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EXECUTIVE SUMMARY

Background

In 1986 the Moura No.4 Underground Coal Mine Explosion cost the lives of 12 men. The Warden's Inquiry (1987) found that the flame safety lamp was the most probable cause of the explosion. In 1989 the Queensland Government decided to carry out further investigation into the incident after new interpretations of the blast and forensic evidence were formally reported to the Chief Inspector of Coal Mines.

A multidisciplinary research team concentrated on forensic and blast evidence and consulted widely with experts in Australia, New Zealand, the United States, the United Kingdom and the Federal Republic of Germany.

It was planned to produce an integrated report with contributions by the members of the project team.

Qualifying Notes

This report consists of work by researchers attempting to use skills and concepts not available to the Warden's Inquiry of 1986. Expert opinions in the three countries visited, without exception, acknowledge that it is very difficult if not impossible to determine the path or paths which the explosion took. The presence of so many 4-way junctions and the unpredictability of the behaviour of explosions when passing along such junctions present a task of major magnitude in attempting to model any explosion, or indeed in trying to decide in which direction the explosion passed through the Moura No.4 Mine roadways.

Recognising the reaction of skilled experienced investigators of coal mine explosions in other countries, it is not surprising that there were difficulties in assembling this report. It is emphasised that individual authors do not necessarily agree with the views of other authors. That will become abundantly evident to the reader and serves to highlight the complexity attached to analysing the available evidence in the network of roadways affected by the explosion. The contributions by various authors have been incorporated **in their entirety** into this report to give full expression of their views. The only exception to this is **modification** of the information supplied by the authors to achieve clarity and consistency in the description of various locations at Moura No.4 Mine.

The Re-Analysis

The network of roadways involved in the explosion and consisting of five headings and a number of cut-throughs (c/t) presented a difficult task to researchers trying to trace the direction of explosion airflows. The explosion was initiated in the goaf area or near to it. The void in the goaf necessarily presented another complication in the research into the path(s) of the explosion.

In addition to these factors there is the matter of the caving of the goaf which may have occurred either immediately before or after the initiation of the explosion. Evidence from personnel who were in the Main Dips Section immediately prior to the disaster indicates that the production crew had no apprehension of immediate danger and the ventilation of the working area was good. The disposition of the face equipment suggests that the crew had made an orderly withdrawal from the working face in anticipation of a substantial goaf fall, immediately prior to the explosion.

The emission of methane was a considerable problem at Moura No.4 Mine and in the Main Dips Section in particular. Methane layering in the goaf area would be normal in these circumstances. In the event of the fall occurring pre-explosion an explosive mixture of methane/air/coal dust could have been created in the vicinity of the goaf as well as within the goaf area.

Various hypotheses have been thoroughly examined in the course of this project in the belief that conclusions drawn from the research would be of benefit to the mining industry in the future. Specifically the work could assist in improving mine design and operation. Should such a disaster occur in the future engineers and scientists would be able to ensure a thorough investigation so that the cause of such an event could be determined beyond doubt.

Whilst the flame safety lamp was considered the probable source of ignition there remained concern that the impact of rock on rock or rock on steel may have provided the ignition source. Because of this concern reports of earlier disasters overseas have been examined and are discussed in Chapter 4. It has to be borne in mind that in these reports, frictional ignition from rock impact was stated to be the likely or probable cause. There is no clear evidence that it was the cause of ignition in any of those explosions. It is also noteworthy that in the past thirty years ignition from the impact of rock on any material has not been viewed as a likely or probable cause by inquiries into coal mine explosions. During this period techniques for investigating mine explosions have been improved and this may have enabled conclusions to be drawn regarding the source of ignition.

Precis of Findings

1. **Forensic Pathology and Modelling**

   These have potential for assistance in determining the path of an explosion and therefore its origin. Modelling has not yet been developed to the degree where it can replace full scale gallery testing. This is certainly true of the Moura No.4 Mine incident. The hypotheses on which re-analysis was attempted in this project have not been sustained.

2. **Source of Ignition**

   The work carried out has not resulted in any better understanding of this. It is still not possible to confirm or deny that the safety lamp was the source. However it can be stated that testing at SIMTARS has shown that the damage to the Moura No.4 Mine safety lamp gauzes could not have been caused by heat from a source external to the lamp. This project has not produced any evidence to challenge the Findings of the Mining Warden's Inquiry.

3. **Structuring of Future Investigations**

There is a need for more thorough investigation involving experienced mining/electrical/mechanical engineers together with scientists with experience in blast/flame/dust and air sampling and analysis/forensic science and pathology. Laboratory services need to be immediately available. The results of the investigation should be assembled by the Chief Inspector of Coal Mines for provision to the Mining Warden's Inquiry.

4. **Liaison**

The Chief Inspector of Coal Mines should establish liaison with Police and Health Departments as well as SIMTARS. Personnel in those organisations together with the Coal Mines Inspectorate should be prepared for any future mine explosion investigation. The role of mining companies and union representatives is of course already defined in practice but these parties must be made aware of liaison established by the Chief Inspector of Coal Mines.

5. **Facilities for Forensic Pathology**

These are required either at regional centres or in Brisbane.

6. **Protection of Life**

The hazard of ignition/explosion can be eliminated by the removal of one of the conditions requisite to such an event. This can be achieved by inertisation or preventing ignition. The work described in the report has again highlighted the need for preventive measures to be adopted and priority needs to be given to these. Ongoing research priorities are goaf inertisation and the elimination of frictional ignition by machines.

FOREWORD

In his book "The Peaks of Lyell" (1954) the eminent Australian historian Professor Geoffrey Blainey wrote of the North Lyell Mining Disaster, Tasmania, 1913. The work contains the following quotation from the report of the Royal Commission which investigated the mine fire -

"We regret that, from lack of convincing evidence on several matters arising in the course of the inquiry, we cannot report with that degree of certainty which we should desire. Forty-two men are said to have lost their lives in various parts of the mine; and, with so many voices lost to us in the silence of death, the evidence is necessarily incomplete, and we can only deplore the fate of those whose testimony concerning the happenings in the mine on the fatal 12th of October will never be given before an earthly tribunal".

These words apply equally to the Moura No.4 Underground Mine Explosion of 1986. This explosion research report produced in 1990, some seventy-seven years after the North Lyell disaster has used all information that it has been possible to glean in the Moura No.4 explosion aftermath without the *"voices lost to us"*.

Many people have given of their best to try to analyse what occurred at Moura No.4 Mine. The authors of this report wish to place on record their gratitude to:

- The many employees of Moura No.4 Mine.
- Experts within Australia and of New Zealand, United States of America, United Kingdom, Federal Republic of Germany, together with their respective organisations.
- The Project Review Committee which included representatives of The Department of Resource Industries, Coal Association, Mining Unions and Police Force in Queensland.

All these people displayed total commitment in assisting the research team and ensuring that the outcome of this project is the best possible in the circumstances.

Disasters such as the Moura No.4 explosion generally occur as a result of a combination of factors. In some cases these include the human factor. There is no indication to even suggest that there was a human factor in the fatal train of events in the Main Dips Section. The evidence examined suggests that the section crew members were overwhelmed by factors beyond their control - the development of an explosive mixture and a source of ignition which still cannot be absolutely determined.

Mining is not the only industry having potential hazards in its operations. In many industries it can never be said that a disaster will not occur. Constant vigilance has to be exercised in most industries and in none of them more so than in mining where the balance of the forces of nature is of necessity upset.

Replacement of recommendation [illegible]

RECOMMENDATIONS

Introduction

The ignition source considered by the Warden's Inquiry to have been the most probable trigger for the Moura No.4 Mine explosion was the flame safety lamp. The use of such a lamp has since been prohibited in Queensland coal mines. Even so it cannot be stated with certainty that removal of the lamp will ensure that such a disaster will not occur in similar circumstances.

Other potential sources must therefore be taken into account despite the fact that it is not possible to determine that any one of them caused ignition resulting in the Moura No.4 Mine explosion. The recommendations are therefore submitted in order of priority and the first of these is aimed at prevention of mine explosions.

1. **Inertisation**

   Research including study of existing overseas practice for rendering inert the atmosphere in a goaf.

2. **Training**

   Underground coal mine personnel to be made aware of risk of frictional ignition by machines impacting on rock where flammable gas is present.

3. **Flame Suppression**

   Research/investigation be undertaken to determine how underground coal getting equipment can be fitted with means of preventing ignition of flammable gas by machines.

4. **Contraband**

   Enforcement of regulations to eliminate use of materials underground in coal mines which are able to cause an ignition of flammable gas. Examples are prohibition of certain alloys and the use of hoses other than the fire-resistant, anti-static (FRAS) type.

5. **Structuring of Scientific Investigation of Mine Explosions**

   The Chief Inspector of Coal Mines to be charged with the responsibility of conducting such investigation into any future incident in the manner described in Section 8.4 of this report. The investigation report should be made available to the Mining Warden for purposes of Inquiry into the cause.

6. **Liaison with other Government Departments**

   To facilitate the foregoing recommendation the Chief Inspector of Coal Mines should arrange close liaison with the Queensland Police Force and the Queensland Health Department as well as SIMTARS to ensure prompt action in the event of an underground mine explosion. It is vital that all personnel who would be involved in explosion investigation be prepared for their roles.

7. Forensic Pathology

Adequate facilities need to be made available in regional centres to obtain the maximum amount of information needed to investigate the cause of an explosion. Alternatively arrangements can be made for speedy transportation to Brisbane and the forensic work carried out there.

8. Recording of Information in the Mine

It is recommended that a photographic record be made of explosion-affected mine workings at the earliest opportunity. If at all feasible this should be carried out before the affected area is disturbed. While the rescue of personnel is paramount it is important that the area be photographed before any, or least, disturbance is caused to the explosion scene.

The use of a video camera complete with voice recording would provide the most effective means of gathering information. The person used for this work would need to be skilled and trained to wear self-contained breathing apparatus.

9. Further Research

Priority should be given to prevention of mine explosions rather than sophisticated methods of post-explosion investigation. This can be achieved by eliminating one of the conditions which have to coincide for an explosion to be possible. These conditions include:

- Presence of flammable gas within a relatively narrow range - and coal dust concentrations.
- Source of ignition.
- Adequate supply of oxygen.

Elimination of one of these conditions is achievable and efforts at SIMTARS should be directed to this end.

REVIEW OF THE COAL MINE EXPLOSION RESEARCH PROJECT REPORT

BY

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The inspection of a coal mine subsequent to an explosion has to be systematic, methodical, and scientifically sound. All available investigatory techniques should be used to provide evidence as to why and how the explosion occurred. All evidence should be permanently recorded so that a review is possible at a later date.

This Report describes in detail all the evidence provided at the Warden's Inquiry into the Moura No.4 Mine explosion, together with other material collected as a result of a further investigation into that disaster. Emphasis has been placed upon the contributions that can be made by forensic science and pathology, plus physical and mathematical modelling.

Unfortunately the Report does not describe a dispassionate consensus view of the reviewing team, there is obvious evidence of individuals promoting their favoured hypothesis.

Deductions and interpretations of photographic evidence must be scientifically sound having considered all possible explanations for the details recorded. As far as possible, other than to save life, all items of note should be photographed in detail before being disturbed. It must be remembered that the after explosion condition and position of any item may not reflect the situation existing at the time of the explosion. In the Moura No.4 mine disaster there were two events, that may have occurred concurrently or sequentially namely:

(1) a major collapse of the roof in the goaf, and

(2) an explosion.

Under such circumstances interpretation, of what is normally an extremely difficult task, becomes almost impossible.

Evidence produced from physical and mathematical models is only as good as the input data and the inherent accuracy of the modelling procedures and assumptions.

In spite of all the extra material provided in this Report I come to the conclusion that there is no evidence that clearly establishes the cause of the Moura No.4 mine explosion.

Nevertheless the report emphasises that:

(1) the flame safety lamp can be a potential source of ignition under certain atmospheric conditions, and

(2) there is a need to provide an inert atmosphere in coal mine goafs where there is the possibility of explosions associated with incendive sparking.

14th June, 1990

CHAPTER 1

BACKGROUND TO PROJECT

By
I. Roberts, P. Golledge

1.1 Introduction

1.1.1 Overview of the Moura No.4 Underground Coal Mine Explosion

An underground mine explosion occurred at Moura No.4 Mine in Central Queensland on 16 July 1986. Twelve miners were killed. They had been employed on the extraction of pillars in the Main Dips Section of the mine. Their bodies were recovered on 23 July 1986 after an extensive recovery operation.

The Warden's Inquiry pursuant to section 74 of the Queensland Coal Mining Act was conducted in Rockhampton from 9 to 27 February 1987.

The Inquiry found that a roof fall had occurred in the Main Dips Section goaf and that the resulting wind blast blew a mixture of methane, air and coal dust into the working area. The Inquiry also found that:

. An explosive atmosphere developed in the working area and in particular around the deputy's flame safety lamp.

. An ignition occurred creating a violent explosion which caused extensive damage throughout the section.

The Warden's Inquiry Report on the Accident on 16 July 1986 considered a number of potential ignition sources but discounted all the sources of ignition considered except for two, namely frictional ignition and the flame safety lamp. The Inquiry Report [1] [1] states -

"The members of the Inquiry are of the view that frictional ignition from sandstone on sandstone of the type found at Moura is highly unlikely to have been the source of ignition."

The Inquiry Report further states -

"Considering all the evidence and the expert opinions presented, the members of the Inquiry have formed the view that the most likely source of ignition was the flame safety lamp."

"The Inquiry considered that the flame safety lamp, although properly assembled, was the most likely source of ignition".

---

1 [ ] Numbers in parenthesis refer to references in Appendix L.

1.1.2 Background to New Research

A coal mine explosion is capable of producing lethal injuries to a large number of persons underground at the time of the explosion, causing widespread damage to equipment and ventilation stoppings within the mine, and damage to mechanical devices and building structures in proximity to the mine entrance. A major mine disaster is also responsible for long term emotional problems for any survivors, the families and friends of the deceased, members of the mines rescue brigade, other mine personnel (including management) and members of the mining community. The loss of coal production can usually be measured in millions of dollars, particularly when the mine is subsequently closed. There are also long term related costs.

The progression of an explosion in a mine is far more complex than an explosion in an open area on the surface due to the presence of many factors which are peculiar to mining. Methane gas which is much easier to ignite than coal dust may be present. Concentrations of fine coal dust occur on the roof, walls and floor of mine roadways as a consequence of mechanised mining operations and such dust is more explosive than coarser dusts which were produced in the days of hand mining. Changes of cross-sectional area of the mine roadway may result in an acceleration or deceleration of the explosion. Levels of stone dusting may be insufficient in all roadways to prevent propagation of an explosion.

Oxygen, an ignition source, and a source of fuel must be present simultaneously for an explosion to initiate. Methane is usually present in mines but the quantity of ventilation is normally adequate to ensure that its concentration is well below the lower explosive limit. With the precautions taken in coal mines nowadays, some combination of unusual circumstances must occur prior to a mine explosion. In a mine with multiple roadways (as was the case at Moura), the problem of determining the site of the ignition source and the progress of the explosion along the roadways is one of great complexity. Such a task requires an input from persons in a wide range of disciplines including:

. Mining, Mechanical and Electrical Engineers.

. Mines Rescue Personnel.

. Mines Inspectors.

. Union Inspectors/Representatives.

. Mine Management.

. Chemists.

. Scientists of various disciplines.

. Physicists.

. Geologists.

. Metallurgists.

. Pathologists.

. Police.

. Various experts in blast analysis, methane emissions, etc.

Investigation of Explosions

In Queensland the responsibility for the investigation of an explosion at a coal mine rests with the coal mine inspectorate of the Department of Resource Industries, under the Coal Mining Act 1925-1981. However, under the Public Safety Preservation Act an emergency situation can be declared by a Commissioned Officer of the Queensland Police. Under this Act an emergency situation includes any explosion or fire or escape of gas, any accident involving a vehicle or any other accident that causes or may cause a danger of death, injury or distress to any person or loss of or damage to property.

For the Moura investigation, technical and scientific support was provided by mine management, mine inspectorate, staff at the Safety in Mines Testing and Research Station (SIMTARS), the Department of Health and the University of Queensland Department of Mining & Metallurgical Engineering. Other experts from Australia and overseas also provided valuable assistance. During this investigation the scope of the scientific and other investigations was under the direction of the Chief Inspector of Coal Mines.

Coal mine explosions have occurred far less frequently in Australia than in overseas countries. Scientific investigation of methane and coal dust explosions has resulted in better understanding of the mechanism of explosions and means to avoid explosions.

With greater concentration of underground production on longwall faces, there should be less likelihood of an explosion because of improvements in ventilation, strata control and environmental monitoring systems. The development and operation of longwall underground coal mines still requires multiple roadways as does room and pillar systems of mining. There is always a risk that an explosion could occur due to the explosive properties of both methane and coal dust, and potential sources of ignition such as electrical equipment and friction.

Because coal mine explosions are nowadays relatively infrequent events in major coal producing countries, there are few experts with depth of experience in the investigation of such explosions. If the present trend continues, and explosions become less frequent in the future, finding the necessary expertise to investigate an explosion will become increasingly difficult. Australia does not have a history of decades of mine explosion research, as does the U.S. with its Bureau of Mines, the U.K. with the Health and Safety Laboratories at Buxton, or Poland with the Experimental Mine Barbara.

In those Countries there is a long history of safety research leading to improved safety in coal mining operations and the removal of hazards which might result in explosions. Whilst that work continues overseas in establishments such as the British Coal Corporations Headquarters at Bretby, there is concern that experts in pure explosion research are becoming rare. This highlights the need for developing experts and facilities for this work in Queensland.

1988 Report on Evidence

In September 1988 a report by Drs Leivesley and Romaniuk which reviewed evidence from the Moura explosion was presented to the Chief Inspector of Coal Mines.

The 1988 Report was initiated when training material was being collected for industry safety programs by Dr Leivesley. One photograph of the Moura explosion effects showed a diesel-engined vehicle known as a Mine Rover. The vehicle front seats showed apparent evidence of occupancy during the explosion and there were apparent directional indicators of the flame and blast pressure waves on the seats.

Detailed examination of the photograph showed then that the apparent outline of the head of one of the victims had been burnt into the driver's seat back. The front passenger seat showed signs of being occupied during the explosion and a rear seat showed what appeared to be a flash shadow of another occupant.

Dr Leivesley and Dr Romaniuk (an oral pathologist who had attended the Moura post-mortems) prepared a formal report to the Chief Inspector of Coal Mines after detailed work was undertaken on the post mortem evidence, photographic evidence of blast, and the mine disaster plan.

The initial hypothesis for the review was that the source of the explosion was in an area of the mine forward and to the right of the mine rover. A study of the photographic evidence revealed that a flash had travelled outbye from the goaf area toward the vehicle and from the right hand side (when looking inbye from the vehicle). The preliminary work undertaken in the report concentrated on establishing which forensic facts supported this hypothesis. Other hypotheses of source of blast in relation to the post impact positions of the 12 victims were also explored.

The recommendations in the report were that overseas experts be involved in further investigation, that industry be involved, and that examination of the explosion be conducted until there was conclusive evidence of the cause of the explosion. There was concern that there could be false assumptions on safety within the industry following the conclusion that the flame safety lamp was the most probable cause.

The report concluded with the statement that the work had been limited and a much more detailed study was required.

Action Taken Following the 1988 Report

Discussions within the then Department of Mines (now Department of Resource Industries) including SIMTARS resulted in a submission to State Cabinet in August 1989. The then Minister for Mines in this submission recommended that funds be allocated for further investigation into the Moura No.4 Underground Mine explosion. In particular the funds were to enable investigation into the use of forensic evidence in the interpretation and understanding of coal mine explosions generally.

The Cabinet Budget Committee on 4 September 1989 decided as follows:

"That the further investigations in aspects of coal mine explosions proceed as outlined in the Submission" (See above).

The Submission provided for the co-operation of the Department of Resource Industries, Department of Health, Police Department and co-ordination by SIMTARS utilising the assistance of various outside expert consultants.

1.1.3 Aims and Objectives

The aim of the investigation is to analyse the Moura No.4 explosion to identify whether the results of forensic pathology, blast analysis, computer modelling and other factors can be used to assist in the establishment of location of ignition source and the development of a coal mine explosion.

The objectives include:

. To determine the extent to which forensic pathology supported by computer modelling can assist the conventional techniques in explosion investigations by providing evidence on blast direction, magnitude of blast pressure, flame temperature, body movement and the like.

. To identify from the forensic pathology evidence relating to the Moura Mine explosion whether there are indications of the direction of the blast and information on the causation of the explosion.

. To identify any additional characteristics of the blast at Moura which provide information on the pattern of the blast and the causation of the blast.

. To identify whether the structuring of all future scientific investigations and inquiries following mine disasters needs to be reconsidered.

. To identify what new information on cause of blast has been generated by the research.

. To identify the implications of all the findings for the protection of life in underground coal mines.

Basic Research Areas

Forensic Pathology - it was necessary to achieve a full analysis of the Moura Mine explosion victims. It was also necessary to obtain all the indications of blast and causation that can be provided by the post mortem evidence.

Blast - there was a need to understand the blast pattern in the case of the Moura Mine explosion and therefore to determine what additional characteristics of blast have to be considered.

Investigation Processes - from this project it may be possible to structure all future investigations and inquiries into coal mine explosions.

Causal Analysis - new information on the source of ignition resulting in the Moura Mine explosion. There could be implications for general safety in underground coal mining.

1.2 Research Program

1.2.1 Structure of Project Team and Review Committee

(a) Project Team

Under the overall general management of Mr P. Dent, Director, SIMTARS a research team was formed in September 1989 consisting of:

. Dr P. Golledge, Project Manager, M.Sc, Ph.D, (Mining) University of Wales, Manager Research and Technical Services, SIMTARS.

. Dr S. Leivesley, a research consultant in the field of emergency planning and major incidents, Ph.D, Social Policy & Administration (London).

. Dr K. Romaniuk, a consultant in oral pathology who was present at the post mortem examinations of the casualties of the explosion at Moura Mine, Ph.D, R.F.D., BDS(NZ) MDS (Otago), Dr.med.dent (Munster), Ph.D., FRACDS.

. Dr A. Green, Manager Research, Londonderry (NSW) Occupational Safety Centre; Ph.D, (Edin) C.Chem, Consultant in Fire and Explosion Phenomena.

. Mr I. Roberts, a Chartered Engineer (Mining) and a consultant in coal mining. Former Chief Inspector of Coal Mines, Queensland with extensive experience in the coal mining industry as mine manager and director of coal mining companies.

Provision was made for consultation with Australian and overseas experts and research organisations as necessary.

(b) **Review Committee**

The Committee under the chairmanship of Mr P. Dent consisted of the above team members and

. Mr J. Torlach, Program Manager, Mine Safety and Technology.
. Mr B. Lyne, Chief Inspector of Coal Mines.
. Mr R. Bancroft, Senior Inspector of Coal Mines.

All of the Queensland Department of Resource Industries

. Mr J. Sleeman, Queensland Coal Association.
. Mr G. Duncan, Occupational Health & Safety Officer, Queensland Coal Association.
. Mr M. Best, District Union Inspector, Queensland Colliery Employees' Union.
Researchers . Mr W. Allison, District Union Inspector, Queensland Colliery Employees' Union.

1.2.2 Timetable and Progress of Research Project

The timetable of the Research Project was designed to allow for work in Australia and with international experts overseas. Weekly research meetings were held throughout the project period (October 1989-June 1990) and monthly review meetings were attended by the Review Committee to receive reports on progress and to contribute to the research program.

Preliminary work in September/October developed two scale models. The scale models of the Main Dips Workings and the workings in the vicinity of the 26 X-cut are shown in Appendix J. Early work concentrated on the review of all literature, reports, photographs and other material that was available on the Moura Mine explosion. Searches of various departmental sources identified a collection of information much of which had not been part of the formal presentation of evidence to the Warden's Inquiry. Case history material was prepared on the 12 victims and documented with assistance of reports and verbal interviews with overseas experts.

A network of Australian and overseas contacts was prepared through the multidisciplinary team contacts and the assistance of the Review Committee. In Australia a specialist from police forensic laboratories in Victoria was consulted. Overseas countries provided a variety of experts representing a core representation of international research on blast and forensic methodology. The countries involved included the United States, United Kingdom, New Zealand, Federal Republic of Germany and Norway. A full summary of the experts involved is supplied in Appendix K.

The Queensland Police Department nominated two officers to work on the project and these officers reviewed internal departmental information on the Incident and prepared material for recommendations to the Police Commissioner on forensic investigation methods for future incidents. The Department of Resource Industries provided assistance in reviewing all information on the project and Inspectors were involved in discussions on the evidence and on the development of further research questions for the team.

Dr Green provided a research link between SIMTARS and Londonderry and commuted to Queensland for various working party/review committee meetings. Dr Green developed with the assistance of Londonderry resources the methodology for computer modelling to test some of the dynamics of the explosion at Moura.

Londonderry also provided further modelling for the testing of the timing of various effects of the explosion. This modelling consisted of a 1:54 scale model with gas experiments which were photographed.

Various hypotheses of the ignition of the explosion were explored by the research team with the help of the physical models. The forensic details on the victims and the equipment underground were used to gain information on the progress of the explosion. Hypothesis testing was a continuous process.

The research team travelled overseas for consultations for three weeks and used portable scale' models to undertake further analytical work with overseas experts. These consultations provided further details on the explosion and forensic evidence and allowed specific hypothesis to be accepted for further consideration and negated other hypotheses which had previously been considered.

Early in the program conclusions on the need for detailed scientific investigations became obvious and work was undertaken on possible recommendations to solve this problem. It was recognised as a joint problem between police, health, and mining departments within State Government and the project provided a basis for representatives to consult and work together on the solutions.

The report was prepared by all researchers with the assistance of the overseas experts detailed in Appendix K.

1.3 Project Structure

The project structure provided for input to the Review Committee from all sections of the coal mining industry. The Committee assisted with the task of interpreting the applications of the findings for industry and relevant safety procedures.

The Review Committee, chaired by the Director of SIMTARS, Peter Dent held monthly meetings with the researchers and participated in all phases of the research. Contributions by the Committee members assisted the core research team with interpretations of the mining conditions at Moura, contacts with relevant persons who had underground experience at Moura, contacts with overseas experts who were to be consulted and expert advice on circumstances of the Moura explosion.

Police Liaison

Two officers with the Queensland Police Department were designated as liaison officers under direction of Superintendent D. Buckly (Operations). Inspector N. Sprenger and Sergeant J. Hopgood provided the police research component for the report.

Australian and Overseas Researchers

For the six months of the Research Program extensive consultation was undertaken with Australian and overseas experts.

Review Consultant Research Project

Professor D. Rowlands, University of Queensland, Department of Mining and Metallurgy reviewed the final report and considered the overall findings independently of the project team.

1.3.1 Methods for Study

The explosion research within the current project was planned in three phases. The first phase was designed to meet the objectives listed above and to be completed by end June 1990.

The work program for Phase 1 is summarised below:

. Undertake a preliminary study over a period of 6 months and at the completion prepare a written report for consideration by Cabinet.

. Orient the research after literature searches and consultation with Australian researchers, mining engineers and overseas experts by means of group discussions and overseas travel as appropriate.

. Seek assistance from specialists including police forensic experts and various scientists particularly where information is not publicly available.

- Develop processes for the modelling stage and allow scientific hypotheses to be formulated.

- Carry out literature searches.

- Undertake further forensic work.

The Phase 1 written report is prepared for submission to the Minister for Resource Industries. The results were intended to indicate any requirement to proceed to further work.

Continuing research could involve a second phase to establish modelling with international assistance for the development of enhanced protection against explosions in underground coal mines and to undertake continued research into forensic science. The work program for this phase would involve construction of small scale models, involvement in large scale modelling in international facilities and developing evidence from forensic science on explosion effects.

1.3.2 Visit to US Bureau of Mines

Drs Golledge and Leivesley and Mr B. Lyne visited the Pittsburgh Research Centre of the U.S. Bureau of Mines at Bruceton on 15 and 16 March 1990. Information on the Moura explosion was presented to the following staff of the Bureau of Mines:

Dr N. Greninger	Chemical Engineer (Fires & Explosions)
Dr W. Courtney	Supervisory Research Chemist
Dr M. Hertzberg	Research Chemist
Dr J. Edwards	Research Physicist
Mr K. Cashdollar	Research Physicist
Mr A. Furno	Supervisory Physical Scientist (Retired)
Mrs L. Snyder	Physicist
Dr Cohen	Physicist

All the above staff have worked at the Bureau of Mines for periods of 10 years or more in many aspects of explosion research both at the laboratory level and in full-scale explosion testing at the Bruceton experimental mine and at the Lake Lynn Laboratory (explosion gallery).

There was general agreement that the ventilation circuit at Moura Mine was very complex and would result in a coal dust explosion the path of which might not be possible to determine. The message was reinforced that the pressure, flame and velocity of coal dust explosions fluctuate widely even in straight explosion galleries with as uniform as practicable dust loading and using a well mixed methane source and an electric ignition source.

At Moura Mine with an ignition source in the area of the shuttle cars or in the goaf it was these experts' opinion that the path of the explosion could not be determined by any known method due to the complexity of mine roadways and the presence of many intersections.

The research work of the Bureau was brought to our attention where it has been demonstrated and is known from coal mine explosions that mild explosions can cause considerable damage if material, equipment or construction work are in its path. Weak explosions are considered to develop an overpressure of about 30 kPa, moderate explosions from 70 to 105 kPa and strong explosions usually in excess of 300 kPa.

On being shown and allowed to examine the flame safety lamp involved in the Moura explosion there was much discussion about the possibility of the lamp being the ignition source compared with an ignition in the goaf. No research into the behaviour of the flame safety lamp has been carried out in the U.S. for several decades. There was general agreement that the effects of heating observed in the lamp were the result of activity within it rather than that of an external flame. With thermal activity over a period of some seconds (about 10) it was recognised that the external gauge temperature might be sufficient to ignite an external atmosphere, particularly if coal dust of appropriate size range were present simultaneously with methane gas.

As to rocks acting as a frictional ignition source it was agreed that this might be possible in a mine situation although very difficult and costly to simulate in the laboratory.

The SIMTARS group was then joined by Mr C. Stephan of the Mine Safety and Health Administration who is the Senior Mining Engineer responsible for providing technical support in the areas of explosion flames and forces. He expressed the view that frictional ignition had not been given as a source of ignition over the past 15 years or so when better methods of investigation had been used to establish the most probable cause. It appears that frictional ignition was given as the cause of a number of explosions on previous occasions when no other explanation had been found.

The simultaneous occurrence of incendive sparking and a methane concentration within the right range is thought to have a very low probability.

Mr Stephan stated that MSHA would not carry out any detailed metallurgical examination of the gauges in any flame safety lamp recovered after a coal mine explosion if the lamp performed in accordance with approval testing procedures.

On 16 March 1990 in the company of Mr K. Cashdollar a visit was made to the Lake Lynn Laboratory of the U.S. Bureau of Mines. A video presentation of mine explosion was given followed by a tour of the explosion gallery.

Experimental work is still confined to a single entry configuration with testing of concrete block stoppings in adjacent c/ts. The data acquisition and computer system, a Micro VAX II operating under VMS, is configured with 68 data acquisition channels to handle data from the single entry configuration. To extend the data acquisition system to cover a room and pillar configuration would necessitate doubling of both data acquisition and computing capacity.

Current full scale explosion research involves the testing of concrete block stoppings against the overpressure developed in a methane explosion. Concrete block stoppings, mortared and of interleaved double thickness blocks supported at the sides and top with steel channel bolted to the roof, floor and ribs and with a central reinforcing column have been tested successfully against a methane explosion with an overpressure of approximately 315 kPa without failure of the stopping. Further experiments are designed to investigate the explosion strengths of different types of block stoppings.

Laboratory demonstrations of a dust deposition meter, incombustible dust monitor, remote methanometer, research on spontaneous combustion and developments in ventilation of longwall to reduce respirable dust concentrations were witnessed.

Research carried out at the Bureau of Mines indicates that failure of block stoppings is likely to occur at about 105 kPa if the stopping is anchored securely into the roof, floor and falls. Without such anchoring failure will occur at lower overpressures.

Implies research [illegible] done?

There was some discussion about the possibility of an ignition produced by a piezzo electric source due to distortion of the quartz crystals by various forces. No research has shown this to be a cause under realistic mining conditions.

1.3.3 Visit to Research and Laboratory Services Division, Buxton, United Kingdom

Dr Golledge and Mr B. Lyne visited the Explosion and Flame Laboratory (EFL) of the Health and Safety Executive and presented information on the Moura explosion to the following:

Dr B. Thomson	Director
Mr P. Williams	Deputy Chief Inspector of Mines, Bootle, Lancs.
Dr J. Barton	Deputy Director
Dr G. Lunn	Fire and Explosion Research
Dr D. Pritchard	Incident Investigation
Mr F. Powell	Retired (Formerly Frictional Ignitions)
Mr R. Brookes	Retired (Formerly Explosion Investigations).

The Buxton staff were very experienced; Messrs Powell and Brookes having spent a working lifetime at Buxton and the remaining staff have at least 10 years experience in this area of research.

The Moura lamp was the source of an interesting discussion. EFL are testing a similar model flame safety lamp in a closed circuit chamber at air velocities up to 15 m/s. To date they have not achieved 'fusing' of dust particles to the glass of the lamp which occurred during the Moura explosion and which has been simulated at SIMTARS. This may be due to intrinsic properties of the dust rather than differences in laboratory techniques. Both EFL and SIMTARS have achieved repeatability of results at their respective laboratories and indeed some degree of reproducibility. EFL has observed the same incandescent burning within the inner gauze and transition to the space between the two gauges at the top and ignition of the external flammable atmosphere without the bonnet on.

There was general agreement that activity in the Moura lamp occurred prior to its movement to its final location behind the offside front wheel of the shuttle car. There was no support for the suggestion that the heating in the lamp was externally caused. It was believed that the lamp and deputy were separated before the lamp reached its final location. Buxton has achieved a flame external to the lamp with the bonnet in place under conditions of high dust concentration. At the time however the tests were being conducted with an external atmosphere which was not explosive. To date the experiment has not been repeated.

It is reasonable to say that an ignition by the flame safety lamp might be possible if the surrounding atmosphere has a methane concentration above the lower explosive limit and a dense coal dust cloud is present.

Information will be exchanged between SIMTARS and Buxton about existing and future research into the behaviour of the flame safety lamp.

Dr Golledge had the opportunity to inspect the experimental apparatus used at Buxton over a number of years to investigate frictional ignition of methane. According to Mr Powell, who was responsible for most of the experimental work of a number of years, no ignition has been achieved in the laboratory with rock/rock contact in methane atmospheres, other than by means of a grinding wheel.
The consensus of opinion was that frictional ignition might occur in a falling goaf, although this has been a rare occurrence but it may not be possible to simulate the combination of circumstances in the laboratory.

With regard to the possibility of a piezzo electric ignition source Powell stated that some research had been carried out on a number of sandstone samples under simulated vertical stress conditions. No incendive spark was produced. During these experiments there was no attempt to simulate a high horizontal stress which characterises many underground coal mines in Australia.

1.3.4 Visit to Experimental Mine Tremonia, Federal Republic of Germany

Dr Golledge and Mr B. Lyne visited the Experimental Mine Tremonia in FRG which has recently become part of the newly formed German Mining Technology group Deutche Montan Technology (DMT) which includes the former Steinkohlenbergbauverein (STBV), Westfalische Berggewerkschaftskasse (WBK) and Versuchsgrubengesellschaft mbH (Tremonia) organisations. Information on the Moura Mine explosion was presented to:

Dr Ing J. Michelis	(Head of Dept of Explosion & Shotfiring)
Mr G. Muller	Physicist
Mr B. Margenburg	Physicist.

and various technical matters were discussed with DMT.

Dr Michelis is a mining engineer who has been involved in explosion research for more than two decades and during this time has carried out a number of post explosion investigations. He still holds a very strong view that the overpressure developed during the Moura Mine explosion has been overestimated in work done in Australia. Tremonia Mine is well instrumented, and according to UK experts, probably the best in the world. Results have been obtained from over 4,000 explosions. The damage to the victims at Moura (photographic and other evidence) are not consistent with the high overpressures of 300 kPa or more suggested by work done in Australia. Dr Michelis has suggested that the maximum overpressure at Moura was probably less than 100 kPa. Experience at Tremonia indicates that at 300 kPa there is massive damage to equipment on a much greater scale than occurred at Moura.

At Tremonia Mine methane and coal dust explosions are usually initiated near the inbye end of the 1,000m long explosion gallery where the cross sectional area is $20m^2$, of the same order as the roadways in Australian coal mines. Explosion proof doors, designed for an overpressure of 300 kPa, and installed in massive concrete bulkheads are used to isolate the explosion from other parts of the experimental mine. The normal dust loading is $300g/m^3$ which ensures that the minimum dust concentration of $125g/m^3$ is achieved during a coal mine explosion when approximately 50% of the dust does not take part. Particle size of the 23% volatile dust is in the size range 22 to 80 micrometres with 90% less than 50 micrometre diameter.

From experiments carried out at Tremonia it would appear that a person standing about 100m from the ignition of an explosion would have about 3 sec in which to react before the arrival of the flame. The sound of the explosion resembles a strong wind rather than the sharp crack of an ignition following explosion by detonation. Microphones in the gallery linked to recorders, together with video cameras and high speed photography have precisely recorded the progress of an explosion to the point of observation. Even from an initiation at the inbye end of the gallery an explosion (methane or coal dust) develops relatively slowly and becomes stronger as it moves outbye.

Experiments also showed that with an explosive wave having a maximum dynamic pressure of approximately 30 kPa, a person could move with a maximum velocity of about 6m/s and could travel some 7m in a time of 3s. The human body can only tolerate a relatively low dynamic pressure but can tolerate overpressures as high as 500 kPa.

The dust deposited on the Moura conveyor rollers was not typical of a German coal dust explosion. This might suggest complex air movement with high dust concentration following rather than at the time the pressure wave and flame were passing.

The explosion at Stolzenbach lignite mine in 1988 was investigated by Dr Michelis. Although the flame from the explosion reached the portal of the mine none of the victims underground were severely burned.

Measurement of oxygen concentration following an explosion at Tremonia has been as high as 5% by volume after a methane or coal dust explosion. The staff at Tremonia and other mines rescue staff regularly enter the explosion gallery immediately after an explosion to restore ventilation, collect samples and any repair work as necessary. Levels of carbon monoxide have been recorded as high as 10% but often do not exceed 1% after a mild explosion.

Movement of bodies was also studied at Tremonia Mine by Dr Michelis and staff and the results of this work were documented in a thesis submitted to the Technical University of Aachen in 1979. A dummy was used of the same mass, surface area and volume as an average miner fitted with a safety helmet, cap lamp and self rescuer. What is quite apparent from studies of movement of the dummy during an explosion is the rotation of the body from the axial plane of the explosion gallery. The dummy in some experiments rotated about the vertical axis and ended up nearly 45° from the centreline of the drift.

Discussion

In most experiments in explosion galleries explosions are ignited at a position that will provide the strongest explosion as soon as possible. This position is at the inbye face end of the explosion gallery. Nagy and Mitchell [3] reported on work carried out at the Bureau of Mines prior to 1963 during which a 15m length of 9.5% concentration of methane was ignited at increasing distances from the face. When ignition occurred at the face the maximum overpressure developed was 175 kPa but when the ignition distance was increased to 14m the maximum pressure developed was reduced to 7 kPa. The confining effect of the face of the drift greatly assists the process of pressure development.

