air permeates in.

## 6.4 Width to Height Ratios

There is no universal safe ratio between the width and height of bulkheads as this ratio is dependant on the basic type of construction and the materials used. The ratios as presented have been tested and found to be relevant for the particular design application. New designs will, however, have to be determined either empirically by testing or by comprehensive analysis.

## 6.5 General

The issue of keeping the refuge bay within reachable distance from the face is seen to be one of the most important aspects identified in this study although it was not part of the original scope. Attention will have to be given to address this problem.

# 7 RECOMMENDATIONS

The following recommendations have been indicated as a result of this study.

A standard should be decided on for the design of refuge bay bulkheads. It is recommended that an overpressure of 140 kPa be used as the most appropriate level of explosion to be protected against.

A method of testing bulkheads for strength and leakage characteristics will have to be established.

In testing these bulkheads use must be made of the same type of construction methods which is used underground. The way that a bulkhead is constructed in practice will have a greater effect on its strength than the way that the bulkhead is designed. It would be of benefit if the actual staff that is going to build these bulkhead do the construction in the test facility.

Such a facility would allow new, innovative and locally appropriate designs to be tested. It further foreseen that the establishment of such a facility could be relatively cheap as the only parameters that would have to simulated would be the explosive pulse in terms of overpressure and time. It is quite conceivable that such a facility could be powered by commercial types of explosion that have been customized to give the right results rather than use methane and coal dust to obtained the explosive forces.

Methods should be found that will enable the ease of building and equipping the refuge bay rather than focus on the cost of labour and materials. If the refuge bay could be built at a significantly faster rate it could be kept close to the working face where it would have the greatest lifesaving potential.

To address the problem of maintaining a close distance to the workers the use of intermediate havens and alternative rescue strategies will have to be looked at. This would entail work into the following aspects.

(i) The concept of intermediate havens closer to the section and refuge bays at more convenient and cost effective locations should be investigated.

(ii) The specifications for the signs and the devices that lead workers to the refuge bay must such that they must have a high probability of surviving the effects of an explosion.

(iii) Considerations should be given to the design of refuge bays that are easy to build and can withstand the effects of an explosion by maintaining the sealing against the ingress of toxic gases rather staying structurally sound.

(iv) The design of methods that will minimize the ingress of poisonous gases during the explosive overpressure.

(v) The use of methods to supply air in a safe haven as well as methods to keep equipment safe from explosion blast in such a safe haven.

## 8 ACKNOWLEDGEMENT

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## APPENDIX A

## SUMMARY OF REFUGE BAY SPECIFICATIONS FOR A GROUP OF SELECTED COLLIERIES

The summary specifications as contained in the tables have been obtained from the codes of practice for refuge bays as obtained from the relevant area directors' offices of the Department of Minerals and Energy.

| Colliery | Type of construction | Site | Refuge Bay indicators | Signaling devices | Borehole to Surface | Ventilation Arrangements |
|---|---|---|---|---|---|---|
| Colliery 1 | Cut into solid coal with a single entry which shall be away from the most probable direction of an explosion and bricked off with two 0 4 m thick stopings equipped with steel man doors | Spaced at intervals not exceeding 1350 m from the downcast shaft or working section Not positioned between an intake airway and return airway | 12 Volt light illuminating a refuge bay sign equipped with a 12 Volt orange flashing beacon displayed at the entrance to refuge bay | 12 Volt siren at the entrance and on the fresh air side of the stoping isolating the return airway from the intake and positioned in the traveling route to the bay | 250 mm diameter Provided with grouted 200 mm casing pipe protruding approximately 1 m above ground level | 12 Volt fan coupled to surface borehole |
| | | | If the refuge bay is situated in a return airway the stoping isolating the return airway from the intake and situated in the route to the refuge bay is to equipped with an airlock and a 12 Volt indicator light in the fresh air side | Sirens to be able to be activated from inside the bay | 2 m2 x 100 mm thick concrete plinth cast around borehole on surface and protected by 2m x 2m x 2m high lockable expanded metal enclosure Site of borehole acessible to equipment and vehicles | Astron KB 55 petrol powered air blower available for each refuge bay To be kept in the mines Rescue Room |
| | | | 220 Volt Refuge bay signs installed at the turn-off points to the refuge bay Number of R/B to be painted inside and outside of bay | | Number of refuge bay to be painted on borehole enclosure | Emergency 12 Volt fans that can be operated from a 12 Volt car battery available in the Proto Room |
| Colliery 2 Mine 1 | | Distance to the refuge bay from the working section not to exceed 1325 m | | | | |
| Colliery 2 Mine 2 Seam 2 | | Distance to the refuge bay from the working section not to exceed between 700 and 800 m | | | | |
| Colliery 2 Mine 2 Seam 4 | | Distance to the refuge bay from the working section not to exceed between 750 and 1800 m | | | | |
| Colliery 2 Mine 2 Seam 5 | | Distance to the refuge bay from the working section not to exceed between 800 and 2750 m | | | | |
| Colliery 2 Mine 2 Seam 2 | | Distance to the refuge bay from the working section or main downcast shaft not to exceed 300 and 1280 | | | | |
| Colliery 2 Mine 3 Seam 4 | | Distance to the refuge bay from the working section between 530 and 730 m | | | | |
| Colliery 3 | Brick walls between two pillars No flammable materials to be used | In the intake airway next to the main traveling route at a distance not greater than 1500 apart and next to a return airway where the pressure differential across the walls will cause leakage to the return airway | Clearly visible reflective or illuminated "Refuge bay" symbolic displayed at the entrance Conveyor belt strip curtain leading from the furthest side of the conveyor adjacent to the refuge bay up to the refuge bay entrance | Flashing light and siren situated outside the Refuge bay interlinked with the borehole fan | Inside diameter not less than 150 mm | Borehole equipped with a battery driven suction fan in the refuge chamber Fan to start automatically when a trip switch mounted on the outside of the bay is activated by a percussion wave |
| | | | Flashing light and siren situated outside refuge bay interlinked with borehole fan | | | Portable blower fan on surface able to be coupled to the top of the borehole to be used as backup Adjustable regulator to be fitted to allow a positive flow of air from the R/C into the U/G atmosphere |

| Colliery | Type of construction | Site | Refuge Bay Indicators | Signaling devices | Borehole to Surface | Ventilation Arrangements |
|---|---|---|---|---|---|---|
| Colliery 4 | Fire resistant materials Double walls plastered on both side to provide effective sealing Must be capable of being sealed off or equipped with an alternative effective means to prevent the entry of noxious gases | Distance from any working section not to exceed 1200 m | International symbolic sign together with the number or name of the refuge bay in reflective lettering to be displayed at the entry | Automatic alarm connected to the emergency power source to be activated automatically during power failures | Cased, 208 mm diameter to surface Casing to be earthed on surface and underground Top borehole casing to be fitted with cap or permanent fitting for blower | Blower unit with all accessories ( 12 V back up power) |
| | | | Bright flashing warning light mounted outbye of the bay in the traveling road and one additional light in the belt road with battery back up provision Conveyor road to be used as the escape way to a refuge bay | Mechanical siren positioned on the outbye and operated from the inside as a back up system | Top of cap to be built of expanded metal to allow air to be drawn in by underground blower when activated Top of borehole to be clearly demarcated | |
| | | | A low wall 1 5 m high is built next to the conveyor structure at the rescue bay position as a means of guiding evacuees to the bay | | Area of 10 x 10 m to be securely fenced around the hole with one main gate Borehole to be earthed with an earthmat and equipped with a lighting arrestor | |
| Colliery 5 | Cut into solid coal with a single entry Brick walls to be hitched in to the rib sides and have an impervious or concrete floor | On a main intake traveling way at intervals not exceeding 1250 metres at every main or secondary development and where the distance from the working face to the nearest point accessible on surface exceeds 1250 metres | Reflective sign at entrance to the bay Orange flashing beacon to be installed outside the bay | Flahing beacon and siren installed outside the bay | Inside diameter 200 mm Top and bottom of borehole casing to be earthed and any cables in the borehole to be bonded to earth at the top and bottom | Battery drive suction fan in the refuge bay to start up automatically when a concussion activates a trip switch mounted on the outside of the bay This switch will also activate the siren and the flashing beacon outside the bay |
| | | | Number of refuge bay to be displayed inside and outside | | | Portable fans on surface to be coupled to the top of the borehole when required |
| Colliery 6 | Mock evacuation drill only | | | | | |
| Colliery 7 | Inside of chamber to be sealed with an effective sealant | At a appropriate distance from working places with consideration given to traveling conditions, capacity of Rescue Pac, ease of access on surface intake ventilation system | Directional arrows along all blue lines along conveyor structure Conveyor belt strips hanging from the roof from the entrance of the refuge chamber across all the intake roadways Audio/visual alarm system at the entrance of the Refuge chamber | audio/visual alarm system able to be activated from the inside of the chamber | 300-350 mm borehole with 250-300 mm casing T exit in a cabin constructed with hollow blocks or expanded metal with a corrugated iron roof | From surface through the borehole by means of a 12 volt battery operated dual fan system with a duty of 0 3m3/s at 300 pa One fan on surface and the other underground on a ring feed system and can be operated from u/g or surface |
| Colliery 8 | Cut into a pillar brickwalls with tight steel doors | Between 500 and 700 metres from the section | R/C outside wall painted with 100 mm red/yellow chevron stripes Number and/name of refuge bay to be painted on the outside Symbolic signs indicating the direction to the refuge bay to be installed every 200 metres along traveling routes | One alarm outside the chamber capable of being operated manually from inside the chamber One audible alarm with connecting jack able to be connected to surface supply | 150 mm, cased and earthed Semicircle radius of 30 metres to be demarcated and prepared for heavy vehicles Borehole casing to be earthed to a earth mat and to be fitted with a lockable cap and permanent blower fitting 100 mm in diameter | Portable blowers on surface |
| | | | Conveyor belt strips in all roadways in the split in which the Refuge Chamber is situated | | All roads to surface sites to be passable by 50 ton truck in any weather conditions | |

| Colliery | Type of construction | Site | Refuge Bay Indicators | Signaling devices | Borehole to Surface | Ventilation Arrangements |
|---|---|---|---|---|---|---|
| Colliery 9 | Robust construction and able to withstand the effect on an explosion | | Reflective type "Refuge Bay" symbolic sign at entrance to refuge bay Escape routes to be marked with recognized symbolic signs or other physical means | Audible signaling device outside the bay | Provided, taking into account access requirements for equipment and vehicles to the borehole site | Reliable source of respirable air so as to ensure proper flushing and create a positive pressure |
| Colliery 10 | Mined out of a solid pillar If this is impossible the walls will be protected against an explosion by stacking rubble at least 3 0 m high against the walls | Not more than 1000 metres from the production section along or as close as possible to the main traveling route | Conspicuous flashing light and effective siren outside the R/B powered from the battery backup Refuge bay symbolic sign at entrance and in vicinity of travelling routes and walkways | Conspicuous flashing light and siren outside the refuge bay | Cased borehole at least 150 mm diameter Proper protection to surface areas about boreholes as well as proper identification to be provided | 12 Volt battery fan connected to the borehole in case of emergency, and able to be switched on from the panel in the refuge bay Able to handle at least 0 1 m3/s of air |
| Colliery 11 | Fire resistent robust materials | Not further than 1200 m fom any point of the mine | Yellow continuous flashing lights in travelling road Red flashing lights and alarm linked to the back up poer supply, installed in the travelling way | R/B to be suitable and clearly numbered outside, inside and on surface Yelllow continuous flashing lights at tunnel doors at each R/B | 250 mm diameter with 200 mm steel casing To be earthed and enclosed in an expanded metal cage with lockable gates Flag with number of R/B installed at any top corner of metal cage | 12 Volt DC emergency fan Non return flap at bottom of steel casing to prevent fan recirculating Amber flashing light and siren on top of metal cage activated from U/G whenever the U/G flashing light and audible device are activated |
| | | | | | Amber flashing light and siren on top of metal cage, activated from U/G whenever the U/G flashing light and audible device are activated Petrol blowers and accessories available on surface to replace the 12 V DC fan | |
| | | | | | All roads to surface sites to be acessible by car even in wet weather They shall be clearly demarcated with symbolic signs and the number of the refuge bay | |
| | | | | | | |
| Colliery 12 | Double flat brick walls between two pillars Rib sides and roof to be teated with gunite after bolting and wiremesh All walls pinned and gunited or plastered on both sides | Within 20 minutes walking distance or approximately 1000 metres of any working place | Reflexive markers and guide aids in all acess routes and refuge bays Flashing amber light outside the refuge bay and working at all times | Mechanical siren situated outbye and operated from the inside | 100 mm diameter | Reliable supply of breathable air to be supplied from surface by utilising a high pressure blower |
| Colliery 13 | Robust construction hitched into the pillar To be gunited inside on both ribsides and stoppings to ensure it is properly sealed | Not more then 1000 metres from the working faces underground | Numbered inside and outside Symbolic sign displayed at both entrances | Where possible audible alarm activated from the inside of Refuge bay, and a conspicuous light outside R/B entrances | If possible | If there is no borehole Oxygen bottle with Regulators and spanner |
| Colliery 14 | Ribsides and roof to be treated with gunite after bolting and wire mesh All walls to be pinned and gunited or plastered on both sides All walls to be constructed of double flat breeze blocks | Within 20 minutes walking distance or approximately 1000 metres of any working place Where this not possible safe places to be intalled within 1500 metres from faces | All refuge bays and acess routes to be demarcated with reflective markers | Audible alarm situated outbye and able to be activated from the inside | No | Two axial flow fans, one on dundas seam, one on Gus seam, with independent power supply from respective seam level In case od mishap in Dundas area, Gus fan to be started Each fan to have separated stop/start stations inside the refuge bay |

| Colliery | Type of construction | Site | Refuge Bay indicators | Signaling devices | Borehole to Surface | Ventilation Arrangements |
|---|---|---|---|---|---|---|
| Colliery 15 | Walls to be built at least 5m from pillar if not located in a dummy pillar (preferred) | Not to be positioned next to a return airway Area well supported and safe and not liable to be flooded Area to offer easy acess by means of inter-seam inclines Sited where possible as a dummy roadway with solid ribside forming back of chamber | | | | Reliable supply of breathable air to be supplied via an incline inter seam escape way suitably equipped with a ladderway |
| | Bay to be cut into the barrier pillar on the intake air side of the section - opposite a pillar whenever possible On a double header section the bay is to be cut into a pillar adjacent to the tractor road | Refuge bays to be constructed once the section has advanced 200 m and thereafter at 300 m intervals or where practical Every 5th built in line with main development will become a permanent refuge bay | | M O S E S **repeater direction alarm system** | **yes, 152 mm diameter** | **Oxygen candles according to the capacity of the refuge bay** |

## APPENDIX B

## RELATIONSHIP BETWEEN DYNAMIC OVERPRESSURE AND WIND SPEED

In describing the effects of explosions on human being the following table has been used to determine the speed of the winds and the dynamic pressure causing them.

Relationship between dynamic pressure and the wind velocities calculated at sea level (Cook, M.A. Shock Waves in Gaseous and Condensed Media. The Science of High Explosives. New York, Reinhold Publishing Corp. 1955. pp 322-352.)

| Maximum Overpressure in PSI (kPa) | Wind Velocity in mph (kph) |
|---|---|
| 0.02 (0.14) | 40 (64) |
| 0.1 (0.70) | 70 (112) |
| 0.6 (4.20) | 160 (256) |
| 2.0 (14.0) | 290 (464) |
| 8.0 (56.0) | 470 (752) |
| 16.0 (112.0) | 670 (1072) |
| 40.0 (280.0) | 940 (1504) |
| 125.0 (875.0) | 1500 (2400) |

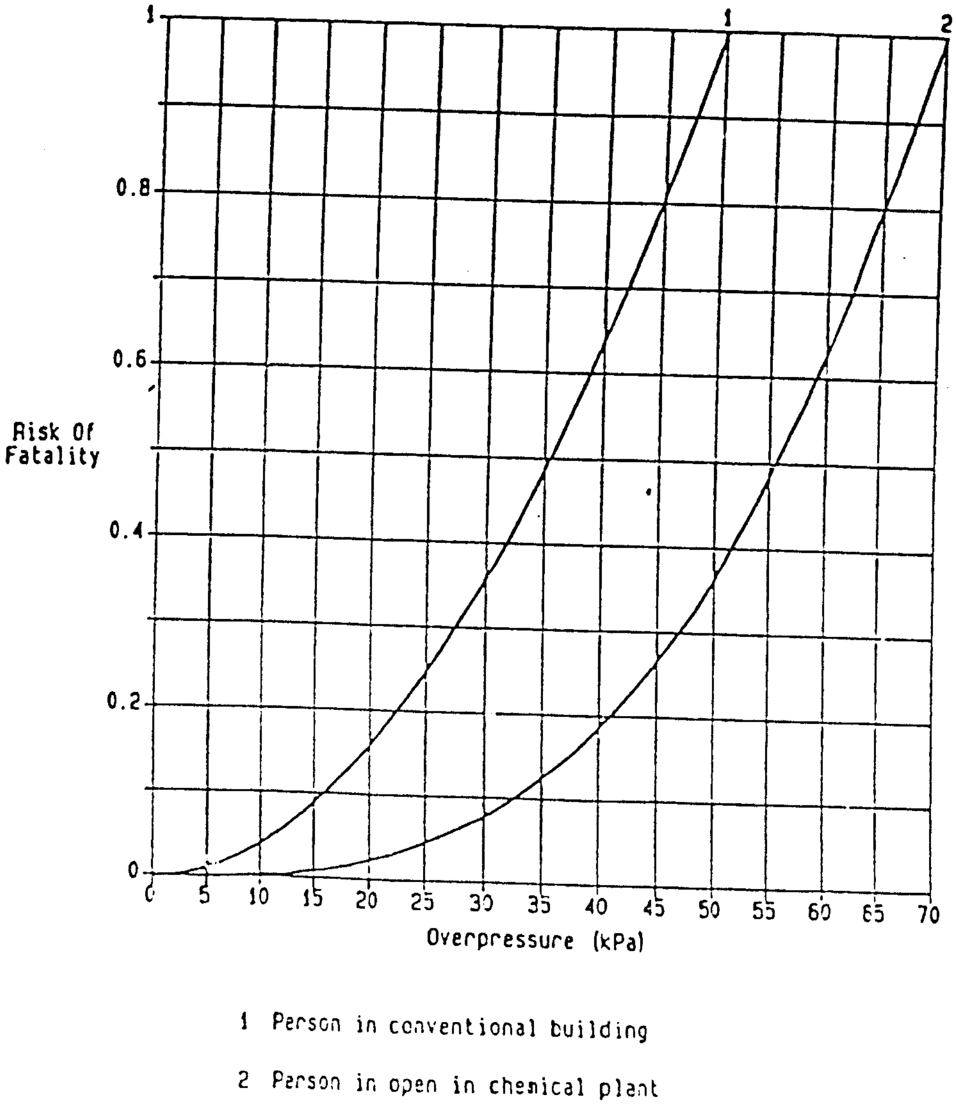
## APPENDIX C

## RISK OF FATALITIES OCCURING FROM A VAPOUR CLOUD EXPLOSION

The following graph graph shows the risk of fatality from an unconfined vapour cloud explosion.

**Hazard Analysis Course Notes,** ICI Engineering. 1988)

Risk Of Fatality From
Unconfined Vapour Cloud Explosion



Note : This is only a rough guide for use in the absence of better information

## APPENDIX D

## EFFECTS OF EXPLOSION OVERPRESSURE

The following table presents the effects of explosion overpressure.