For the Moura Mine explosion two hypotheses have been advanced to explain the ignition source. One is that a frictional spark occurred in the goaf as a consequence of some movement or falling of the roof. In an area some 60m by 50m by 7m high there may have been little confining due to the open nature of the goaf. If this were the case the explosion may have had great difficulty in reaching any reasonable overpressure by the time the pressure wave reached any roadway. There is a large volume to absorb any expansion caused by combustion of the methane or coal dust.

If the ignition occurred in the belt roadway between the continuous miner and the shuttle car the start of the explosion could also have been relatively slow but may have been assisted by the presence of those items of equipment.

Expert opinions from the three countries visited, without exception, acknowledge that it is very difficult if not impossible to forecast the path or paths which the explosion took. The presence of so many 4 way junctions and the unpredictability of the behaviour of explosions when passing along such junctions present a task of major magnitude in attempting to model any explosion, or indeed in trying to decide in which direction the explosion passed through the Moura mine roadways.

If the German experience is recognised and accepted, then the assumptions that the overpressure exceeded 300 kPa and that there was a near detonation velocity in No.4 Supply Road between c/t Nos.22 and 23 (Hereafter this location is referred to as the "taj mahal" so called because of the extensive roof fall which had occurred long before the date of the explosion.) are incorrect. Even for relatively weak explosions the experimental explosion galleries ensure that components which are required to remain in place are heavily braced or anchored to ensure that they are not moved out of position by the force of the explosion. Relatively low dynamic pressures can move steel supports which are not securely anchored. Damage to other metallic objects at Moura was not consistent with a strong explosion but representative of a weak to moderate explosion.

(Roberts/Golledge)

Replacement of
recommendation [illegible]

RECOMMENDATIONS

Introduction

The ignition source considered by the Warden's Inquiry to have been the most probable trigger for the Moura No.4 Mine explosion was the flame safety lamp. The use of such a lamp has since been prohibited in Queensland coal mines. Even so it cannot be stated with certainty that removal of the lamp will ensure that such a disaster will not occur in similar circumstances.

Other potential sources must therefore be taken into account despite the fact that it is not possible to determine that any one of them caused ignition resulting in the Moura No.4 Mine explosion. The recommendations are therefore submitted in order of priority and the first of these is aimed at prevention of mine explosions.

1. **Inertisation**

   Research including study of existing overseas practice for rendering inert the atmosphere in a goaf.

2. **Training**

   Underground coal mine personnel to be made aware of risk of frictional ignition by machines impacting on rock where flammable gas is present.

3. **Flame Suppression**

   Research/investigation be undertaken to determine how underground coal getting equipment can be fitted with means of preventing ignition of flammable gas by machines.

4. **Contraband**

   Enforcement of regulations to eliminate use of materials underground in coal mines which are able to cause an ignition of flammable gas. Examples are prohibition of certain alloys and the use of hoses other than the fire-resistant, anti-static (FRAS) type.

5. **Structuring of Scientific Investigation of Mine Explosions**

   The Chief Inspector of Coal Mines to be charged with the responsibility of conducting such investigation into any future incident in the manner described in Section 8.4 of this report. The investigation report should be made available to the Mining Warden for purposes of Inquiry into the cause.

6. **Liaison with other Government Departments**

   To facilitate the foregoing recommendation the Chief Inspector of Coal Mines should arrange close liaison with the Queensland Police Force and the Queensland Health Department as well as SIMTARS to ensure prompt action in the event of an underground mine explosion. It is vital that all personnel who would be involved in explosion investigation be prepared for their roles.

7. **Forensic Pathology**

Adequate facilities need to be made available in regional centres to obtain the maximum amount of information needed to investigate the cause of an explosion. Alternatively arrangements can be made for speedy transportation to Brisbane and the forensic work carried out there.

8. **Recording of Information in the Mine**

It is recommended that a photographic record be made of explosion-affected mine workings at the earliest opportunity. If at all feasible this should be carried out before the affected area is disturbed. While the rescue of personnel is paramount it is important that the area be photographed before any, or least, disturbance is caused to the explosion scene.

The use of a video camera complete with voice recording would provide the most effective means of gathering information. The person used for this work would need to be skilled and trained to wear self-contained breathing apparatus.

9. **Further Research**

Priority should be given to prevention of mine explosions rather than sophisticated methods of post-explosion investigation. This can be achieved by eliminating one of the conditions which have to coincide for an explosion to be possible. These conditions include:

- Presence of flammable gas within a relatively narrow range - and coal dust concentrations.
- Source of ignition.
- Adequate supply of oxygen.

Elimination of one of these conditions is achievable and efforts at SIMTARS should be directed to this end.

EXECUTIVE SUMMARY

Background

In 1986 the Moura No.4 Underground Coal Mine Explosion cost the lives of 12 men. The Warden's Inquiry (1987) found that the flame safety lamp was the most probable cause of the explosion. In 1989 the Queensland Government decided to carry out further investigation into the incident after new interpretations of the blast and forensic evidence were formally reported to the Chief Inspector of Coal Mines.

A multidisciplinary research team concentrated on forensic and blast evidence and consulted widely with experts in Australia, New Zealand, the United States, the United Kingdom and the Federal Republic of Germany.

It was planned to produce an integrated report with contributions by the members of the project team.

Qualifying Notes

This report consists of work by researchers attempting to use skills and concepts not available to the Warden's Inquiry of 1986. Expert opinions in the three countries visited, without exception, acknowledge that it is very difficult if not impossible to determine the path or paths which the explosion took. The presence of so many 4-way junctions and the unpredictability of the behaviour of explosions when passing along such junctions present a task of major magnitude in attempting to model any explosion, or indeed in trying to decide in which direction the explosion passed through the Moura No.4 Mine roadways.

Recognising the reaction of skilled experienced investigators of coal mine explosions in other countries, it is not surprising that there were difficulties in assembling this report. It is emphasised that individual authors do not necessarily agree with the views of other authors. That will become abundantly evident to the reader and serves to highlight the complexity attached to analysing the available evidence in the network of roadways affected by the explosion. The contributions by various authors have been incorporated **in their entirety** into this report to give full expression of their views. The only exception to this is **modification** of the information supplied by the authors to achieve clarity and consistency in the description of various locations at Moura No.4 Mine.

The Re-Analysis

The network of roadways involved in the explosion and consisting of five headings and a number of cut-throughs (c/t) presented a difficult task to researchers trying to trace the direction of explosion airflows. The explosion was initiated in the goaf area or near to it. The void in the goaf necessarily presented another complication in the research into the path(s) of the explosion.

In addition to these factors there is the matter of the caving of the goaf which may have occurred either immediately before or after the initiation of the explosion. Evidence from personnel who were in the Main Dips Section immediately prior to the disaster indicates that the production crew had no apprehension of immediate danger and the ventilation of the working area was good. The disposition of the face equipment suggests that the crew had made an orderly withdrawal from the working face in anticipation of a substantial goaf fall, immediately prior to the explosion.

The emission of methane was a considerable problem at Moura No.4 Mine and in the Main Dips Section in particular. Methane layering in the goaf area would be normal in these circumstances. In the event of the fall occurring pre-explosion an explosive mixture of methane/air/coal dust could have been created in the vicinity of the goaf as well as within the goaf area.

Various hypotheses have been thoroughly examined in the course of this project in the belief that conclusions drawn from the research would be of benefit to the mining industry in the future. Specifically the work could assist in improving mine design and operation. Should such a disaster occur in the future engineers and scientists would be able to ensure a thorough investigation so that the cause of such an event could be determined beyond doubt.

Whilst the flame safety lamp was considered the probable source of ignition there remained concern that the impact of rock on rock or rock on steel may have provided the ignition source. Because of this concern reports of earlier disasters overseas have been examined and are discussed in Chapter 4. It has to be borne in mind that in these reports, frictional ignition from rock impact was stated to be the likely or probable cause. There is no clear evidence that it was the cause of ignition in any of those explosions. It is also noteworthy that in the past thirty years ignition from the impact of rock on any material has not been viewed as a likely or probable cause by inquiries into coal mine explosions. During this period techniques for investigating mine explosions have been improved and this may have enabled conclusions to be drawn regarding the source of ignition.

Precis of Findings

1. **Forensic Pathology and Modelling**

   These have potential for assistance in determining the path of an explosion and therefore its origin. Modelling has not yet been developed to the degree where it can replace full scale gallery testing. This is certainly true of the Moura No.4 Mine incident. The hypotheses on which re-analysis was attempted in this project have not been sustained.

2. **Source of Ignition**

   The work carried out has not resulted in any better understanding of this. It is still not possible to confirm or deny that the safety lamp was the source. However it can be stated that testing at SIMTARS has shown that the damage to the Moura No.4 Mine safety lamp gauzes could not have been caused by heat from a source external to the lamp. This project has not produced any evidence to challenge the Findings of the Mining Warden's Inquiry.

3. **Structuring of Future Investigations**

There is a need for more thorough investigation involving experienced mining/electrical/mechanical engineers together with scientists with experience in blast/flame/dust and air sampling and analysis/forensic science and pathology. Laboratory services need to be immediately available. The results of the investigation should be assembled by the Chief Inspector of Coal Mines for provision to the Mining Warden's Inquiry.

4. **Liaison**

The Chief Inspector of Coal Mines should establish liaison with Police and Health Departments as well as SIMTARS. Personnel in those organisations together with the Coal Mines Inspectorate should be prepared for any future mine explosion investigation. The role of mining companies and union representatives is of course already defined in practice but these parties must be made aware of liaison established by the Chief Inspector of Coal Mines.

5. **Facilities for Forensic Pathology**

These are required either at regional centres or in Brisbane.

6. **Protection of Life**

The hazard of ignition/explosion can be eliminated by the removal of one of the conditions requisite to such an event. This can be achieved by inertisation or preventing ignition. The work described in the report has again highlighted the need for preventive measures to be adopted and priority needs to be given to these. Ongoing research priorities are goaf inertisation and the elimination of frictional ignition by machines.

CHAPTER 4

IGNITION SOURCE FOR THE MOURA EXPLOSION

By
P. Golledge, I. Roberts

4.1 Fire or Spontaneous Combustion

4.1.1 Roadways and Cut Throughs

A fire occurred in 24 c/t between No.2 Transformer Road and No.3 Belt Road but was considered to be the result of the explosion. The belt road was inspected by Mr Bayles and Mr Foden prior to the explosion, however, no evidence of a fire was noted.

4.1.2 Goaf Area

Carbon monoxide levels recorded on the continuous monitoring system in the Main Dips Section return airways were low prior to the explosion and there was no evidence of any build up of carbon monoxide due to a spontaneous heating.

4.2 Electrical Apparatus and Cables

4.2.1 Apparatus

A comprehensive examination of all electrical apparatus underground was carried out by Electrical Inspector of Coal Mines Mr A. McMaster with the assistance of Senior Inspector Electrical Testing Mr T.G. Hislop (SIMTARS).

The underground telephone system voltage and currents were tested and found to be within the required values. The high voltage protection system was also found to be satisfactory. An in-situ examination was made of the substation and the fault protection system was later checked at the surface, together with the faces of doors and other fittings. No faults were found. The remote control for the belt conveyor was removed for subsequent intrinsic safety testing at SIMTARS and was found to be operating safely. All electrical enclosures in the section were carefully examined to check on the gap at the flameproof flange and for any signs of any internal ignition within the enclosure. For each enclosure the gap was well below the maximum allowed in the relevant Australian Standard.
The two telephone sets had been incinerated and destroyed by the explosion.

Assumption
no supporting evidence

The lights and fittings at the crib room were found damaged. It is believed that they were damaged by the blast wave of the explosion.

4.2.2 Other Electrical Equipment

A digital watch was recovered and examined at SIMTARS and found to be in operating condition. The interior of a digital watch was recovered during the subsequent cleaning of a shuttle car and also tested at SIMTARS. With a similar watch no ignition occurred in a hydrogen/air atmosphere with either a series spark circuit or a direct short circuit.

Two fully-charged cap lamp batteries were also tested at SIMTARS with the No.3 Break Flash and the German Break Flash apparatus. Two types of tests were done, one with the lamp filament on and the other with a short circuit test across the test apparatus contact points.

The gases used in the tests were methane, propane, ethylene and hydrogen. No ignition occurred even with hydrogen. One cap lamp, considered as a possible ignition source due to a snapped battery cable, was examined carefully for any evidence of arcing during the process of snapping. The bulb filament load is itself non-incendive and tests showed that the battery had retained its charge. Furthermore, no short circuit was detected in any electrical testing of the cable.

The automatic firedamp detector on receipt at SIMTARS was completely discharged. Short circuit tests were carried out on the battery and failed to achieve an ignition in the break flash apparatus, even with hydrogen.

The belt slip controller was also tested at SIMTARS with hydrogen gas without any ignition.

The mine rover reversing light was tested for dimensional measurements at the Workshop of the Drilling Sub-Program and found to be within the tolerances for flameproof construction. Further testing at the Queensland University Experimental Mine at Indooroopilly failed to cause an ignition with propane gas.

4.3 Electro-Static Discharge

4.3.1 Hoses

The hose associated with the trickle stone duster was considered as a source of ignition.

A sample of new air hose from the same manufacturer was tested at SIMTARS. The resistance measurement of the test sample gave a value in the range 10^{11} ohms which was far outside the range of 30 x 10^{3} to 10^{6} ohms as was required by Australian Standard AS2660.

Rwonich The stone duster was not in use at the time of the accident and the hose was on the floor and may have been coated with a thin film of dust. It was considered that an electrostatic charge would not occur during any air movement caused by the fall in the goaf.

(Golledge/Roberts)

With this type of resistance level, decay time order 1 sec. - sufficiently long to [illegible] electrostatic charge does ~~not occur~~, will form in air velocity $\geq 5 \, m s^{-1}$. $\boxed{\text{guide 75 [illegible] p 3.3}}$
Water/moisture reduces resistance by 2 orders of mag [illegible] 10^{9} ohms [illegible] basis for [illegible]

4.3.2 Brattice

No detail given on measurements.

A sample of the brattice similar to that used underground at the mine was tested at SIMTARS to determine whether the surface resistance value was within acceptable limits. At that time instruments were not available at SIMTARS to measure directly the anti-static properties. The resistance measured was within the acceptable range and it was concluded that an electrostatic charge was unlikely. In the conditions which would have prevailed underground, that is, increased moisture in the atmosphere, it was concluded that any charge would have dissipated more rapidly.

4.3.3 Piezzo Electric Sparking

[illegible] but has been [illegible] included in Moura work.

Although not considered as a potential ignition source during the Moura Inquiry, subsequent investigations overseas have shown that this mechanism of ignition has been the subject of scientific study in a number of mining research facilities.

Experiments conducted under simulated mining conditions have failed to demonstrate that an incendive spark can be produced by piezzo electric sparking.

4.3.4 Other Equipment as Electro Static Discharge Sources

There was no evidence either from mine records or that tendered to the Moura Inquiry that electrostatic sparking had occurred from any other potential source underground at Moura.

4.4 Mechanical Equipment

Mr A. Hepburn, Principal Mechanical Inspector of Coal Mines, accompanied by Mr T. Faber, Mine Mechanical Engineer carried out extensive tests on the mechanical equipment which could have provided an ignition source.

4.4.1 Joy Continuous Miner (JCM-12CM3-BVW)

An underground inspection was first carried out and nothing was found to indicate any problem. The machine was later removed to the mine surface where further examinations were made. A series of tests confirmed no indication of either localised heating or any source of ignition.

4.4.2 Joy Shuttle Cars (15SC/48/MCHPVW, Nos.31 and 30)

Initial inspection of both s/c was carried out underground by Mr M. Bell, Mechanical Inspector of Coal Mines and Mr Faber, as above. Both vehicles were removed to the surface for further examination. Although there was some minor damage, there was no evidence of any mechanical deficiency likely to contribute to sparking or ignition.

It was noted in Mr Hepburn's report that the usual practice was for s/c No.31 to be parked in 26 c/t between the belt road and the supply road, where the power supply cable was anchored.

4.4.3 Main Dips Belt Conveyor

Mr Bell, accompanied by Mr Faber and Mr R. Curran (Photographer) inspected the belt conveyor underground and at a later time on the surface with other professional and technical assistance.

The conveyor was inspected throughout its approximate length of 550m with the exception of the section buried in fly ash between 25 c/t and 24 c/t.

There was no evidence of any heating or sign of frictional sparking.

The grizzly screen off the boot end which has a mass of approximately 0.2 t was displaced some 5m inbye.

The tail end of the conveyor was displaced inbye some 750mm outbye on the right-hand side and some 500mm outbye on the left-hand side, as viewed from behind the drum.

4.4.4 No.9 Mine Rover

Accompanied by Mr T. Faber, Mr Bell and Mr Curran inspected and photographed the mine rover underground. It was observed that the driver's backrest and left-hand passengers backrest were badly damaged and that the foam fillings showed no evidence of fire.

No evidence was found to indicate that the engine was running or that the vehicle was other than parked normally at the time of the explosion.

As stated earlier a rear light and the alternator were examined and tested at SIMTARS and found to be safe and satisfactory.

There was no evidence to suggest that the vehicle had contributed to the explosion.

4.4.5 Miscellaneous Mechanical Equipment

Pneumatic chain saws were examined as part of the mechanical investigations and were found to be in a satisfactory condition. There was no evidence of any malfunction of the surface air compressors nor of any abnormal heating from their operation.

Some of the air hoses in use at Moura were not fire resistant and antistatic, however no evidence was discovered that indicated an explosion initiating from an electro-static spark.

4.5 Aluminium Entonox Cylinder

Parts of the Entonox bottle were retrieved from underground and initially examined on the surface and then removed to Rockhampton for further, more detailed scrutiny and investigation.

The cylinder and regulator assembly were microscopically examined by Dr I. Smith, then Assistant Professor in the Queensland University Department of Mining and Metallurgical Engineering. An examination of the fracture at the neck of the bottle suggested that a bending overload was responsible for the failure. The opinion was given that the level of impact loading required to fracture the brass fitting would be substantially higher than that expected from a fall of about 1.5m on to a coal surface. The only component of the regulator assembly and the bottle which showed the effects of exposure to high temperature was the polymeric handle on the regulator which was charred. The paint on the bottle was relatively unaffected. An examination of the microstructure of the brass fitting showed no sign of exposure to elevated temperature since processing. There were no signs of exposure to high temperature in the alloy from which the bottle was made. Dr Smith concluded that the bottle was damaged by flying debris in the explosion, with no evidence of the bottle having exploded or having been exposed to high temperature for a significant period of time.

Further tests and experiments were carried out at Capricornia Institute of Advanced Education with the assistance of CIG (manufacturers of the Entonox bottle). These tests were carried out to try and assess the possibility that the Entonox valve was broken by being knocked whilst being carried by a miner. The conclusions from the tests and experiments were that the damage to the Entonox bottle assembly was not caused by a miner striking it against a solid item; the damage to the assembly was consistent with a blow from a heavy object, travelling at high speed, which struck the corner of the carrier furthest from the regulator while the Entonox assembly was stationary. In the absence of any other explanation, the damage to the Entonox assembly occurred as a result of the explosion with no evidence that 'rocketing' of the bottle initiated the explosion.

The matter of a possible ignition by the discharge of the contents of the Entonox bottle was considered by Dr A.F. Roberts, at that time Director of the Health and Safety Executive Flame Laboratory at Buxton, UK. Dr Roberts expressed the opinion that the combustion of coal dust by combustion of the O_2/N_2O mixture, assuming it was 100% O_2 would only have filled the cross-section of the c/t for a distance of about 2m. The pressure rise from this combustion, estimated to be about 10 kPa would be insufficient to cause a coal dust explosion.

Not if it was occurring while coal dust was adequately dispersed prior to ignition.

4.6 Frictional Ignition

Although there is almost an intuitive belief that frictional sparks can ignite methane/air mixtures, laboratory research over 100 years has demonstrated that ignition can only be achieved under conditions which one would not expect with a goaf roof fall.

what are these conditions?

Mallard, Le Chatelier and Chesneau [8] were unable to ignite firedamp by the

probably a larger ignition source than the FSL if valve opened by someone under these conditions sparks obtained by pressing a steel bar on a rotating emery wheel. Edwards [9] and Stirling and Cadman [10] showed that if the wheel was made of sandstone then an ignition of firedamp could occur. However, ignition was not caused by the sparks but by the bright yellow flash which occurred at the point of impact as were shown by Burgess and Wheeler [11]. Subsequent work by Blickensderfer [12], and others up to the time of the Moura explosion and since have confirmed the earlier conclusion of Burgess and Wheeler.

This is incorrect because experiments in [illegible] did not use a constant force.

All investigators have found that even for the most incendive rocks tested, it was necessary to hold the specimen against the rotating wheel at a constant force for a number of revolutions before an ignition would occur. In practical terms this meant that one piece of rock was stationary while the other was rubbing against it at a constant velocity over the same rock surface and with a constant force for some distance and for a time period varying from less than one second to many seconds before ignition occurred. The combination of circumstances for a frictional ignition, if they exist must occur very infrequently otherwise explosions from this cause would be relatively common.

It is known from research work currently underway at SIMTARS that even with hydrogen gas ignition by single impact of rock against rock can only be achieved under certain conditions. The combination of gas concentration, specimen orientation and velocity must be within a narrow range for an ignition to occur even with hydrogen. In spite of many repeated attempts it has not been possible to ignite any concentration of methane/air under similar experimental conditions.

In experiments at Buxton to investigate the influence of surface area on the ignition temperature of methane Rae et al [13] showed that a temperature of over 1100°C was needed for a heating source 400m² in area in a 7% methane/air mixture but the temperature had to be increased to 1600°C to ignite an area of 6.25mm.

Sparks from frictional heating of rocks are passive in relation to oxygen in that they do not enter into a chemical reaction. Typical examples of such particles are those from sandstones and other quartzitic type rocks which are themselves oxides. It is known that the temperature of sparks from such rocks is limited by the plasticisation temperature of quartz, that is, about 1200°C. The ignition capacity of these particles depends on the temperature and size of the exposed rock surface and on the particle concentration in the area of contact.

Some other particles such as steel, pyrites, aluminium and magnesium are active in the presence of oxygen in that they are exothermic and therefore provide additional energy and ignition capacity. At the one end of the scale particles of steel burning in air may attain temperatures of 1700°C and particles from aluminium and magnesium alloys 3700°C, as quoted by Rae [14].

Experiments at Experimental Mine Barbara in Poland reported by Lobejko [15] with high speed film showed that an ignition of methane/air from friction experiments with a cutter head against sandstone was caused by the concentration of incandescent particles attached to the rubbing surfaces.

Two hypotheses are examined for the circumstances at Moura No.4 Mine regarding an ignition caused by friction. Firstly it is assumed that ignition occurred through frictional contact between rocks during falling. One rock is assumed to be at an angle on the floor and is hit by another piece of rock which falls afterwards through a total height of approximately 7m. For an ignition to occur in a time of just over 1.2 secs a sufficient area of rock must be heated to over 1000°C or alternatively a sufficient density of rock particle sparks at about 1200°C must be produced to act as an ignition source. The methane concentration in the vicinity must be within the explosive range and must be stationary or at very low velocity.

With fragmentation characteristics during caving it seems unlikely that one fixed and one moving piece of rock could remain in contact whilst falling under the conditions necessary for a frictional ignition to occur.

The second hypothesis assumes that ignition occurs at the point of impact when the falling rock hits a piece of rock already on the floor in the goaf area. In this scenario the temperature conditions from either a heated part of the rock or a cloud of sparks would need to be achieved in something less than 100ms. The inability to achieve this with grinding wheel experiments with methane air mixtures suggests that this scenario is highly improbable.

If the ignition were to be caused by friction between steel and rock, again it is necessary to create a cloud of hot particles of sufficiently and possibly a hot area of rock or metal that would provide an ignition source. At roof elevation the velocity of rock movement is nearly zero and could not be expected to provide either a significant hot spot on the contact surface or a dense cloud of sparks. Were contact to occur during falling the production of sparks is dependent upon maintaining frictional contact.

It is known from grinding wheel experiments that frictional contact between the fixed specimen and the rotating wheel causes fusion of the quartz particles, or the intergranular materials in the rock and it is the hot spot produced by this fused area that acts as the ignition source. In all experiments referred to in the research literature the grinding wheel has rotated for some revolutions in order to cause the fused surface. In reality the same moving rock surface is being contacted repeatedly by the fixed specimen. Such a set of circumstances would be difficult to visualise during a goaf fall in a coal mine.

Nagy and Kawenski [16] examined, amongst other things, the potential of frictional ignition by impact. No ignitions were produced in 533 drop tests with a weight falling onto an inclined specimen, although visible sparks generally were observed at the instant of contact. Material for the falling mass included roof bolts and pieces of sandstone, while the inclined surface was sandstone, a roof bolt and shale. A 7% methane/air mixture was used for these experiments. Pulverised coal dust and sand, or both were sprinkled on the surface in some of the tests.

The scenario that the ignition at Moura was caused by frictional ignition therefore relies on some critical temperature conditions either from a hot spot or sparks as a source of the ignition. Such conditions are difficult to

Poppitt [illegible] that conditions [illegible]

produce under controlled laboratory conditions where critical factors can be optimised. It seems therefore that an ignition due to frictional causes, while remaining possible, must be considered to be highly improbable.

As a result of the Moura No.4 mine explosion records of explosion inquiry reports have been searched and the result of that is appended below in respect of explosions where friction by rock/rock or rock/steel was deemed to have been the ignition source.

The reports emanated from mine explosion investigations in Canada, South Wales and the USA.

Before discussing those earlier records it is necessary to place the matter in context by referring to the Moura No.4 Explosion Inquiry.

The members of that Inquiry considered eleven possible ignition sources but eliminated all except two - namely frictional ignition and the flame safety lamp. The Inquiry report states [1]

(a) "The members of the Inquiry are of the view that frictional ignition from sandstone on sandstone of the type found at Moura is highly unlikely to have been the source of ignition and,

(b) "The evidence of tests undertaken by Mr Poppitt reinforces the view that sandstone striking steel is unlikely to have been the source of ignition."

Mr Poppitt was employed as Geologist-Underground Operations at Moura. Along with two chemists Messrs Lyons and Kelly he conducted tests at the Mining Company's Laboratory at Gladstone. His report of 11 February 1987 describes test work on "Frictional Ignition of Methane with Sandstone Samples from Moura No.4 Mine Main Dips Section". The test work was carried out on 10 February 1987. The sandstone for the test work was obtained from "Roof from 7m fall one pillar inbye fender" at the extraction taking place immediately prior to the time of the explosion.

The aim of the work was to test empirically if any of the samples were capable of igniting methane in air (with varying proportions) under frictional load. The work was conducted with a bench grinder with sandstone wheels (cut from a Moura drillcore). The gas stream of metered methane/air was applied. The dilution factor was unknown but when lit with a match the mix burned readily with a lean blue flame.

Mr Poppitt in his report states the results of the testwork as follows:

Sandstone/Sandstone Contact

Ignition of the methane/air mixture was readily achieved with sandstone/sandstone contact.

Twelve (12) tests were done with sandstone/sandstone, and in each test ignition was rapidly reached.

This is a difficult test to achieve success according to Roberts AF & Powell [illegible] However the point remains that ignition was achieved.

Mean time for ignition was 2.5 seconds, with a range from 1.5 to 5 seconds.

The mechanism for ignition of methane/air was NOT sparking, as was observed for propane/air mixtures. Rather, the 1-2mm wide point of contact around the edge of the sandstone wheel became heated very quickly, and reached ignition temperature within 1-5 seconds.

Observation within the 1st second showed the contact area on the edge of the wheel to become heated to a bright orange, and within the next second to white heat. At that point, ignition could occur.

Sandstone/Other Materials Contact

No ignition was achieved with steel on sandstone, or pyrites on sandstone.

Both of these materials, although producing showers of dull red sparks, were too soft to heat the sandstone to ignition temperature. The steel butterfly plate, roofbolt washer and roofbolt simply wore away too quickly to produce the heat required.

Whether the results of such testwork with a grinding wheel can be related to a situation of impact resulting from, say, a fall of roof in a goaf, is questionable - to say the least.

During cross-examination at the Inquiry (Transcript Page 876) Mr Poppitt was questioned about "rubbing friction created over large surface areas". He was asked "... but we can't, at this stage - would you agree - discount the possibility of that being the source of ignition in this case."

Mr Poppitt's reply - "No, I don't believe I've discounted it. I think it's highly improbable, but I've just not discounted it".

There are records of coal mine explosions resulting from both rock/rock impact and rock/steel impact in other Countries - notably Canada and Wales.

Canada - In their paper Stirling and Cadman [10] the authors referred to the Bellevue explosions in Alberta in 1910 and 1911 and also made reference to the Maindy Pit in Wales in 1896.

The following facts are taken from the above Institution of Mining Engineers Transactions to briefly describe three Bellevue Explosions:

> *No.1 - An explosion of some violence occurred on the morning of Monday October 31, 1910. There were no persons in the mine because it was a holiday. Work belowground had been suspended at midnight on the previous Saturday and no-one had been in the mine since that time. The fan had been stopped for 9 hours - 7.30am to 4.30pm on the Sunday. The mine was explored and a large roof fall discovered. Evidence collected at the time indicated that the fall was the point of origin of the explosion. The Inspector of Mines "boldly" attributed the occurrence to an ignition caused by sparks from the falling roof*

but others "were not inclined to accept the theory on such indirect evidence".

No.2 - Occurred December 9, 1910 - approximately six weeks later. Thirty miners were killed and public inquiry held. The authors stated "There is no doubt that the explosion was caused by an ignition of fire-damp ignited by sparks emitted from the falling roof.

No.3 - After No.2 explosion there was a general strike throughout the district and the Bellevue Mine was not re-opened. In January 1911 another explosion occurred. The exact date is not known as the explosion was not observed at the time of the occurrence.

On January 25, 1911 (prior to this No.3 explosion) an official inspection was made of part of the workings. A new manager was appointed on January 28, and the effects of this explosion were observed a few days later. The fan had not been operating since shortly after the explosion of December 9, 1910 but was operated from January 13 to 25, 1911 in order to prepare for the Government inspection. It was stopped again after the explosion.

That this third explosion had occurred was discovered on January 30. Subsequent investigation revealed that the explosion had originated at a point where a heavy roof fall had occurred. The mine remained untouched for some months due to the strike and the authors made an examination in August 1911.

An experiment was conducted in the mine with a piece of the hard siliceous roof material weighing some 60 or 70 pounds. This rock was dropped into the "shoot" on the floor of which lay some of the fallen roof. As the piece of rock rolled down the shoot a "brilliant display of sparks" was observed.

The roof rock was microscopically examined and found to contain about 50% quartz.

Experiments were conducted in which the rock was attached to a spindle revolving at 200 to 300 rpm. By allowing another piece of the rock to contact the revolving piece" sparks of sufficient intensity could be produced to ignite coal-gas and methane".

The account of the explosions and investigation includes the following:

It is clear, however, that sparks of sufficient intensity can be produced by rubbing together pieces of the roof of No.1 Seam to ignite methane, which has an ignition-temperature - according to Dixon and Coward - of from 556 to 700° Cent., and as other hydrocarbons have been shown to be present, the temperature of ignition will be less, and an explosive mixture will be more readily ignited.

The writers are satisfied, however, that they have established the fact *that sparks can be produced by falls of roof in the No.1 Bellevue Seam sufficient to bring about the ignition of inflammable gas; and as subsequent examinations after each explosion shown that falls did occur, in which large masses of the roof fell, in areas where gas was in all probability present, it seems perfectly clear that the cause of three explosions at Bellevue has been satisfactorily explained.*

South Wales - In his report on the Six Bells Colliery explosion in 1960 H.M. Chief Inspector of Mines and Quarries states as follows:

"No one can say with certainty where or by what means the explosion at Six Bells Colliery started. But after careful consideration I think that:

(1) The explosion started as an ignition of fire damp in the roadhead roof ripping of 0.10 intake.

(3) The cause of ignition was frictional heat produced by the impact of a piece of quartzitic rock falling for a distance of about six feet from roof exposed by shotfiring, onto a steel girder ....".

The Report describes the thorough investigation of this disaster. The results of the investigation enabled the discounting of safety lamps, and the electrical and mechanical plant as possible causes of ignition. This meant that the known possible causes remaining for consideration were contraband, shotfiring and frictional sparking.

Evidence enabled the Chief Inspector to rule out contraband and in the case of shotfiring he stated *"I do not think it at all probable".* His statement that he thought the ignition was caused by the impact of rock on steel resulted from a process of elimination of other known possible causes.

The following is extracted from that part of the above Report which discusses frictional ignition.

75. The S.M.R.E. has also examined the possibility of ignition of firedamp by friction between rock and rock. The results of tests by Burgess and Wheeler were reported on in 1928[3]. Other tests of this kind have been made recently and reported on in S.M.R.E. Annual Report for 1959[4]. The apparatus used consists of a rock 'slider' which is pressed with known force against the periphery of a rotating rock wheel in an explosive atmosphere; the pressure between the surfaces is measured and the time between the application of the load and any ignition of firedamp is taken. Ignition has been obtained with quartzitic rock. The greater the speed of the wheel and the longer the duration of the friction, the more likely it is to occur.

76. From the experiments it is deduced that, to produce an *incendive condition, a suitable rock would first have to fall a distance sufficient to gain the necessary speed and then slide some distance on another rock; the shorter the fall of the rock, the longer would have to be the slide.*

77. *I have carefully examined the available records of ignitions believed to be due either to the impact of rock on rock or of rock on steel; the latter must, in the nature of things, include the possibility that the incendive impact may have been between rocks. The subject is of such importance that I have summarised the records in Appendix III. Four of the explosions referred to occurred in Canada. So far as this country is concerned, six of the seven instances mentioned were in South Wales. Sir Henry Walker, then Chief Inspector of Mines, in his report on the Marine Colliery disaster in 1927 [5], considered that the explosion may have been due to a stone falling on stone. He cited as supporting evidence for this view possible similar incidents which had occurred between 1896 and 1927 at Maindy, Ferndale and Lletty Shenkin Collieries. In more recent years, other incidents have occurred at Cwm Colliery in 1949 [6] and at Lewis Merthyr Colliery in 1956 [7].*

78. *It seems clear that, if quartzitic rock falls and strikes either a steel object or possibly pieces of similar rock with sufficient impact, an incendive condition may result. Hartwell suggested that the impact of the mechanised pick used in the experiments he described would have been about equivalent to that of rock weighing 260lbs. falling for a distance of three and a half feet onto a steel object. He thought that the most probably cause of the explosion was that there was a fall of rock bringing down with it firedamp that had accumulated at the ripping and that one of the larger pieces of rock struck the canopy in such a way as to produce an incendive condition and so cause inflammation of the surrounding atmosphere. Pieces of quartzitic rock, the largest being estimated to weigh about 240 lbs. were, in fact, found on the ground and on the canopy under 0.10 intake ripping (Plate I). Some of it could have fallen a distance of six feet.*

79. *The mechanics of firedamp being brought down from near the roof by falling stone and then mixing with air have been demonstrated with perspex models, made at the Buxton Station of the S.M.R.E., of the roadheads at which the explosions occurred at Lewis Merthyr Colliery and at Sutton Colliery in 1957[8]. I commend to all mining engineers the film which has been made to illustrate these demonstrations.*

80. *The evidence was not completely satisfying, but I incline to the view that firedamp was brought down by a fall of roof and was ignited by frictional heat at the point of impact between a quartzitic stone and the steel girder forming the top of one side of the canopy. I refer later to methods of minimising the*

risks associated with falls of hard rock from a high cavity and from near the face of high rippings.

81. *If a fall of stone of a not uncommon nature for a distance of six feet or so may be dangerous, the question immediately raised is the degree or risk involved in the routine collapse of roof in wastes. There is, however, no recorded experience of ignition of firedamp from this cause in longwall wastes in this country. This may well be because, for ignition to occur, there must be the remote coincidence of a number of conditions including the fall of a certain kind of rock, the right type and strength of impact and the presence at or about the point of impact of a firedamp-air mixture within a relatively narrow range.*

South Wales - An explosion occurred at Lewis Merthyr Colliery in 1956 and a report was prepared by H.M. Divisional Inspector of Mines [18].

The explosion occurred at the centre road on a double unit longwall advancing face and immediately behind the coal face. All machinery in this district was operated by compressed air. No electrical power was installed. The following is extracted from the Divisional Inspector's Report -

III - EVENTS PRIOR TO THE EXPLOSION

On the night of 8/9th November, 1956, an extensive fall of roof occurred in the roadhead of the centre road from the inbye permanent support practically to the face of the roadhead, a length of some 16 feet. One steel arch was left standing between the inbye end of the fall and the coal face. The cavity was the full width of the roadway and exposed the Three Coals seam some 24 feet above. For some time earlier a small fault had been working down the left hand face towards this road. At the time of the fall this fault was less than ten yards from the left hand side of the road. There was no evidence of this fault in the cavity, 'but it was obvious that the thick bed of clift above the seam had changed to become weaker than normal and lacking in it usual cohesion. The fall was cleared and 14-feet steel arches were erected beneath the cavity. These arches were covered with wood lagging which in turn was covered with a "cushion" of rubbish some four feet thick, the top of which would thus be some eight feet from the top of the cavity. The roof and sides of the cavity above this packing were not supported in any way. The production of coal was resumed on Monday, 12th November, 1956.

Work proceeded without untoward incident until the night of 19/20th November, 1956, when a second fall occurred at the roadhead. This was an extension of the earlier fall. The cavity now extended to the coal head and was some 30 feet long and 30 feet high. It had also widened to about 30 feet exposing a slicken-sided slant some ten feet to the left of the fault previously mentioned, which was now crossing *the middle of the centre road. There had been no earlier indication of the presence of this slant. This second fall made coal production impossible and this situation was unchanged on 21st November. By the afternoon shift of this day, the fall had been cleared and the erection of steel arches beneath the cavity was begun. This work was being carried on by the night shift when, at about 3.00 a.m. on 22nd November, four of the six newly erected steel arches were displaced by a stone weighing about three tons which fell from the cavity. The colliery manager, accompanied by the morning shift overman, arrived at the scene at about 5.30 a.m. He decided to erect an "umbrella" of ten-feet arches covered by wood lagging beneath which the gate conveyor could run. These ten-feet arches could be erected without disturbing the 14-feet arches displaced by the fall. The stone which had fallen was broken up by means of a pneumatic pick and the work of erecting the steel arches begun. By this time the men employed on the morning shift had begun to reach the meeting station at the junction of the left hand supply road with the intake airway. A few of these men were brought forward to assist with the work and the remainder told to stay at the meeting station until they received further instructions.*

IV - NARRATIVE OF THE EXPLOSION

By about 7.15am three of the ten-feet arches had been erected. Fourteen persons were variously engaged in the work. Two workmen were standing on a staging, tightening the fishplate bolts, and four others were holding the legs of the arches. The night shift deputy had gone back in the road some 30 yards to a point where a repairer was preparing wood struts for use between the arches. The others were standing, prepared to cover the arches with wood lagging, when a further fall occurred from the cavity. The fall was of some two tons of stone, most of it in one piece. Almost coincident with the fall there was a flame. One of the workmen on the staging stated in evidence that he heard the fall and jumped from the staging. As he jumped he saw the flame. The deputy heard the fall and looked inbye. He stated that fall and flame were simultaneous.

All the persons present were enveloped in flames and suffered severe burns. Two died from their burns at the scene and seven others died later in hospital.

The men at the meeting station noticed a "puff" of wind and a cloud of dust. A collier who had passed into the left hand face returned to say that he had seen flame in the centre road. The work of rescue was quickly organised. The first aid and rescue work will be dealt with in a later section of this report.

V - THE CAUSE OF THE EXPLOSION

The Nature of the Explosion

From all the evidence it was obvious that an explosion of firedamp had occurred in and beneath the cavity. Flame had been projected some 70 yards outbye along the centre road, for about 15 yards along the left hand face and 25 yards along the right hand face. The severe nature of the burn injuries sustained by many of the casualties suggested that flame had persisted for an appreciable time in the vicinity of the cavity. There was no sign of violence and no indication that coal dust had played any part in the explosion.

The Source of the Firedamp

Tests made during the investigation showed an explosive mixture of firedamp and air nine feet down from the top of the cavity; the methane content at the top exceeded 80 per cent. The normal emission of firedamp from the seam, probably augmented by emission from the Three Coals Seam exposed by the fall, would naturally produce these conditions in an unventilated cavity such as this and it can safely be assumed that similar conditions obtained immediately before the explosion, although the presence of inflammable gas in the cavity had not been detected.

Immediately after the fall on 20th November the under-manager and the deputy climbed up on the debris, examined to the top of the cavity and found it clear. At this time the heap of fallen debris was, of course, deflecting at least part of the air current into the cavity. As the fall was cleared the top of the cavity became increasingly inaccessible both to the air current and for examination. No steps were taken to direct an air current to the upper part of it or to enable examinations to be made there. When the fall was finally cleared the cavity was entirely unventilated and could not be examined as no means of access had been provided. About two hours before the explosion, the night shift deputy stood on the tops of the steel arches and tested for gas at the highest point he could reach, but this was about 15 feet above the floor and 18 feet from the top of the cavity.

The Igniting Medium

All possible means of ignition were carefully investigated and considered.

The electric and flame safety lamps which were in the district at the time of the explosion were sent, in the condition in which they were brought out of the mine, for examination and testing at the Safety in Mines Research Establishment. None of the flame lamps exhibited any defect likely to constitute a hazard. All the electric lamps showed signs of heating and in three cases the heat had been so intense that the cable sheathing and the core insulation had been burned away so as to expose the bare conductors. This damage had obviously been caused by the flame of the explosion. Only one of these electric lamps showed signs of damage other than that caused by heat. In this case the headpiece had been broken so as to expose the main and pilot bulbs, both of which were broken. The filament of the pilot bulb was intact and was bright and clean, showing that it had not been heated in air. The whole of the coiled centre portion of the filament of the main bulb was missing, only small portions of the straight part of the filament remaining attached to the filament supports, which had been bent over sideways to an almost horizontal position. The filament supports were nearly touching, but there were no signs of arcing when examined under a microscope. Microscopic examination also showed that the filament ends, where broken, were angular rather than rounded, suggesting breakage and not fusion. The only occurrence at or about the time of the explosion which might have caused this damage was the fall, and investigation revealed that the person using this lamp was standing at least five yards outbye from the point where the stone fell. The damage could easily have been caused in the confusion following the explosion.

On this evidence it was concluded that none of the safety lamps was the igniting medium.

After the explosion, the compressed air hose from a manifold on the centre road to the turbine of the right hand face conveyor was found to be leaking badly from a hole. There was also a slight leak of compressed air from a joint in the two-inch pipe range laid along the floor. These items of equipment were cut out and sent to the Safety in Mines Research Establishment for examination. In both cases the damage was found to be post explosion, and they were dismissed as possible means of ignition.

A compressed air lamp was found lying in the roadside some 30 yards outbye the cavity. This lamp had been used at the face conveyor transfer point during coaling operations, but there was conclusive evidence that it had not been in use since the second fall occurred.

Except for two mining type telephones, electricity was not used in the district. These telephones were found to comply fully with their certification specification and standard of safety when tested at the Safety in Mines Research Establishment. Later evidence disclosed that these telephones had not been in circuit for some days before the explosion.

Nothing was found in the investigation to suggest that the use of any article of contraband was responsible for the explosion.

The only possible source of frictional heating lay in the belt conveyors. There was definite evidence that none of the conveyors had run during the shift.

It will be recalled that the statements of survivors left no doubt that the explosion was coincident with the fall of roof. This led to a careful investigation of the possibility of incendive sparks having been produced by the fall. The stone which fell was estimated to weigh nearly two tons and was composed of hard clift containing ironstone. The only ground of this nature was near the top of the cavity. The stone had therefore fallen fully 20 feet before reaching the arches.

Samples of the stone which fell were sent to the Safety in Mines Research Establishment and were subjected to a variety of tests. These tests did not produce a conclusive result but, after consideration of all the factors involved, including an appreciation of ignitions previously obtained experimentally using similar stones, the opinion was formed that incendive sparks could have been produced by the impact of a piece of the hard clift from the top of the cavity on one of the steel arches about 20 feet below. Although no trace of inflammable gas was found before or after the explosion at the horizon where the stone struck the arches, tests carried out at the Safety in Mines Research Establishment showed that, under certain conditions, an object falling from near the top of a cavity containing a high concentration of methane could bring down enough methane to produce an explosive mixture at the base of the cavity.

Careful consideration of all the available evidence has led me to form the following conclusions:

1. *After the fall had been cleared and while the steel arches were being erected, the upper part of the cavity contained a high concentration of methane.*

2. *The stone falling from near the top of the cavity brought down enough methane to produce an explosive mixture at the horizon of the steel arches.*

3. *The impact of the stone striking the steel arches produced an incendive spark which ignited the explosive mixture, whereupon flame spread to the extent described earlier in this report and persisted until all the methane had been consumed.*

South Wales - There is a number of other reports on explosions which are believed to have resulted from ignition of gas by a roof fall. They include Maindy Colliery 1896; Ferndale Colliery 1907; Lletty Shenkin Colliery 1913, Marine Colliery 1927 and Cwm Colliery 1949. No purpose would be served here in attempting to precis all or any of these. Suffice it to say that there is substantial evidence to support the conclusion in a number of cases that ignition was caused by impact between rocks or between rock and steel. In some cases that evidence has been given by eye witnesses who survived the explosion.

Research in the USA - the Bureau of Mines published in 1960 a report by Nagy and Kawenski [16].

The report describes work carried out on rubbing friction, impact friction, roof bolt broken in tension and on a bolthead pulled through a washer and roof plate. The research was conducted following a mine explosion in 1958.

The following extracts are of interest -

"The explosion, which killed two men, occurred in April 1958. Gas

was ignited during an induced roof fall in a section where electric circuits had been deenergised and face equipment had been removed. The gas had accumulated because ventilation had been disrupted in the area. Miners 50 to 75 feet from the fall reported seeing sparks and a flash of fire in the vicinity of the falling roof just before the explosion. The witnesses stated that during previous falls streaks of fire had been seen, and sparks had been observed when the roof bolts ruptured.

Limited experiments in the laboratory with specimens of mine rock from a Virginia bituminous coal mine indicate that natural gas-air mixtures can be ignited by sparks generated by rubbing friction of sandstone against sandstone, shale against sandstone, sandstone against (roof-bolt) steel, and shale against steel. Such sparks, generated during a roof fall, may have initiated a recent gas explosion in this Virginia mine, although this cannot be stated with certainty.

No ignitions of gas were produced by sparks or heat generated by impact friction between mine rocks or steel, during tension breaks of roof bolts, or by pull tests of roof bolts through their washers and roof plate. However, this negative result of limited experiments does not preclude the possibility of gas being ignited by these conditions.

In limited experiments performed gas was ignited by friction sparks between mine rocks and between mine rocks and roof-bolt steel.

Of the materials studied, incendive frictional sparks were formed at the lowest speed and smallest load with sandstone-sandstone contact. Gas ignitions were produced readily with shale rubbing on a sandstone wheel and less readily with sandstone or shale rubbing on a roof-bolt wheel. The lowest peripheral speed of the rotating wheel for ignition would be equivalent to a free fall of 2.2 feet - a distance readily obtained in the Virginia coal mine. In our tests a 7 percent gas-air mixture was more readily ignited by frictional sparks than an 8 or 9 percent mixture. The incendivity of the sparks increased with the load and the speed of the wheel. Although ignitions occurred within 1 second of the time of contact of the surfaces, more often they occurred in 10 to 30 seconds. The presence of visible sparks cannot be taken as a criterion of incendivity, as visible sparks occurred whether ignition resulted or not.

Ignitions were not obtained by impact friction, by roof bolts broken in tension, or by roof boltheads pulled through a washer on the roof plate. Sparks generally were visible in the drop trials but not in the pull experiments. These tests cannot be considered as conclusive evidence that such sources may not cause ignitions under some circumstances. The energy expended by falling masses of rock and the rate of tensile loads applied on roof bolts during a mine roof fall could far exceed those studied in the laboratory.

Because incendive sparks can be produced so readily and with so little expenditure of energy, it is virtually impossible to eliminate them in *coal mining. Gas ignitions by this source must be prevented by other measures. One of the most effective measures is adequate ventilation to prevent an accumulation of gas."*

Discussion

The preceding paragraph extracted from the Nagy/Kawenski report is most relevant to this project. It must be accepted that ignition from friction cannot be eliminated in the case of the Moura No.4 Mine explosion. It follows then that the atmosphere in which such an ignition might occur must be rendered inert. In many situations it is not practical to deal with an explosive atmosphere by normal ventilation - namely the provision of fresh air. This is clearly the case where spontaneous combustion can occur in a goaf.

In Britain nitrogen is used to reduce the risk of spontaneous combustion in the goaf of longwall faces. The same treatment can be applied to the prevention of ignition by rock/rock and rock/steel impact in a goaf.

In 1986 the New South Wales Mines Rescue Board investigated "The most recent advances of using liquid nitrogen to combat fires and heatings in coal mines". The investigation was conducted in West Germany, France and Britain. The report of that investigation by Messrs Mackenzie-Wood and Enright of the NSW Mines Rescue Service is comprehensive and makes clear recommendations on the matter of inertisation for every mine in NSW. Specifically the report recommends that high-risk mines should install a dedicated pipe range to the commencement of each district of the mine.

The installation of a nitrogen range at underground coal mines in Queensland represents a practical means of reducing risk from frictional ignition as well as from spontaneous combustion in a goaf. Such an installation would also provide an immediately available facility for dealing with an underground mine fire.

There are problems with the supply of liquid nitrogen to Queensland coal mine sites. In the case of the Moura disaster supply was effected from NSW. Evaporators for the use of liquid nitrogen are not available in Queensland. There are therefore logistical problems to be overcome. It would seem that adequate on-site liquid nitrogen storage is essential.

4.7 Flame Safety Lamp from Moura No.4 Mine

Initial Examination

The flame safety lamp from Moura No.4 mine was examined and disassembled at SIMTARS.

As received the lamp was very dirty externally with loose dust or soot inside the lamp. The upper part of the metal bonnet and part of the metal base near the locking ring had been distorted by the lamp either hitting another object, or having been hit by some other object which would have been travelling at considerable velocity. The distorted base had been subject to some heating since the metal had been discoloured. — [illegible]

In [illegible] light might [illegible] lamp it is more likely that the FSL has been [illegible] explosion [illegible] be projected [illegible] fixed [illegible] The deformation is consistent with [illegible] imparted [illegible] lamp and [illegible] than the [illegible] agreed as occurred.

[illegible] difficult [illegible] fusion has occurred [illegible]
particularly from [illegible]

The outer surface of the glass cylinder and the outer surface of the bonnet had been coated by a film of dust which had 'fused' to the metal or glass. A similar observation was made about the inner surface of the glass and the inner surface of the bonnet.

The glass was not cracked and the top and bottom faces were parallel within the tolerance limits permitted by the manufacturer. There was no evidence of distortion of the glass by heat. The sealing washers at the top and bottom of the glass cylinder were in position and sealing properly against the glass. The lamp was closed properly and locked. There was no lamp oil left in the reservoir.

There were approximately 5gm of soot particles inside the lamp.

The lamp handle had been stretched beyond its normal curved position. — pulled off hanging point

Examination of Gauzes

The inner and outer gauzes showed no sign of physical damage although closer examination subsequently revealed evidence of exposure to heat. There appeared to be clearance between the inner and outer gauzes when they were assembled in the lamp but when the gauzes were checked outside the lamp it was possible to rotate the gauzes to a position where the gauzes were in contact.

but not found in this condition

Examination of Bonnet

Samples of the particle deposit on both the inner and outer surface of the bonnet were taken and examined by Mr P. Lynch using the electron microscope at the Queensland Institute of Technology. Electron micrographs and comments by Mr. Lynch are contained in a Memorandum to the Chief Engineer.

If surface cleaned of particles [illegible]

On cleaning a strip of the outer surface of the bonnet to expose the metal surface a visual examination was made for discolouration of the metal by heat. No discolouration was observed.

Evidence from electron microscopic examination of the particle deposit on both inner and outer surfaces of the safety lamp shows quite clearly that the particles have been subject to heating consistent with a coal dust explosion.

Research into Flame Safety Lamp Prior to Moura Inquiry

Investigations into the behaviour of an identical flame safety lamp showed that some of the conditions observed in the lamp recovered from the Moura No.4 Mine could be reproduced in the laboratory. In particular it was demonstrated that heating of both inner and outer gauzes would occur as a result of incandescent combustion starting within the inner gauze after the flame had extinguished. This heating was measured with calibrated thermocouples and found to be approximately 1000°C. Further experiments showed that the addition of coal dust particles to the methane passing the lamp would result in

(Golledge/Roberts)

I do not believe that particle could fuse without giving some local heating effect around that particle area.
requires > 1000°C to fuse on [illegible] and [illegible] requires > 1500°C

some particles entering the gauze and burning with a flame which could fill the whole volume of the inner gauze with the bonnet on. Under combined methane/coal dust conditions sufficient heat was produced on the inner surface of the lamp glass to cause 'fusing' of hot dust particles to the surface of the glass.

The experiments referred to above where conducted in an explosion chamber with a closed loop, that is an arrangement where the atmosphere is recirculated by the lamp. No external ignitions were achieved with recirculation of the atmosphere and it is believed that this was due to the build up of CO_2 and the simultaneous reduction of O_2 following combustion activity within the lamp. Air velocities were limited by the apparatus to an upper value of 2.7m/s.

A series of tests were carried out to see if it were possible to cause heating of the gauzes from an external explosion flame. When the lamp was placed in a 3m long explosion chamber it was subjected to the effects of heat from a flame generated by the ignition of a range of methane concentrations up to 10% and with methane/coal dust using the equivalent of 1000g/m³ of coal dust. With optimum mixing of the methane and methane/coal dust, very hot flames were produced. In none of the tests was it possible to heat the outer gauze above 350°C (estimated from charring of paper) and no discolouration of either gauze occurred. In the most severe test there was some slight discolouration of the bonnet but none to either gauze. It was not possible during any of the experiments with an external flame to produce a film of particles fused wither to the glass or bonnet of the lamp.

A series of tests with the flame at the height normally used when carrying the lamp in a mine established that the average flame temperature was 820°C with a standard deviation of 14.6°C.

In a further series of tests the outer gauze and inner glass temperatures were measured with different flame heights. With a flame height of 1cm the outer gauze was 62°C and the inner glass 36°C.

Adherence of coal particles on to the surface of the lamp glass was also measured in a series of laboratory experiments. The lamp glass was heated in a muffle oven until the temperature reached 80°C and quickly removed from the oven and placed on its side 2cm below a Bunsen burner flame. A sample of coal dust from Moura No.4 mine was crushed and sieved to provide a size fraction below 75 micrometre particle diameter. A small amount of this dust was allowed to fall through the Bunsen flame, the temperature of which was measured at 1150°C, and to impinge on the glass surface. Particle adherence was measured by the ease with which it could be removed after cooling to normal temperature. Adherence of particles did not occur until the glass temperature was above 600°C.

Experiments were also made to measure the transfer of heat through the glass from the outside surface to the inside. With a Bunsen flame at 1150°C on the external surface of the glass it took 29 seconds to reach 270°C on the inside and 50 seconds to reach 450°C.

Subsequent to the initial investigations some changes were made to compensate for the lowering of oxygen and increasing CO_2 in the closed loop explosion chamber. Oxygen was allowed to enter the system in such a manner as to keep the O_2 level to the value that would exist in a mine with normal air flow past the lamp. Under such conditions it was shown that the lamp without the bonnet could heat sufficiently to cause an external ignition of a methane/coal dust atmosphere.

Research into Flame Safety Lamp Post Moura Inquiry

With the assistance of a NERDDP support grant the investigation of the flame safety lamp continued at SIMTARS.

A section of duct was constructed with an axial flow fan to provide a range of air velocities up to 6m/s. An inner duct was used to provide a gas concentration past the lamp of up to 10%. The temperature of significant parts of the lamp was measured with four thermocouples and a thermal imaging infra-red camera for general temperature measurement. Air velocity was measured with a calibrated anemometer and the methane concentration sampled with a tube near the lamp and analysed with an infra-red analyser. For experiments involving coal/methane/air mixtures a hopper containing a dust was suspended from an adjustable stand positioned alongside the experimental gallery. Dust from the hopper was injected into the inner duct where it was allowed to mix with the methane airstream.

Signals from each monitoring device were connected to a data acquisition board which was connected to a personal computer. Data acquisition is triggered at the computer keyboard, at the start of each experiment. A commercial software package was used for data acquisition and a program written by SIMTARS staff to analyse the data collected.

An opening in the wall of the outer duct opposite the lamp position allowed viewing of the activity with a video camera, or the infra-red camera, or both.

Without the bonnet on the lamp there is a threshold area of methane concentration and air velocity conditions within which an ignition may or may not occur. Below this threshold area no ignition occurs. Above the threshold level ignition occurs in the lamp under velocity and methane conditions which could easily occur in a mine.

Modifications made recently have resulted in a duct of smaller cross-sectional area which permits the air velocity to be varied up to 17m/s. The only other change has been a minor change in the dust injection system.

Experiments with the bonnet in its normal operating position have confirmed research carried out prior to the Moura inquiry. Heating commences within the inner gauze after the flame has extinguished as long as the air velocity is above a minimum value. The temperature increases as long as the airflow and methane concentrations are maintained. With only methane incandescent combustion occurs within the gauze without any visible flame. As heating continues, the top of the gauze, as seen through the holes in the bonnet, changes colour from dull red to near white, while the temperature increases to is the [illegible] ?

over 1000°C on the inner gauze. The presence of coal dust results in a flame within the inner gauze which at times is seen to project into the area of the glass. In some experiments the inner surface of the glass has been heated sufficiently to allow some fusion of heated coal particles to the surface, as occurred in the Moura lamp. [illegible]

At the time of compilation of this report four external ignitions have been achieved with the bonnet of the lamp in its normal position. Two of these were with methane only and the others with methane and coal dust.

It has been shown experimentally that the flame safety lamp, if it were alight at the time of a methane/coal dust cloud formed as the result of a fall, is capable of providing an ignition source for a coal mine explosion.

Conclusion

A review of the evidence presented to the Warden's Inquiry and available for this project does not enable a decision on whether the impact of rock/rock or rock/steel provided the ignition source for the explosion. It is possible that the goaf fall, as was anticipated, occurred before the explosion. If frictional ignition in the goaf is assumed to have initiated the explosion then it has to be recognised that some blast damage could have resulted from the fall prior to the explosion.

(no — pressures too low on values you gave earlier)

It follows that all of the blast damage which occurred cannot be assumed to have resulted from the explosion. This renders the task of investigation even more complex than would have been the case if all blast damage had resulted from the explosion. That task would be difficult enough given the network of roadways and c/t involved.

There are other alternatives which also cannot be ruled out.

no details have been given and no evidence to demonstrate this has been given to the external consultants (word only)

This is totally incorrect

CHAPTER 5

THE INVESTIGATION OF A COAL MINE EXPLOSION

By
P. Golledge

FORENSIC SCIENCE EXAMINATION OF RECORDS AT MOURA NO.4 MINE EXPLOSION, 1986

By
R. Barnes, K. Romaniuk, S. Leivesley

5.1 Investigation of a Coal Mine Explosion

An investigation of a coal mine explosion involves an objective analysis of all the relevant factors. The prime responsibility for making the necessary investigation lies with the Inspectorate of Coal Mines. Many branches of science, engineering and medicine including forensic science and forensic pathology assist in the investigation process.

This chapter discusses the scientific methods used over many years to establish the course, nature and immediate cause of a coal mine explosion. The contribution of forensic pathology is discussed and the application of forensic science.

5.2 Methods of Examination at the Mine

According to Tideswell [19] *"The tracing of the course of a mine explosion to its source and the determination of its nature are often surprisingly difficult. There are two complementary methods of approaches. One, the intuitive approach, is based on experience and knowledge of the pit and of the mining operations in progress; the other, the analytical approach, which is the peculiar task of the scientist to follow, is based on a dispassionate survey of all the evidence recoverable. Both approaches are needed and must be related. The intuitive approach suggests the most likely answer, but taken alone may lead to conflicting views. Moreover, experience teaches that the apparent explanation is not always the true one and that the most unlikely events may have contributed. Meticulous documented evidence is needed to establish the course of events and it is important that the immediate observations, on which the conclusions are based, should be as comprehensive and as accurate as possible."*

Observations are made concerning:

- Violence.
- Burning.
- Fires.
- Coked dust.

- Explosion Dust.

- Composition of Roadway Dust.

- Collection of Specimens and Samples.

5.3 Use of Forensic Pathology in Coal Mine Explosion Investigation

Identification of the body has important psychological significance to the next of kin and is also important for legal implications. Visual identification is normally used but this may not be possible when bodies have not been recovered for some months. In such cases the forensic pathologist relies on dental records and X-ray data to establish the identity of the deceased.

Establishing the time of death is usually reasonably accurate in the case of an explosion when the consequences of the explosion cause damage to the main fan, disrupt the power supply, telephone system all of which are usually indicated at the surface of the mine.

The manner of death, or the way in which a person met his death can be classified into natural, accidental, suicide, homicide or undetermined. In the case of a coal mine explosion the deaths are classified as accidental.

The cause of death is the most significant underlying pathological entity which led directly to death. Other conditions which did not cause death directly are considered to be contributing factors. Experience in many countries that have experienced coal mine explosions record the cause of death as injuries, burns, or asphyxia or in some cases a combination of all three.

The cause of the accident can only be determined after all factors have been considered and also the results of an internal and external examination of the body, clothing and other personal effects. It would normally be necessary to send the clothing to another laboratory so that fibres in the cloth can be examined for evidence of exposure to flame or heat, or both.

If at all possible the forensic pathologist should visit the scene of the accident.

Forensic examination may provide information on the magnitude, direction and duration of the force from the explosion pressure wave as well as some idea of the temperature to which the body was exposed.

Toxicology can assist in identifying the presence of any drugs, including abused substances, alcohol and those prescribed medically.

The forensic examination can also give information on whether the victim survived the initial explosion, and if so the time of survival, whether the injuries were survivable and also whether the victim was conscious or unconscious after the event. Whether or not the victim had used the self-rescuer and its effectiveness may also be determined.

Dust and soot in the respiratory tract and also carbon monoxide in the blood indicate the victim was breathing after the explosion.

Carbon monoxide levels may reach as high as 10% after a methane or coal dust explosion and at this concentration blood saturation of carboxyhaemoglobin in excess of 50% would occur in 50 seconds or less. Carbon dioxide levels may also reach a level at which hyperventilation occurs. Oxygen may be as high as 5% after an explosion but may be as low as 1% depending on the strength of the explosion and other factors.

In one other way an examination of lung tissue from the victim will give a measure of the presence of pneumoconiosis. This information when related to dust exposure measurement can determine the effectiveness of dust control technologies and provide data on particle size distribution.

5.4 Forensic Science Examination of Records at Moura No.4 Mine Explosion 1986

Introduction

The remainder of this chapter places the work of the forensic scientists into perspective and describes the background of the information used from the Moura No.4 explosion. The second part of the chapter focuses on the work of the Forensic Science Laboratory, Victoria and gives details of the effects of the explosion on the mine, equipment and the forensic pathology of the victims.

The discussion covers analysis of the effects of blast and heat on equipment, including the flame safety lamp and the forensic pathology of the victims. The aim of the work is to relate patterns of inquiry to the course of the explosion using details from the post-mortems, photographic evidence and expert evidence. In describing injuries to the victims of this disaster there is a full understanding of the sadness of the relatives, miners and mines rescue teams.

The full examination of each victim of this disaster is rigorous in its detail. This is done not only to describe what has happened to one group of victims but to try to ensure that other miners do not become victims in the say way.

The mining industry is one of the most safety conscious industries in the world and no-one works underground without concern for the safety of everyone else. There is in the industry a real commitment to ensuring that everything possible is done to protect life.

It is the purpose of this chapter to open the field of forensic science for the mining industry and to describe the contribution of the specific pathological findings towards understanding the direction and source of an underground explosion. It is only with this information that work can start to be done to protect other miners from a similar incident.

5.4.1 Forensic Science

Forensic science provides an objective analysis of an incident using relevant scientific procedures which are co-ordinated and generally following an established procedure.

A description of the main assumptions used in scientific investigations of explosion has been provided by Yallop [20] who was head of the Explosives Forensic Science Laboratory at Woolwich Arsenal.

In explosions, examination of the damage is the usual starting point of an investigation into the cause of the explosion. Observable damage may be divided into permanent distortion of objects, displacement of objects and flame and heat effects.

With a dispersed explosion the region of maximum damage may be remote from the explosion centre. As the explosion progresses it encounters objects with resistance and this increases the turbulence and the speed of propagation and hence the pressure. The region of maximum damage is likely to be remote from the explosion centre.

Investigators can make estimates of pressure from purely theoretical calculations using values for the gas concentrations.

However the more reliable method according to Yallop is to use observations from the scene to estimate pressures actually generated. Information is also available from fragments at the scene. Yallop [20] states:

"It is a cardinal principle of explosion investigation that as many primary fragments as possible should be recovered for examination."

The damage caused by primary fragments can sometimes be used to determine the direction in which the fragment was travelling. The fragment can be examined for penetration, gougemarks and pitting.

Yallop further describes the approach to the scene of an explosion. He says:

"Fire fighters and rescue workers must, in the course of duty, take calculated risks. While the first explosives expert on the scene must not attempt to tell such people how to do their job we would be failing in his responsibilities if he did not place at their disposal his specialist knowledge of the dangers involved. ... It is vital that at the earliest possible moment the scene should be 'frozen'; that is preserved in the immediate post explosion state."

Yallop's advice is that the more spectacular the explosion the more likely it is to attract high ranking police or military officers or politicians. Such visits serve no useful purpose and are liable inadvertently to destroy evidence and should be resisted tactfully with a brief explanation of the need for the apparent discourtesy.

5.4.2 Forensic Pathology

Forensic pathology describes the injuries on the victims from the explosion and provides an understanding of the circumstances in which victims have died.

Marshall [21] provides a comprehensive description of the analysis of explosion injuries. It involves the recovery of the parts of the body that remain after an explosion, the identification and an investigation of the cause of death.

In explosions there can be very high temperatures from the explosive gases and contact with the momentary flame causes burns. People outside this range can be burned by the radiated heat. Heat radiation of high intensity can be stopped by solid objects and clothing. Persons tend to get these burns on the unclothed parts of the body, usually the head and hands.

Flash burns usually affect an area, perhaps on the face or one side of a limb more or less uniformly.

Flame burns from burning clothing and objects tend to be less uniform. Clothing is set alight by fire in the vicinity or by radiated heat - this is more likely in dark coloured clothing. Burns from clothing occur on both clothed and unclothed areas.

When the environment is set on fire the whole of the body may be burned.

The biophysics of air blast injury involve the striking of the body surface by the shock wave, part of which is deflected and part absorbed. The shock wave passes through relatively homogeneous tissues such as the heart, thigh and solid organs but air-containing organs are very vulnerable - ears, lungs and segments of the large bowel. Lung lesions take the form of alveolar haemorrhage which when severe has the respiratory passages filled with blood and froth causing suffocation.

Desaga [22] describes the action of dust in an explosion. He states that dust particles, even if very minute have quite a considerable velocity and particles of a fraction of a millimetre may penetrate deeply into the skin and cause "dust tattoos".

It has been generally known that in mine explosions Marshall [21]:

"Some miners die at once from the blast without any external signs. Some die from injuries sustained when they are hurled by the blast or buried under roof falls. Some die from the effects of the momentary fire, having sustained burns; since the flame travels nearer the roof than the floor, the upper half of the bodies is burned more than the lower half. Most, however die from the inhalation of the postexplosion fumes called afterdamp, the principal poisonous constituent being carbon monoxide. Many victims have first been immobilised by blast, injuries, or burns."

5.4.3 Recovery of the Victims at Moura

The report of the Queensland Mines Rescue teams which undertook the rescue Brady [23] describe the actions of each team that went underground and their expert observations.

The first contact with the victims of Moura occurred after Team No.6 led by Chris Glazbrook entered the mine at 10.25pm of the evening and returned to the surface by midnight reporting contact had been made with 10 bodies. Visibility was extremely poor and blast debris and a thick dust haze had made walking conditions very difficult.

Samples at 26 c/t No.4 Supply Road were 3.2% methane, 400 ppm CO, 0.5% CO_2. Ventilation movement was not detected. The team found the first body tangled in machine cables just outbye of 26 c/t in No.4 Supply Road.

In 26 c/t just south of No.4 Supply Road and near the inbye rib was a body and inbye of 26 c/t in No.4 Supply Road a body was found jammed between a vehicle (Mine Rover) and the Southern rib. The body was half under the vehicle and could not be identified. Six bodies were found at the intersection in 26 c/t No.3 Belt Road to No.2 Transformer Road. Another body was located in 26 c/t No.3 Belt Road to No.4 Supply Road.

The body recovery was carried out by five teams commencing at 12.45pm on Wednesday 23 July (seven days after the incident). One body was found on the right hand side of the roadway just outbye of 26 c/t. The body was on its left hand side, face down and entangled in "bull hose". Another was on the junction of 26 c/t No.4 Supply Road and on the inbye side of the c/t lying on his back. A third was jammed between the rib and the mine rover. This body was on its back and partially under the vehicle while another was in 26 c/t between No.4 Supply Road and No.3 Belt Road on his back.

One victim was found under the front of the cable reel compartment of s/c No.31. Only the lower portion of the legs was visible. A jack was used to lift up the shuttle car and coupled with hand removal of coal permitted the body to be pulled free.

The body was supine and appeared to be in good condition with all clothing still intact. The shirt was still tucked into the trousers. The cap lamp was on the body but the cord had been pulled apart.

Four bodies were grouped together across the c/t and at an angle to the shuttle car; one on back, two on face, and another on its back and on top of the other bodies.

The bodies were then photographed when brought out of the mine, placed in a helicopter and flown to Rockhampton for post mortem examinations.

5.4.4 Post Mortem Reports

The post mortems were carried out on the 24 July, eight days after the incident. The pathologist's tasks were to determine the injuries sustained to the bodies and to ascertain the cause of death. The bodies were photographed prior to the commencement of the post mortem examination by a police photographer. Because decomposition of the bodies was considerably advanced after eight days, no detailed sampling of the tissues could be undertaken. Observations of the external injuries, as far as could be ascertained, were recorded, and a record was kept of the clothing of each victim and the extent of their damage.

In the Inquiry the pathologist reported on cause of death and was cross-examined on the injuries to the body found beneath the shuttle car. It was announced in the Inquiry that the pathologist, Dr Ansford, would not be questioned in detail to avoid further pain and suffering to relatives in the Court.

5.5 Examination of Records

It has been well documented that the timely application of established forensic procedures to the investigation of an explosion is the only means of reliably establishing the circumstances surrounding the explosion.

The actions taken at the explosion scene will be significantly influenced by the nature of the incident. In particular, the environment in which the explosion occurred; the amount of damage and dispersal of debris; the number of casualties and their distribution within the scene; the location of the incident; the weather conditions prevailing and the likelihood of further (related) incidents. However, the essential consideration from the incident investigators viewpoint is preservation of the scene in its totality. Clearly and rightly, this consideration cannot be met without significant compromise in relation to preservation of life and property.

5.5.1 Classification of the Incident

The type of incident largely dictates the manner in which the explosion is to be investigation. For this purpose, explosions can be conveniently divided into two broad categories:

- Explosions Where the Essential Nature is Obvious -

  In these cases the investigation will be a limited one designed to determine some specific point only. Consequently, the plan of action can be likewise limited. Thus, in an incident of a legitimate nature, say the ignition of bulk fireworks during manufacture, the cause of ignition becomes the primary object of the investigation.

- Explosions Where the Essential Nature is Not Obvious -

  In these cases, the investigation may well be very comprehensive. Explosions of this type include large disasters leading to substantial demolition of building, the reduction of a room by an explosion in which no explosive is to be expected, the destruction of an aircraft in flight such as occurred in PANAM Flight 103 over Lockerbie on 21 December 1988, or the explosion which occurred within Moura No.4 Mine.

The plan of action arising from these deliberations will be unique to the particular incident and largely dependent upon the experience of the investigator and the support he has available. However, the nature of mine explosions is such that an immediate response plan may be generated which will provide a reliable framework which will ensure as far as is possible, firstly, that all necessary and appropriate emergency services are committed in a timely manner and secondly, that the scene is properly processed.

5.5.2 Approach to the Scene: Immediate Actions

Following a mine explosion, a number of actions are of immediate priority. Clearly, any necessary fire fighting and medical treatment and evacuation of injured must be undertaken but there are certain actions which should only be undertaken by specialist personnel. Most important is the "rendering safe" of the scene.

Regardless of whether or not the explosion was the cause by a solid, liquid or dispersed explosive, there is always the possibility that further unexploded material may be within the mine and can be in such a sensitive or hazardous condition that it may be initiated by those moving about the scene.

Any explosion which has caused structural damage may generate new hazards by the release of gas or vapours. Similarly, such damage may provide sources for ignition, for example electrical wiring may produce sparks. Where the explosion has given rise to a fire, the potential for further explosions almost always exists. Clearly, the advice of an experience explosion scene investigator is crucial in the early stages of the post-explosion management plan.

The scene of a mine explosion is one of considerable confusion, moreover, many aspects are transient in nature and can easily be lost if the investigation is not adequately managed. Therefore, it is essential that once the scene has been secured, all possible witnesses are identified and interviewed - once they have left the scene, the information they possess may be lost forever. Similarly, allowing the scene to become a "Tourist Attraction" for any person not directly involved in the investigation, may well enhance the difficulties faced by the post-blast analysis team, and significantly detract from the final investigative outcome.

The identification of the seat of the explosion and the source of ignition is a matter of vital importance and the primary object of the post explosion investigation. In the case of dispersed gas explosions, the region of the seat of the explosion will not contain the most severe blast damage. From this point the progress of the blast and fire front can be determined providing all "indicators" are preserved. These "indicators" include all material and deceased personnel within the mine disaster scene.

It should be noted that personnel who have been subjected to an explosion will display complex injuries. The examination of the deceased must be undertaken in two phases. Firstly, in situ by the explosion scene examiner and subsequently at autopsy by the pathologist in concert with the explosion scene examiner who will recover all objects which have penetrated the bodies and assess the extent of blast and other explosion indicators. In the case of injured personnel, every effort must be made to ensure recovery and retention of fragments from wounds and record the nature and extent of injuries.

5.5.3 General Characteristics of the Explosion

The characteristics of a dispersed gas explosion of the types which occurred within the Moura No.4 mine may be summarised as follows:

. The point of initiation may be remote from the bulk gas explosive source.

. The flame front will engulf objects and personnel close to the point of initiation (causing all round burning).

. With confinement such as that available with the Main Dips Section, a rolling flame front will develop.

. Where multiple tunnels are available for flame front progression, complex flame front interactions may develop. Modelling will assist interpretation of interactions.

. Flame front velocity is relatively low; however flame duration is short (compared to condensed explosives). Therefore burning of objects and personnel arising from the explosion will be relatively short-lived.

. Without detailed flame front progression modelling, interpretation of post blast burning patterns at nodes is difficult.

. The blast pressure front velocity is relatively low (compared to condensed explosives) but of significant duration. That is, significant displacement of objects will occur but little or no fragmentation of materials will be observed.

. Restrictions (objects within the roadways) will cause added turbulence and increase the velocity of propagation of the explosion front.

. The tunnels and objects within them will cause "shadowing" and blast/flame front reflections.

These dispersed (gas) explosion characteristics have produced a range of terminal effects on both material and personnel within the mine. However, most of the available information has been lost or obliterated due to an inadequate post blast investigation. Failure to properly examine and record in-situ the condition of the deceased miners, in particular, the presence of blast damage, fragment attack and flash burn has severely restricted subsequent explosion investigation.

NOTE:

Sub-sections	5.5.4	"Observed Personal Effects" and
	5.5.5	"Condition of Deceased Miners after Explosion"

have been deleted from the published report as they contain medical details which could cause unnecessary stress for relatives and friends of the deceased miners and persons in the coal mining industry.

Any person who has a legitimate need for the information may obtain it by writing to:

The Honourable K.H. Vaughan MLA
Minister for Resource Industries
61 Mary Street
BRISBANE Q 4000
AUSTRALIA.

5.5.6 Observed Material Effects

The following explosion effects were apparent:

. Displacement of Objects; and

. Flash burn/blast damage.

However, this examination of records is restricted to material WEST of 25 c/t and is limited by the previously stated inadequacies in post blast processing of the scene. It must be emphasised that the use of small, light objects as indicators of displacement (and therefore overpressure magnitude and direction) should not be undertaken where there exists the possibility of complex pressure wave interactions and venting paths. For this reason, significance has been placed on the displacement of large heavy objects whereas the general movement of smaller objects only has been regarded as indicative.

Displacement of Objects

It was noted that displacement of smaller objects has been EASTERLY (outbye) from the goaf and is indicative of explosion front progression in an EASTERLY (outbye) direction from the goaf. The displacement of heavy objects in No.4 Supply Road is indicative of explosion front progression in an EASTERLY (outbye) direction. In the region of the intersection of 26 c/t displacement of the crib room table is consistent with complex explosion front progression which had continued outbye on No.4 Supply Road turned SOUTH down 26 c/t and been initially hampered and turned by the stopping NORTH on 26 c/t (the probable crib room). The displacement of the mine rover indicates explosion front progression EAST (outbye).

The observed positions of s/c No.31 and s/c No.30 are consistent with explosion front progression in an EASTERLY (outbye) direction along No.3 Belt Road and SOUTH down 26 c/t causing s/c No.31 to rotate clockwise (when viewed from above) and pushing shuttle car 30 counter clockwise (when viewed from above).

Flash Burn/Blast Damage

Significant blast and flash burn damage was noted on the mine rover situated in No.4 Supply Road. The roof had been lifted and significant flash burning had occurred to the back of the seats. This damage was consistent with the explosion/flame front progressing in an EASTERLY (outbye) direction along No.4 Supply Road striking the front of the mine rover which has been lifted and pushed into the SOUTH wall of the tunnel. There was no evidence of significant explosion/flame front impingement to the rear of the vehicle.