**TABLE EFFECTS OF EXPLOSION OVERPRESSURE**

| Explosion Overpressure | Effect |
|---|---|
| 3.5 kPa (0.5 psi) | • 90% glass breakage<br>• No fatality and very low probability of injury |
| 7 kPa (1 psi) | • Damage to internal partitions and joinery but can be repaired<br>• Probability of injury is 10%. No fatality |
| 14 kPa (2 psi) | • House uninhabitable and badly cracked |
| 21 kPa (3 psi) | • Reinforced structures distort<br>• Storage tanks fail<br>• 20% chance of fatality to a person in a building |
| 35 kPa (5 psi) | • House uninhabitable<br>• Wagons and plants items overturned<br>• Threshold of eardrum damage<br>• 50% chance of fatality for a person in a building and 15% chance of fatality for a person in the open |
| 70 kPa (10 psi) | • Threshold of lung damage<br>• 100% chance of fatality for a person in a building or in the open<br>• Complete demolition of houses |

Hazard Analysis Course Notes, ICI Engineering. 1988)

## APPENDIX E

## EFFECTS OF EXPLOSION OVERPRESSURE (2)

Information as supplied by Clete Stephan of MSHA (USA) to the Moura working group no.5 to be the levels used by them for fatalities caused by blast overpressure.

| Explosive Force Expressed as Pressure in kPa | Effect |
|---|---|
| 1 | Ears pop |
| 4 | Glass breaks |
| 7 | Knocks person down |
| 14 | Trees blown down |
| 35 | Rupture ear drums |
| 100 | Damage to lungs |
| 240 | threshold of fatalities |
| 340 | 50 % fatalities |
| 450 | 99 % fatalities |

## APPENDIX F

## EFFECTS OF OVERPRESSURE (3)

Based on observation made in Japan, various nuclear tests, experiments in shock tubes, high explosive tests and theoretical analysis the following effects (of value to this study) on structures of blast damage has been determined.

For certain structural elements with short periods of vibration (up to 0,05 second) and small plastic deformation at failure the conditions can be expressed as a peak overpressure without considering the duration of the blast wave. These structure would be similar to the building of stoppings or walls without reinforcement or other methods in the underground environment. These structures fail in a brittle fashion and thus there is only a small difference between the pressure that cause no damage and those that cause complete failure.

Conditions of failure of overpressure sensitive elements.

| Structural element | Failure | Approx. side-on peak overpressure in kPa |
|---|---|---|
| Glass windows, large and small. | Shattering usually, occasionally frame failure. | 3.5-7 |
| Corrugated asbestos siding. | Shattering. | 7-14 |
| Corrugated steel or aluminium panelling. | Connection failure followed by buckling. | 7-14 |
| Brick wall panel, 8 inch or 12 inch thick not reinforced. | Shearing and flexure failures. | 21-70 |
| Wood siding panels standard USA house construction. | Usually failure occurs at the main connections allowing the whole panel to be blown in. | 3.5-7 |
| Concrete or cinderblock wall panels , 8 inch or 12 inch thick ( not reinforced. | Shattering of the wall. | 10.5-38.5 |

# TEST SUMMARY : Plain Concrete (1:2:4)

| Material | Agency | Date | Passage Cross section | Stopping Thickness | Recesses | Appurtenances | Types of Explosion | Maximum Pressure on Stopping (psi) | Test Results |
|---|---|---|---|---|---|---|---|---|---|
| | USBM (Bureau of Standards) | 1926 | 4ft x 4ft | 8in | none | none | static pressure | 10 | Failed |
| | | | | 8in | restrained at ribs | none | black powder | 107, 146 | Withstood 107, failed at 146 |
| | | | | 12in | unrestrained | none | static pressure | 23 | Failed |
| c = 2500 psi | USBM (Experimental mine) Stopping 2 | 1928 - 1930 | 4ft x 7ft | 19.2in | recessed 18in in each rib | none | black powder enclosed | up to 148 | Remained intact |
| c = 3300 psi | USBM (Experimental mine) Stopping 3 | 1928 - 1930 | 8ft x 7ft | 12in | recessed 18in in each rib | none | black powder enclosed | up to 125 | Remained intact |
| c = 3300 psi | USBM (Experimental mine) Stopping 3A | 1928 - 1930 | 8ft x 7ft | 12in | recessed 4in in each rib | none | black powder enclosed | 60 | Cracks developed |
| | | | | | | | | 69 | Cracks grew |
| | | | | | | | | 86 | Stopping disintegrated |
| c = 3300 psi | USBM (Experimental mine) Stopping 4 | 1928 - 1930 | 8ft 7in x 7ft 2in | 12in | recessed 6in in each rib | none | black powder enclosed | 42, 98, 100 | At 100 psi, spalling occurred, leakage occurred at the roof and a large vertical crack developed |
| c = 2500 psi | USBM (Experimental mine) Stopping 5 | 1928 - 1930 | 15ft 7in x 7ft 5in | 12in | recessed 12in in each rib | none | black powder enclosed | 175, 26.5, 35.5, 41, 55, 45 | At 55 psi, leakage occurred at roof; and cracks at the edge of the inby face and the centre of the outby face indicated that strength had been exceeded. In the next test (45 psi) bulkhead failed completely |
| c = 2000 psi | USBM (Experimental mine Stopping 6 | 1928 - 1930 | 12ft 8in x 6ft x 10in | 9.5in | recessed 6in at each side | none | black powder enclosed | 22 | Bulkhead failed, forming central crack |
| = 3200 psi | USBM (Experimental mine) Stopping 7 | 1928 - 1930 | 16ft 3in x 6ft 10in | 19.5in | recessed 7.7in at each rib | none | black powder enclosed | 20, 36, 50, 55 | Failed at 55 psi |

# TEST SUMMARY : Masonry and Composite Bulkheads

| laterial | Agency | Date | Passage Cross section | Stopping Thickness | Recesses | Appurtenances | Types of Explosion | Maximum Pressure on Stopping (psi) | Test Results |
|---|---|---|---|---|---|---|---|---|---|
| sonry | ECCS (King Ludwig Mine) | 1964 - 1965 | 43ft² | 2.5ft | none | none | coal dust | 27.4 | Both bulkheads withstood all explosives |
| | | | 135ft² | 2.5ft | | | | 19.2 | |
| | ECCS (Hagenbeck Mine) | 1965 - 1968 | 134.5ft² | 2.5ft (3 layer stone) | none | none | coal dust side on | >24 | Survived 19.5 psi, failed at >24 psi |
| | | | 134.5ft² | 1.7ft (2 layer stone) | none | none | coal dust | 25 | Survived 15 tests up to 25 psi; failed No 17 at 18 psi |
| | | | 64.5ft² | 1.7ft (2 layer stone) | none | 2.94ft x 6.6ft steel door | coal dust | 22.5 | Survived one test |
| | ECCS (Kaiserstuhl Mine) | 1965 - 1968 | 107.6ft² | 2.5ft (3 layer stone) | none | 2.94ft x 5.24ft steel door | coal dust | 30.5 | Shifted slightly |
| | ECCS (Scholven Mine) | 1965 - 1968 | 129ft² | 1.7ft (2 layer stone) | none | steel door | coal dust | ≤23 | Withstood 11.6, failed at 23 |
| onry ncrete ) | USBM | 1970 - 1971 | 14.5ft x 6.5ft | 1.3ft | recessed 0.65ft into ribs: 1.0ft into floor | none | methane-air from 250ft side-on | ≤48 psi<br>7.1 psi - sec | Withstood 9 blasts up to 48.5 psi |
| nposite | ECCS (Tremonia Mine) wood-rock dust-masonry | 1965 - 1968 | 9ft x 9.5ft | masonry 0.8ft<br>rock dust 18ft | none | none | coal dust | ≤11.6 | Outby wood brattice destroyed at 11.6 psi |
| | masonry-rock dust-masonry | 1965 - 1968 | | masonry 0.8ft<br>rock dust 18ft | none | none | coal dust | ≤62 | Up to 41 psi, inby wall had slight deformation destroyed at 62 psi |
| | masonry-rock dust-masonry | 1965 - 1968 | | masonry 1.7ft<br>rock dust 18ft | none | none | coal dust | ≤319 | 66.7, 151 psi without damage; slight deflection of inby wall at 160 psi; 0.65 ft deflection of inby wall at 319 psi |
| | ECCS (Dorstfeld Mine) masonry-rock dust-masonry | 1964 - 1965 | 240ft² | masonry 2.5ft<br>rock dust 4ft<br>masonry 2ft | none | 27in dia. pipe | methane-air at 250ft | 4, 36, 19, 49 | Bulged 8in in centre at 36 psi; moved an additional 2in at 49 psi |

# TEST SUMMARY : Gypsum

| Material | Agency | Date | Passage Cross section | Stopping Thickness | Recesses | Appurtenances | Types of Explosion | Maximum Pressure (psi) | Test Results |
|---|---|---|---|---|---|---|---|---|---|
| Plaster of Paris w/s = 0.5 | ECCS (Tremonia) | 1961 | 86ft$^2$ | 4.9ft | none | none | methane-air | 55 | Bulkhead undamaged |
| | | | | 9.8ft | none | none | methane-air | 71 | Bulkhead undamaged |
| w/s = 0.75 | ECCS (Tremonia) | 1965 - 1968 | 9ft x 9.5ft | 10.8ft | none | none | methane-air | 29, 54, 23 | Bulkhead undamaged |
| w/s = 0.5 | ECCS (Dorstfeld) | 1964 - 1965 | 237ft$^2$ | 8.2ft | none | none | methane-air | 4 | Bulkhead undamaged |
| | | | | | | | | 49 | Failed after 0.5 sec |
| w/s = 0.75 | ECCS (Dorstfeld) | 1964 - 1965 | 237ft$^2$ | 13.1ft | none | none | methane-air | 30 | Shattered at top, then repaired |
| | | | | | | | | 64 | Completely destroyed |
| w/s = 0.68 | ECCS (Kaiserstuhl) | 1965 - 1968 | 151ft$^2$ | 12.5ft | none | 27in diameter ventilation tube | | 18.8 | No damage |
| | | | | | | | | 23 | No damage |
| w/s = 0.35 (with retarder) | USBM (Experimental Mine) | 1970 - 1971 | 9ft x 6.5ft | 2ft<br>3ft | none<br>none | | methane-air | 9 explosions maximum 48.5 psi 7.1 psi-sec | No visible damage. Air leakage not affected |
| | | | 14.5ft x 6.5ft | 4.6ft | none | | side-on | | |
| Hardstem | NCB (Welden Mine) | 1965 | 10ft x 8 ft | 10ft | none | 27 in vent + instrument tubes | black powder and coal dust 30ft confined chamber | 76 psi | No damage to bulkhead<br>Ventilation tube hatch developed leaks |
| Saaralit | ECCS (Tremonia) | 1965 - 1968 | 9ft x 9.5ft | 3ft | none | none | methane-air | 16, 58, 217, 275 | Damaged at 275 psi |
| | ECCS (Scholven) | 1965 - 1968 | 220ft$^2$ | 5ft | none | none | methane-air | 70 | No damage |
| | EMC | 1968 | ? | 4.9ft | none | 30in diameter vent tube | | 4 explosions 17.5 to 84 | Slight damage<br>seal intact |
| Anhydrite w/s = 0,36 | EMC (Tremonia) | 1968 | 108ft$^2$ | 3.3ft | yes (22ft$^2$) | none | methane-air 41in chamber in front of bulkhead | 6 explosions from 21.8 to 261.5 | Seal remained intact |
| | ECCS (Scholven) | 1965 - 1968 | 194ft$^2$ | 3ft | no | 27in diameter vent tube | methane-air | to 65 psi | No damage |
| | | | | | | | coal dust | to 87 psi | |