The Flame Safety Lamp recovered from Moura No.4 Mine was examined. The body of the lamp displayed impact damage consistent with it having struck a hard object. Some blackening was present on the lamp body. The damage and blackening are consistent with the lamp having been subjected to a short duration explosion flame front. The damage did not appear to be consistent with the Flame Safety Lamp having initiated the explosion.

Examination of a Report on Examination of Two Gauzes from Flame Safety Lamp Moura No.4 Mine Explosion has revealed the following:

. The inner and outer gauze are microstructurally different.

. The grain size is not uniform between gauzes.

. The new gauzes are dissimilar to the gauzes removed from the Moura No.4 Mine flame safety lamp.

The presence of grain size variation in ferritic wire of the type shown may arise during manufacturing processing. The extent of grain growth present in the gauzes from the Flame Safety Lamp Moura No.4 Mine Explosion is not great and given the dissimilarities identified between each of the gauzes cannot be regarded as definitive.

It is considered that the absence of significant blast damage to the lamp, the inconclusive nature of the metallurgical examination of the gauzes removed from Flame Safety Lamp Moura No.4 Mine Explosion, and the explosion source indicators already discussed rule out the Flame Safety Lamp as the initiation point of the explosion.

5.6 Discussion

The terminal effects detailed may be explained by an explosion initiated within the goaf propagating outbye along No.3 Belt Road with the major explosion/flame front propagating outbye along No.4 Supply Road turning (in part) SOUTH down 26 c/t. Considerable turbulence would be experienced at the junction of No.4 Supply Road and 26 c/t initially due to the temporary obstruction caused by the stopping NORTH of the crib room and explains the extensive flash burn experienced by one of the deceased. The injuries sustained by victim No.9 are consistent with partial shielding by the mine rover. The injuries to and placement of the victim No.11 are consistent with his being in the vicinity of the crib room. The injuries to and placement of victims Nos.1 and 2 are consistent with their being projected outbye along No.3 Belt Road. The injuries to and placement of victims Nos.3, 4, 5, 6, 7, 8 and 12 are consistent with their being projected SOUTH down 26 c/t by the explosion pressure front.

There is no evidence to suggest the explosion was initiated either in or near the junction of No.3 Belt Road and 26 c/t or the junction of No.4 Supply Road and 26 c/t.

5.7 Summary

Explosion scene investigations are based on the premise that everything at the scene prior to the explosion is still, at least in part, in existence in some form. While the explosion can in some instances destroy material which was in close proximity to the seat of the explosion, most of the items that were present before the explosion will remain, although their size, shape and appearance may be altered radically. Explosion scenes are often difficult to secure due to their size, location or nature. However, experience has shown that providing sound explosion scene examination procedures are followed much significant information and evidence can be recovered. These procedures require the full cooperation of all emergency services attending and a dispassionate approach to all material and deceased personnel within the disaster scene.

CHAPTER 6

MINE EXPLOSION ANALYSIS

By
A. Green

Following a mine explosion there is a need to establish the factors that led to the incident in order that the incident can be made avoidable in future. This objective can only be achieved by thorough investigation and analysis of the incident. Collection of data and its analysis is not straight forward because:

- The source of ignition can be well away from the centre of maximum heat damage or maximum pressure damage.

- The positions of objects found following the explosion are not necessarily the positions of those objects prior to the explosion.

- Maximum heat damage does not necessarily occur with maximum pressure damage.

- The time elapsed.

- Delayed access to the site.

As a consequence, detailed calculations are required to establish the pressures and movement of objects that were likely to exist during the explosion and from which different hypotheses on the course and cause of the explosion can be tested.

This chapter contains a brief outline of research methods and a detailed discussion on the movement of objects and modelling techniques which assist the investigation process.

Finally these techniques are applied to the explosion at Moura No.4 Mine, based on the data taken by persons at the time of the investigation and given as evidence to the Inquiry.

6.1 Investigation Techniques

In any investigation with an explosion (whether mine or otherwise) it is essential to obtain as much data as possible so that the incident can be reconstructed. For example, following an overseas hotel bombing, several thousand buckets of blast fragments were collected from this hotel and surrounding area to assist with the reconstruction in the explosion. In the case of the Lockerbie plant disaster, plane fragments were collected and reassembled to establish the location and size of the bomb on the aircraft. Although this approach is mainly applied to bombs, the same philosophy can be applied to mine explosions. In the Golborne mine explosions, [24] detailed examination of the ventilation system followed by modelling of the ventilation established the course of the build up of methane in the mine which subsequently was ignited.

In all these cases, the first objective was to establish the course of the explosion. This is achieved by systematically looking at pressure, heat, flow and other directional indicators.

The way the pressure develops relative to the way maximum heat damage occurs, or indicators of the direction of flow can be used to establish a set of criteria against which different hypotheses can be tested.

Often there are one or two factors that are decisive in establishing the area of ignition. In the Flixborough explosion [25] for example, directional indications from lamp posts on the site blown over by the air movement caused by the explosion indicated the area from which the explosion developed. Further investigation of pipework in that area established which pipe in the area had fractured and what had occurred.

Once the course of the explosion has been established, then factors leading to the cause of the explosion can be identified. Usually more than one factor is responsible for the explosion.

To complete the analysis, alternative hypotheses have to be tested against the critical factors on the course of the explosion and then against the requirements for a build-up of a flammable mixture, and an ignition source. Explosions resulting from large gas leaks in surface installations can be triggered by any one of numerous sources. Underground, ignition sources are well controlled and so there is a need to establish both the mechanism of obtaining the flammable mixture and the mechanism for ignition. The normal procedure is to concentrate on well known sources in the area and excluding them before looking at more exotic sources. Often there is more than one mechanism both for flammable mixture build up and for ignition. This highlights the need to establish a course for the explosion as it limits the number of potential ignition sources. Generally the larger the area considered, the more ignition sources there are in that area. For example, the Moura explosion has ten potential mechanisms for ignition between 23 c/t and the goaf in the Main Dips area of the mine. The Inquiry only considered 3 in detail, namely frictional ignition from rock and from the Entonox bottle, and the flame safety lamp.

6.2 Australian and Overseas Forensic Research

Research into explosion debris analysis has centred on three main areas:

- Eestimating overpressures by the type and amount of damage incurred.
- Estimating overpressures from the movement of objects.
- Estimating flame pattern from the heat damage incurred to objects.

Physical models of the incident are used to study flame development and propagation allowing the researchers to piece together the relative timing of different events and to show how the observed patterns of pressure, heat and air flow have been obtained by Hjertager [26] and more recently mathematical models are being used for this purpose as well Hjertager [27].

Pressure and heat effects on materials are time dependent. The mechanical damage is related to the impulse (that is the pressure-time integral) received from the explosion at the material surface. Heat damage is related to the heat impulse (that is the heat flux-time integral) at the material surface. Obviously a large pressure pulse over a short duration will give the same degree of damage as a pulse 1/10th as high over 10 times the previous duration as long as the threshold to damage is exceeded. This is similar with the degree of heat damage. Studies of typical damage due to pressure or heat where the time duration is known, gives a baseline against which actual incidents can be compared. It is this process that provides the basis for analysis of the course of an explosion.

6.2.1 Estimating Overpressures from Damage to Structures

Table 6.1 contains the range of overpressures observed for different degrees of observed damage to buildings and other structures. The table is compiled from various sources and is based on data from chemical and nuclear explosions. In general the overpressures are typical of the onset of such damage. They are valuable in defining the minimum overpressures for such damage.

The data on the collapse of a brick wall can be applied directly to the collapse of brick stoppings in a mine explosion. From Table 6.1 various levels of brick damage occur depending on which source reference, the type of bonding and the type of reinforcing in the wall. Collapse of unreinforced 16″ blocks of the type used at Moura occurs at about 30 kPa.

Christopherson [28] has shown that the response of a brick panel to an unsteady lateral pressure can be described by a simple equation involving the average deflection of the wall, the mass of the wall, the pressure as a function of time and a function describing the resistance of the wall with time. Knowledge of the pressure function and resistance function allows computation of the deflection time history and the time at which the wall collapses. Wiehle and Bockholt [29], Wiehle and Bockholt [30], Wiehle [31] calculated the resistance functions for a given maximum deflection corresponding to the maximum deflection for the elastic phase. After cracking the resistance per unit width decreases linearly to zero at a deflection equivalent to the wall themselves. Such an analysis allows the initial debris velocity and damage to be calculated.

Cantilevered structures such as the long exposed ends of roof bolts, barrier supports etc can also be used to assess the overpressure. A transient pressure pulse can cause rotation of the structure about a point near to its fixing point, if the resistance to movement is overcome by the pressure force. The final deflection can be related to the movement by pressure force and the inertia about the plastic hinge that is formed Roberts and Pritchard [32].

6.2.2 Displacement of Objects

The movement of objects by the explosion is governed by the basic equation of motion where the acceleration is related to the incident pressure through an acceleration coefficient and the resistance to movement. Integration of the equation will yield the velocity and displacement of the object. This method can be used to calculate the distance any object has been displaced, whether a mine rover, bricks, pieces of steel or people. Fletcher and Bowen [33], Longinow [34] and Fletcher et al [35].

Objects and people can be in a number of orientations relative to the incident blast wave, upright or prone, side on or face on etc. For many objects the centre of mass is not at the same height as the centre of drag. Consequently orientation of the object will change during the motion. Any calculations based on maximum exposed area will lead to the minimum explosion pressure required to move the objects a given distance.

Various studies Bowen et al [36], Iverson [37] and Fletcher et al [38] and Harris [39] have been done on the fragmentation and displacement of windows in surface explosions. However, few studies have been done on materials directly applicable to the movement of objects in mine explosions.

A number of experiments have been undertaken to look at the behaviour of bodies as they are displaced by the blast. Taborilli et al [40] examined the velocity and distance histories of anthropomorphic dummies. The most interesting observation as shown in Figure 6.1, is the way the head and feet move relative to the centre of mass. Michelis [41] repeated this type of experiment at Tremonia explosion gallery with dummies wearing miner's helmets, cap lamp, belt, battery and self rescuer. He found that the head was displaced forward. The difference in the result is due to the centre of mass being lowered while the centre of drag is raised compared with the former study.

The work on deceleration of mannequins suggests that body alignment is not retained for more than a few metres. The bodies at Moura were not in random orientations and as will be shown in Section 6.2.3 have moved a considerable distance. There seems to be a disagreement between what was observed at Moura and overseas work on body alignment. It should be noted, however, that the work done overseas was (1) on hard surfaces (concrete) unlike the compacted floor of a mine roadway and (2) the bodies were subjected to no impulse or one that had a static pressure impulse of similar duration to the dynamic impulse. These two conditions are very different from a mine explosion and could be the reasons for the discrepancy. There is however a need for much more detailed research in this area for mine explosions.

6.2.3 Heat Damage

Heat damage to plastic materials, fibres and other surfaces is highly dependent on the incident heat flux and the duration of flame. Brookes and Rae [42] showed that a radiant coal dust explosion will produce varying degrees of blistering in a single entry heading, with no samples showing signs that they had reached their ignition temperatures and only a few showing evidence of pyrolysis.

The recent development of better test methods of assessing the fire behaviour of materials Brabauskas [43], Green et al [44] and Green et al [45] give the correlation between flame residence time and time to ignition for a given material. That correlation can be used to assess flame residence times in explosions from microscopic examination of materials in the incident.

There has been very little work on the effect of long residence times under explosion conditions, i.e. high incident heat fluxes, due to the restriction in geometry of experimental galleries around the world.

6.3 Modelling of Explosions

There are two broad classes of modelling techniques that can be used to assist in understanding how an explosion will develop in complex and confined geometrics: Physical and Mathematical models. The former generate physical data which can be compared with the explosion case to be studied. Mathematical models generate details of the physics that cannot be measured in practice and can give both a qualitative and quantitative understanding as to what has occurred.

6.3.1 Physical Models

Physical models are full or scaled models of the case to be studied. Since explosions are very complex phenomena, there is a limit as to how small a model can be made and still yield results of use. Since explosions are fluid problems, similarity in the fluid flow should be maintained if at all possible. For example, the Reynolds number is one parameter that characterises air flow in a mine roadway. Any model of the roadway should have a similar Reynolds number in addition to being geometrically scaled. In practice, this requires the velocity or viscosity to be changed as the dimensions are changed.

Full and scaled models are being used to assist investigation of accidents. After the Kings Cross Fire in London, UK, a 1/3rd and 1/50th scale model of the conveyor system were constructed by the HSE and Edinburgh University to assist with the investigation. Currently the Christian Michaelson Institute is building a scale model of the piper Alpha Oil Platform to assist the Norwegian Government with continued investigation of that accident.

In an explosion there are about 20 dimensionless parameters similar to the Reynolds number which control different processes. It is impossible to scale more than one of these accurately so models at a reduced scale can only be used as a qualitative guide of what is occurring.

A 1:54 scale model of a section of the Moura No.4 Main Dips Section was constructed between 25 c/t and 27 c/t over all roadways to help visualise the changes that occur when the ignition source is systematically moved around the model under controlled conditions.

6.3.2 Mathematical Models

Over the last few years mathematical modelling of fires has been used to assist with the investigation of serious fires. Most of this work has been pioneered by Dr G. Cox at the Fire Research Establishment, Barhamwood, UK [46]. Among the application of these field techniques were the Bradford Football Stadium Fire and the Kings Cross fire. The UKAEA establishment at Harwell also undertook studies on the Kings Cross fire which pointed the way for experimenters to confirm what actually occurred.

The use of modelling techniques for explosion accidents is somewhat more limited. Currently there is some work being undertaken by Hjertager on the Piper Alpha explosion but this is in a very early stage of development. The only other work in this area is being undertaken by Green who is applying his own code to the problem in hand concerning Moura No.4 Mine.

An explosion involves a propagating pressure front with gases at high temperature and pressure following it. The temperatures may be high enough to ignite gas and may contain a flame front as well. Hence an explosion simulation has to include prediction of the fluid flow and combustion. The fluid flow itself is a complex phenomenon with the effects of convection and diffusion brought about by viscosity and turbulence. Combustion adds to this complication and requires chemical kinetics to handle it.

Any general flow is governed by the Navier Stokes equations and these are used in conservative form with additional equations for gas species written in terms of fuel mass fraction and mixture fraction. A two equation model of turbulence, the K - Epsilon model, is used to describe the effects of turbulence. A simple one step combustion process is used because a reaction scheme for methane involves 54 basic reactions. Solving these equations can be done but is computationally very expensive. A simplified approach is justified given the complexities in solving the flow equations.

Eight equations have to be solved simultaneously for a 2 dimensional flow (9 for a 3D case). Only a few methods have been used to solve combustion problems of this type. One method employed by Hjertager [47] is based on the SIMPLE method by Pantanka and Spalding [48]. This is an implicit method which in principle can use any value of timestep. This claim is justified when it comes to steady state problems, but with transient flows there is always a timestep limitation. Another method is the Flux Corrected Transport (FCT) method of Boris and Oran [49]. This is an explicit method and so has a limitation on the timestep value for steady state and transient problems. The advantage of the FCT method is that it can control numerical diffusion in the solution so that shock fronts remain as shock fronts and do not degrade.

The method that is being developed by Green and Srinivas [50] to solve the equation set is a Total Variation Diminishing (TVD) scheme and is similar to the FCT method, being able to control numerical diffusion in the solution. The region to be simulated is divided into finite volumes and for each of the volumes a modified Runge-Kutta method is used to solve the governing equations. This scheme has some very desirable properties:

. The scheme is explicit and consequently boundary conditions are easily implemented.

. A larger timestep can be used compared with other explicit codes.

. The scheme renders itself to parallel processing. This feature can make an explicit scheme yield a solution far more quickly than an implicit scheme even though the latter can accept a higher timestep size.

. The code can readily be setup with body fitted coordinates so that explosions in very complex geometrics can be studied.

. Additional diffusion is used to handle large pressure gradients through an artificial diffusion term. This acts as a diffusion limiter and compensates for the numerical diffusion in the solution.

In running the code the procedure given below is used. The code has been written for a parallel architecture, such as found on a transputer system, where the code is partitioned according to the geometry of the problem to be solved and the number of processors available. The same size problem should therefore take (much) less time to run than on a single processor.

The procedure for the calculation is the same for both scalar and parallel schemes:

. The geometry of the problem is divided onto a grid defining finite volumes or cells and when run in a parallel configuration cells are automatically grouped together to share the computational work equally between processors and with minimum communication between processors.

. The starting conditions for each cell are provided.

. A timestep is calculated for each cell based on Courant number considerations. The global minimum is used throughout the next timestep calculation.

- Artificial Dissipation and viscous flux terms are calculated for each cell and are then kept frozen through the four levels of the solving algorithm at each timestep.

- The convective fluxes are summed for every cell and at every sweep of the solving algorithm.

- Boundary and source terms are calculated.

- The new solution is calculated and steps 5 and 6 are repeated for the four levels of the solver.

- Steps 3 to 7 are repeated until the desired level of real time is reached. Data values are periodically written to disc according to user requirements.

The code has been validated against a number of aerodynamic and combustion problems. Figure 6.2 shows the pressure measured experimentally for a 10m ignition tube with rings at two locations. Figure 6.3 shows the computed solution for the same locations. As can be seen good agreement both on the overall shape and magnitude is obtained. Further work to validate the code against velocity and turbulent data for an explosion is in hand. This process will take several months. In the meantime this work is being used in an uncalibrated state on the Moura Explosion to gain insight into the processes which are occurring during the explosion and the likely sequence of events.

6.4 Reanalysis of the Moura No.4 Mine Explosion

At the Inquiry, the only evidence pertaining to the establishment of the course of the explosion was that given by Green [51]. Pressure and air velocities were presented based on the destruction of brick stoppings. In that analysis the velocities and distances were calculated using a specific case for the equations of motion which did not include the deceleration phase of the brick on impact with the ground. In the re-analysis that follows a more general equation of motion is used which did not include the deceleration phase.

In the original evidence, calculation involving the movement of the shuttle cars, the mine rover and the continuous miner were all based on assumptions of the direction of the blast. With the presentation of an alternative hypothesis by Leivesley and Romaniuk [2], this original assumption was called into question. A reanalysis of the movement of miscellaneous objects is presented based on the more general equation of motion with associated deceleration phase.

The velocities pressures and impulses obtained in the reanalysis were then applied to the likely movement of bodies, to define the likely distances such objects would have been moved.

6.4.1 Brick Stoppings

The analysis of the distribution of debris follows that by Fletcher et al [35]. In this analysis the displacement X is given by:

$$\frac{d^2X}{dt^2} = a\,P - F$$

where t is the time, a is the acceleration coefficient which is a function of the drag coefficient, the mass of the object and cross-sectional area presented to the oncoming blast wave. P is a pressure function which mimics the force applied to the object. F is a friction function.

For brick stoppings, the pressure function is assumed to be dependent on the dynamic pressure as the equilibration of the static pressure over 0.08m is 3ms, much shorter than the timescale for the dynamic pressure (150-800ms). The friction factor F is assumed to be a simple function of the weight of the brick. The coefficient of friction is taken as 0.1. This is less than the value normally assumed for an object moving over a surface (0.3) to account for:

. The effect of powdered compacted coal dust and limestone dust on the floor (a reduction of approximately 33%); and

. The effect of some bouncing rather than strict translational movement along the floor (a reduction of 50%).

Such a low value for the friction coefficient leads to a minimum range of velocity and pressure.

Table 6.2 contains the maximum and minimum distances that a brick will move for a given velocity. The maximum distance is based on a brick 2.5m above the ground, while the minimum distance gives that of a brick 0.25m above the ground. Four cases are considered, each with a different duration for the wind blast; 100ms, 200ms, 400ms, 600ms respectively. The impulse on the brick has been calculated and is also given in Table 6.2. Figure 6.4 shows the maximum and minimum distances that a brick from a stopping will move for a given impulse. The curves given in this figure are not dependent on the wind duration. Consequently the calculated impulse from brick stoppings can be used to relate the loadings on objects whose position before the explosion were not known.

The damage to brick stoppings submitted to the inquiry is contained in Table 6.3. The velocity range based on the four different wind durations is given in Table 6.4 The damage to the stoppings are best correlated with the associated impulse, (that is the pressure time integral) on the bricks. The associated range of impulses are also given in the table. In the original report by Green [51], the estimation of static pressure was based on the acoustic approximation of Rae. There has been some criticism that the estimated pressures were too high. This criticism seems to have ignored the size of the estimated errors stated in that report. In this report an alternative and more accurate method has been employed. The pressures are computed from shock wave considerations and are included in Table 6.4.

The reanalysis has given values for the velocities that are consistent with those obtained from those presented at the Inquiry, and which show the same trend. The computed pressures are lower than those given to the inquiry but follow the same trend and are towards lower limit values stated at the Inquiry. The exact values are dependent on the duration of the winds. The wind duration is no longer than 0.6 seconds as a longer time would fail to knock down the stoppings in 27 c/t and 21 c/t (north side). As will be shown later modelling techniques can be used to decrease the uncertainty in this value. The range of impulses however is not as dependent on this factor and can be used to estimate the travel of other objects.

The main feature of this reanalysis is confirmation of the development of pressure away from 27 c/t in a uniform and consistent manner similar to that presented at the original inquiry.

6.4.2 Movement of the Shuttle Cars

In the original analysis, it was tacitly assumed that the direction of blast would be along No.3 Belt Road rather than down 26 c/t. This assumption is questionable in the light of [2]. In this reanalysis Shuttle Car No.30 is assumed to rotate about the end near to the continuous miner due to a targeted force created by a wind blast coming down 26 c/t from No.4 Supply Road.

The equation of motion is similar to that used in the preceding section. The equation relates angle of rotation about a vertical axis, ϕ, to the moments of applied force and resistance

$$\frac{d^2 \phi}{dt^2} = a P - a_1 f$$

a is an acceleration coefficient dependent on the drag coefficient, the area over which the pressure force is applied, the distance of the applied force from the point of pivoting, and the moment of inertia. P is the applied pressure which, for the same reason as the brick stopping calculation, is taken as the dynamic pressure. a_1 is a deceleration coefficient dependent on the distance to the centre of mass and the moment of inertia.

The friction factor F is assumed to be a function of the shuttle car mass (18 tonnes). The coefficient of friction will be close to 1.0 until the shuttle car starts to move after which it will be expected to drop towards a value of 0.3, typically found for one surface moving over another.

Integration of this equation with a friction coefficient of 1.0 will thus yield the minimum angle through which the shuttle car will move. The distance that the end of the shuttle car moves sideways rotating about the other end is given in Table 6.5 for the four wind durations considered in Section 6.2.1. This distance as a function of the applied impulse is given in Figure 6.5. The brick stoppings at 26 c/t, 25 c/t on the north wide and 25 c/t on the south side had impulses in the range 4.2kPa.s and 6.6kPa.s. A linear interpretation on these three points would put the impulse at 26 c/t and No.3 Belt Road, between 4.6kPa.s and 5.6kPa.s.

These values are shown on Figure 6.5 and correspond to movement of s/c No.31 of between 0.6m and 0.9m. It should be emphasised that this range is a minimum. A coefficient of friction of 0.3 would yield a range of movement of between 2.0m and 3.5m.

This analysis confirms that the s/c No.31 has been moved sideways with an impulse consistent with that on the brick stoppings adjacent to this area of the mine. The direction of the wind blast would have to have been along 26 c/t from No.4 Supply Road to cause observed position of the shuttle car against the south rib. A wind blast along 26 c/t from the south goaf would have moved the shuttle car towards the north rib. This is not observed. Furthermore, not only would a wind force along No.3 Belt Road from the goaf not have moved s/c No.31, s/c No.30 would have been blown against the outbye rib rather than finishing toward the inbye rib. The wheel angle on this latter vehicle would suggest some movement, which could be achieved by a wind along No.3 Belt Road from the boot end of the conveyor. However a force from this direction would not move s/c No.31. The slight movement of s/c No.30 could be caused by a vortex shedding around s/c No.31. This would have been a clockwise rotation looking from above and is in the correct direction to achieve the observed movement.

6.4.3 Movement of the Bodies

At the Inquiry no consideration was given as to the position of bodies before the explosion. A brief analysis of the likely distances that the bodies were moved is given. The analysis is the same as that given in section 6.2.1. The friction factor, f, is taken as that given by Fletcher and Bowen [33] for a body undergoing decelerative tumbling. Two body positions are considered; Standing face (or back) to the wind and standing side on to the wind. The acceleration coefficients for these two postures were taken from Table 2.2.1 of Hadjipavlou and Carr-Hill [52].

The body displacement for the four wind durations considered previously are given in Table 6.6. The distance travelled is plotted as a function of Impulse in Figure 6.6. The three bodies found near 26 c/t and No.4 Supply Road would have been subjected to an impulse of between 4.3kPa.s and 5.2kPa.s. This corresponds to a displacement of between 5m and 26m. The impulse in the region of 26 c/t and No.3 Belt Road as indicated in Section 6.2.2 is between 4.6kPa.s and

5.6kPa.s. This corresponds to a displacement between 8m and 29m.

This analysis confirms:

. That the bodies would have been moved by the explosion some considerable distance.

. That the three bodies in the vicinity of the crib room would have been moved less than the others.

6.4.4 Discussion

In this analysis an alternative method, to that presented at the Inquiry, was used to calculate the pressures, impulses and air velocities required for the observed damage. The reanalysis confirms the trends in pressures away from the goaf in the earlier analysis. The calculated pressures in this reanalysis are lower than the mean pressures calculated previously but are within the error estimated in the previous report. Modelling studies are required to elucidate the likely time duration of the winds in this explosion and hence the likely pressures involved.

There are two additional points of interest. Preliminary calculation for the movement of other items in the area around the crib room and No.4 Supply Road suggest that similar impulses to that at the brick stopping have moved objects around the mine. This analysis has not been completed due to the deadlines in preparing this report. There is, however, one exception. The MPV tray in 25 c/t that moved from the stopping across No.4 Supply Road could not have moved this distance without a much larger impulse on this object. This seems to be an anomaly but could be explained by an accelerating flow along No.4 Supply Road. This hypothesis involves interaction of the reflected pressure wave from the rib in No.5 North Return Road after breaking the stopping, with the combustion wave moving out along No.4 Supply Road.

Initial calculation would suggest that only the stoppings at 26 c/t and 25 c/t would have produced this type of interaction as further outbye, the reflected wave would arrive too early to interact with the combustion wave. This process would account for distribution of material from the crib room and the apparently strong wind velocity moving along 26 c/t towards No.3 Belt Road. This hypothesis is only tentative at this stage and could only be shown to be correct from modelling the system.

The second point relates to the water barrier in No.3 Belt Road between 24 c/t and 23 c/t. The calculated impulses on these barriers from the earlier report are between 1.5kPa.s and 1.7kPa.s.

Although these values could be in error due to the dominant effect of the mass of water in the tubs at the time of the explosion (an unknown factor), they are much lower than the values of the stoppings on either side. This would suggest that the barriers were having a positive effect in quenching the explosion even though the explosion was eventually quenched by water in the swilly. However, their position in the absence of the swilly would not have quenched this explosion. It is therefore recommended that further work on barrier location for this type of mining system be undertaken, involving modelling studies.

This reanalysis shows positively that the shuttles were moved by the explosion to their observed position. Only a flow along 26 c/t from No.4 Supply Road towards No.3 Belt Road could have produced this result. This should be taken as a very positive indication in discussions on the course of the explosion (see Chapter 7).

The reanalysis also shows that the bodies of the miners killed would have been moved some considerable distance with those nearer to No.3 Belt Road being moved on average further than those near to No.4 Supply Road. There is a question mark that needs further research, over whether or not the alignment of bodies observed at Moura were coincident or not. A preliminary statistical analysis would suggest not but this seems at odds with research in the UK and the USA. It is not clear from the work of Michelis whether the alignment that he found is totally random or whether it is within a narrow sector confined to $\pm 45°$ from the axis of flow.

6.5 Modelling Studies

6.5.1 1:54 Scale Model Experiments

A 1:54 scale model of part of the Main dips section of Moura No.4 Mine was constructed in a manner that it could be easily extended to cover a larger area of the mine. The model was of the area between 25 c/t and 27 c/t across all headings and included part of the goaf. This area is shown in Figure 6.7 together with the positions of 4 pressure and 6 flame sensors. Each experiment was also monitored with high speed cameras and video cameras.

A number of experiments have been carried out in which the ignition point has been systematically varied with the objectives:

. Identify the differences in flows from different ignition sources.

. Measure the relative time of arrival and direction of blast at the positions of the mine rover and shuttle cars.

. Measure the relative flame duration at the mine rover and at the shuttle cars.

The ignition points were chosen as representative alternative ignition locations to test how moving the ignition would affect the interpretation of the evidence given at the Inquiry and involved in the preceding section. The ignition points are also given in Figure 6.8.

For example ignition at point 1 is intended to simulate an ignition in the crib room. In some scenarios ignition has started in the goaf. Since most of the goaf is not included in the model, simulation near 27 c/t (north side) for example, is simulated by ignition at point 2, whereas ignition deeper in the goaf (north side) is simulated by simultaneous ignition at points 2 and 3, in an attempt to take some account of the increased strength and wider dispersion of such an ignition before it enters the area depicted by the model.

In each experiment, a methane air mixture was circulated throughout the model prior to ignition with matchhead detonators. The gas concentration was monitored until a steady concentration was observed throughout the model.

One of the problems encountered was that of achieving a uniform concentration throughout the model. A number of alternative recirculation patterns and techniques were tried before obtaining a satisfactory distribution throughout the model ($\pm$ 0.5%).

A uniform gas distribution was used throughout in an attempt to simulate total fuel conditions prevailing at the time of the incident. In any scenario of ignition, a goaf roof fall must have occurred to obtain enough fuel in the atmosphere to propagate an explosion. This fuel could have been either methane, coal dust or a combination of the two. The total fuel content would have been evenly distributed throughout the area of the mine by the wind blast accompanying the fall of the goaf. Furthermore, coal dust would also have been picked up by the explosion. Given other limitations of the model such as size, a uniform gas distribution is a reasonable starting point for simulation of a total gas and coal dust mixture.

In the time available to the project only a limited number of experiments have been undertaken. In all experiments, the brick stoppings were simulated by balsa wood partitions, but no models were used to represent the positions of the miner, mine rover, shuttle cars or conveyor belt. Although at the outset this was intended to include a series of experiments with these models in position, these experiments have not been concluded in time for this report.

Figure 6.8 shows a sequence of video photos for ignition in the south goaf (PT .5 of 6.8). Each photograph in the sequence corresponds to a 40ms elapsed time. Flame expands radially from the goaf reaching 27 c/t between 120ms and 160ms. The flame then progresses slowly into No.3 Belt Road and No.4 Supply Road. At the same time (240-280ms) flame rapidly moves along 26 c/t from the south goaf and back towards the goaf along No.3 Belt Road and No.4 Supply Road. On the video it is clear that the flame from the two opposite directions pass through each other in both No.3 Belt Road and No.4 Supply Road.

Between 260ms and 400ms flame is travelling along No.2 Transformer Road towards 25 c/t. The flame then goes both ways along 25 c/t. The northern leg produces a flow towards the goaf along No.3 Belt

Road (440ms) while the southern leg produces a flow back into the goaf along Nos.1 and 1A South Return Roads (440-460ms) reigniting the goaf in the process. It should be noted that residual burning occurs at the corner of 25 c/t and No.1A South Return Road (600ms). The stopping at 26 c/t between No.1 South Return Road and No.2 Transformer Road failed but not the others on the north side.

These results show that the general flow is from south to north and that this ignition does not simulate:

. A flow from No.4 Supply Road toward No.3 Belt Road along 26 c/t. This flow is required to account for <u>both</u> shuttle car positions (see section 6.2.3).

. The direction of flow in No.1A South Return Road and a very strong flow at 440ms is opposite to that observed.

. The strong directional movement of objects from the crib room area along No.4 Supply Road towards 25 c/t. Flow indications are that the flow is generally towards the goaf.

Figure 6.9 shows a similar sequence of video photographs taken after ignition occurred at point 2, the intersection of 27 c/t and No.4 Supply Road. 40ms after ignition, flame has almost reached the position of the mine rover. After 80ms a strong flow develops along No.4 Supply Road moving outbye and 26 c/t moving towards No.3 Belt Road. At 120ms the complete model is covered with flame except for No.1A South Return Road. Flame has extended along 26 c/t and 27 c/t into the goaf. It was difficult to tell from the videos which way the flow moved along No.3 Belt Road. At 160ms residual burning occurred in the crib room while flame was moving out from the goaf area into No.1A South Return Road. This flow continued until after 240ms moving along 25 c/t towards the belt roadway. Residual burning occurs at the corner of No.1A South Return Road and 25 c/t about 280ms.

These results simulate:

. A flow along No.4 Supply Road capable of moving objects in an outbye manner.

. A flow from No.4 Supply Road toward No.3 Belt Road along 26 c/t. This can account for both shuttle car positions.

. The direction of flow along No.1A South Return Road is in the correct direction with no reverse flow observed and a relatively long residence time for flame at the junction with 25 c/t that could account for the fire and high devolotization of coal dust observed in this position.

. The direction of flow along 25 c/t is also consistent with the bending of the belt structure towards the north.

. The flow along 27 c/t from No.4 Supply Road is also compatible with tipping the MPV tray in this c/t.

There is apparently no conflict with the evidence observed at the mine although factors such as the likely movement of objects out of the crib room cannot be determined from this experiment without more details of the pressure and velocities obtained.

In Figure 6.10, the sequence of photographs shows ignition from point 3, the intersection of 26 c/t and No.3 Belt Road. The explosion initially propagates radially from the point of ignition before moving more rapidly into the goaf and down No.3 Belt Road towards the goaf at about 80ms. By 120ms the explosion covers the majority of the mine except for No.1A South Return Road and No.4 Supply Road between 26 c/t and 25 c/t. The direction of movement along 27 c/t and 25 c/t is from No.2 Transformer Road towards the north. At 160ms flame starts moving into No.1A South Return Road from 25 c/t reaching the goaf about 240ms.

These results of this simulation do not agree with the following:

. A flow from No.4 Supply Road towards No.3 Belt Road along 26 c/t, required to account for the unusual position of the shuttle cars.

. The direction of flow in No.1A South Return Road is in the reverse direction to that observed.

. There is not a particularly strong flow outward along No.4 Supply Road needed to move objects from 26 c/t towards 25 c/t.

. The direction of flow along 27 c/t would tip the MPV tray in the wrong direction.

The results however, are consistent with:

. The movement of the belt structure at 25 c/t.

. A long residence time for flame in No.1A South Return Road which could account for the fire and high devolatilisation.

6.6 Computer Simulation Experiments

A number of computer simulations were undertaken in part of the Main dips section of Moura No.4 Mine. The simulations were two dimensional and the area between 27 c/t and 26 c/t and No.3 Belt Road and No.4 Supply Road as depicted in Figure 6.11 was grided on a 0.5m grid. The mine rover, continuous miner, shuttle cars and belt structures were included as fixed structure in the calculation.

The initial conditions in the model assumed an even distribution of fuel, zero velocity and atmospheric pressure throughout the simulation domain. Ignition is described by a 10% reduction in fuel at one or more cells. This corresponds to a strong ignition source over one cell or a number of cells. One cell describes a weak ignition at a specific site while reduction over a number of cells simulates a much stronger and more extensive ignition. For example, an explosion moving onto the computational domain from the goaf would be simulated by a line of cells corresponding to the width of the roadway at the boundary, while ignition by an electrical arc would be simulated by one cell.

The boundaries on the computational domain simulates either wall or an open boundary. The open boundary will automatically allow flow into or out of the domain depending on the physical conditions existing immediately inside the boundary.

In the simulation, the Pressure, Temperature and Velocities were computed at the points shown in Figure 6.11. The different ignition points are also shown in this figure.

Figures 6.12 to 6.14 show the pressure, velocity parallel to No.4(u) and velocity perpendicular to No.4(v) for ignition at the intersection of 27 c/t and No.4 Supply Road. A positive u velocity corresponds to movement along No.4 Supply Road away from the goaf. A positive v velocity corresponds to movement from No.3 Belt Road towards No.4 Supply Road. In this simulation the stopping at 26 c/t is present and all the vehicles and conveyor are in the positions shown in Figure 6.12.

The time histories of 4 points are shown in Figures 6.12 to 6.14 corresponding to points 10, 7, 2 and 3.

The first pressure peak at point 10 corresponds to a strong combustion wave moving outward (+u) at 28m/s followed by a second peak at about 42m/s moving in the reverse direction. The v velocity oscillates indicative of circulating flows moving past a point. Comparison with a similar experiment without the stopping at 26 c/t being present show that subsequent peaks in the pressure are due to reflections from the stopping. The second pressure peak is due to reflection from the mine rover.

At point 7 the first pressure peak corresponds to a strong outward flow and the second peak is a reflection. The third peak is a reflection from the stopping and is absent when there is no stopping with a high flow towards No.5 North Return Road. Subsequent reflection of different surfaces leads to a complex pattern of peaks.

This complexity is also found in the physical model. Figure 6.15 shows the pressure at this intersection for the same ignition conditions although this corresponded to an 8.3% methane air mixture as opposed to a 9.4% methane air mixture. The ignition source is also much weaker than that simulated in the computer experiment, hence the lower pressures and longer timescales for the physical model experiments. At point 3, the first peak is 50% higher than that at point 7 and corresponds to a very intense flow along 26 c/t from No.4 Supply Road(v). This strong flow also set up an outward flow (+u) along No.3 Belt Road due to the obstruction of the two shuttle cars. The second peak is due to a reflection from s/c No.30 in 26 c/t.

The pressure curve is complex at point 2, due to multiple reflections from the continuous miner and shuttle cars. The initial direction is towards the goaf (-u) while the second series of pressure peaks after 84m seems to be due to reflection from the continuous miner. The transverse velocity oscillates wildly, again indicative of vortex formation.

Figures 6.16 to 6.18 show the pressure the velocities for an ignition in 9.4% methane air mixture at the intersection of 26 c/t and No.3 Belt Road.

Point 3 is nearest to the ignition point and the pressure is the lowest of those shown but still displays a complex pattern due to reflections off nearby surfaces. Both the u and v velocities fluctuate due to these reflections. At point 2 the flow is towards the goaf (-u) with reflection from the continuous miner.

At point 7 the initial pressure pulse and combustion wave move towards the stopping away from the shuttle cars along 26 c/t. The second peak is a reflection from the intersection sides of the mine rover and moves in the +u direction.

At point 10 the pressure pattern is complex with the initial peaks corresponding to movement into the goaf with strong transverse oscillation.

Both sets of simulation corresponds to detonation in the mine. As such they are unrealistic simulations of this incident. The reason for the high pressure, velocities and temperature observed could be due to a number of reasons:

- The time frame required for this report did not allow proper calibration of the model against known benchmarks. As a consequence some of the parameters could be improperly prescribed or there could still be an error in the code.

- The ignition description corresponds to an extensive ignition source particularly for the case where a number of cells are prescribed to cover an ignition source. This could have lead to overdriving the accelerative process in the model leading to rapid detonation. An alternative description of ignition with laminar conditions and an induction delay, typically observed for a weak ignition source has not as yet been added to the model.