# TEST SUMMARY : Cementitious and Miscellaneous Materials

| Material | Agency | Date | Passage Cross section | Stopping Thickness | Recesses | Appurtenances | Types of Explosion | Maximum Pressure on Stopping (psi) | Test Results |
|---|---|---|---|---|---|---|---|---|---|
| Fly Ash-Cement<br>62% fly ash<br>7% cement<br>31% water | USBM (Experimental Mine) | 1970 - 1971 | 14.5ft x 6.5ft | 2.9ft<br>4.6ft | none | none | methane-air 250ft from bulkhead side-on | 9 explosions up to 48.5 psi<br>7.1 psi-sec | Vertical crack occurred at 45 psi<br>otherwise no damage |
| Rock Dust cement<br>48.5 tons rock dust<br>7.6 tons cement | ECCS | 1961 | 86ft² | 19.7ft | none | none | methane air 260ft from bulkhead | 28<br>33<br>57 | Failed tested a few hours after poured<br>Undamaged, tested after a few days<br>Undamaged - tested after 3 weeks |
| Reinforced Concrete<br>1660 < $\sigma_c$ <3240 psi | USBM (Experimental Mine) Stopping 1 | 1923 | 4ft x 7ft | 8.5in | 1ft in each rib | none | black powder in closed chamber | 34, 70, 297 | Full length vertical crack |
| | USBM | 1926 | 4ft x 4ft | 8in | entire perimeter recessed ½ft simply supported | none | black powder<br>closed chamber | 46<br>76 | Average maximum pressure resisted<br>Average pressure causing failure |
| Sandbags<br>(Jute sacks) | ECCS | 1961 | 65ft² | 8.2ft | none | none | | 20 | Maximum safe pressure determined from earlier tests |
| | ECCS (Tremonia Exp Mine | 1961 | 86ft | 20ft | none | 27in diameter vent tube | methane air from 260ft | 43 | Seal moved 8in and leakage occurred at the top |
| Brattice and Rock Dust | ECCS | 1961 | 86ft | 11ft | none | none | methane air from 260ft | 14 and 28 | Bulkhead disintegrated at both pressures |

# TEST SUMMARY : Cementitious and Miscellaneous Materials

| Material | Agency | Date | Passage Cross section | Stopping Thickness | Recesses | Appurtenances | Types of Explosion | Maximum Pressure on Stopping (psi) | Test Results |
|---|---|---|---|---|---|---|---|---|---|
| Fly Ash-Cement<br>62% fly ash<br>7% cement<br>31% water | USBM (Experimental Mine) | 1970 - 1971 | 14.5ft x 6.5ft | 2.9ft<br>4.6ft | none | none | methane-air 250ft from bulkhead side-on | 9 explosions up to 48.5 psi<br>7.1 psi-sec | Vertical crack occurred at 45 psi<br>otherwise no damage |
| Rock Dust-cement<br>48.5 tons rockdust<br>7.6 tons cement | ECCS | 1961 | 86ft$^2$ | 19.7ft | none | none | methane air 260ft from bulkhead | 28<br>33<br>57 | Failed tested a few hours after poured<br>Undamaged, tested after a few days<br>Undamaged - tested after 3 weeks |
| Reinforced Concrete<br>1660 < $\sigma_c$ <3240 psi | USBM (Experimental Mine) Stopping 1 | 1923 | 4ft x 7ft | 8.5in | 1ft in each rib | none | black powder in closed chamber | 34, 70, 297 | Full length vertical crack |
|  | USBM | 1926 | 4ft x 4ft | 8in | entire perimeter recessed ½ft simply supported | none | black powder<br>closed chamber | 46<br>76 | Average maximum pressure resisted<br>Average pressure causing failure |
| Sandbags<br>(Jute sacks) | ECCS | 1961 | 65ft$^2$ | 8.2ft | none | none |  | 20 | Maximum safe pressure determined from earlier tests |
|  | ECCS (Tremonia Exp. Mine | 1961 | 86ft | 20ft | none | 27in diameter vent tube | methane air from 260ft | 43 | Seal moved 8in and leakage occurred at the top |
| Brattice and Rock Dust | ECCS | 1961 | 86ft | 11ft | none | none | methane air from 260ft | 14 and 28 | Bulkhead disintegrated at both pressures |

## APPENDIX H

## SUMMARY OF REFERENCES PUBLISHED BETWEEN 1981 AND 1993

Source : Contract Report No. BX2125600 5665. CSIR: Division of Building Technology, November 1995.

# TEST SUMMARY : Solid concrete block seals

| Bulkhead configuration | Nominal thickness inches (m) | Maximum overpressure psig (bar) | Impulse per area psi - s | Damage | Post explosion air leakage rates cft/min | | Assessment (20 psig criterion) |
|---|---|---|---|---|---|---|---|
| | | | | | 1 in water | 4 in water | |
| Standard seal, thick wall, wetwall, pilaster, floor and rib keying | 16 (0,4) | 22 (1,52) | 4,55 | None | 87 | 94 | Passed |
| Thick wall, wetwall, pilaster, no floor keying | 16 (0,4) | 21 (1,45) | 4,03 | Large opening at roof, 2 large cracks at left outby side, bottom displaced about 1 in | NA | NA | Failed |
| Thin wall, wetwall, pilaster, floor keying, coating on inby side | 8 (0,2) | 19 (1,31) | 2,98 | All blocks removed except bottom row | NA | NA | Failed |
| Thin wall, wetwall, pilaster, rib and floor keying, coating on outby side | 8 (0,2) | 15 (1,03) | NA | Large crack at top, blocks missing on outby side, pilaster sheared off | NA | NA | Failed |
| Thick wall, wet wall, no pilaster, floor keying | 16 (0,4) | 17 (1,17) | 3,74 | Minor damage, stopping intact, mortar removed at top, some half blocks removed at roof line, approx 1ft² leak area formed | NA | NA | Marginal at <20 psig pressure |
| Thin wall, drywall, pilaster, rib and floor keying, coating on both sides | 8 (0,2) | 18 (1,24) | 2,45 | Destroyed, only a few blocks remained on and near ribs | NA | NA | Failed |
| Thick wall, drywall, pilaster, rib and floor keying, coating on both sides | 16 (0,4) | 20 (1,38) | 3,17 | All blocks removed except a few along both ribs and on floor | NA | NA | Failed |

# TEST SUMMARY : Cementitious foam seals

| Material compressive strength psi (MPa) | Nominal thickness feet (m) | Maximum overpressure psig (bar) | Damage | Post explosion air leakage rates cft/min | | Assessment (20 psig criterion) |
|---|---|---|---|---|---|---|
| | | | | 1 in water | 4 in water | |
| 200 (1,38) | 8 (2,44) | 29 (2,00) | None | 0 | 31 | Passed |
| 200 (1,38) | 4 (1,22) | 22 (1,52) | Hairline cracks on inby side | 52 | 114 | Passed |
| 100 (0,69) | 4 (1,22) | 22 (1,52) | Slight cracks, appearing continuous through seal | 47 | 114 | Marginal |
| 50 (0,34) | 8 (2,44) | 21 (1,45) | Significant cracks on both sides of seal, having about ¼ inch gap | 180 | 420 | Failed |
| 50 (0,34) | 4 (1,22) | 13 (0,90) | Seal was totally destroyed | NA | NA | Failed |
| 208 (1,4) | 4 (1,22) | 26 (1,79) | none reported * | 21 | 21 | Passed |
| 157 (1,1) | 4 (1,22) | 25* (1,72) | none reported * | 21 | 60 | Passed |
| 376 (2,6) | 4 (1,22) | 22 (1,52) | none reported * | 31 | 85 | Passed |
| 219 (1,5) | 4 (1,22) | 22 (1,52) | none reported * | 52 | 152 | Passed |
| 168 (1,2) | 4 (1,22) | 21 (1,45) | hairline cracks, appearing to extend through seal | 61 | 154 | Marginal |

* results are stated to be valid only for 125 ft² (11,6 m²) or smaller openings larger openings said to require either higher strength material or be thicker

## TEST SUMMARY : Low density, glass-fibre reinforced, foam blocks

| Number and size of pilasters see note * | Nominal thickness feet (m) | Maximum overpressure psig (bar) | Damage | Post explosion air leakage rates cft/min | | Assessment (20 psig criterion) |
|---|---|---|---|---|---|---|
| | | | | 1 in water | 4 in water | |
| 2 of 48 inches x 48 inches | 2,7 (0,82) | 20 (1,38) | no damage reported | 21 | 52 | Passed |
| 2 of 48 inches x 48 inches | 2,0 (0,61) | 21 (1,45) | none reported, but some damage implied in results | 140 | 294 | Marginal |
| 1 of 56 inches x 72 inches | 2,0 (0,61) | 20 (1,38) | no damage reported | 39 | 87 | Passed |
| 1 of 48 inches x 48 inches | 2,0 (0,61) | 19 (1,31) | no damage reported | 63 | 139 | Passed |

* All seals had special mortar joints, with rib and floor keying, with a fibreglass reinforced coating on both sides

# TEST SUMMARY : Cementitious foam seals

| Material compressive strength psi (MPa) | Nominal thickness feet (m) | Maximum overpressure psig (bar) | Damage | Post explosion air leakage rates cft/min | | Assessment (20 psig criterion) |
|---|---|---|---|---|---|---|
| | | | | 1 in water | 4 in water | |
| 200 (1,38) | 8 (2,44) | 29 (2,00) | None | 0 | 31 | Passed |
| 200 (1,38) | 4 (1,22) | 22 (1,52) | Hairline cracks on inby side | 52 | 114 | Passed |
| 100 (0,69) | 4 (1,22) | 22 (1,52) | Slight cracks, appearing continuous through seal | 47 | 114 | Marginal |
| 50 (0,34) | 8 (2,44) | 21 (1,45) | Significant cracks on both sides of seal, having about ¼ inch gap | 180 | 420 | Failed |
| 50 (0,34) | 4 (1,22) | 13 (0,90) | Seal was totally destroyed | NA | NA | Failed |
| 208 (1,4) | 4 (1,22) | 26 (1,79) | none reported * | 21 | 21 | Passed |
| 157 (1,1) | 4 (1,22) | 25 (1,72) | none reported * | 21 | 60 | Passed |
| 376 (2,6) | 4 (1,22) | 22 (1,52) | none reported * | 31 | 85 | Passed |
| 219 (1,5) | 4 (1,22) | 22 (1,52) | none reported * | 52 | 152 | Passed |
| 168 (1,2) | 4 (1,22) | 21 (1,45) | hairline cracks, appearing to extend through seal | 61 | 154 | Marginal |

* results are stated to be valid only for 125 $ft^2$ (11,6 $m^2$) or smaller openings larger openings said to require either higher strength material or be thicker

## TEST SUMMARY : Low density, glass-fibre reinforced, foam blocks

| Number and size of pilasters see note * | Nominal thickness feet (m) | Maximum overpressure psig (bar) | Damage | Post explosion air leakage rates cft/min | | Assessment (20 psig criterion) |
|---|---|---|---|---|---|---|
| | | | | 1 in water | 4 in water | |
| 2 of 48 inches x 48 inches | 2,7 (0,82) | 20 (1,38) | no damage reported | 21 | 52 | Passed |
| 2 of 48 inches x 48 inches | 2,0 (0,61) | 21 (1,45) | none reported, but some damage implied in results | 140 | 294 | Marginal |
| 1 of 56 inches x 72 inches | 2,0 (0,61) | 20 (1,38) | no damage reported | 39 | 87 | Passed |
| 1 of 48 inches x 48 inches | 2,0 (0,61) | 19 (1,31) | no damage reported | 63 | 139 | Passed |

* All seals had special mortar joints, with rib and floor keying, with a fibreglass reinforced coating on both sides

## APPENDIX J

## PROPOSED CONCEPTUAL DESIGNS FOR THE CONSTRUCTION OF REFUGE BAY BULKHEADS

(Capita Selecta from Contract Report No. BX2125600 5665. CSIR: Division of Building Technology, November 1995, and further correspondence with Dr. B.L. Lunt of Boutek.)

### 1.0 INTRODUCTION

Lunt and Barker, on behalf of Miningtek, devised design proposals for the designs of refuge bay bulkheads according to South African standards. Initially doubts were expressed about the validity of the strength requirements as determined by the specified overpressures and pulse lenghts. The original explosion characteristics, hoever, are so similar to those proposed by this study as well as those used by the USA and Australia that these designs can be considered to be quite valid for use in local conditions. This appendix sets out a capita selecta of the presented report. the designs and motivation of the design principles used.

### 2.0 Background

A literature survey indicated that there are several tried and tested bulkhead construction methods used overseas that could be used as a guide in local refuge bay construction. The established forms of construction of interest to this project were essentially of two kinds, namely mass plugs and heavy wall constructions.

Discussion with one of the modern mines (Khutala) indicated that these forms of construction could be followed and in addition, because of the experience and practices relating to ventilation stoppings and other wall constructions, two further options would be viable as well.
The discussions at Khutala regarding constraints within the mine, that might influence forms of construction, revealed that in a modern mines there were in fact few serious constraints.

### 5.2 Constraints in the mine

The possible constraints associated with materials handling, equipment, manpower and construction time were discussed at Khutala. It has been concluded that in a relatively modern mine there would be very few restrictive constraints on materials and equipment as vehicular transport of materials such as cement, aggregates, concrete blocks and equipment could be readily accommodated and mixing water for concrete would be available.

### 5.2.1 Materials

Materials such as in-situ concrete, shotcrete and solid concrete blocks, are frequently used. Dump rock was generally not available and fragmented rock and coal was not suitable as it was brittle and contained pyrites.

### 5.2.2 Materials handling

The main requirement would be that objects be of a size and mass that would allow them to be man-handled, for example, conventional large sized concrete blocks and 20 litre drums would be ideal from a handling point of view. Large drums such as 44 gallon drums would be difficult to handle and therefore unsuitable. Transport of cement and concrete aggregates would not pose a problem and reinforcing mesh for shotcrete is commonly used. Containerised transport of 8 ton and 3 ton sizes can also be accommodated in certain mines; in others the mass may need to be limited to a half a ton.

### 5.2.3 Equipment

Any equipment that is transportable on a small truck may be used in a mine like Khutala. Appropriate electrical equipment is also used.

### 5.2.4 Time restrictions

At Khutala it was not considered essential to be able to construct a wall very rapidly and a five day construction period with a longer curing period would be regarded as acceptable. (It was said that equipping the refuge bay could take about two months, in relation to which the construction time was not too critical.)

## 5.3 Proposed refuge bay construction methods

In all of the forms of construction described below, except for the options using roof trusses, it is essential that the base and sides of the bulkhead are keyed (recessed) into the floor and ribs. (Bulkheads required to withstand the horizontal force of a blast wave would ideally be keyed into all the surrounding rock-faces - footwall, hangingwall and ribs, but keying into the hangingwall may be difficult to achieve in practice.) The proposed designs are all for an opening nominally 6 m wide and 3,5 m high, with a 1,8 x 0,9 m doorway and two 150 mm diameter vent holes, as indicated in Figure 2. Figures 3 to 7 illustrate the conceptual designs and give constructional details.

The parameters of importance in selecting materials for evaluation to provide low strength, bulky structures for refuge bay enclosures are cost, strength, durability and absence of noxious effects under both normal and disaster circumstances. The criteria for strength and durability are not extreme (strength requirements being low for mass plugs) and, while durability can be a serious problem for concrete in a coal mine, the relatively short service life for a refuge bay reduces the importance of this aspect of performance to a degree.

### 5.3.1 Mass plug type of bulkhead

These are plugs made of materials that cen be cast in place, preferably by pumping the wet mix between the most convenient kind of formwork. At this stage, the two materials regarded as most appropriate are foamed concrete (with minimum aggregate content) and stabilised fly-ash (for collieries with nearby power stations as a source of fly-ash).

Where major power generating facilities are situated close to the mines for which refuge bays are required, ash can be utilised for low strength, bulky structures. Test data for mixes incorporating ash and different forms of stabiliser/activator for the ash which are being investigated are tabulated below. These details pertain to the second series of mixes which adopted the most promising of the binder systems identified in the initial tests but allowed for by-product rather than the commercial form of activator in one instance and extended the series to include coal in the mixes to simulate the use of mine waste.

| Flyash | Cement | Slagment | Hemi Hydrate | Gypsum | Coal | 7 Day Str MPa | 28 Day Str MPa |
|---|---|---|---|---|---|---|---|
| 100 | | 4 | 4 | | | 0,4 | 0,8 |
| 100 | | 4 | | 4 | | 0,5 | 1,3 |
| 100 | | 8 | 8 | | | 0,5 | 1,9 |
| 100 | | 8 | | 8 | | 0,5 | 1,8 |
| 100 | 8 | | | | | 1,1 | 1,7 |
| 100 | 16 | | | | | 2,7 | 4,5 |
| 50 | | 4 | 4 | | 50 | 0,4 | 0,9 |
| 50 | | 4 | | 4 | 50 | 0,4 | 1,1 |
| 50 | 8 | | | | 50 | 2,1 | 3,3 |

The mixes are described in terms of the ratios of the constituents, and with the density of the principally flyash mixes being of the order of 1 500 kg per cubic metre and the water contents of these mixes being 350 litres per cubic metre, actual masses per cubic metre are approximately tenfold the values tabulated. The mixes with a blend of coal and flyash are moderately denser and had lower water contents so the multiplier is approximately twelve for the tabulated figures to covert to quantities per cubic metre. Final quantities will vary slightly from these approximate values depending upon the mix consistency as dictated by construction practice and depending upon the mix constituent ratios.

In addition to strength tests on the mixes as tabulated above, specimens have been stored partially immersed in coal mine water for four months with no evidence of deterioration during this period. Approximate stress strain relationships to failure have also been recorded for all nine combinations of material. It is worth noting that while the mixes incorporating coal did not display any improvement in strengths relative to those with the total "filler" consisting of flyash as would have been expected from the lesser water requirements, they did display a capacity to sustain a high proportion of the failure load as deformation was continued. This could be a highly useful attribute in the field if several successive explosions occurred.

For relatively small openings, in the order of 4 m x 2 m, these plugs could be between 1,2 m and 1,3 m thick, for material compressive strengths of 1,5 MPa and 1,0 MPa respectively, based on reported test data. For larger openings, such as seen at Khutala, up to about 6 m x 4 m, the required thickness of the plug is suggested at (height of opening)/1,6 to (height of opening)/1,5 for a material strength of 2 MPa. See Figure 3 for typical details.

The option for construction shown in Figure 3 is a very thick barrier of unreinforced low strength cementitious material such as foamed concrete. This is essentially the same kind of stopping that has been used in Europe, cast in Gypsum and the cementious foam seals tested in the USA. These stoppings work in the same way as a plug in a basic and because they are typically unreinforced and of large thickness they have been referred to as mass plug types. This type of bulkhead or stopping has been shown in full scale tests to work well under moderate to very high blast pressures in relatively small tunnel cross sections (between 8 and 20 m$^2$).