- This model couples the reaction rate to the levels of turbulence. This coupling originally caused numerical instabilities in the sequential version of this code which were overcome. The corrections, to the code were included in the parallel code used for these simulations but the more complex geometrics could still cause unrealistic turbulence levels and hence two high a reaction rate.

Further work is required to calibrate the model. There are two relevant benchmarks against which this model can be tested. Professor Hjertager has used his simulation model against a 10m ignition tube problem. In discussion with him it was agreed to use this as one benchmark against which both explosion codes could be tested and developed further. The second benchmark is that of a detonation of gas in a shock tube. Experiments by Lee can be used as the basis for this benchmark. The reason for using both a supersonic and subsonic benchmark is to test whether these are constraints on the use of the code.

Further work is also required to assess alternative strategies for coupling the chemical kinetics into the model. Discussion on this point with Drs Oran and Hjertager highlights two alternative approaches. In one the chemistry is decoupled from the turbulence. A single Arrhersius reaction rate is used for the chemical source term. This would normally lead to overprediction of the reaction rate but this can be overcome by averaging the temperature field for the cell where reaction rate is being calculated. In the second approach, the chemistry remains coupled to the turbulence but severe restraints are imposed on the growth of turbulence. This has the advantage that it is empirical and easy to implement and would be suitable for flows where there is plenty of obstacle generated turbulence. It has disadvantages when there are few obstacles and requires recalibration for different types of problems.

It is also suggested that the scale model be used to calibrate the computer model for the Moura explosion in further work. The calibrated model can then be used to assess alternative hypothesis for the Moura explosion.

Computer simulation is the only method by which details of flow and combustion can be predicted for an explosion in a cost-effective manner. Physical modelling will give an insight into what is occurring but even sophisticated and costly laser diagnostic techniques are not fast enough to obtain information on velocities, turbulence and chemistry in a fully developed explosion. Such techniques are difficult to use even in steady non-combustion flows.

There is, however, a need to calibrate and validate the computer code. This was not possible in the time frame for this report but the technique highlights its potential use for forensic studies in the future:

- The ability to determine the pressure field with time for every point in the domain of computation. The impulse can be estimated directly from these calculations. Theories on the movement or deformation of objects in an explosion can readily be assessed.

- The ability to determine the temperature field with time for any point. The heat load can be estimated for any material surface from these calculations and the likely heat damage can readily be assessed for a given explosion.

6.7 Discussion

The use of modelling has shown their potential in assisting with understanding what occurs in a mine explosion. For example the physical modelling undertaken to date has shown that the only way of obtaining a one way flow along No.1A South Return Road is with a relatively strong explosion travelling through the south goaf from 27 c/t. The flow ahead of this type of explosion seems to prevent even a strong explosion moving along 25 c/t toward No.1A South Return Road from the wrong direction to that observed. Such an explosion is forced along No.1 South Return Road towards the goaf. A weak explosion along 27 c/t into the south goaf area does not show the same trend. To date, only two ignition points have given a flow in the correct direction at No.1A South Return Road and that is from the intersection of 27 c/t and No.4 Supply Road and from the crib room.

Much more work is required, however to say that these are the only ignition areas in the mine that can simulate the observed effect. Similarly the mathematical modelling with computers has the potential to accurately simulate the flow around obstacles, the reversal in flows, the pressure and impulses on objects and elucidate the observations following an explosion. Much more work is required to develop this method as it has many applications for hazard assessment and control in the mine environment apart from its application to investigation.

TABLE 6.1 PRESSURE DAMAGE FROM CHEMICAL AND NUCLEAR EXPLOSION

OVERPRESSURE ;psi	;kPa	DAMAGE
0.03	0.2	Occasional breaking of large glass windows already under strain.
0.1	0.7	Breaking of small windows already under strain.
0.15	1.0	Normal limit for glass breakage.
0.25	1.7	50% window glass breakage.
0.3	2.0	>10% window glass broken. Some damage to house ceilings Missile limit "Safe distance" (0.05 probability of no serious damage beyond this limit).
0.4	2.8	Limited minor structural damage.
0.55	3.8	90% window glass breakage.
0.5-1.0	3.5-7.0	Large and small windows usually shattered and occasional damage to window frames.
0.7-0.75	4.8-5.0	Minor damage to house structures. 20-50% tiles displaced and breakage of small windows not under strain.
0.9	6.2	Roof damage to oil storage tanks. Branch damage to trees.
0.9-1.0	6.2-6.9	Nearly all window glass broken.
1.0	6.9	Partial demolition of houses, made uninhabitable.
1.0-1.5	6.9-10.3	Branch damage to trees. Asbestos cladding blown off buildings.
1.0-2.0	6.9-13.8	Asbestos cladding shattered. Fastenings of corrugated steel and aluminium panels fail and panels distorted. House tiled roof lifted and replaced.
1.3	9.0	Steel frame of clad buildings slightly distorted.
<1.5	<10.3	Houses lightly damaged (Category D damage), but remain inhabitable after repair.
1.5	10.3	Most window glass broken, but only light damage to window frames and doors. Moderate plaster damage. Most tiles displaced, but laths intact.
1.5-6.0	10.3-41	Houses severely to moderately damaged (Category C damage).
2.0	13.8	Partial collapse of walls and roofs of houses. Load bearing brickwork unaffected 30% trees blown down.
2.0	13.8-17.2	Some frame distortion of steel girder framed buildings.
2.0-3.0	13.8-20.7	Concrete or cinder block walls (8-12" thick, but not reinforced) shattered. Deflection of steel posts.
2.3	15.9	Lower limit of serious structural damage.
2.5	17.2	50% destruction of house brickwork, rafters and laths broken.
3.0	20.7	90% trees blown down. Steel framed building distorted and pulled away from foundations. Heavy machines (3000 lbs) suffer little damage. Frameless, self-framing, steel panel buildings demolished.
3.0-4.0	20.7-27.6	Rupture of oil storage tanks. Collapse of self-framing steel panel buildings.
3.5	24.1	Oil storage tanks distorted.
3.5-4.5	24.1-31	Collapse of steel posts.
4.0	27.6	Cladding of light industrial buildings ruptured.
4.0-5.0	27.6-34.5	Severe displacement of motor vehicles.
4.5	31	Severe distortion to frames of steel girder framed buildings.
5	34.5	Wooden utility poles snapped.
5-7	34.5-48	Nearly complete destruction of houses.
6-8	41-55	Houses irreparably damaged (Category B damage).
7	48	Loaded rail cars overturned.
7-8	48-55	Brick panels (8-12"), but not reinforced fail by shearing or flexure.
7-9	48-62	Collapse of steel girder framed buildings.
7-10	48-70	Cars severely crushed.
8-9	55-62	Brick walls severely cracked.
8-10	55-70	Brick walls completely demolished.
9	62	Collapse of steel truss type bridges. Loaded train box-cars completely demolished.
>10	>70	Total destruction of houses (Category A damage) and most buildings. Heavy machine tools (7000 lbs) moved and badly damaged. Very heavy machine tools (12000 lbs) survive.
13	90	18" brick walls completely destroyed.
17	120	Oil storage tanks completely destroyed.
20	140	Virtually complete destruction of all buildings, other than reinforced concrete aseimic designs.
70	480	Collapse of heavy masonry or concrete bridges.
280	2000	Limit of crater lip.

Sources: Astbury [53], Brasie [54], Clancy [55], Glasstone [56,57], Health & Safety Commission [58], Home Office [59], Jenett [60], Roberts [61].

Table 6.2 Maximum and Minimum movement of brick debris

Velocity	P	t_d = 100ms			t_d = 200ms			t_d = 400ms			t_d = 600ms		
		d_{Max}	d_{Min}	I	d_{Max}	d_{Min}	I	d_{Max}	d_{Min}	I	d_{Max}	d_{Min}	I
	Bar	(m)	(m)	(kPas)	(m)	(m)	(kPas)	(m)	(m)	(kPas)	(m)	(m)	(kPas)
50	0.22	0.35	0.10	0.145	0.66	0.15	0.29	1.17	0.17	0.58	1.51	0.17	0.87
100	0.48	1.47	0.46	0.580	2.94	0.92	1.16	5.84	1.81	2.32	8.68	2.66	3.48
150	0.78	3.58	1.31	1.305	7.68	3.18	2.61	17.29	8.49	5.22	28.6	15.8	7.83
200	1.13	7.01	3.02	2.320	16.2	8.36	4.64	39.90	25.4	9.28	69.3	49.7	13.92
250	1.53	12.2	6.07	3.625	30.0	18.3	7.25	77.4	57.5	14.50			
300	1.99	19.7	11.06	5.220	50.4	34.7	10.44						
350	2.50	30.1	18.60	7.105									
400	3.08	43.7	29.4	9.280									

t_d is the wind duration (msec.)

d is the distance of brick travel

I is the impulse on the brick

Table 6.3 - Damage sustained to brick stoppings

ct	Head	Condition	Projected Outward Distance m	Projected Inward Distance m
27	4/5	Partly gone.	Bricks either side of wall but not to a great distance (<3m).	
26	4/5	Gone: projected mainly towards rib.	7.5-15 (18)*	6-10 (20)*
25	4/5	Gone: majority against rib.	10-23	-
24	4/5	Gone: all against rib.	10-12	-
23	4/5	Gone: projected mainly towards rib. Door moved out 7m.	3-13	-
22	4/5	Partly gone: projected mainly towards rib. Door moved about 2m.	0-10	-
21	4/5	Partly gone: not projected any distance.	0-3	-
25	1/2	Gone: projected in both directions, door moved 7m	12-18 (25)*	0-7 (25)*
24	1/2	Gone: projected mainly against rib. Door moved 18m outward	15-20	- (8)*
23	1/2	Gone: projected mainly against rib.	11-16	- (30)*
22.5	1/2	Gone: projected towards rib.	3-10 (17)*	-
23/ 22.5	2	Gone: projected into water in heading.	10->30	-
23/ 22.5	1	Gone: projected into water in heading.	10->30	-
22	1/2	Intact	-	-
21	1/2	Intact	-	-
20A	1/2	Intact	-	-

* Distance of furthest brick from wall.

Table 6.4 Air Velocities and Impulse based on Maximum and Minimum brick displacements

ct	Heading	Impulse kPas	td = 0.1ms V_{max} m/s	P_{max} Bar	V_{min} m/s	P_{min} Bar	td = 0.2ms V_{max} m/s	P_{max} Bar	V_{min} m/s	P_{min} Bar	td = 0.4ms V_{max} m/s	P_{max} Bar	V_{min} m/s	P_{min} Bar	td = 0.6ms V_{max} m/s	P_{max} Bar	V_{min} m/s	P_{min} Bar
27	4/5	0-1.05	150	0.77	0	0	110	0.52	0	0.	80	0.36	0	0	65	0.28	0	0
26	4/5	4.27-5.21	200	1.13	270	1.71	205	1.17	180	0.18	150	0.77	140	0.70	120	0.58	110	0.52
25	4/5	5.34->6.27	>310	2.10	290	1.90	>220	1.29	210	1.29	>160	0.84	150	0.77	>130	0.65	125	0.61
24	4/5	>5.34	>290	1.90	290	1.90	>210	1.21	210	1.21	>150	0.77	150	0.77	>125	0.61	125	0.61
23	4/5	1.91-4.01	250	1.54	200	1.13	175	0.95	150	0.77	130	0.64	110	0.52	110	0.52	100	0.47
22	4/5	0-3.20	230	1.37	0	0.	155	0.81	0	0.	120	0.58	0	0	105	0.49	0	0
21	4/5	0-1.05	150	0.77	0	1.	110	0.52	0	0.	80	0.36	0	0	65	0.28	0	0
25	1/2	6.09-6.65	340	2.40	325	2.25	240	1.45	230	1.37	170	0.91	165	0.88	135	0.68	130	0.65
24	1/2	>7.04	-	-	345	2.45	-		245	1.50	-	-	175	0.95	-	-	140	0.70
23	1/2	>5.72	-	-	310	2.10	-		220	1.29	-	-	153	0.81	-	-	120	0.58
22.5	1/2	1.91-4.99	295	1.95	200	1.13	205	1.71	150	0.77	145	0.74	110	0.52	115	0.55	100	0.47
22	1/2	0	0	-	-		0		-		0	0	-		0	0	-	-
21	1/2	0	0	-	-		0		-		0	0	-		0	0	-	-

1 Bar = 100 kPa = 15.2 psi

Table 6.5 Movement of Shuttle Car No. 31

Air Velocity	t_d = 0.1		t_d = 0.2		t_d = 0.4		t_d = 0.4	
	d m	I kPas	d m	I kPas	d m	I kPas	d m	I kPas
50	0.00	0.145	0.00	0.29	0.0	0.58	0.0	0.87
100	0.004	0.580	0.02	1.16	0.06	2.32	0.13	3.48
150	0.04	1.305	0.16	2.61	0.65	5.22	1.47	7.83
200	0.15	2.320	0.60	4.64	2.43	9.28	5.48	13.92
250	0.39	3.625	1.58	7.25	6.36	16.50		
300	0.84	5.220	3.40	10.44				
350	1.59	7.105						
400	2.75	9.280						

d is the distance that one end of the shuttle car has moved about the other end.

Table 6.6 Body Displacement

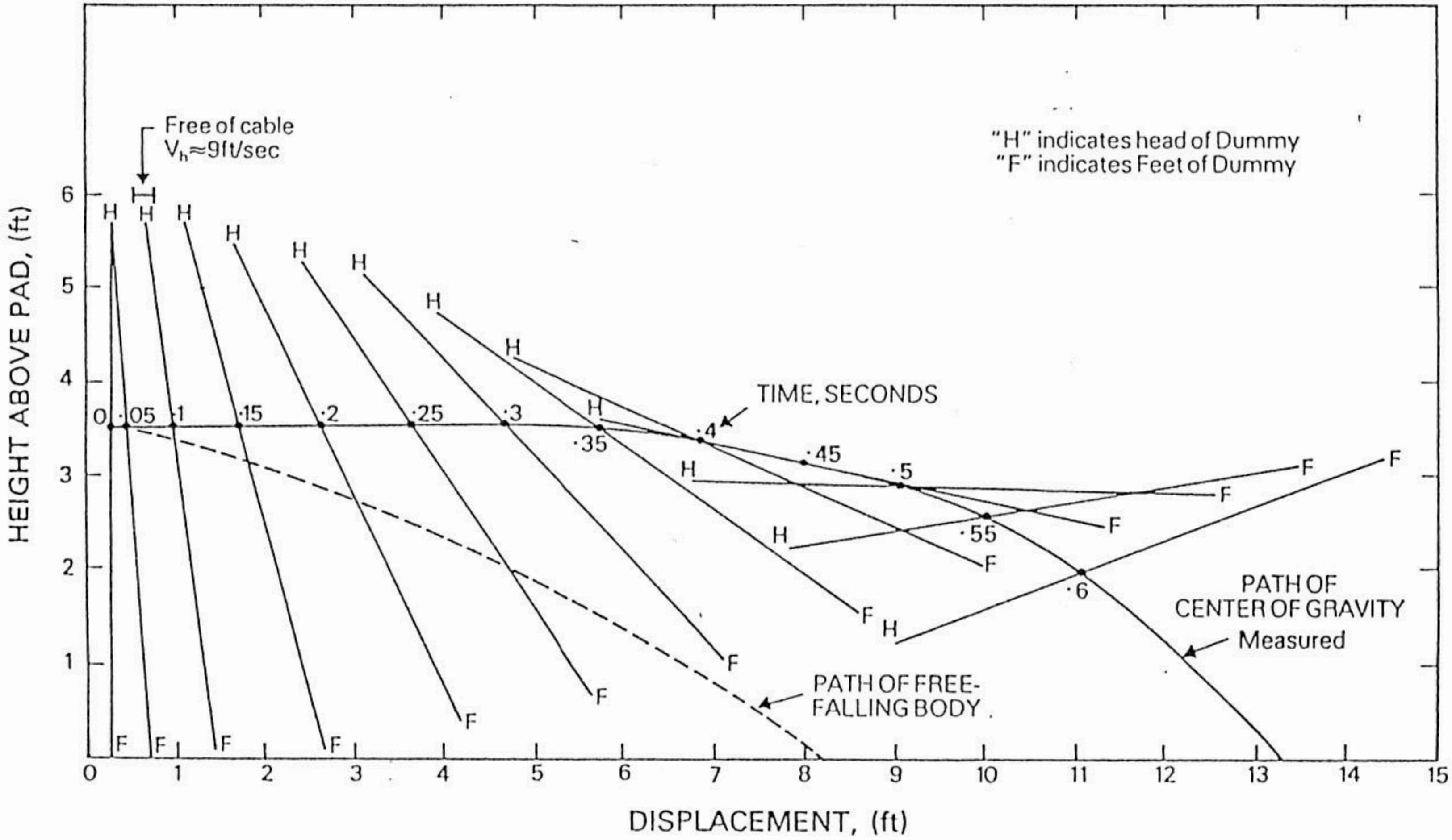
Velocity	t_d = 0.1			t_d = 0.2			t_d = 0.4			t_d = 0.6		
	Displacement SF	SS	I kPas	Displacement SF	SS	I kPas	Displacement SF	SS	I kPas	Displacement SF	SS	I kPas
50	0.06	0.01	0.145	0.15	0.03	0.29	0.38	-	0.58	-	-	-
100	0.69	0.16	0.580	2.03	0.45	1.16	5.73	1.28	2.32	10.6	2.10	3.48
150	2.77	0.68	1.305	8.28	1.98	2.61	24.4	5.64	5.22	95.6	10.3	7.83
200	7.24	1.81	2.32	21.8	5.38	4.64	65.4	15.8	9.28	123	29.2	13.92
250	15.1	3.84	3.625	46.1	11.5	7.25	138	34.2	14.50	263	64.1	21.75
300	27.6	7.05	5.22	84.3	21.3	10.44	-	63.7	20.88			
350	45.8	11.7	7.105									
400	71.0	18.3	9.28									

SF - standing face on

SS - standing side on

FIGURE 6.1

Plot of the position of the dummy during translation as viewed at the side of the vertical plane in which it moved



(From Taborelli et al. [40])

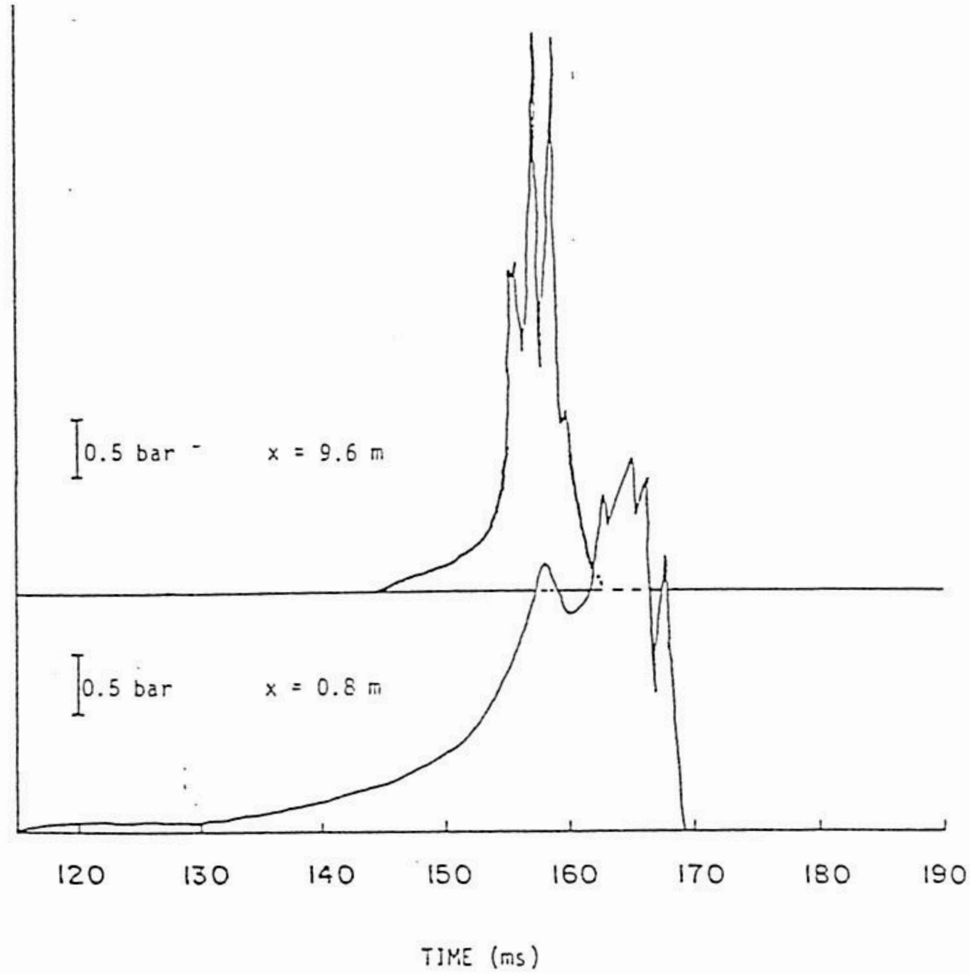


Figure 6.2 10m Ignition Tube - Experimental Pressures.

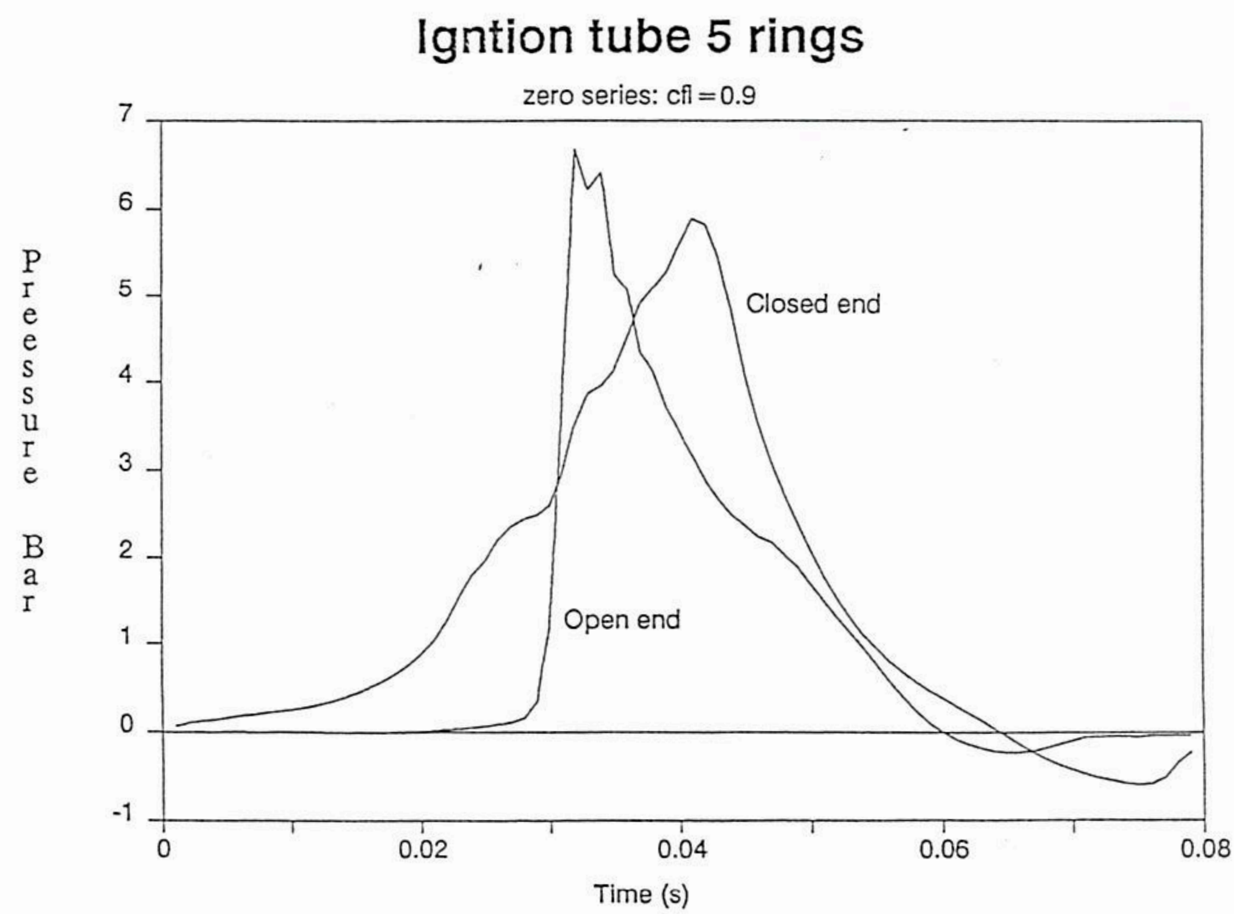


Figure 6.3 10m Ignition Tube - Calculated Pressures.

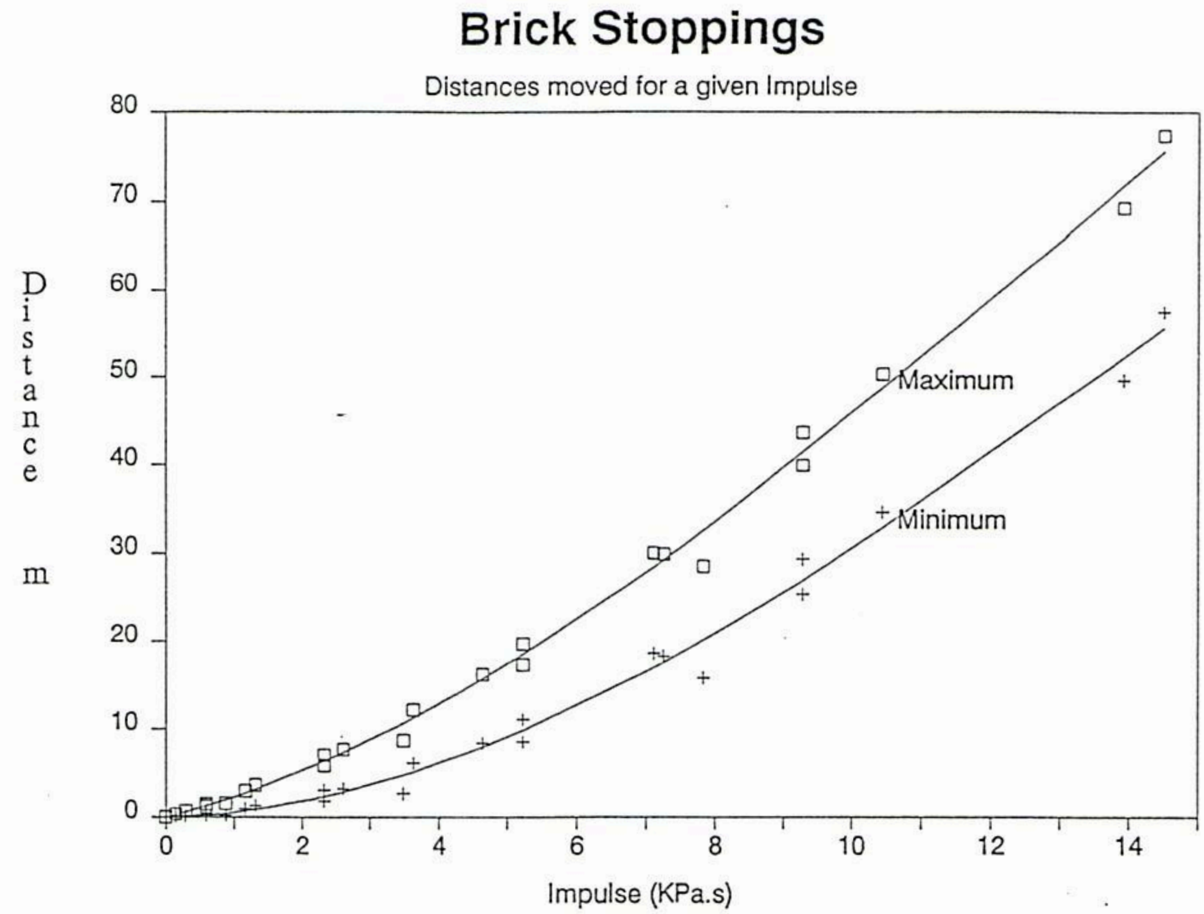


Figure 6.4 Movement of Mine Stopping Debris.

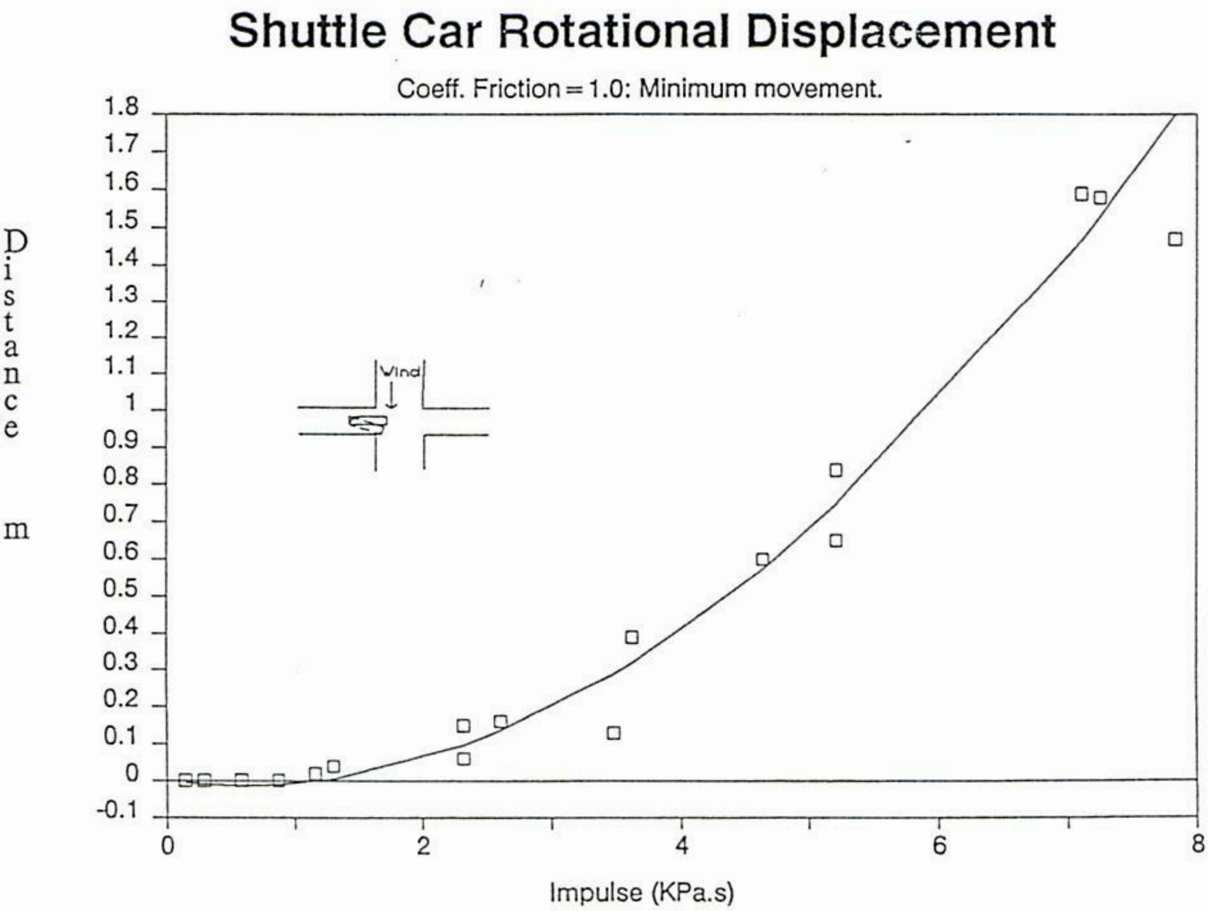


Figure 6.5 End Displacement of Shuttle Car 31

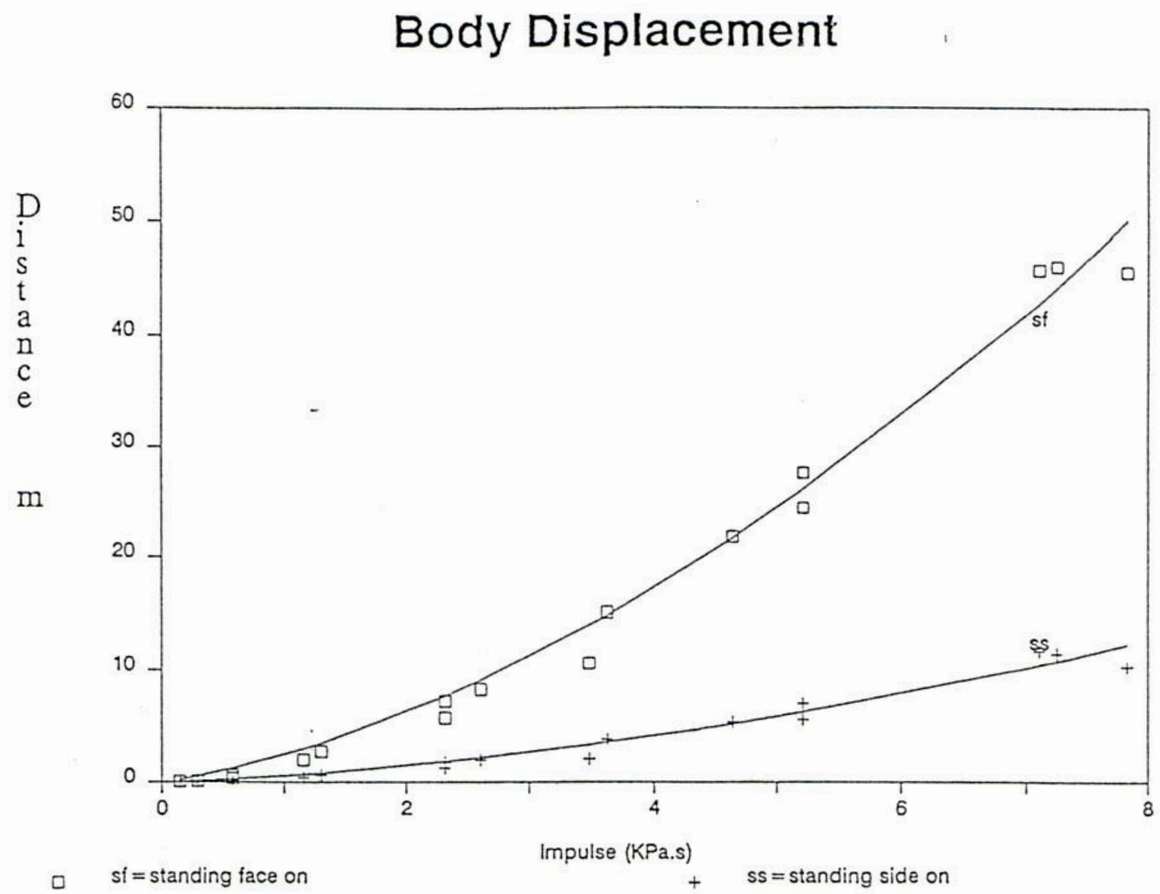


Figure 6.6 Body displacement.