The thickness of 2-3 metres suggested in Figure 3 for the range of compressive strengths between 1 and 2 MPa are considered to be adequate to resist the relatively low over pressure of 1 bar specified in the brief. Because only very low material strengths are needed, it is possible to utilise pumped foamed concrete successfully. The mass plug may be considered viable because it is a simple structure, easy to build and requiring only the raw materials and unsophisticated formwork such as rough timber. The only equipment required that may not normally be found in coal mine would be a mortar/concrete pump.

### 5.3.2 Hybrid type bulkheads

Two forms of "hybrid" bulkhead have received attention, one having a foam concrete or other low strength concrete core with reinforced gunite outer layers, the other consisting of two solid concrete block walls with a concrete core containing roof trusses.

The conceptual design of the first hybrid bulkhead consists of 60 mm to 80 mm thick gunite outer layers, reinforced with a heavy mesh (9 mm diameter at 200 mm centres) or Y10 bars at 300 mm centres, with additional reinforcement around the door opening. The core would consist of 2 MPa foam concrete about 1 metre thick to give an overall thickness of 1,1 to 1,2 metres for the bulkhead. See Figure 4.

The form of construction illustrated in Figure 4 of BOU/C29 is called a hybrid because it combines the use of both low strength and reinforced high strength concrete in a fairly thick composite wall. Because of the thickness of this wall, its structural behaviour combines flexural resistance with internal arching action. The idea of using this type of construction was prompted by the observation of the use of reinforced gunite (shotcrete) at Khutala mine.

The construction of such a bulkhead would be in two stages. The first stage would be casting of the low strength core material between rough shuttering which would be removed before fixing the reinforcement of the outer layer that would be completed with gunits. It is essential that the steel links between the two outer layers be provided throughout the bulkhead. The core material could be the same foam concrete as used in a mass plug bulkhead.

The advantage of this form over the mass plug would be the smaller volume of aggregate required and the more durable surfaces of the bulkhead.

The second conceptual design consists of two 200 mm thick solid concrete block walls spaced about 300 mm apart, with a 20-25 MPa concrete core. The core would contain trusses spanning horizontally above door height and trusses would be installed vertically on either side of the doorway. 8 mm diameter ties would be built into every second course of the blockwork walls at horizontal spacings of 500 mm, to link the two walls together. See Figure 5.

This form of construction illustrated in figure 5 of BOU/C29 makes use of a combination of solid concrete blockwork walling and pre-tensioned anchor trusses that are well known in the mines. It combines the structural resistances of regular solid concrete black walls with the strengthening effect of a tensioned net created by the trusses. The overall thickness of this type of wall would be somewhat less than the type 1 hybrid and keying into the floor and ribs is considerably aided by the anchorage or the trusses into the root, floor, and ribs.

### 5.3.3 Heavy wall type bulkhead

This is essentially a wall based on the American "standard" bulkhead built of solid concrete blocks, stiffened with one or more pilaster.

For relatively small openings, in the order of 4 m x 2 m, these bulkheads could feasibly be built exactly like those tested by the USBM. These bulkheads were 406 mm thick with a single centrally located 812 mm pilaster. For larger openings it would be necessary to have more pilasters, with as many as three for openings of about 6 m x 4 m. It would be important that quality control on the construction of such bulkheads was good. Also, keying of the pilasters to the floor and roof would be essential.

The heavy masonry bulkhead illustrated by Figure 6 of BOU/C29 is based directly on the descriptions of solid concrete block masonry referred to in the USA literature as a standard type seal and on the structural principles for the design of load-bearing masonry. The design shown in the report makes-use of the horizontal spanning capability of masonry between vertical restraints, which in this case are provided by the recess into the ribs and floor and by the heavy pillars (pilasters in American terminology) which limits the magnitude of the horizontal spans.

The use of fully bonded solid concrete block masonry was regarded by the American mines as the most convenient method of construction, probably because of the availability of blocks and of block-laying skills. The large size of blocks generally used makes it possible to build a wall very rapidly, but it must be emphasised that in order to be successful, all the bedding and perpend joints must be completely filled with mortar of good quality.

The structural action is regarded as largely the arching action that does develop in masonry which is restrained against in-plane movement at its perimeter.

One of the advantages of this form of construction is the ease of transport of the basic construction components.

### 5.3.4 Reinforced concrete bulkhead

This form of construction, shown in Figure 7 in the report, is commented on ahead of the two hybrid forms, because it will make the term hybrid type easier to understand.

This type of bulkhead corresponds to the slender wall bulkhead referred to in our report of November 1994. The conceptual design consists of a 400 to 450 mm thick reinforced wall of 25 MPa concrete with a layer of reinforcement near each face. The reinforcement would be 20 mm diameter bars at 250 mm centres in the vertical direction and 16 mm diameter bars at 400 mm centres horizontally when all edges are keyed in recesses. The two layers of reinforcement would be linked by sets of closely spaced stirrups and additional reinforcement would be required around the doorway. Figure 7 shows reinforcement details for two kinds of main reinforcement.

The design shown in Figure 7 is a moderately thick wall made of reinforced concrete which resists lateral loading such as blast pressures by virtue of its flexural strength. It acts in the same way as a suspended reinforced concrete floor, of a building, which is supported at its edges. The volume of 25 MPa concrete in this type of wall would be about 1/5th of the volume of 2 MPa material in a mass plug type of wall, but it has two layers of steel reinforcement in it wherever the mass plug has no reinforcement. The reinforcement concrete type of wall would be suitable in mines where reinforced concrete is a familiar construction material underground. The concrete could be either conventionally placed and compacted or pumped generate could be used.

## 5.4 Steel doors

An important item to be considered is the access door to a refuge bay through the bulkhead. The door opening considered would have a height between 1,5 and 1,7 metres, a base width of 900 mm and a top width of 800 mm with the hinged edge sloping and the opposite edge vertical, following the same pattern as currently in use at Khutala, if the self-closing action is required. Alternatively, the door opening could be a right rectangle of 800 mm width and the hinges could be offset at an angle to give a self-closing action.

Two options for the steel self-closing doors to be fitted to bulkheads have been considered. The first option for door construction would be a flat steel plate of substantial thickness. For the proposed door opening size a flat plate of 12 mm thickness would be required, which is very heavy (145 kg). The second option is a fabricated light sheet steel door that is fairly light in comparison (56 kg). This type of door consists of a thin curved steel plate, 1 mm thick, with concave surface facing the blast overpressure, with a stiffening frame around the perimeter. See Figure 8.

The pros and cons of these doors are:

The heavy door is simpler and therefore probably cheaper than the light weight door, but would be more difficult to open and very substantial well anchored hinges would be required. The light weight fabricated door would be easier to operate and require lighter hinges, but will need to be built by a specialist fabricator and may be more expensive.

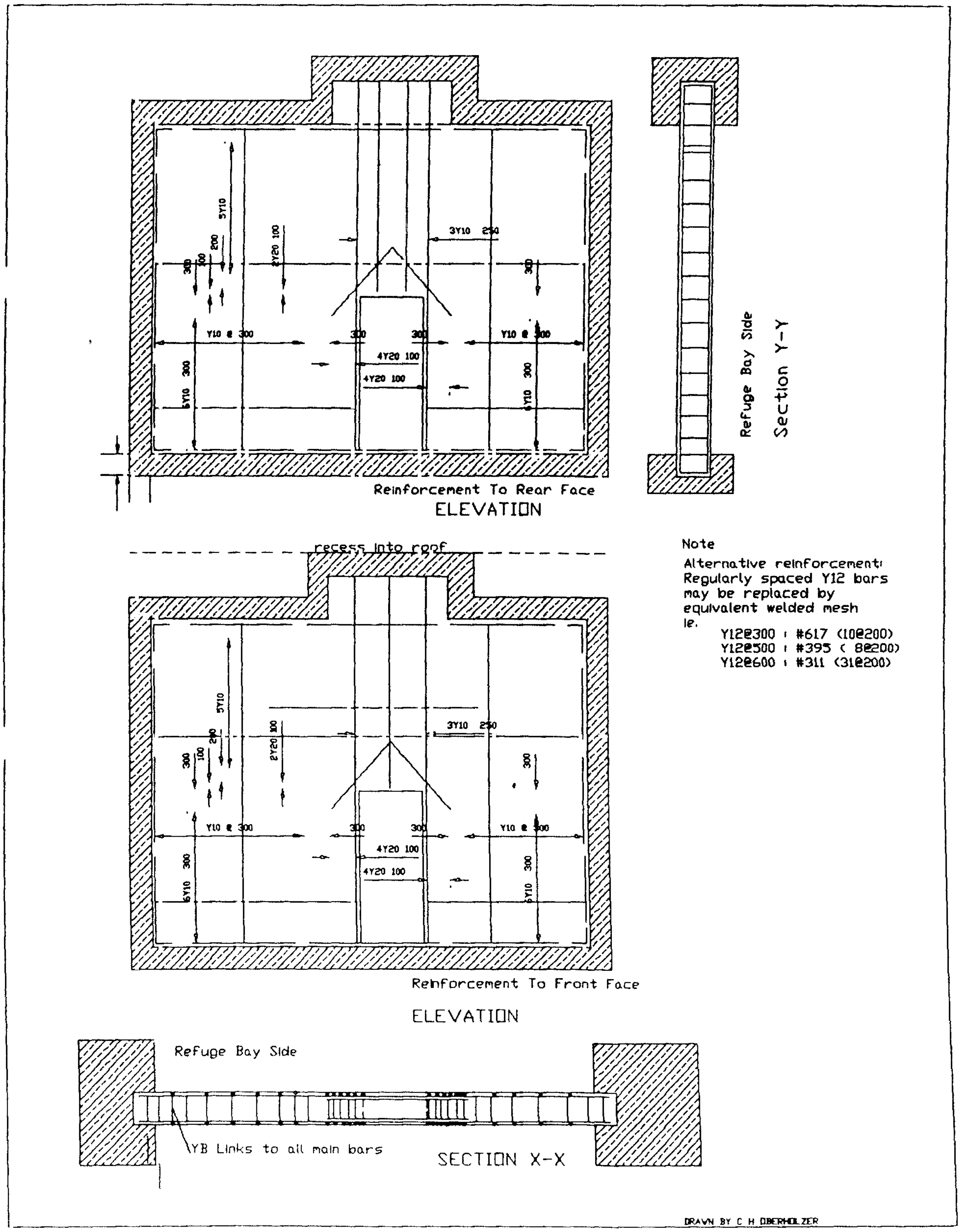
For both types of door, a steel door frame should be built into the bulkhead. It could consist of moderately heavy angle iron and be well anchored into the wall. If fully airtight closing is a real requirement, then elastomeric seals would be necessary around the perimeter, between the door and the frame as indicated in Figure 8.