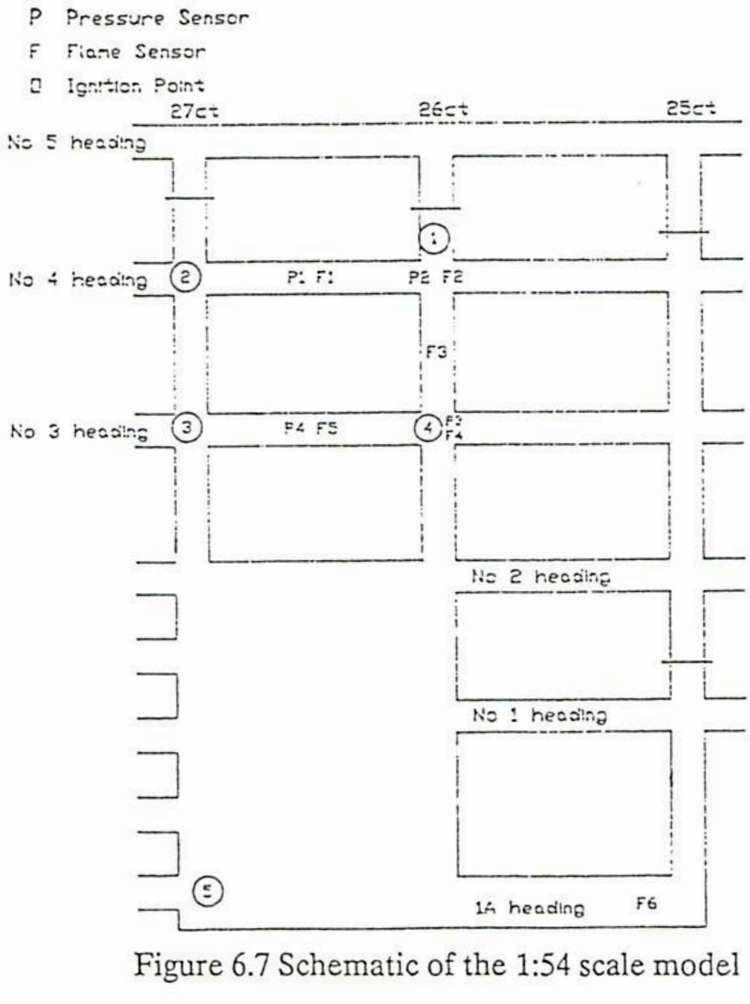


Figure 6.7 Schematic of the 1:54 scale model

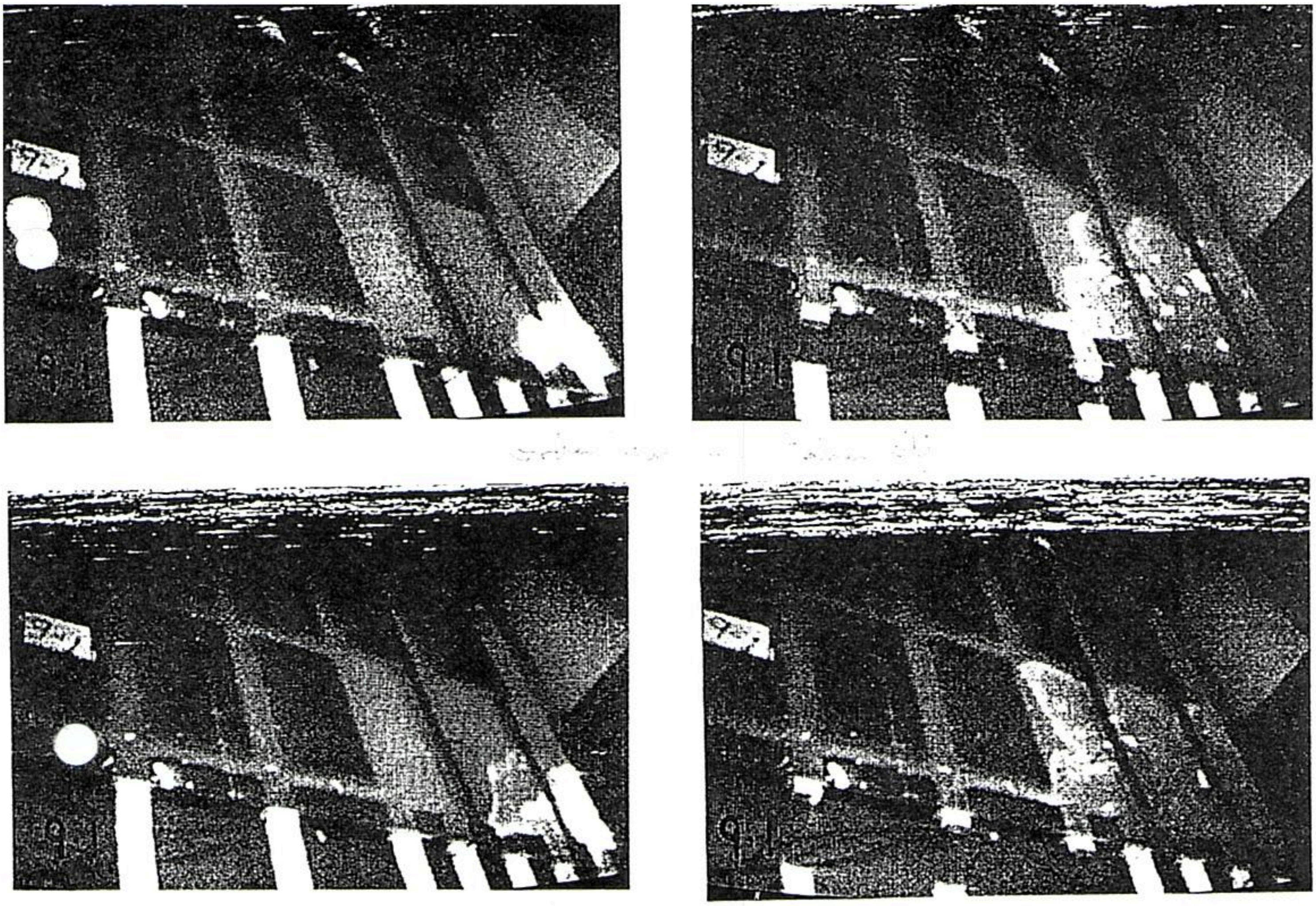
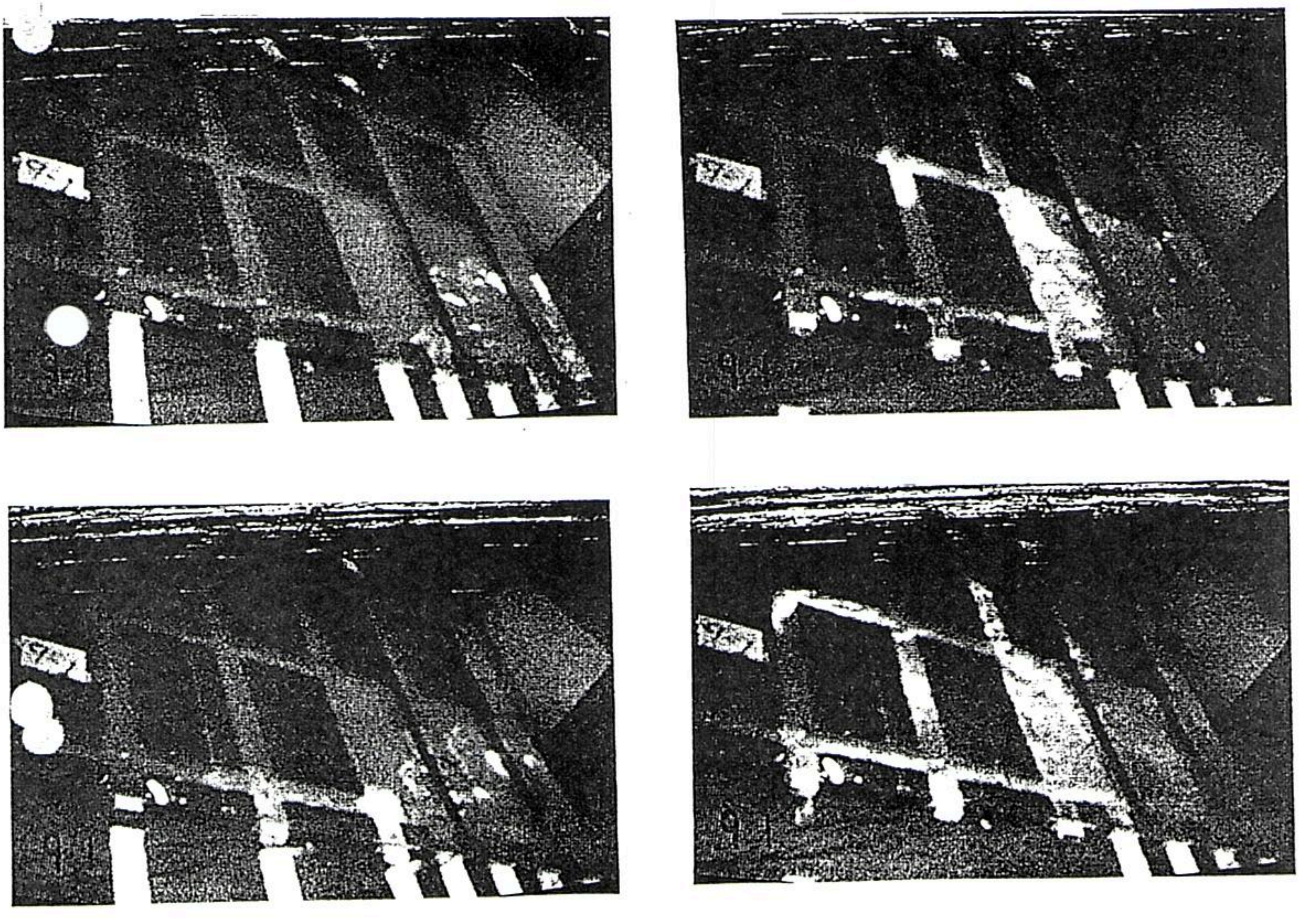


FIGURE 6.8 IGNITION: SOUTH GOAF



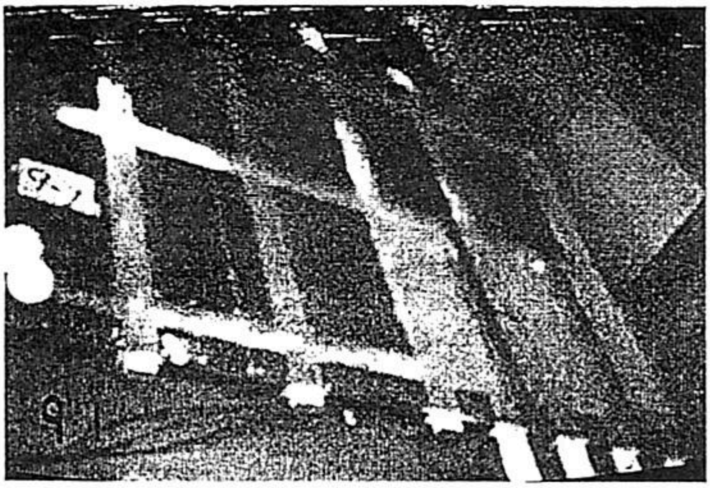
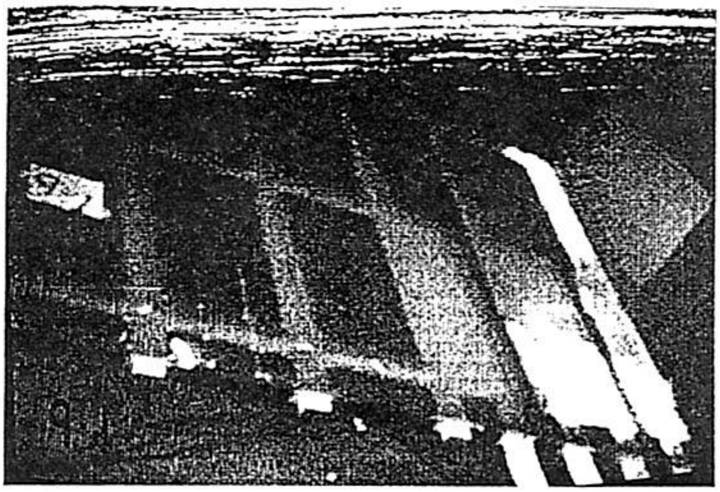
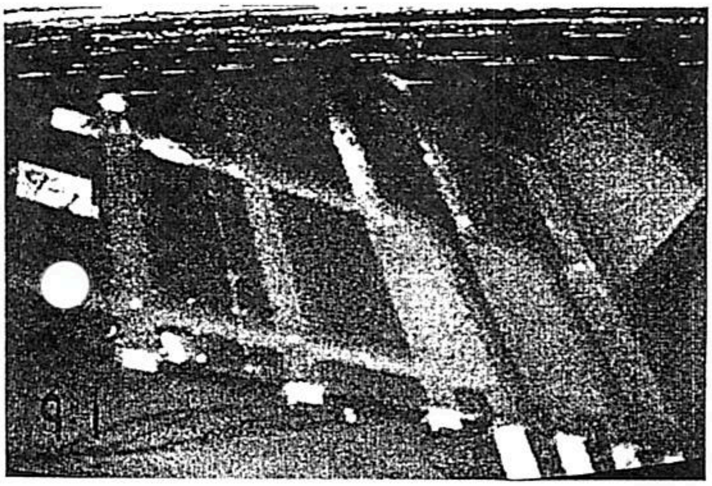
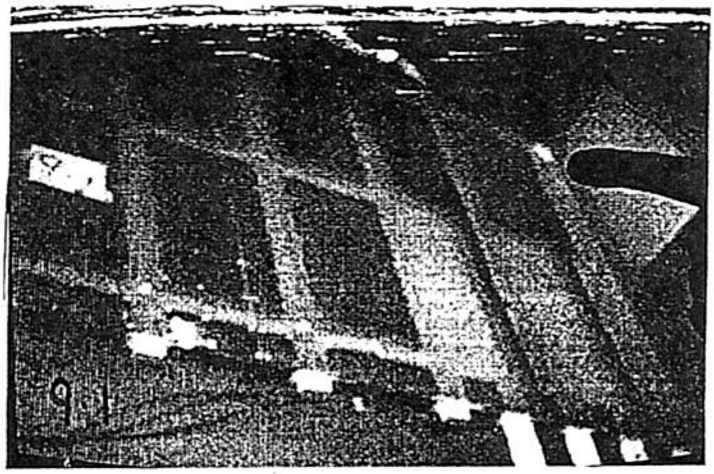
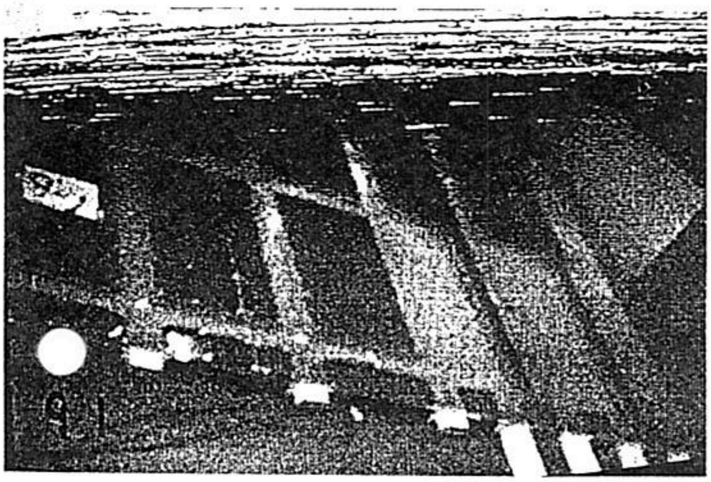
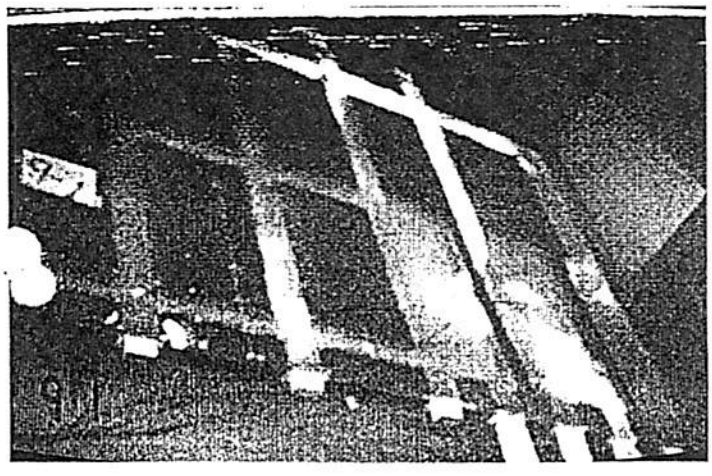
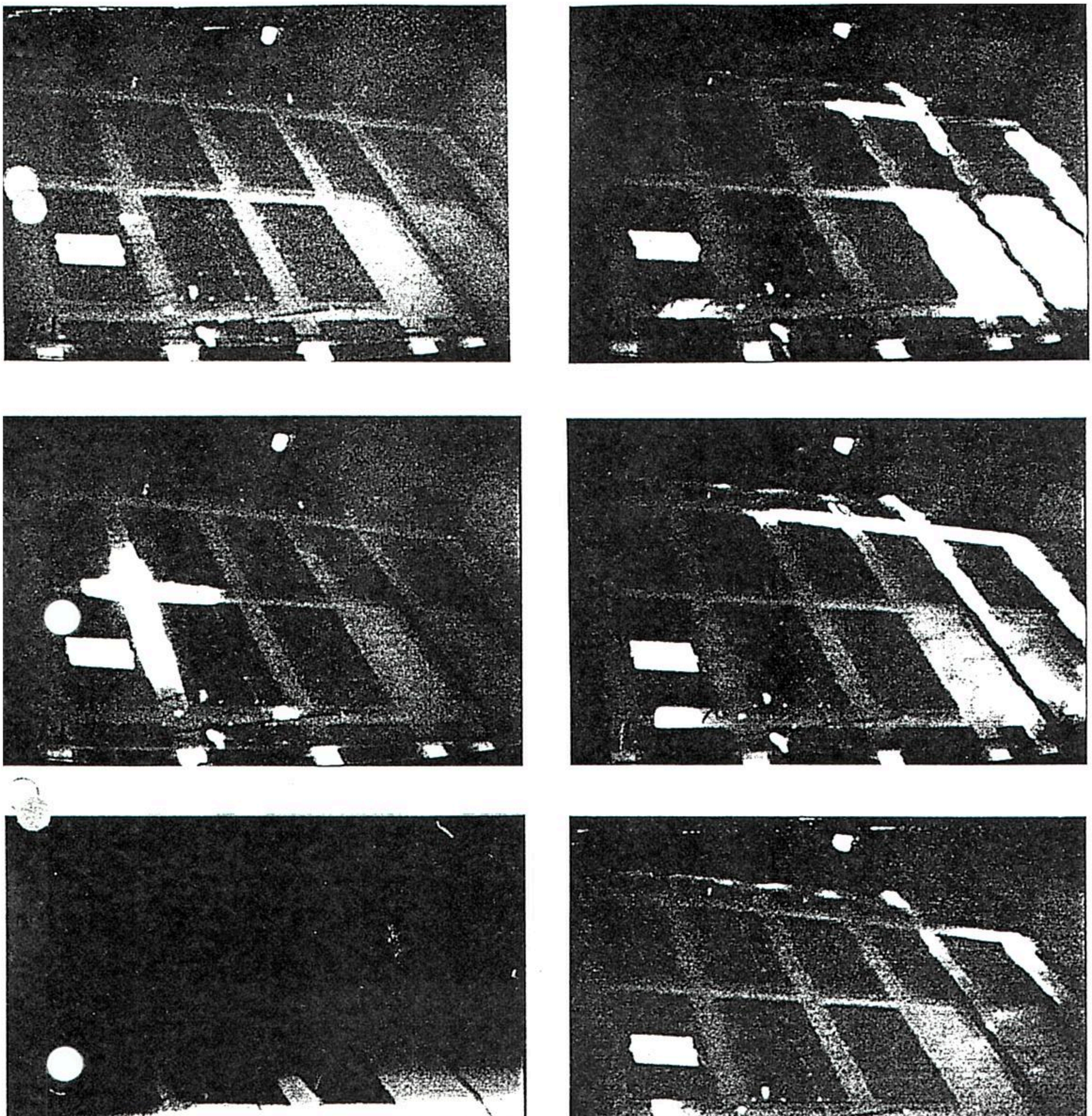







FIGURE 6.8 CONTINUED



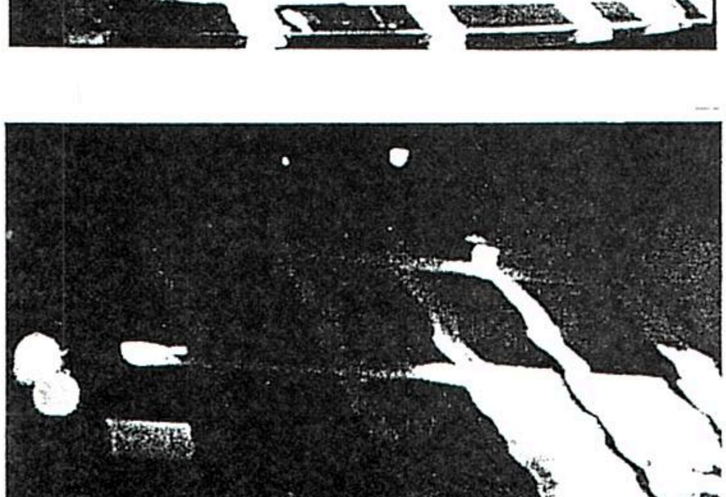
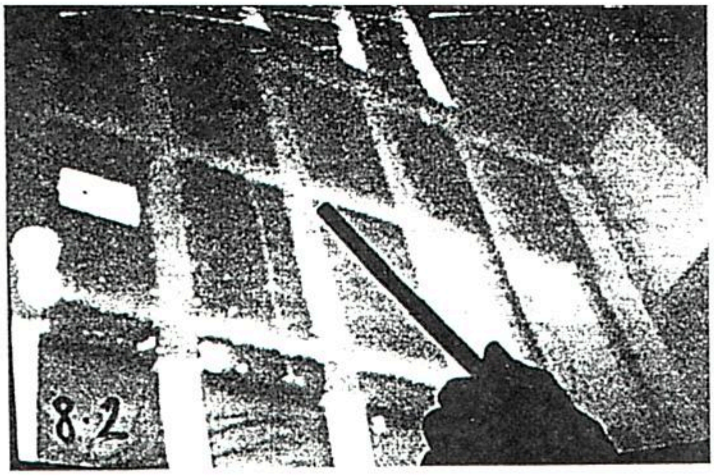
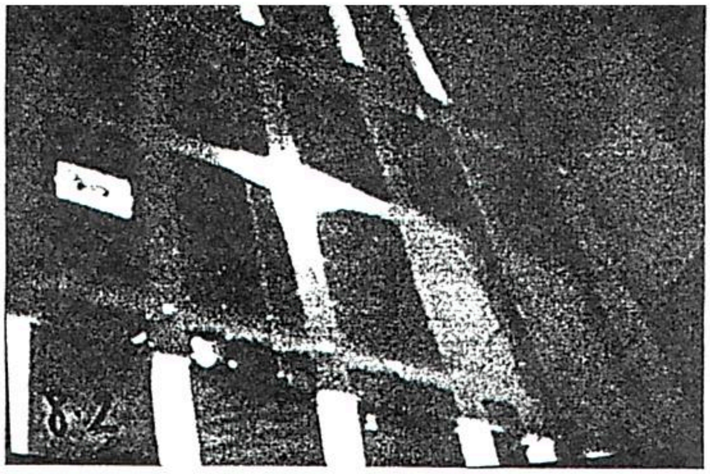


FIGURE 6.9 IGNITION: 27C/T AND
NO.4 SUPPLY ROAD





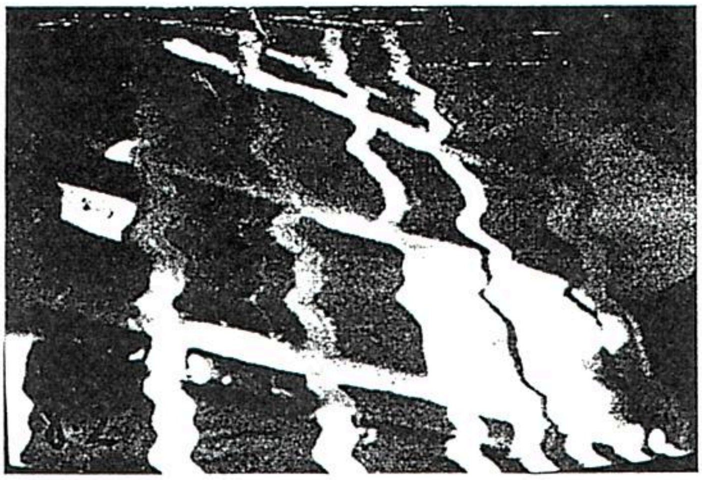
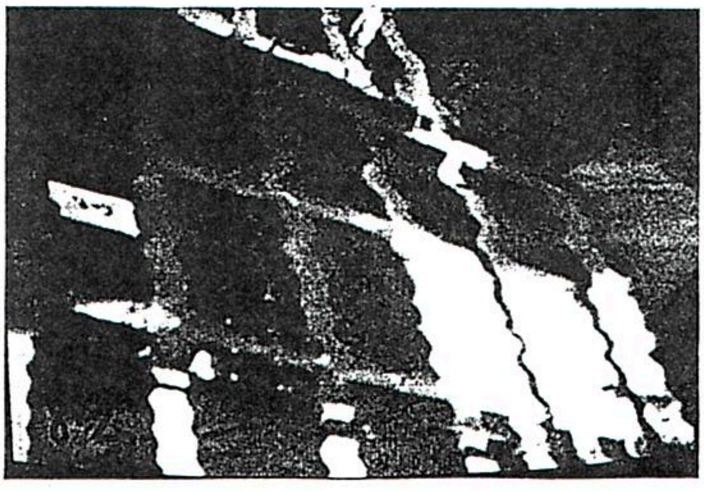
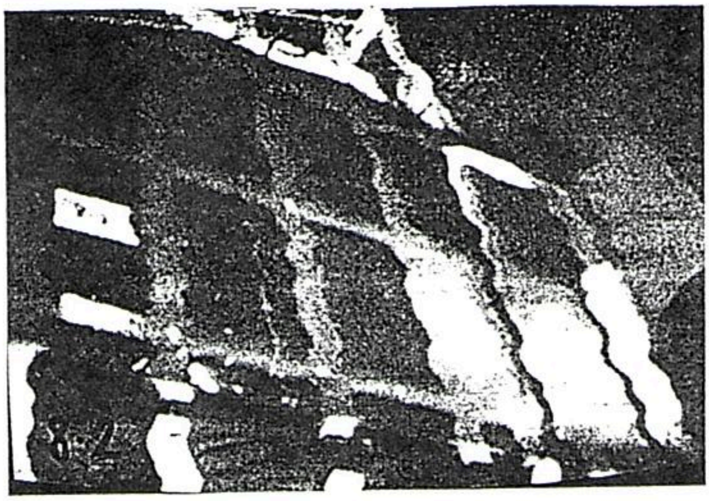



FIGURE 6.10
IGNITION: 26C/T AND
NO. 3 BELT ROAD



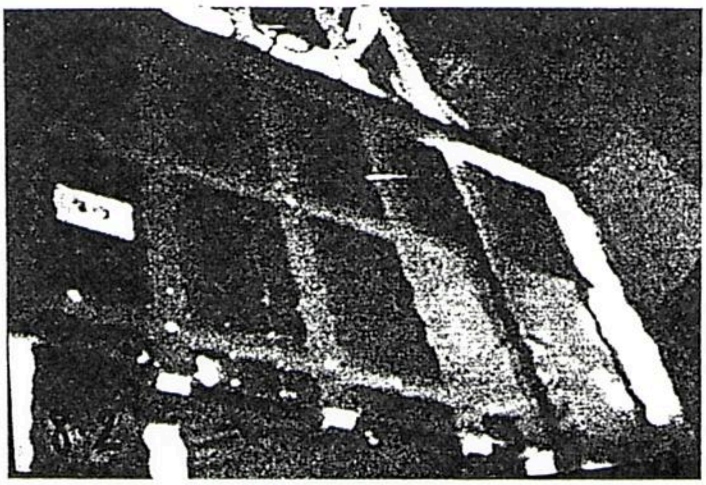


FIGURE 6.10 CONTINUED

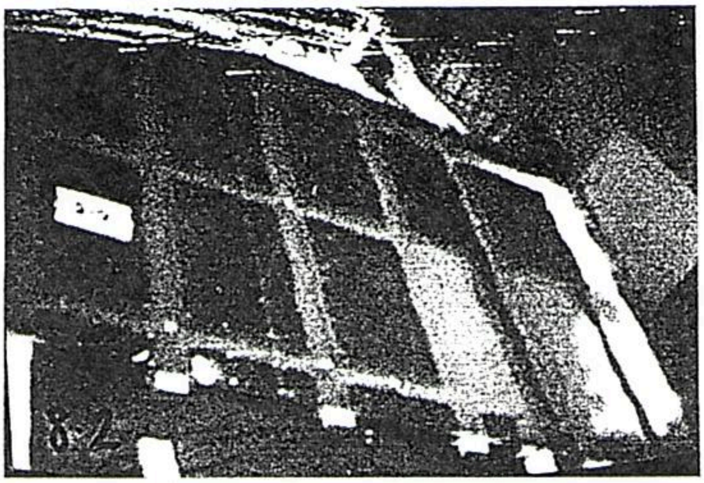
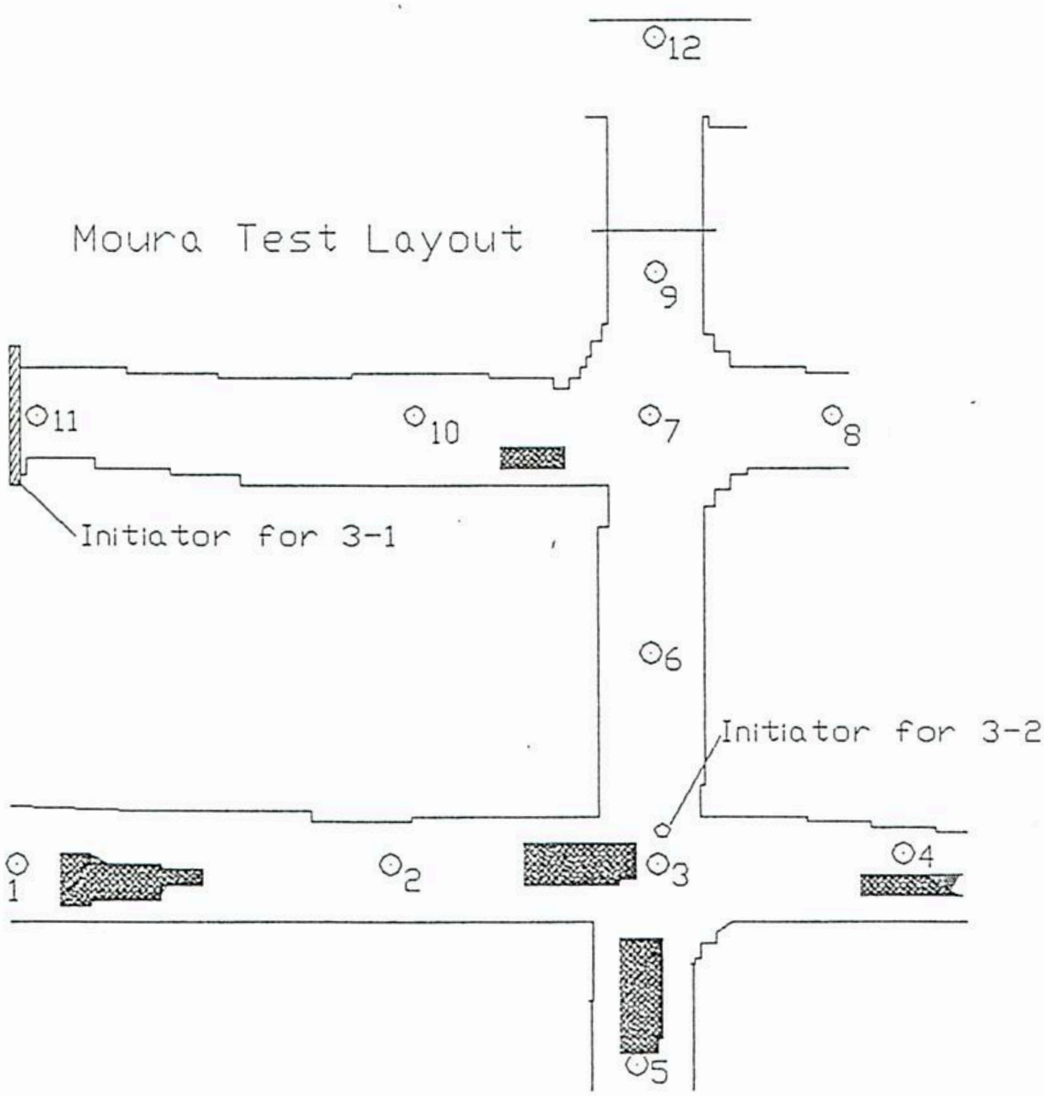