## 5.5 Ventilation holes through bulkhead

It is understood that permanent ventilation holes through the bulkhead will be required. Provided these are of roughly circular cross-section and not more than about 150 mm in diameter, such holes should not have any practical influence on the structural capability of the bulkhead designs proposed.

## 6 LOCATION OF BULKHEAD WITHIN EXCAVATED OPENING

The face of the bulkhead subject to blast pressure should be built as close to the tunnel wall as practicable (nominally flush with the tunnel wall) to avoid the unfavourable pressure increases that can develop in a recess through reflected wave effects.



Reinforcement To Rear Face

ELEVATION

Reinforcement To Front Face

ELEVATION

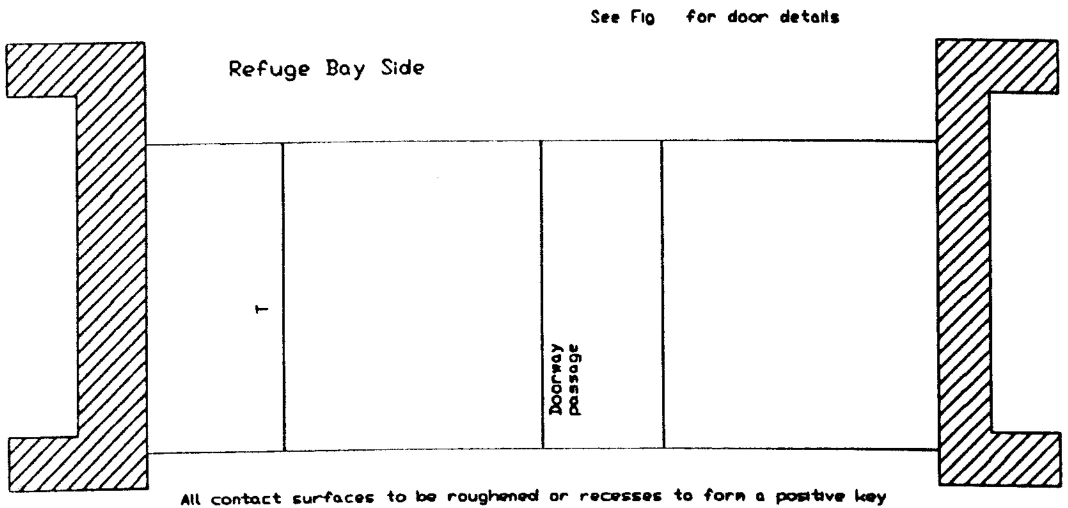
SECTION X-X

Note

Alternative reinforcement: Regularly spaced Y12 bars may be replaced by equivalent welded mesh ie.

Y12@300 : #617 (10@200)
Y12@500 : #395 ( 8@200)
Y12@600 : #311 (3@200)

DRAWN BY C H OBERHOLZER



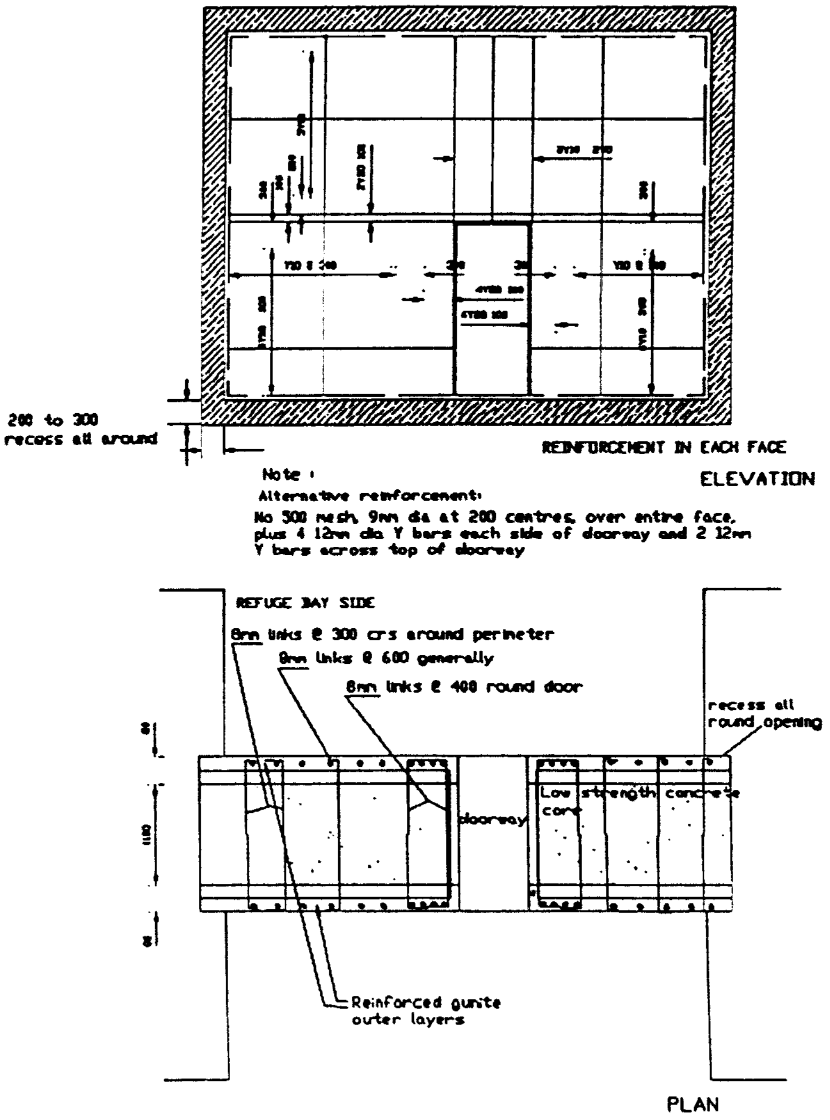
All contact surfaces to be roughened or recesses to form a positive key (including roof and floor)

Thickness of bulkhead for different material compressive strength

| Compressive strength MPa | Thickness 'T' M |
|---|---|
| 1.0 | 2.8 |
| 1.5 | 2.2 |
| 2.0 | 1.9 |

Figure 3 Sectional plan of mass plug bulkhead

DRAWN BY C H OBERHOLZER



Note :
Alternative reinforcement:
No 500 mesh, 9mm dia at 200 centres, over entire face,
plus 4 12mm dia Y bars each side of doorway and 2 12mm
Y bars across top of doorway

FIGURE 4 HYBRID BULKHEAD TYPE 1

DRAWN BY C H [illegible]