FIGURE 6.11

GRID USED FOR THE MATHEMATICAL
SIMULATIONS: RESOLUTION 0.5M



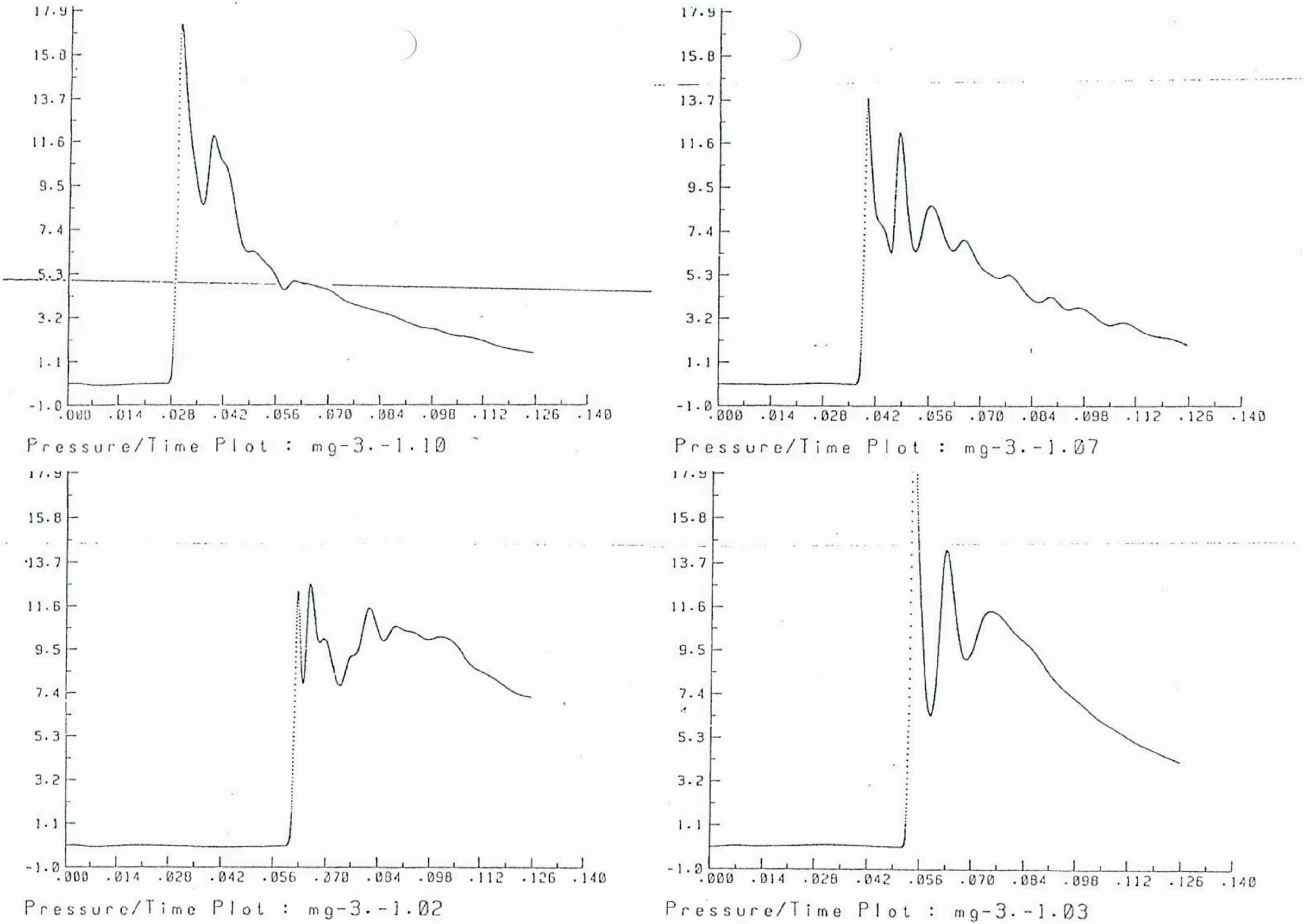


FIGURE 6.12 PRESSURE: IGNITION AT 27C/T AND NO. 4 SUPPLY ROAD

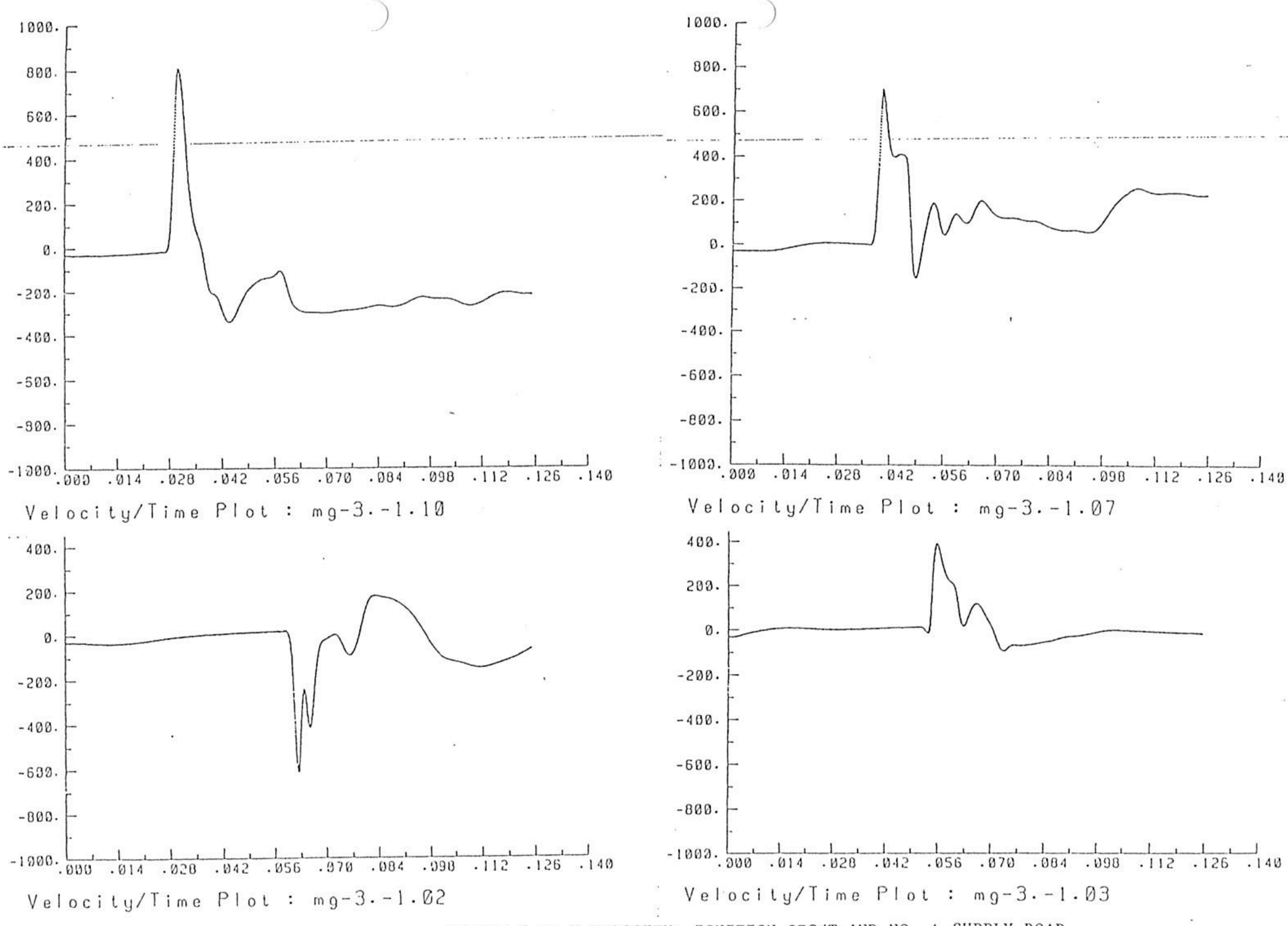


FIGURE 6.13 U VELOCITY: IGNITION 27C/T AND NO. 4 SUPPLY ROAD

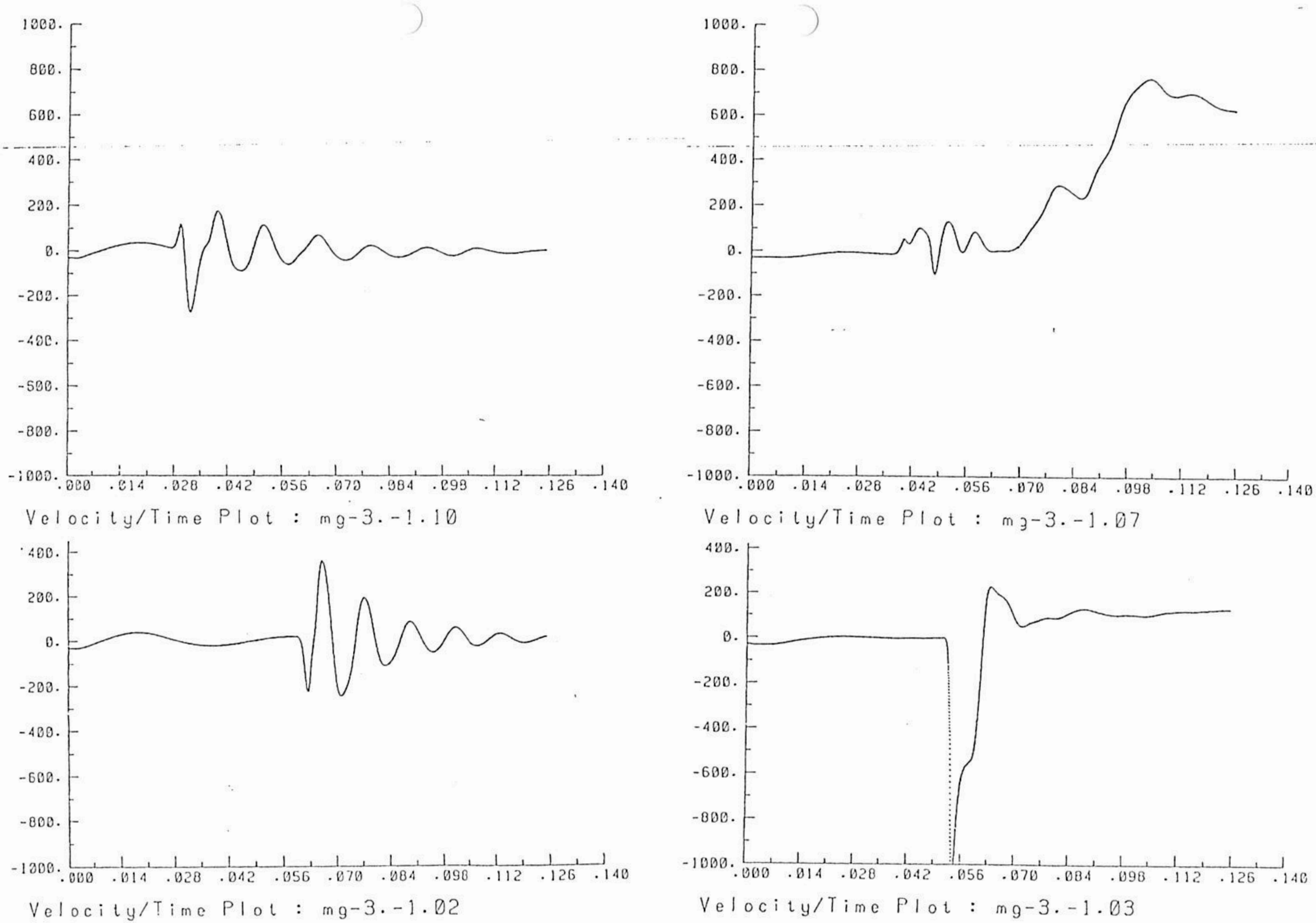


FIGURE 6.14 V VELOCITY: IGNITION AT 27C/T AND NO. 4 SUPPLY ROAD

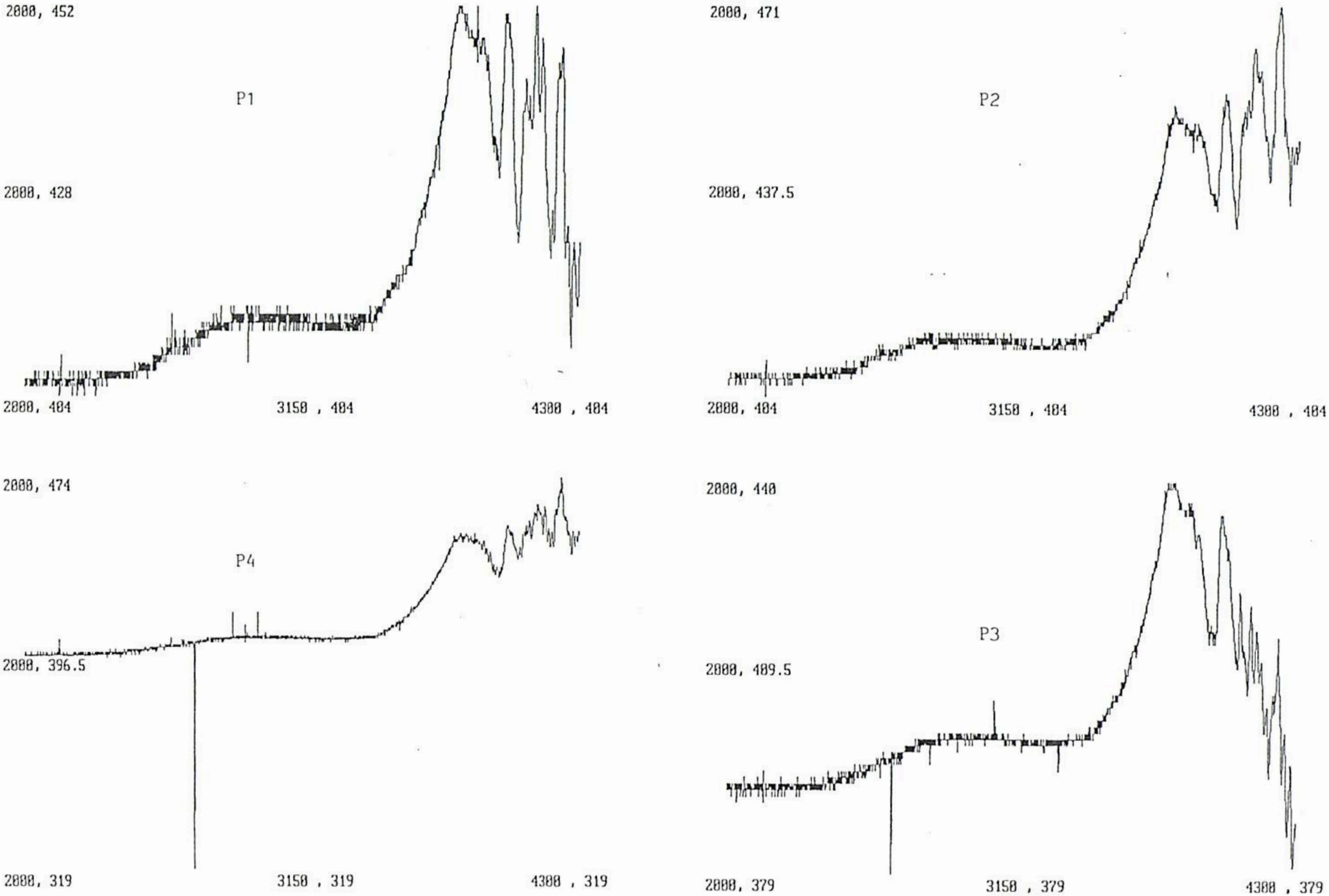
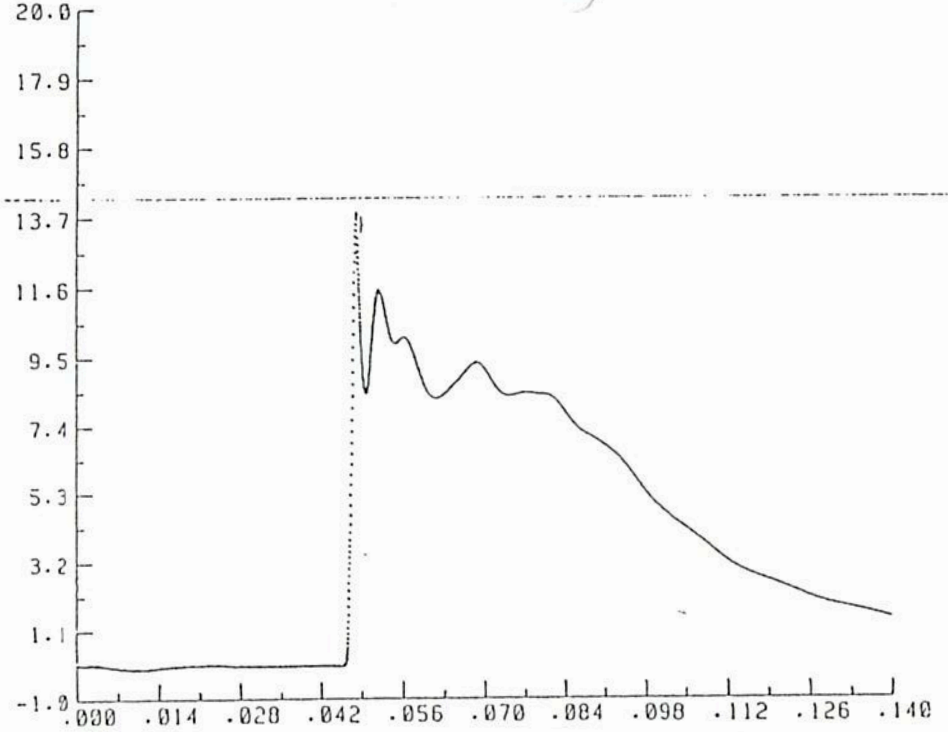
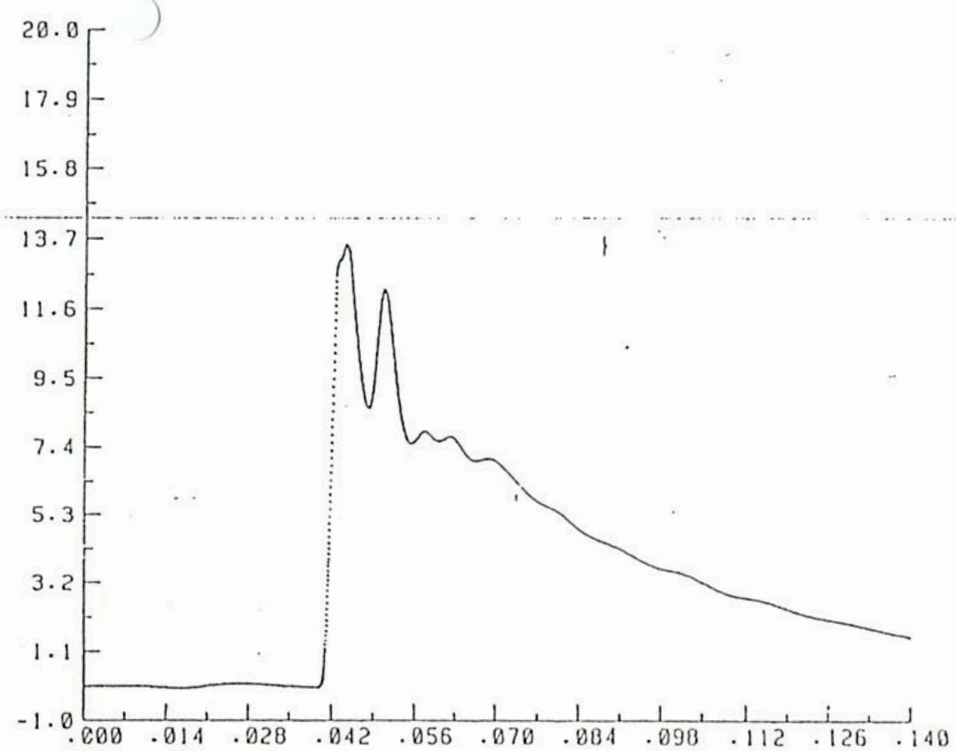


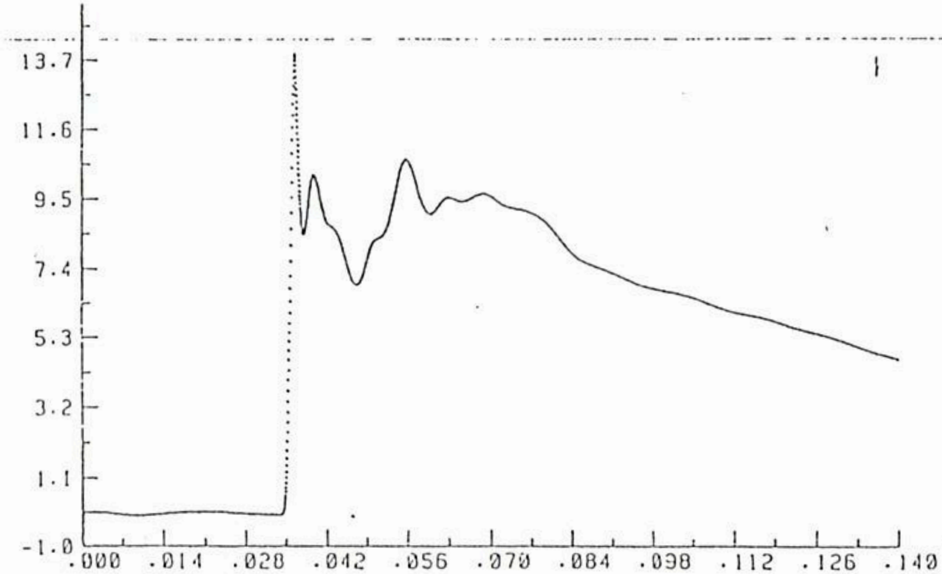
FIGURE 6.15 PRESSURE FROM SCALE MODEL EXPERIMENTS: IGNITION AT 27C/T AND NO. 4 SUPPLY ROAD



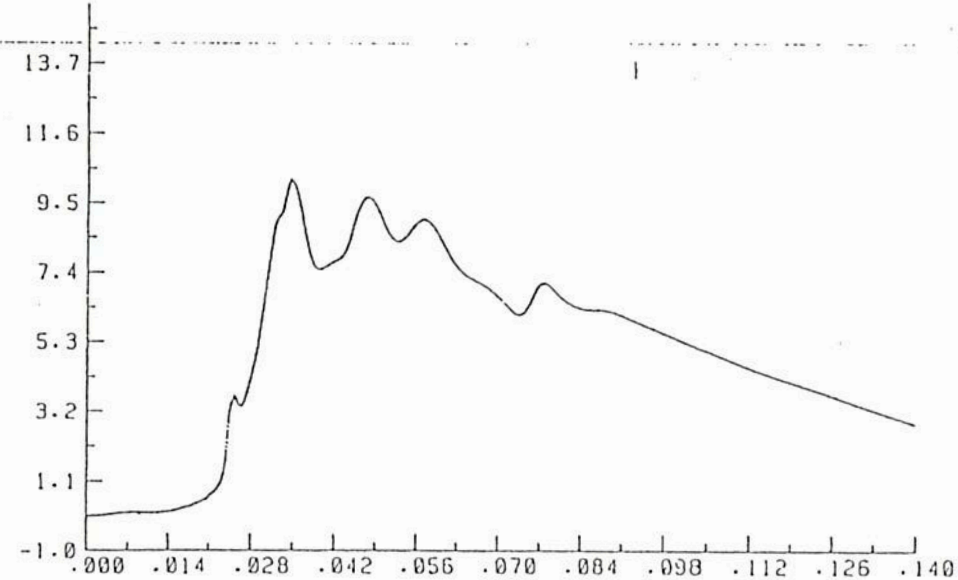
Pressure/Time Plot : mg-3.-2.10



Pressure/Time Plot : mg-3.-2.07



Pressure/Time Plot : mg-3.-2.02



Pressure/Time Plot : mg-3.-2.03

FIG 6.16 PRESSURE IGNITION AT 26C/T & NO. 3 BELT ROAD

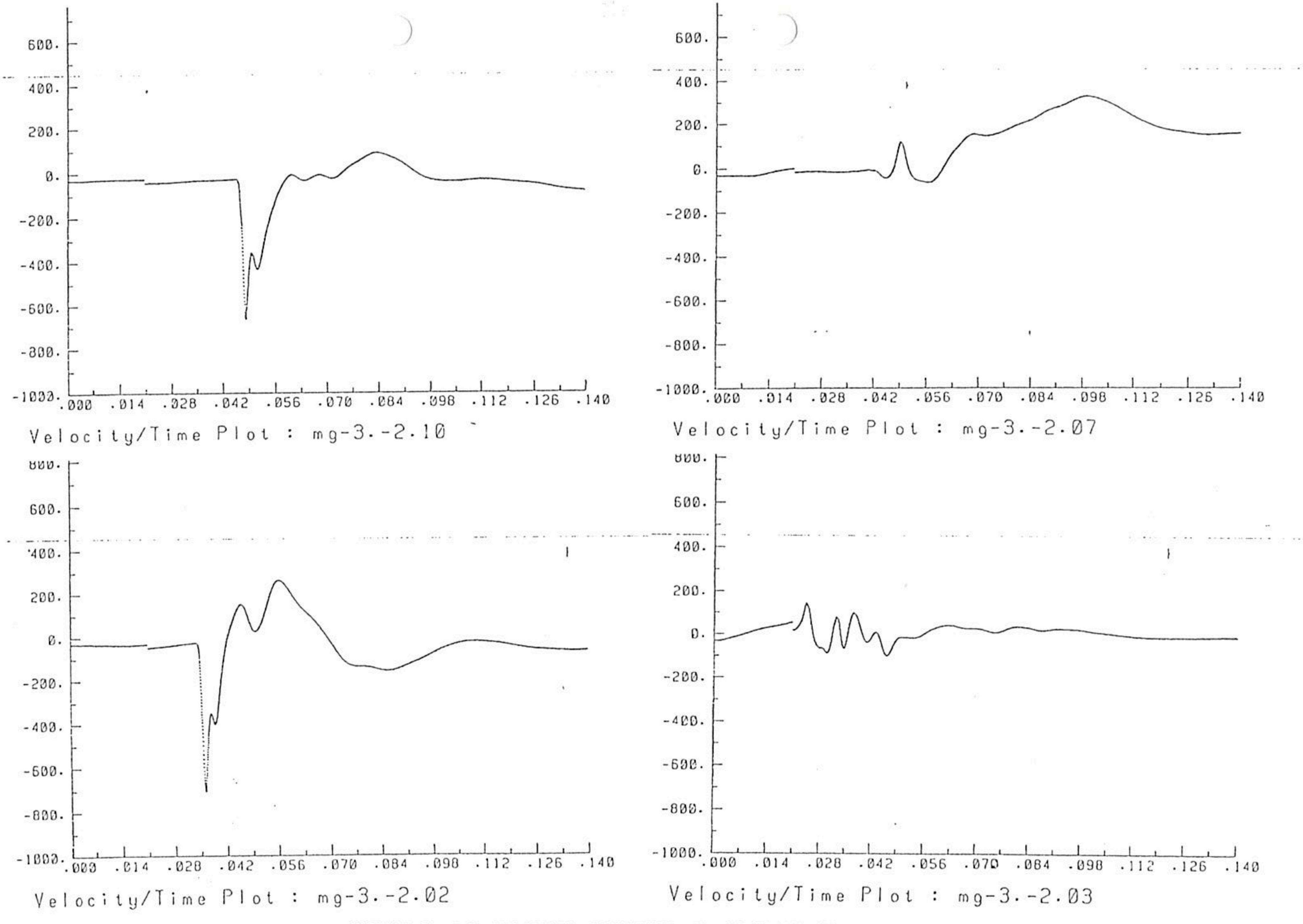


FIGURE 6.17 U VELOCITY: IGNITION AT 26C/T AND NO. 3 BELT ROAD

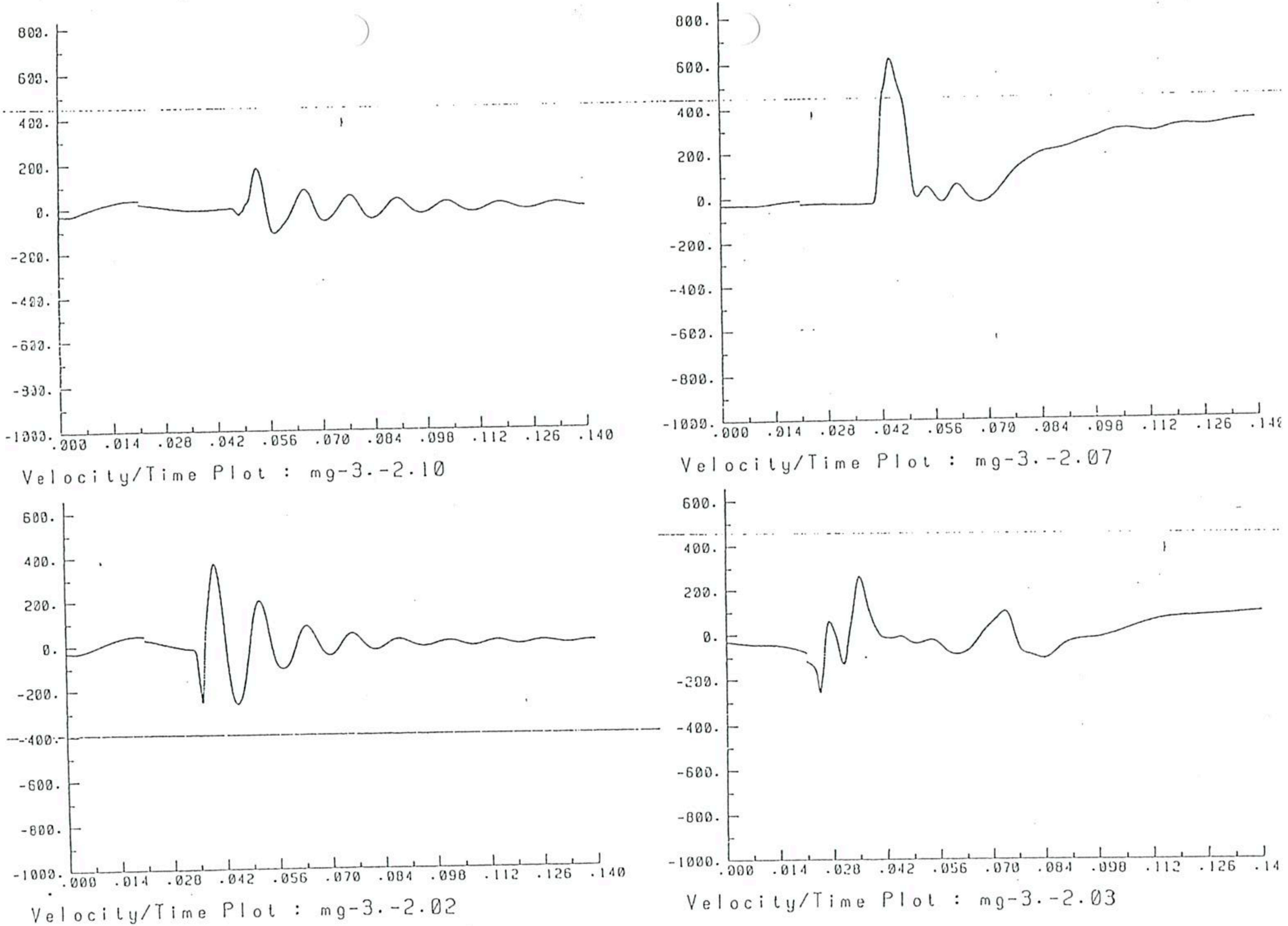


FIGURE 6.18 V VELOCITY: IGNITION AT 26C/T AND NO. 3 BELT ROAD

CHAPTER 7

SOME FINDINGS ON RE-ANALYSIS OF MOURA EXPLOSION

By
A. Green, S. Leivesley

The aim of this Chapter is to discuss the analysis of the course of the explosion at Moura based on evidence which is detailed in the preceding two chapters.

Forensic science provides for the use of evidence from blast, heat air flow and observations of the victims. The use of modelling can assist with the interpretation of this evidence allowing discrimination between what is or is not plausible. These methods allow the establishment of the course of the explosion with the various factors providing corroboration or elimination.

With this method all the known information is used to establish or eliminate findings on the course of the explosion.

In the first part of the chapter, a critical data set is established. Various hypotheses are then tested against this data. Finally there is a discussion on the likely areas of ignition sources capable of having caused the Moura explosion.

7.1 The Critical Data Set

There is a critical data set which defines the course of the explosion and against which all hypotheses should be tested to see whether they give the same type of damage or flow effects and pathology as the data in this critical set. Table 7.1 is a compilation of this critical data set extracted from Chapters 3 and 4.

The items in the critical data set relate to pressure, air flow, heat and body damage. Not every piece of information has been included in this critical list. Items such as the movement of steel from the area of the "Taj Mahal" or the general movement of the conveyor outbye 24 c/t appear to be common to all scenarios tested and have therefore been deleted from the list. Small items such as helmets and seats are too small to form part of the critical set as they tend to be easily transported by every flow past them and so are not good indicators of the initial blast direction. Such items have also been omitted from the list. The items in the critical data set are:

- A low pressure is observed at the stopping in 27 c/t compared with other stoppings on the north side of the mine.

- A uniform increase in pressure is observed moving away from the goaf area on both the north and south side of the Main Dip Section.

- The pattern of the alignment of the bodies that is observed including the relationship of the bodies in relation to the shuttle cars and the pattern of blast damage to clothing and severe head injuries.

- The observed positions of the shuttle cars.

- The observed direction of flow in No.1A South Return Road is outbye with no sign of a flow into the goaf in that road.

- A fire had occurred at the corner of No.1A South Return Road and 25 c/t with associated high devolatilisation of coal dust in that area.

- A bi-directional movement of crib room material at 26 c/t towards the shuttle cars, mine rover and outbye along No.4 Supply Road was observed. The tool bench top was moved from a point about 5m outbye 26 c/t on No.4 Supply Road in to the back of the mine rover some 3m inbye 26 c/t. Related equipment from that area ended up near the mine rover while some material from the crib room ended up 50m along No.4 Supply Road.

- The MPV tray found at the junction of No.4 Supply Road and 25 c/t had been moved from the opposite side of No.4 Supply Road spilling it's load of timber props which ended up parallel to No.4 Supply Road.

- The MPV tray in 27 c/t between No.3 Belt Road and No.4 Supply Road had been tipped in a direction towards the goaf and towards No.3 Belt Road.

- High devolatilisation of coal and high heat on plastic materials was observed between the continuous miner and s/c 31 in No.3 Belt Road.

- A fire occurred in 24 c/t.

- High heat was observed around the mine rover.

- The mine rover vehicle shows directional flame information with the flow of the flame and blast being sharply angled from the direction of the goaf.

- The pattern of burning on the bodies with severe burning of one body in No.4 Supply Road.

- The observed movement of fire extinguishers and hook in No.3 Belt Road outbye 27 c/t was towards the goaf. The hook on which the extinguishers were hung was also pointing towards the goaf.

- The observed movement of fire extinguishers in No.3 Belt Road outbye 26 c/t was towards 25 c/t.

- The belt structure at 25 c/t had been displaced towards No.4 Supply Road.

These 17 observations form the critical data set. All hypotheses have to be tested against this critical set to see which can be eliminated and which are more likely to be valid.

7.2 The Flame Safety Lamp

The major finding in the re-analysis is that there are a number of facts which negate the hypothesis of a course of an explosion emanating from 26 c/t and No.3 Belt Road. A comparison of the flame safety lamp hypothesis with the critical data set suggests the following:

- The findings of the Inquiry did not identify or relate ignition sources to a course of explosion. Consequently alternative ignition sources are still possible and cannot be eliminated until the course of the explosion is fully detailed.

- The pressure damage to the stopping in 27 c/t which is that closest to the goaf, is not consistent with an ignition in the region of the shuttle cars. Such an ignition would have displaced the stopping further against the rib than was observed. The expected damage would have been the same or greater than that observed at the stopping in 26 c/t since the stopping at 26 c/t would have been the closest stopping. The explosion would have been less intense at 26 c/t than 27 c/t.

- The blast evidence is that pressure increases away from the goaf area in what appears to be a consistent manner. The course of an explosion from close to the shuttle cars in 26 c/t or between the shuttle cars and the miner would produce the stopping in 26 c/t with the lowest pressure and more severe blast damage to the stoppings in 27 c/t and 25 c/t. This is not observed. There would not be a uniform pressure increase away from the goaf and there would be some signs of pressure increase towards the goaf. This is not observed.

- The pathology of the victims is not consistent with an ignition in the vicinity of any of the 12 men since all have been affected by substantial blast and some to intense directional flame. The evidence would suggest that the majority of bodies were moved by the blast between 3 and 25 metres.

- There is no substantiation of a flow of blast pressure originating within the vicinity of the shuttle cars being able to cause the positions of the shuttle cars where No.31 has moved towards the rib and No.30 has also been moved towards the rib.

- The air flow pattern observed in No.1A South Return Road is not consistent with ignition in the vicinity of 26 c/t and No.3 Belt Road. The preliminary indications from modelling studies show that ignition around the shuttle cars leads to a flow in a direction which is contrary to the evidence observed in No.1A South Return Road.

- The heat evidence is that the flame safety lamp coking and fusion has been caused by factors external to the lamp. The critical data set shows a high heating between the miner and s/c No.31 which is close to the position the lamp was found. Consequently fusion of material on the outside and inside of the lamp is not clear cut - it could be from ignition or due to external factors. This means that the experimental findings on the flame safety lamp are not absolutely in accord with an ignition within the lamp being the sole factor which can account for coking and fusion of dust on the internal lamp glass.

- There is no substantiation that the maximum devolatilisation occurred in this area (where the lamp was found) due to the blast flow originating in this area. Maximum devolatilisation occurred because of recirculation and extended burnout around the continuous miner and shuttle cars as the explosion moved past them (Flame brush burnout).

- The physical evidence of the lamp suggested it had been picked up by the explosion and impacted at a high velocity causing indentation and deformation of the base of the lamp and bending of the bonnet top.

- The reasonably uniform pattern of dust deposition on the outside of the lamp together with the impact damage suggests that it is consistent with being immersed and travelling with the flow of the explosion.

- The dust within the lamp is consistent with it being forced into the lamp due to a difference in internal and external pressure either caused by the blast or relative windspeeds.

- The coking within the lamp cannot be reproduced in a simple explosion and this mechanism remains unexplained but could be due to flame passing over the lamp more than once. It has been established that dust adheres to the surface in a single explosion flow. Dust adhering to the surface in this way will be preferentially heated by radiation from a second flame front due to its high absorption coefficient compared with the glass or metal surfaces. Rapid conduction of heat to the glass or metal surface will fuse the particles to that surface. Conduction will only occur where there are particles. Consequently, heating of the glass or metal is also localised and general discolouration of the metal surface does not occur.

- International attempts to replicate the experimental data presented at the Inquiry have failed to replicate the effect and have suggested that the addition of oxygen in Golledge's experiments caused an unwitting decrease in the flame arresting capabilities of the lamp's gauzes. The only experiment where ignition took place with the bonnet on used a spray gun discharging a pure coal dust jet held about 200mm away from the bonnet orifices. The pressure drop across the spray outlet was approximately 140 kPa. This corresponds to an air velocity substantially higher than that likely to be obtained from a wind blast due to a goaf fall.

- The ignition mechanism proposed for the flame safety lamp involves the creation of a jet flame in the direction of the air flow. This frame contains a substantial energy (an order of magnitude calculation would suggest 100 kJ). This is some 4-5 orders of magnitude greater than that required to ignite an external coal dust air mixture. The violence of this event would have left an indication on the direction of the flow and this is not seen in the evidence available.

- The air flow patterns around the mine rover due to the explosion are not consistent with ignition in the vicinity of 26 c/t and No.3 Belt Road. The direction of flame over the mine rover is also inconsistent with the flow from this area.

- The preliminary experiments with the physical scale model have not replicated a flow pattern which is consistent with the critical data set. An ignition source in the vicinity of the shuttle cars caused flows in all directions away from the source of ignition. This is exactly the reverse of the flow from the crib room and from in front of the mine rover and the flow responsible for moving s/c No.31. It also did not replicate the flow in No.1A South Return Road and was in the reverse direction to that observed.

- A scenario for the flame safety lamp being at the centre of the explosion would give low pressures radiating from the region of the lamp over distances of 25 m, low blast pressure damage to the bodies, i.e., no shredding of clothing, serious translational injuries, radial effects of burns and pressure damage rapidly escalating away from the centre of the explosion.

- The reliance on differences in the crystal microstructure of the two gauzes as an indicator of an event inside the lamp is not definitive, Manufacturing processes could be responsible for this difference.

Comparison of the flame safety lamp hypothesis with the critical data set shows there are two points of definite agreement, two of partial agreement and six points of definite disagreement and possibly a further three other negating factors. Three points cannot be determined because of inadequate information - points that may be determined at a later stage with modelling.

7.3 The Course of the Explosion

The main thrust of this work is to determine the course of the explosion. After examination of the flame safety lamp area as one potential area for ignition, a number of alternative areas were examined as to how the explosion would be expected to develop relative to the critical factors:

- The Conveyor boot end.

- The fire in 24 c/t.

- The shuttle cars.

- The crib room and area immediately in front of the mine rover.

- The continuous miner.

- The northern section of the goaf adjacent to No.4 Supply Road and

No.3 Belt Road.

. The southern section of the goaf adjacent to 27 c/t and 26 c/t.

Each hypothesis is tabulated against the critical factors in Table 7.1 and discussed separately below.

7.3.1 The area in 24 c/t and from the direction of the Boot End

The positive relationships are:

. The movement of the fire extinguishers at 27 c/t and No.3 Belt Road is in the correct direction.

. High devolatilisation between the shuttle cars and the continuous miner is more than likely with a strong flow in this direction but further work on burnout times from modelling studies is required.

. The fire in 24 c/t can be explained if the explosion started in that vicinity, but it is unclear if ignition towards the boot end of the conveyor will produce a long residence time for a fire to occur here. Further work with models is required.

The negative relationships are:

. The stopping pressure at 27 c/t is too low compared with that observed at 26 c/t.

. The pressure gradient observed is in the wrong direction for ignition in this area.

. The alignment of bodies is inconsistent with a flow from this direction. Such a flow could conceivably account for the accumulation of bodies by the shuttle car if the alignment of the bodies is considered as coincident rather than due to the explosion, but this type of flow could not account for the positions or state of the bodies near the mine rover.

. The position of the shuttle cars can not be explained with a flow from this direction.

. The bidirectional movement of material from the crib room is not consistent. The flow along 26 c/t would have blown the stopping and scattered debris from this area behind it before a flow down No.4 Supply Road towards the goaf took debris in towards the goaf area. Debris would not have travelled up to 300m out along No.4 Supply Road with this scenario.

. The movement of the MPV tray in 25 c/t is inconsistent as the blast would have moved up 25 c/t towards No.4 Supply Road. This movement would not have picked up the MPV tray in the manner observed.

- The direction of flame over the mine rover is not consistent with a flow along 26 c/t toward No.4 Supply Road and then into the goaf, obtained from this hypothesis.

- The movement of fire extinguishers at 26 c/t and No.3 Belt Road is in the wrong direction for ignition in this area.

- The lateral movement of the belt structure at 25 c/t is not consistent with this hypothesis.

- The movement of the MPV tray in 27 c/t is probably inconsistent for a flow down No.3 Belt Road and along 27 c/t towards No.4 Supply Road. Although the MPV tray was tipped towards the inbye rib, it was also skewed in the wrong direction for this hypothesis to be likely.

- The severe burning of the body in 26 c/t and the high heating observed around the mine rover seems to be inconsistent with this hypothesis but further modelling is required.

This hypothesis agrees with 1 critical factor and possibly a further 2 factors. It disagrees with 9 factors and possibly a further 3 while one is unknown.

7.3.2 The Crib Room and Surrounding Area

The positive factors with this hypothesis:

- The alignment of the bodies near the shuttle cars and at the intersection of 26 c/t and No.4 Supply Road is consistent with a flow and blast from the crib room along 26 c/t towards the shuttle cars, although the bodies that moved along No.3 Belt Road outbye might not occur with this scenario.

- The position of the shuttle cars can be explained with a flow along 26 c/t towards these vehicles.

- The crib room material will be moved in a cone as observed. The movement of material 300m out along No.4 Supply Road is probably consistent but further modelling work is required.

- The pattern of burning on the body in 26 c/t would be consistent.

- The high degree of heat around the mine rover area is explained.

- The movement of the fire extinguisher at 26 c/t and No.3 Belt Road is in the correct direction.

- This hypothesis could possibly explain the movement of both the MPV tray's at 25 c/t and 27 c/t but further modelling work is required.

- Preliminary modelling indicates that the flow at No.1A South Return Road is in the correct direction.

There is inadequate information to explain the fires at 24 c/t and No.1A South Return Road, the high devolatilisation between the miners and shuttle cars, and the movement of fire extinguishers towards 27 c/t - this information may come from modelling studies.

The negative factors:

- The pressure observed at 27 c/t stopping is too low relative to that at 26 c/t.

- The uniform pressure increase away from the goaf is inconsistent.

- The direction of flame around the mine rover is incorrect.

- The lateral movement of the belt at 25 c/t is probably not in the correct direction for ignition here but further work is required to verify this point.

The hypothesis agrees with 5 critical factors and possibly a further 4. It disagrees with 3 factors and possibly a further 1. There are 2 neutral factors and 2 unknown.

If the source of ignition is moved from the crib room to around the mine rover, the negative factors with regard to the stopping at 27 c/t and the pressure gradient become less certain, tending to move towards the positive the further the area is moved along No.4 Supply Road towards the goaf. The direction of flame over the mine rover becomes consistent and the movement of the MPV tray in 27 c/t becomes more positive. All other factors remain the same as for the crib room scenario.

Within the crib room area there are several potential ignition sources such as the lights, the entonox bottle as a frictional ignition source and as a spontaneous ignition source from oxygen release. The mine rover cannot be ruled out either. It was not tested in a flameproof enclosure to eliminate it as a potential source although the testing done on the vehicle would suggest this to be unlikely.

7.3.3 The Area Around the Continuous Miner

The positive factors are:

- The stopping at 27 c/t has the correct relative pressure to that at 26 c/t.

- The uniform pressure gradient away from the goaf is consistent.

- The high devolatilisation between the shuttle and continuous miner is explained.

- The movement of fire extinguishers outbye 26 c/t is in the expected direction.

- The movement of MPV tray in 27 c/t is in the correct direction to tilt it but not to skew it in the direction observed. This requires further modelling.

- The lateral movement of the belt at 25 c/t may be consistent but further modelling is required.

There is one factor which is unknown until further modelling studies are undertaken.

- The movement of the MPV tray at 25 c/t and No.4 Supply Road.

The negative factors are:

- The alignment of the bodies around the shuttle cars is not consistent although the bodies at the junction of 26 c/t and roadway 4 could be consistent if flame went back towards 27 c/t and then outbye along No.4 Supply Road. Preliminary modelling would suggest that the flow would move along 26 c/t towards No.4 Supply Road rather than in the reverse direction.

- The position of the shuttle cars is inconsistent and needs explaining.

- The flow in No.1A South Return Road and the associated fire.

- The crib room material movements depend on the relative timing of flows arriving up 26 c/t and along No.4 Supply Road from the goaf. Preliminary indications from modelling are negative.

- The movement of the fire extinguishers and hook towards 27 c/t is unlikely as it is too near the source of the explosion to get a sustained drag effect on the hook and bend it in the manner observed.

The hypothesis agrees with 4 critical factors and possibly another 4. It disagrees with 3 factors and probably 3 others. There are no neutral factors and 3 unknowns.

The ignition source in the vicinity of the miner would have been an electrostatically charged hose of the trickle duster or frictional ignition in the goaf adjacent to the roadway.

7.3.4 The Northern Section of the Goaf

The positive factors for ignition in this area are:

- The stopping damage at 27 c/t is consistent with damage to the other stoppings.

- The pressure gradient is consistent with this ignition.

- The pattern of alignment of the bodies is consistent. The severe burning of the body in 26 c/t may be consistent but requires testing in modelling studies.

- The position of the shuttle cars can be explained.

- The crib room material would be directional as observed with material being taken along No.4 Supply Road.

- The movement of the MPV tray in 25 c/t can be explained.

- The direction of flame front over the mine rover is consistent.

- The movement of fire extinguishers at 26 c/t and No.3 Belt Road is in the correct direction.

- Preliminary tests in the scale model suggest that the direction of flow in No.1A South Return Road is as observed as being in one direction only and then outward from the goaf with a relatively long flame burnout time. This requires further testing of modelling.

- The movement of the MPV tray in 27 c/t can possibly be explained but this requires further modelling.

- The high heat around the mine rover may be explained but again needs further modelling.

Two items are unknown. The high devolatilisation between the miner and shuttle cars and the fire in 24 c/t need explanation.

There are two possible negative factors for this scenario both of which need testing:

- The movement of fire extinguishers at 27 c/t and No.3 Belt Road.

- The lateral movement of the belt at 25 c/t.

There could be other contra indications which will show up in modelling. The inclusion of fusion on glass requires detailed modelling.

This hypothesis agrees with 8 factors with further agreement with 4 other factors. It disagrees with a possible 2 factors and there are 2 other factors which are unknown.

The possible ignition sources in this area are frictional ignition of rock and piezoelectric ignition in either the rock as it collapsed or between rock and rock or between rock and steel roof bolting material as it collapsed.