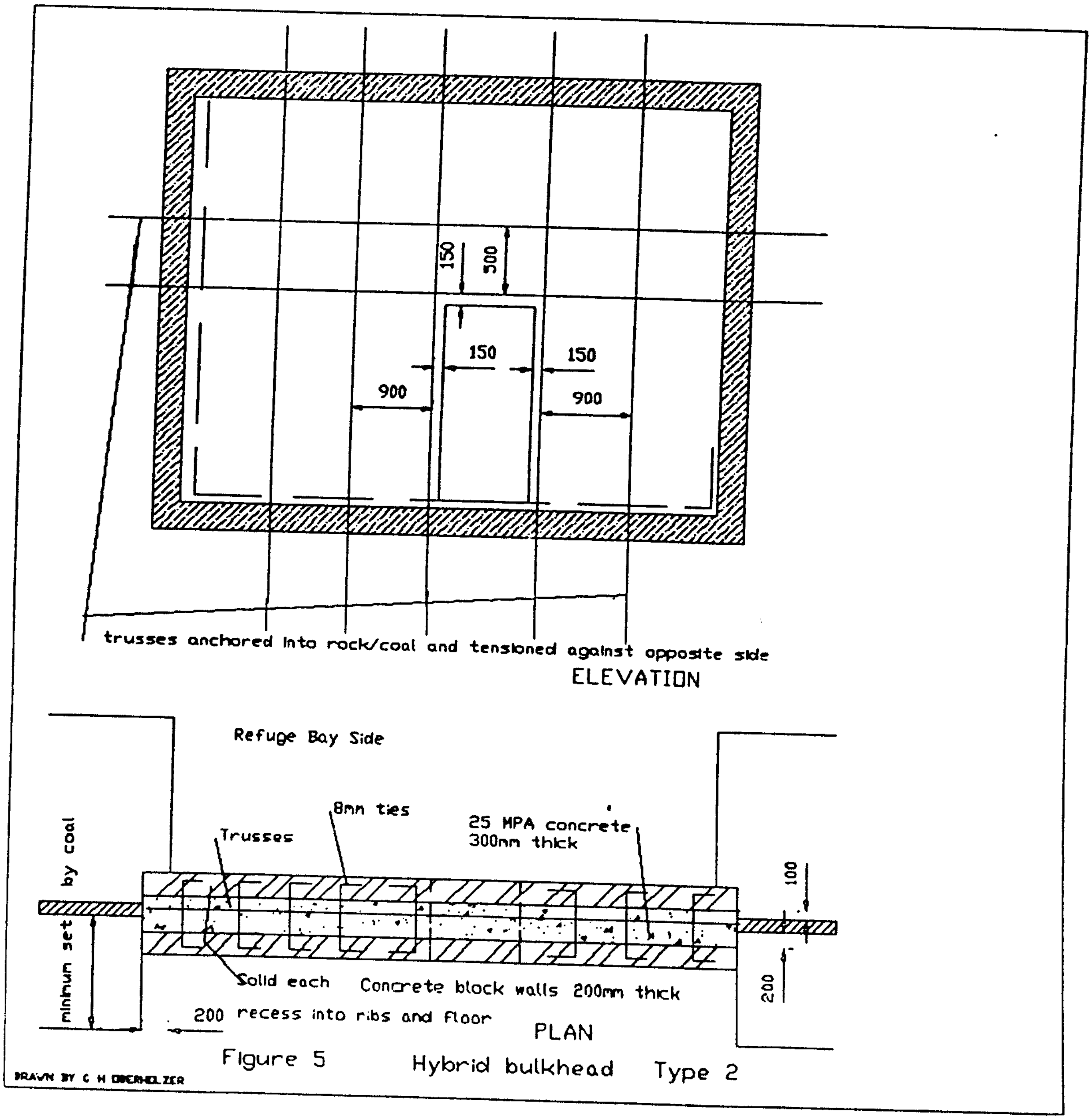


Figure 5 Hybrid bulkhead Type 2

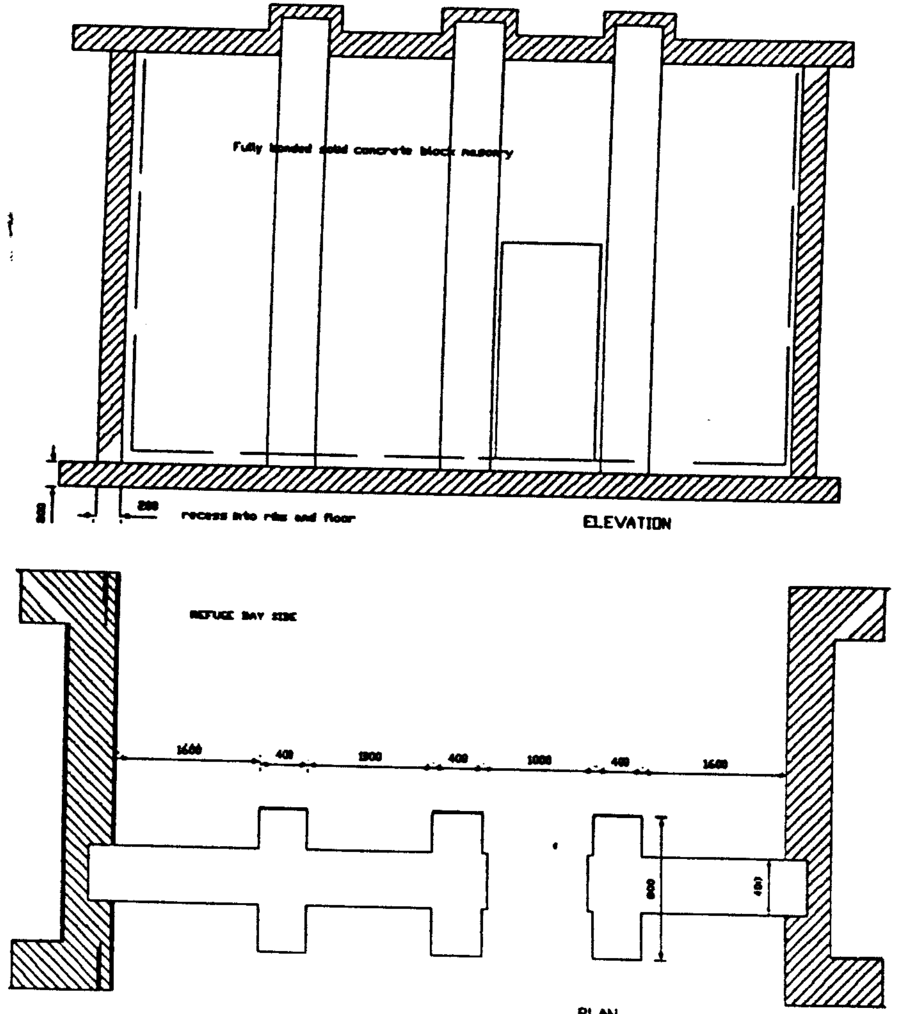
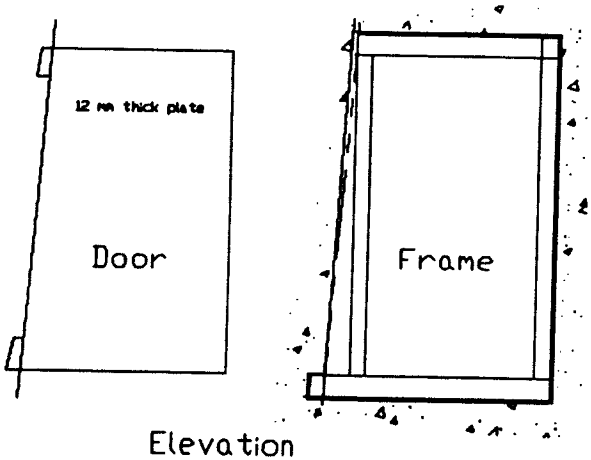
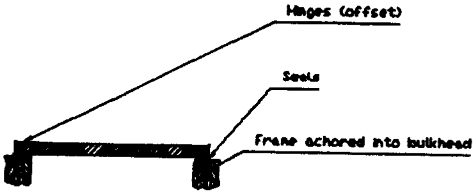


Figure 6 Heavy masonry wall

## HEAVY FLAT STEEL DOOR



Elevation

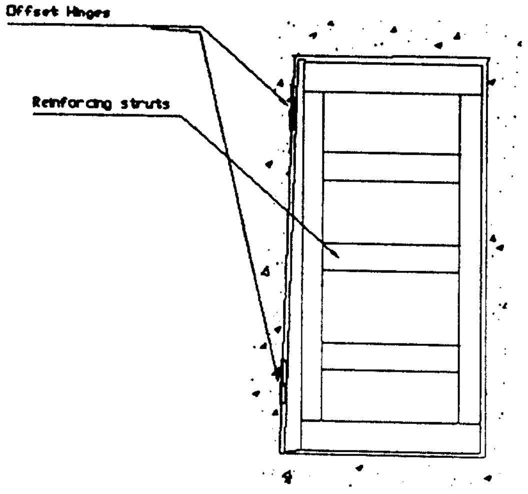


section

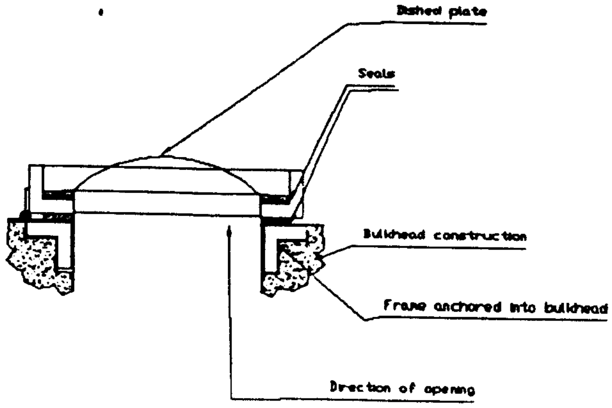
Doors open outward on offset hinges. Force of explosion presses door against frame and seal. Frames anchored into bulkhead construction.

## LIGHTVEIGHT FRAMED STEEL DOOR

Angle-Iron Frame
dished plate covering.



Elevation



Section

Door in frame

Not to scale

FIGURE 8 STEEL ACCESS DOOR

Drawn by C H [illegible]

## APPENDIX K

## PROPOSED OUTLINE OF ALTERNATIVE STRATEGY FOR THE USE OF REFUGE BAYS

A change in the present strategy for affording workers safety in the aftermath of an explosion or fire has been identified. This change is due to the following issues identified during the execution of this project.

1. It is doubtful if a present day mine would be able to keep a refuge bay, in the traditional sense, within 500-600m from the working face.
2. The incidence of building fully equipped refuge bays due to "required" distance is too high to be practical for mines.
3. The practical distance that would be required is significantly less than the "required" distance. This is due to the width of the sections involved. For example to maintain a 600m distance for a longwall the refuge bay would have to be kept within 400m from the maingate when the face width is in the order of 200m. This would mean that for a 2km panel ther would have to be 5 fully equipped refuge bays.
4. The closer to the face the stronger the structure needs to be. This increases the time rquired to establish such a bay as well as the costs to build such a structure.
5. There are serious implications with regard to the surface installations especially if the surface rights do not belong to the mine.
6. The duration of the selfcontained selfrescuers cannot be increased due to the fact that the mines have already invested significant amounts to provide them to workers.

## PROPOSED STRATEGY

The rescue of workers in the aftermath of an incident should be divided into two phases. The first phase is where a principle of self rescue applies. The second part is where the rescue effort will be assisted by efforts and infrastructure from the mine.

### Self Rescue phase.

The thirty minute selfcontained self rescuer is used to reach a safe haven within easy reach of the set. This means that this haven must be within the range of the set when used in a sitauation of no visibility. It can be assumed that no direct guidance can be afforded to this safe haven and workers would have to reach this point based on their familiarity of the section and where this haven is placed.
This place or haven should be so designed that;

1. It is quick and easy to construct, less than a day.
2. It should have a contained method of providing air or oxygen for an intermediate period .
3. It should not be incapacitated by the explosive forces although it need not withstand them.

( Further work should be done to enable such systems to survive explosion effects rather than witstand them.)

4 The support system in this haven should be directed at supplying isolation from poisonous atmospheres and provide life sustaining first-aid only.

5 The main purpose of this have will be to workers suffering from the effects of an incident a place the know they can reach, a place where they can regroup and consolidate befor venturing out to a place of safety amd from where they know there is infrastructure to allow them to reach this place of safety.

6 Stored in this haven will be a method that will allow the worker to travel to this further refuge bay where he can saty for extended periods.

Assisted Rescue Phase

After those that were able to reach the safe haven have consolidated their position and hace waited a long enough time to be sure that those who could reach the haven would have done so they can move out to the more permanent refuge bay. Movement to this bay will be done under the following general conditions.

1 The movement of workers will be done using established infrastructure that will enable them to reach the refuge bay even in conditions of zero visibility.

2 The infrastructure should be such that it will enable all workers to reach this refuge bay.

3 This infrastructure should be such that it will survive the effects of an explosion and be usable after such an incident.

4 The route followed should be such that it does not hamaper the progress of workers to the refuge bay.

5 The air supply given to workers should be such that it will allow workers to reach the refuge bay with a level of safety built in.

The requirements for the refuge bay in this second phase would be the same as for the present refuge bays.

The effect of this altered strategy is thus to assist the workers to negotiate the distance between the working place and the refuge bay by introducing an additional stage which can be reached and where they can obtain an air-supply to travel the longer distances. From this point there will also be a clear indication of how to reach the refuge bay.