7.3.5 The Southern Section of the Goaf

This hypothesis has the following positive factors:

. The stopping at 27 c/t and the uniform pressure increase is consistent for the major part of the southern section of the goaf. As the area is moved towards the line of 26 c/t the weaker these two factors become.

. The movement of the fire extinguishers at 26 c/t and No.3 Belt Road and the lateral movement of the belt at 25 c/t is consistent with this area of ignition.

The negative factors are:

. The position of shuttle car 30 might be explainable by a flow from this direction but the position of s/c No.31 is definitely inconsistent.

. Preliminary modelling shows that the flow in No.1A South Return Road and the high heat in this roadway is inconsistent. Two flows are observed in opposite directions which is not seen in the evidence.

. Preliminary modelling also suggests that neither the movement of material from the crib room nor the pattern of body alignment is consistent with the observed evidence.

. The movement of the MPV tray in 27 c/t is inconsistent as is the movement of fire extinguishers at 27 c/t. These negative factors become weaker as the area of ignition approaches the line of 26 c/t.

. Preliminary modelling suggests that the direction of flame over the mine rover is inconsistent with flame travelling along 26 c/t toward No.4 Supply Road into the goaf.

There are several unknown factors at the present time:

. The high devolatilisation between the miner and shuttle cars and the fire in 24 c/t.

. The effect of flow on the MPV tray in 25 c/t is not known.

. The high heat around the mine rover and the pattern of burning on the body in 26 c/t requires further modelling.

This hypothesis agrees with 4 factors. It disagrees with 4 factors and possibly a further 4. There are 5 unknowns.

The ignition sources in this area are the same as for the northern section of the goaf.

7.4 Discussion

Figure 7.1 plots a percentage probability of ignition for several hypothesised ignition zones. The scaling has been based on +2 for a positive factor, +1 for a positive factor that needs further testing, 0 for a neutral or unknown factor, -1 for a negative factor that needs further testing and -2 for a negative factor. This process results in a value for each hypothesis between +34 and -34. This range has been converted to a percentage probability.

It is clearly seen that the regions above 50% probability lie in an arc from the goaf area to the west of the continuous miner around to the crib room area. The maximum value occurs in the north goaf in front of No.4 Supply Road.

The area around the shuttle car, boot end conveyor and outbye towards 24 c/t on No.3 Belt Road and the south goaf have a probability below 50%.

The above analysis relies on giving equal weighting to the seventeen critical factors in Table 7.1. In reality certain factors should carry more weight than others. For example agreement with the position and alignment of twelve bodies over what appears to be two distinct areas together with an explanation of burn marks, drag marks and pressure effects on the bodies should carry more weight than the movement of the fire extinguishers which would be more easily moved in subsequent winds following the primary flow. Similarly events which are hard to explain or appear unusual should carry more weight such as the one way flow in 1A heading or the movement of the MPV tray at 25 c/t across No.4 Supply Road.

Applying this additional weighting, the critical data set is reduced to six factors, Nos.3, 4, 5, 7, 8 and 13 given in Table 7.1. This reduced set is also plotted in Figure 7.1.

The additional weighting increases the likelihood that ignition started in the north goaf as far round as in front of the mine rover. The crib room area still remains high but the area in the goaf adjacent to the continuous miner is much less likely and is now compatible with the likelihood of ignition having occurred in the south goaf. The other scenarios around the shuttle cars and outbye the boot end of the conveyor become substantially less and can be considered unlikely areas of ignition for this explosion.

Although further verification through the application of modelling techniques is required, the indications are that the explosion started in the vicinity of the north goaf adjacent to No.4 Supply Road of No.3 Belt Road and possibly as far round as the crib room. In this region of the mine there are a number of potential ignition sources that cannot be ruled out on the basis of evidence presented at the inquiry.

Frictional ignition of rock on rock is the most likely frictional ignition mechanism. Tests attempted by both Poppit and Green independently show that rock hitting metal is unlikely to have occurred. Poppit showed that under at least one set of circumstances rock rubbing on rock could rapidly ignite methane. This mechanism cannot be ruled out even though it is not known how rocks break up or how they hit or slide down one another as the roof collapses. It should also be noted that both quartzitic and pyritic strata occur on either side of the shear plain near 27 c/t.

An alternative mechanism for ignition could be a piezzo - electric effect in the rock. The roof rock at Moura did contain bands of quartz. Two such bands close together under pressure could produce such an effect if the rock sheared between them. As the rock is distressed an impedance is set up in the quartz which can build up sufficient charge to cause sparking. A similar effect can be caused by a quartz band and a steel plate or roof bolt.

An electrostatic discharge from the trickle duster hose cannot be ruled out. This hose was apparently not antistatic. A goaf fall could have produced sufficient dust flow over the hose at a high enough velocity to produce a charge on the surface of the hose, leading eventually to ignition.

The mine rover, although thoroughly checked and inspected after the incident was never tested in a flameproof enclosure to ensure that ignition could not have occurred at start up or after a few minutes running.

In the crib room, the fluorescent lights were destroyed by the explosion. Consequently these remain potential sources of ignition as a fault may have developed in the electrics.

There was also an entonox bottle constructed of aluminium containing 50% oxygen and 50% nitrous oxide. This mixture is equivalent to a 70% oxygen atmosphere. Although the valve had been sheared at the cylinder head, expert testimony at the inquiry stated that the valve had been sheared in a violent impact consistent with its being projected by the explosion rather than being dropped or manually thrown against a wall. Frictional ignition from this source is therefore unlikely. However, release of high oxygen atmospheres over oil mist and greases causes spontaneous ignition and many such causes of explosions are documented. It is possible that this auto ignition will occur with coal dusts particularly when they are in suspension, since it is in this state that they behave like oil mists. This hypothesis does however require further testing.

There remains the question of the availability of fuel for ignition. There is substantial evidence to suggest that methane, present in the goaf, would have been pushed out from the goaf towards both the north and south returns. Furthermore, roof and floor heave associated with destressing of the strata could have contributed methane from the seams above and below Main Dips Section. There were signs of floor heave immediately inbye 27 c/t. One or more roof falls over a short period of time would have short circuited the air flow which would have resulted in a flammable methane in coal dust mixture throughout a substantial volume of the mine inbye 25 c/t, and possibly further out along certain headings.

In spite of this, the critical indicators point to the seat of the explosion occurring inbye the mine rover and No.4 Supply Road.

What is the likelihood that the ignition source was remote from this area? The only way a remote ignition could produce agreement with those critical indicators is for the ignition to result in a laminar flame which tracks, due to the concentration gradients of methane and coal dust, to the northern area of the goaf. This is more likely within the goaf, where the ignition is relatively uncontained compared with the roadways. This degree of unconfinement would suggest that turbulence levels even after a roof fall, would be much less than in the headings.

The flame safety lamp could not be the source of ignition if it was in either No.3 Belt Road or 26 c/t as it produces a highly turbulent directional and energetic jet that would rapidly accelerate the explosion. This would have left contrary indicators to that observed unless the lamp at the time was in the goaf. But this assumption creates other difficulties particularly, how the lamp was moved to the position it was found. Being at the ignition point, it would not be moved by the initial blast and subsequent air movement would probably be in the wrong direction due to over expansion of the initial blast.

It cannot be ruled out, however, that another ignition source producing a weak ignition could have been present outbye 27 c/t along No.3 Belt Road, causing the indications observed. There are no obvious candidates for this hypothesis.

.5 Conclusion

The reanalysis into the Moura explosion has been based on information that was available to the inquiry and expert international and Australian experts who have been consulted by the team over the past 6 months.

The general response by forensic scientists, mining engineers, scientists working in the mining field, forensic pathologists and explosives experts is that the lack of detailed information gathering at the time of the incident and the failure to provide a systematically gathered data set does not allow a full reconstruction of the incident.

However, this re-examination of the incident has shown that:

- The flame safety lamp scenario for ignition is inconsistent with the determined course of the explosion.
- The highest probability for the ignition zone is from the north goaf adjacent to No.4 Supply Road but could have occurred as far as the crib room area.
- In this region of the mine, there were a number of ignition sources that could have caused ignition and about which further research is required to elucidate the mechanism for ignition.
- The fuel could have been methane or a mixture of methane and coal dust. The ignition zone in the north goaf is coincident with the natural area for migration of methane within the goaf. Sufficient methane could have accumulated without the need for coal dust to participate in the ignition process.
- The use of modelling in this reinvestigation has shown that both physical and mathematical modelling of the incident are useful tools to assist the forensic

scientist in interpretation. Of the two methods, mathematical models are potentially the more powerful of the two methods as long as they have been calibrated against experimental data, because they can:

- Give details of pressure, velocities and temperature throughout the region of interest and with time.

- Allow the direct calculation of impulses and heat fluxes on objects. As a consequence the likely damage or movement of an object can readily be assessed.

- Can form a link between scaled physical models and the full scale event as it should predict phenomena in both scales.

Further research is necessary to develop modelling techniques.

Table 7.1 Critical Factors for Scenario of Ignition

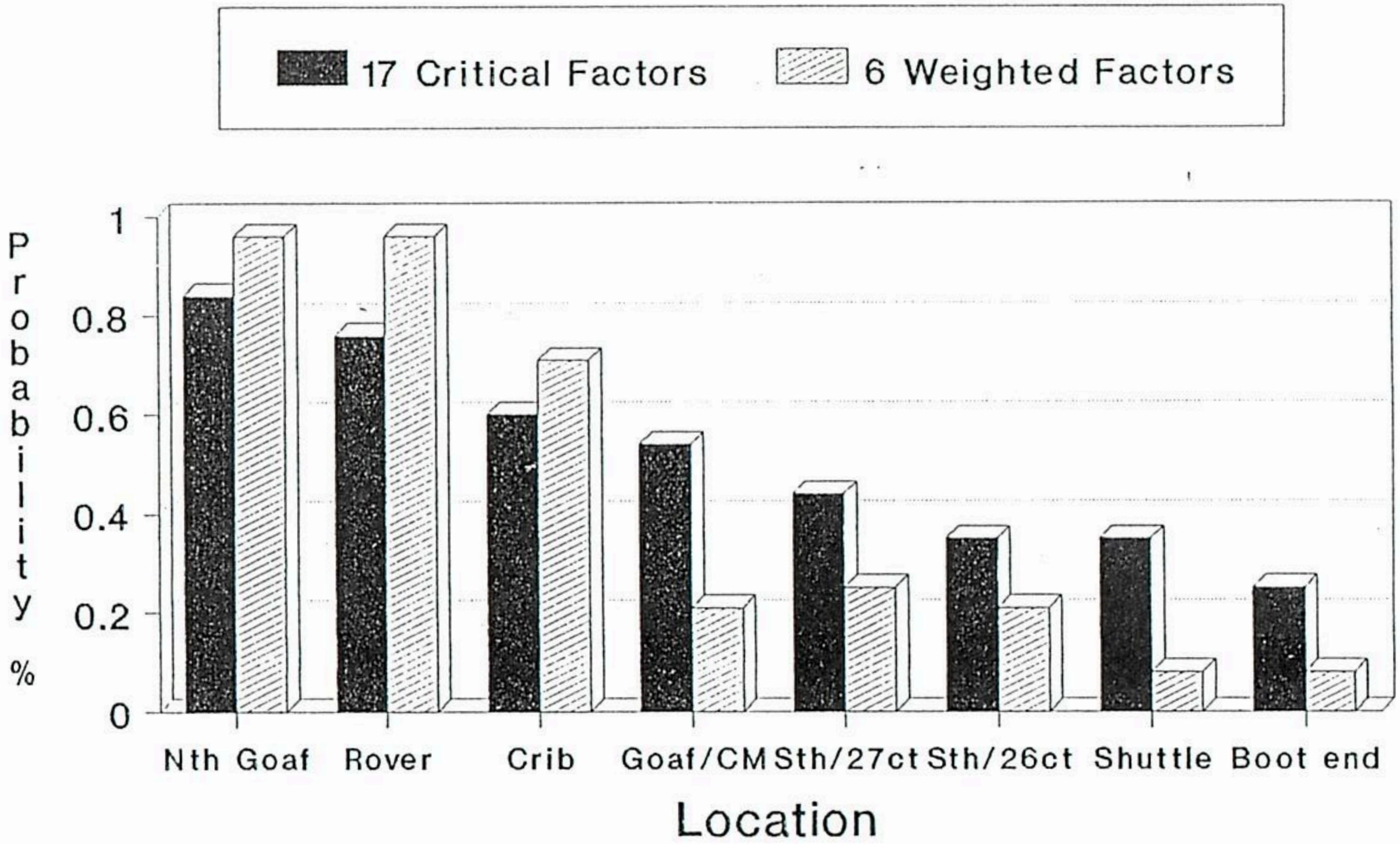
Factor	Ignition Area					
	Boot End out Outbye Conveyor	Shuttle and Car	Crib Room	Continuous Miner	North Goaf	South Goaf
1) Relative Low Pressure at 27 c/t Stopping North Side	N	N	N	Y	Y	Y
2) Uniformly increasing pressure moving away from Goaf	N	N	N	Y	Y	Y
3) Pattern of alignment of bodies around shuttle cars & mine rover	N	N	Y?	N	Y	N
4) Position of Shuttle Cars	N	N	Y	N	Y	N
5) One way flow out of the goaf in No.1A South Return Road	–	N?	Y?	N?	Y?	N?
6) To a fire in this heading	–	N?	–	–	Y?	N?
7) The bidirectional movement of material from the Crib Room area	N	N	Y	N?	Y	N?
8) The movement & tipping of the MPV tray in 25 c/t	N	N?	Y?	–	Y	–
9) MPV tray movement in 27 c/t	N?	N?	Y?	Y?	Y?	N
10) High devolatilisation of coal around the continuous miner	Y?	Y?	?	Y	–	–
11) Fire in 24 c/t	Y?	–	–	–	–	–
12) High heat around the mne rover	N?	–	Y	Y?	Y?	–
13) Directional flame from front of the mine rover	N	N	N	N?	Y	N?

Factor	Ignition Area					
	Boot End Out Outbye Conveyor	Shuttle and Car	Crib Room	Continuous Miner	North Goaf	South Goaf
14) Pattern of burning on body	N?	-	Y	Y?	Y?	-
15) Movement of fire extinguishers and hook outbye 27 c/t towards 27 c/t	Y	Y	?	N	N?	N
16) Movement of fire extinguishers and hook outbye 26 c/t towards 25 c/t	N	Y	Y	Y	Y	Y
17) Movement of belt structure at 25 c/t towards No.4 Supply Road	N	Y?	N?	Y?	N?	Y
No. Position factors (Y)	1	2	5	4	8	4
No. on Balance Position (Y?)	2	2	4	4	5	0
Neutral Factors (?)	0	0	2	0	0	0
No.on Balance Negative (N?)	3	4	1	3	2	4
No. Negative factors (N)	9	6	3	3	0	4
No. Unknown (-)	2	3	2	3	2	5

Note - The area around the shuttle car is assumed to be in the area of the interaction of 26 c/t and No.3 Belt Road rather than towards the continuous miner.

Figure 7.1 Ignition Sources

Probability for various locations



Note: Rover relates to area immediately in front of the vehicle.

ARG 15/5/90

CHAPTER 8

OVERALL FINDINGS

By
P. Golledge, I. Roberts

Introduction

These are based on the examination of information presented to the Warden's Inquiry together with advice and comment received from Australian and Overseas consultants. These consultants included forensic scientists, forensic pathologists, mining engineers, scientists from a range of disciplines with experience in coal mine explosion research and explosives experts.

As to the Moura explosion it has been found that the collection of data from the area of the mine affected by the explosion was not adequate to re-construct the incident. The explosion occurred either in the goaf or immediately adjacent to it. The geometry of the affected area of the mine cannot be simulated to the extent necessary for an accurate finding to be obtained from experimentation with a physical or computer model.

Most of the experimentation and testing carried out in world-renowned explosion galleries are mostly confined to a single entry. The multiplicity of roadways and c/t's in the area of the mine affected by the explosion allowed for an explosion path of great complexity. The void created by the goaf added to the complexity. Further, it is not known how much of the caving of the goaf occurred prior to, during, and subsequent to, the explosion. The damage to ventilation stoppings created by a roof collapse in the goaf area cannot be determined and therefore it is not possible to estimate the damage by the explosion with any accuracy. not true

It is pertinent to quote here the work of Dr. F.V. Tideswell who carried out scientific investigation of a considerable number of coal mine explosions in his capacity as Senior Principal Scientific Officer of the Safety in Mines Research Establishment in Britain.

He stated in 1952 *"The tracing of the course of a mine explosion to its source and the determination of its nature are often surprisingly difficult. There are two complementary methods of approach. One, the intuitive approach, is based on experience and on knowledge of the pit and of the mining operations in progress; the other, the analytical approach, which it is the peculiar duty of the scientist to follow, is based on a dispassionate survey of all the evidence recoverable. Both approaches are needed and must be related."*

There is clearly a need to adopt the two approaches to explosion investigation and to combine the two results. Scale models should be constructed in order to carry out the explosion investigation. The benefit of having scale models such as that depicted in this report, has been considerable. It is suggested that such models should be provided for use in the Warden's Inquiry in addition to plans.

The aims and objectives of the Report are set out in section 1.1.3 and the findings resulting from an attempt to achieve them are set out below in the same sequence:

8.1 Forensic Pathology and Computer/Physical Modelling

Forensic Pathology

Well established techniques used in forensic pathology can identify the victims of a coal mine explosion. The time of death is more difficult to determine and relies on consequences of the explosion, such as damage to the power supply or telephone system. The manner of death is a matter of classification but the cause of death may be a combination of more than one factor.

Forensic examination can provide information on the magnitude, direction and duration of the force from the explosion pressure, as well as some idea of the temperature of the flame. When more than one pressure wave traverses the mine roadway the interpretation of the forensic examination is much more difficult.

Toxicology can assist in identifying the presence of CO and even CH_4 in the blood. Forensic examination can give information about the possibility of the victim surviving the explosion and whether or not a self-rescuer was used. Dust and soot in the airways can be examined to determine their source. Lung tissue can indicate the presence of pneumoconiosis which when related to dust exposure measurement can determine the effectiveness of dust control technologies.

Computer Modelling

The application of computer modelling to the analysis of coal mine explosions is still in its infancy. Even under controlled experimental conditions in explosion galleries there are considerable variations in flame velocity, dynamic pressure and static pressure with distance from the ignition point.

Although research is proceeding in overseas mining research centres with the development of computer models for coal mine explosions reliance is still placed on testing in explosion galleries.

The results from limited computer modelling of two roadway junctions of Moura No.4 Mine cannot be validated, at the present time, by experiments in an explosion gallery.

but irrelevant because the [illegible]

Physical Modelling

The physical model of the Moura No.4 Main Dips Workings, on a scale of 1:300, was of considerable benefit during this project. Part of the workings in the vicinity of 26 c/t was also modelled, on a scale of 1:50 and also of benefit to the project team and others who assisted.

However, in using a physical model for small scale explosion experiments there are scaling problems which cannot be overcome. The correct sequence of events concerning the fall in the goaf area is not known. Furthermore, it is difficult to reproduce the dynamic conditions which probably existed prior to the ignition.

(Golledge/Roberts)

As with computer modelling the results of any scale model testing would need to be validated in an explosion gallery. The potential exists for use of forensic science and modelling, the basis of this project. However, the hypotheses on which this project was based have not been sustained. The work carried out has not enabled a conclusion to be drawn on the Moura No.4 Mine explosion.

8.2 Identification of Evidence from Forensic Pathology (Moura)

Forensic pathology techniques were able to establish a number of important findings about the victims of the explosion.

An analysis of the photographs of the victims taken during the autopsies showed evidence on some bodies of exposure to flame and also some shredding of clothes due to the effects of the blast. No samples of clothes from the victims were taken for forensic analysis to obtain an estimate of exposure to flame, heat or blast. Deductions based on the presence of clothes shredding are therefore of uncertain value.

There was evidence in the mine of movement of an explosion blast wave in both directions along parts of No.3 Belt Road and other roads in Moura No.4 Mine.

8.3 Identification of Additional Characteristics of Blast (Moura)

A number of hypotheses has been considered in this report regarding the ignition source and the most probable direction of the blast. At the time of the inquiry a number of questions could not be answered due to the lack of evidence. The passage of nearly four years since the explosion at Moura No.4 Underground Mine has not provided any additional evidence.

Information collected during the investigation of the Moura explosion in 1986 and 1987 have been analysed differently from earlier reports submitted to the Warden's Inquiry. Hypotheses have been advanced suggesting that the source of ignition was other than the flame safety lamp. Such hypotheses rely on assumptions which cannot be proved or disproved and they fail to explain the behaviour and condition of the flame safety lamp gauzes involved in the Moura explosion.

Further research at SIMTARS has demonstrated that a properly assembled flame safety lamp, similar to the one used at Moura, is capable of acting as an ignition source for a methane or methane/coal dust explosion under mine ventilation conditions which could occur following a large goaf roof fall.

This project has not produced any evidence to challenge the Findings of the Mining Warden's Inquiry.

8.4 Structuring of Future Scientific Investigations

It is necessary to again refer to the above quotation from the work of Dr. Tideswell. The intuitive approach has to be combined with the analytical approach to obtain a proper result. The results of the two approaches has to be combined by the Chief Inspector of Coal Mines. The necessary scientific resources need to be made available to him. The basic work of examining and sampling the explosion area requires the services of engineers experienced in mining/electrical/mechanical engineering together with scientists with expertise in blast/flame/dust and air sampling and analysis/forensic science and pathology. In addition there will be a need for this work to be supported by suitable laboratory services. The whole of this investigative work should be co-ordinated by an experienced mining engineer who could be a Senior Inspector of Coal Mines, or other person trained for this work.

The results of the investigation with conclusions should be assembled in one official report for presentation by the Chief Inspector of Coal Mines to the Warden's Inquiry prescribed by the Queensland Coal Mining Act. The report and subsequent inquiry would then result in precise recommendations with regard to future mine operation and research, if necessary.

Whilst there is need for preparation for dealing with an event such as a mine explosion, it has to be realised that throughout the world the incidence of such disasters is continuing to reduce. Increased safety has undoubtedly contributed to this but we must realise that in some countries with the longest underground coal mining history there has been, and continues to be, a decline in coal production. Consequently experts in mine explosion investigation are becoming rare.

There is a need in Queensland to select and train staff in the area of coal mine explosion investigation who would in such an event be responsible for the meticulous investigation essential to establish a generally acceptable explanation of the cause and circumstances of the explosion.

8.5 Protection of Life in Underground Coal Mines

The matter which has priority is that of the ultimate prevention of coal mine explosions. This report deals at some length with the potential for disaster from impact of rock in a goaf. The only practical method of dealing with this potential ignition source is to render the goaf atmosphere inert. This is already under consideration for Queensland and has been practised for several years in coal mines overseas. Its application in Australia has been limited to date to dealing with an emergency.

The potential for explosions/fires from frictional ignition by machines requires attention particularly where there is a potential for contact with rock of high incendivity.

The work on this Project has required discussion regarding the value of stonedust in the arrest of a coal dust explosion. Research work in explosion galleries has shown that whilst stonedusting of roadways can be effective in arresting a coal dust explosion, the presence of methane combined with coal dust reduces that effectiveness. It is considered that the Main Dips Section roadways were adequately stonedusted to arrest a coal dust explosion. However, the presence of methane (possibly displaced by a goaf fall) allowed the explosion to extend along the roadways further than would have been the case without the presence of methane.

With regard to water and dust type barriers it is essential that all roadways have similar protection. However the elimination of explosion at source should have priority over this. To be specific with regard to dealing with the risk of fire/explosion from frictional ignition in the goaf it is worth repeating here an extract from the report on the Six Bells Colliery explosion (U.K. 1960) -

If a fall of stone of a not uncommon nature for a distance of six feet or so may be dangerous, the question immediately raised is the degree of risk involved in the routine collapse of roof in wastes. There is, however, no recorded experience of ignition of firedamp from this cause in longwall wastes in this country. This may well be because, for ignition to occur, there must be the remote coincidence of a number of conditions including the fall of a certain kind of rock, the right type and strength of impact and the presence at or about the point of impact of a firedamp-air mixture within a relatively narrow range.

Inertisation would prevent the remote coincidence in the goaf of conditions requisite to ignition/explosion. Ongoing research priorities are **goaf inertisation** and the **elimination of frictional ignition by machines.**

8.6 Liaison Between Government Departments

The Chief Inspector of Coal Mines should arrange close liaison with the Queensland Police Force so that there is a clear understanding of the role of both Departments in the event of an emergency. The same liaison is necessary between the office of the Chief Inspector of Coal Mines, SIMTARS and the Health Department. Personnel in those organisations together with the Coal Mines Inspectorate should be prepared for any future mine explosion investigation. The role of mining companies and union representatives is of course already defined in practice but these parties must be made aware of liaison established by the Chief Inspector of Coal Mines.

8.7 Facilities for Forensic Pathology

This report would not be complete without mention of the need for adequate facilities to enable the proper conduct of forensic pathology procedures in the regional centres of Queensland. For accident investigation such as that required for the Moura disaster there is a need for professional and ancillary staff to be made available at short notice at such regional centres. This would enable the maximum amount of information to be available for investigation of the cause of an incident.

The alternative is to provide suitable means for the transportation of bodies to Brisbane where the necessary facilities exist.

8.8 Summary

One of the features of the Warden's Inquiry Report which received a good deal of attention during this project was the source of ignition. It will be seen in this document that there is opinion to the effect that the flame safety lamp was not the ignition source. It has recently been demonstrated that a properly assembled flame safety lamp is capable of providing an ignition source for a methane/coal dust explosion under air velocity and methane concentrations which might occur following a goaf fall. In the absence of any experimental or other evidence of frictional ignition as a source it could still be argued that the flame safety lamp was the most probable source of the ignition at Moura. No

The situation is that the use of a flame lamp is now prohibited in Queensland coal mines and its potential for causing ignition has been removed.

If the flame safety lamp were not the source of the ignition of the Moura No.4 Mine explosion, the heating of both gauzes to approximately 1000° C and the deposition of dust on the inner glass surface have to be accounted for by some other means. Testwork at SIMTARS and at Buxton to date has failed in every attempt to demonstrate such heating and deposition by any external source.

As to other sources of ignition it can be argued that there are many. The examinations at the Mine and in laboratories discount the entonox bottle, the mine rover and others with the exception of frictional impact by rock on rock or other material. Risk of ignition by rock impact can be dealt with by inertisation and means of achieving that are currently being considered.

Beyond that, no further research is recommended as a direct result of this project. That does not preclude work on other potential sources being considered for the future. That is being done by the SIMTARS Mines Safety Research Advisory Committee. It is stressed that it is well within the capacity of mine employees to maintain standards necessary to avoid ignition from items such as the entonox bottle, mine rover etc. which were considered as potential ignition sources at Moura. The underground coal mining industry is one of the most safety-conscious industries. No one works in an underground mine without concern for his own safety and that of others in the mine. There is in the industry a real commitment to avoid loss of life and injury.

It is a clear function of mine management to continuously audit safety procedures at underground coal mines. The accent should therefore be on prevention rather than how to deal with an emergency. Whilst the prime concern of management is the protection of life there is potential for serious economic loss including the closure of a mine and the sterilisation of huge reserves. The cost will vary in relation to the nature of the explosion and resultant damage. Since 1972 there have been five coal mine explosions in Australia. In all but one loss of life resulted. In two cases abandonment of the mine occurred as an immediate result of explosion.

The likely economic cost of an explosion in a new mine equipped with the technology currently available is likely to be in excess of $60 million where recovery is possible and mining operations resumed. Where a similar mine is abandoned the cost could exceed $250 million ignoring the possible loss of the remaining resource. Whilst such cost is not the prime concern it is in itself adequate reason for doing everything possible to prevent such an event.

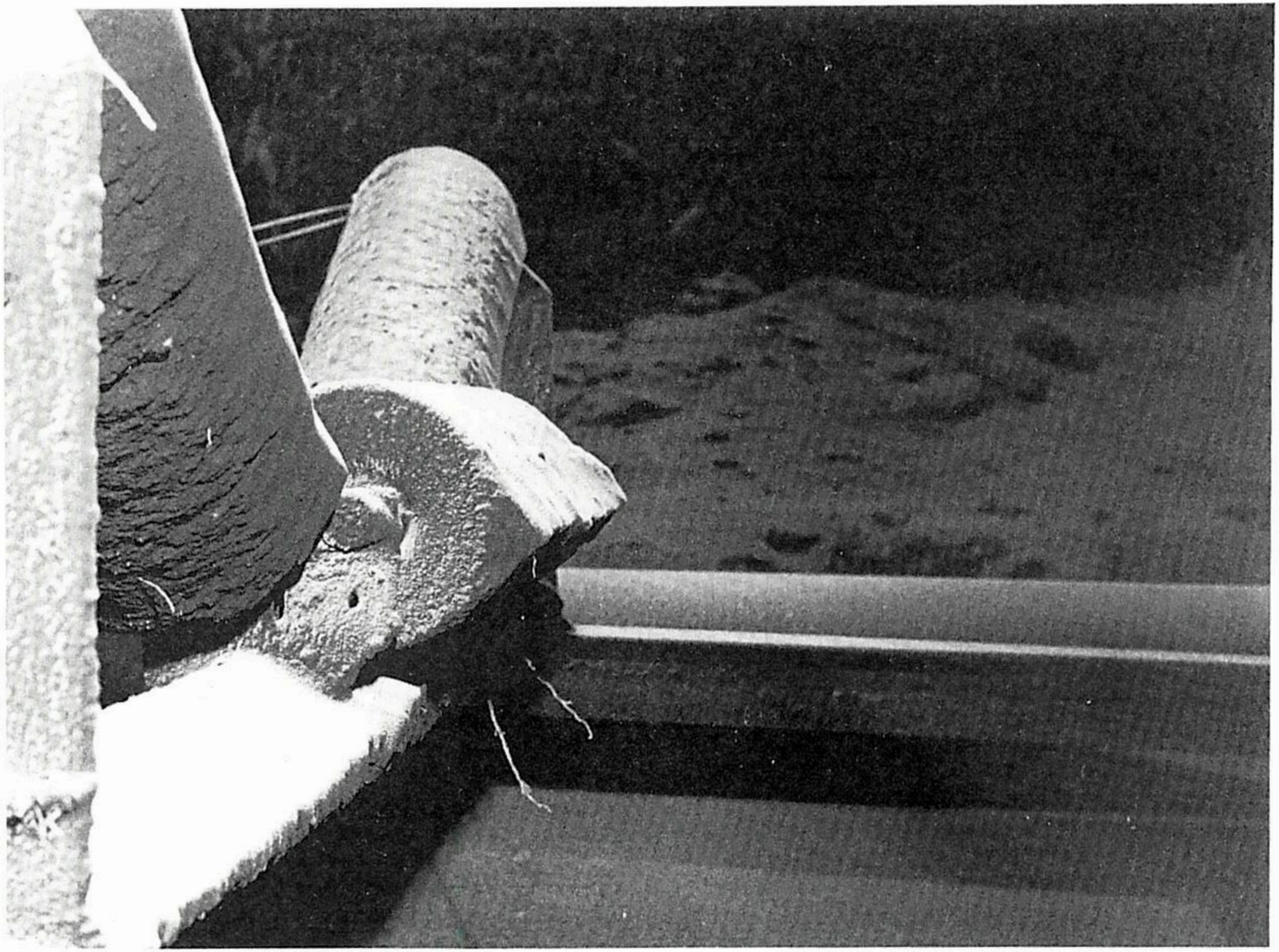


Plate 1
Deposition of dust on top conveyor rollers No. 3 Belt Road, looking outbye of 21 Cut-Through.

Plate 2

Blast damage to steel and timber from 'Taj Mahal' structure looking inbye in No. 4 Supply Road between 21 and 22 Cut-Through.

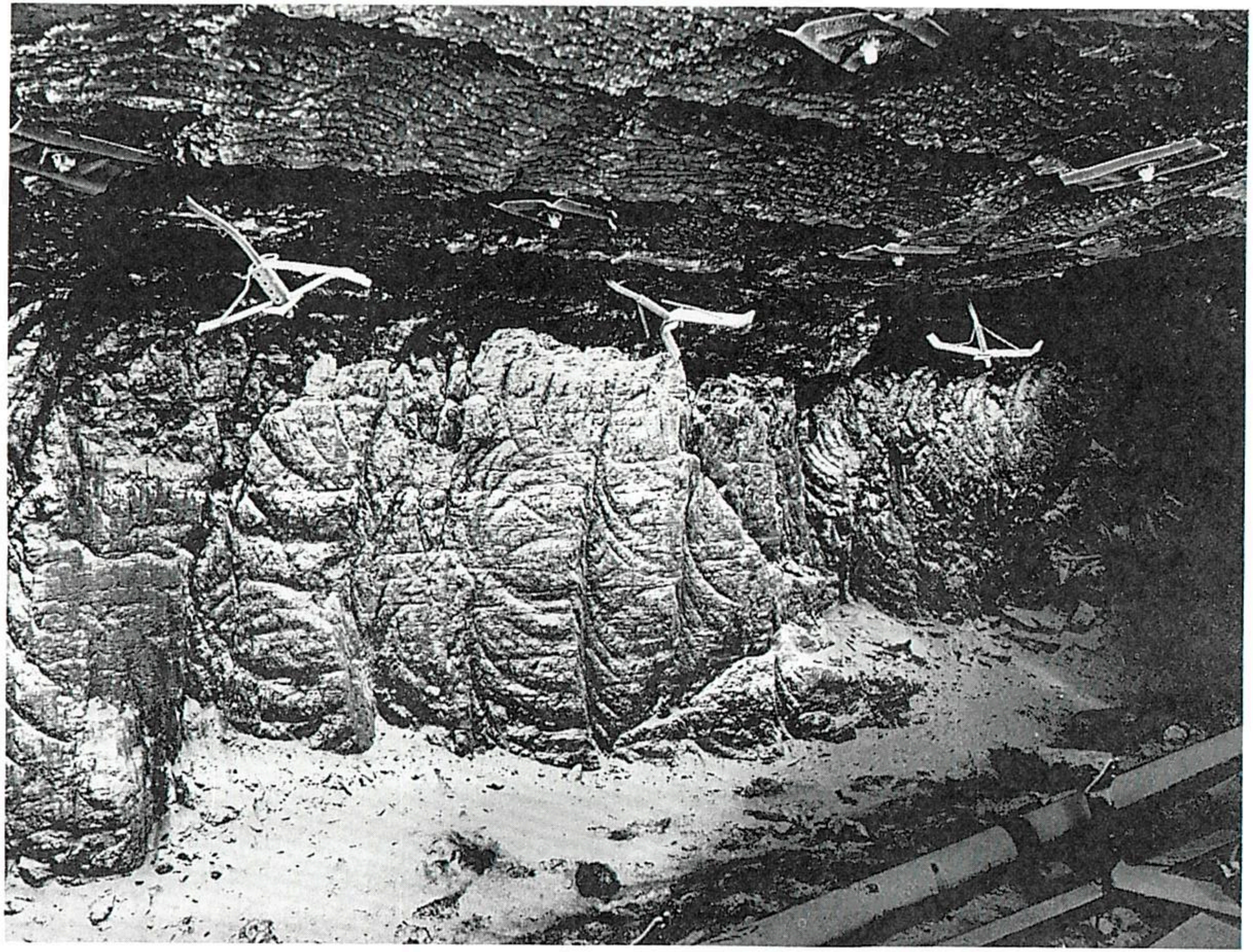


Plate 3

Water barrier hooks between 23 and 24 Cut-Through on No. 3 Belt Road bent in outbye direction by force of blast.

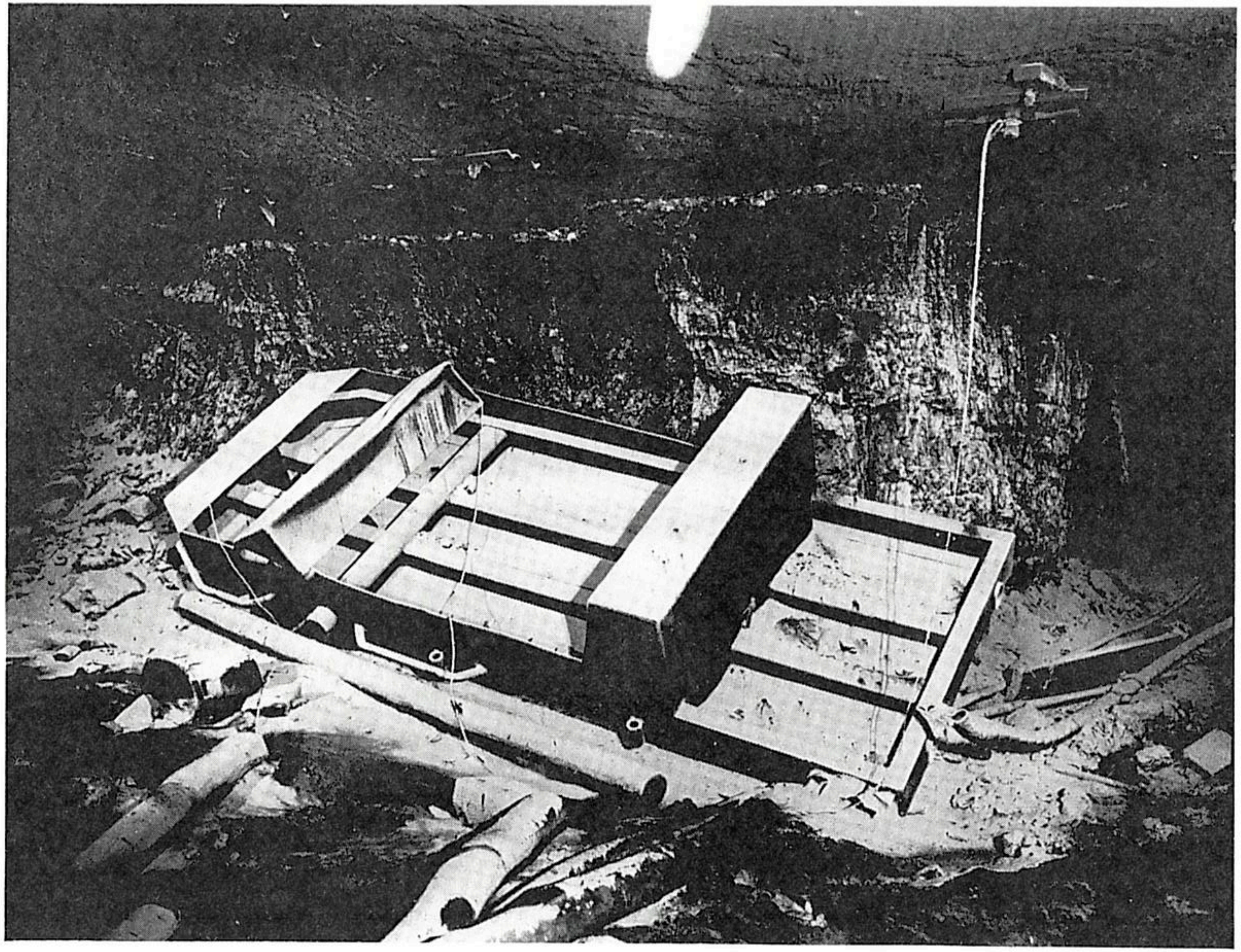


Plate 4

MPV Tray at junction of 25 Cut-Through and No. 4 Supply Road. Moved and overturned by force of blast.

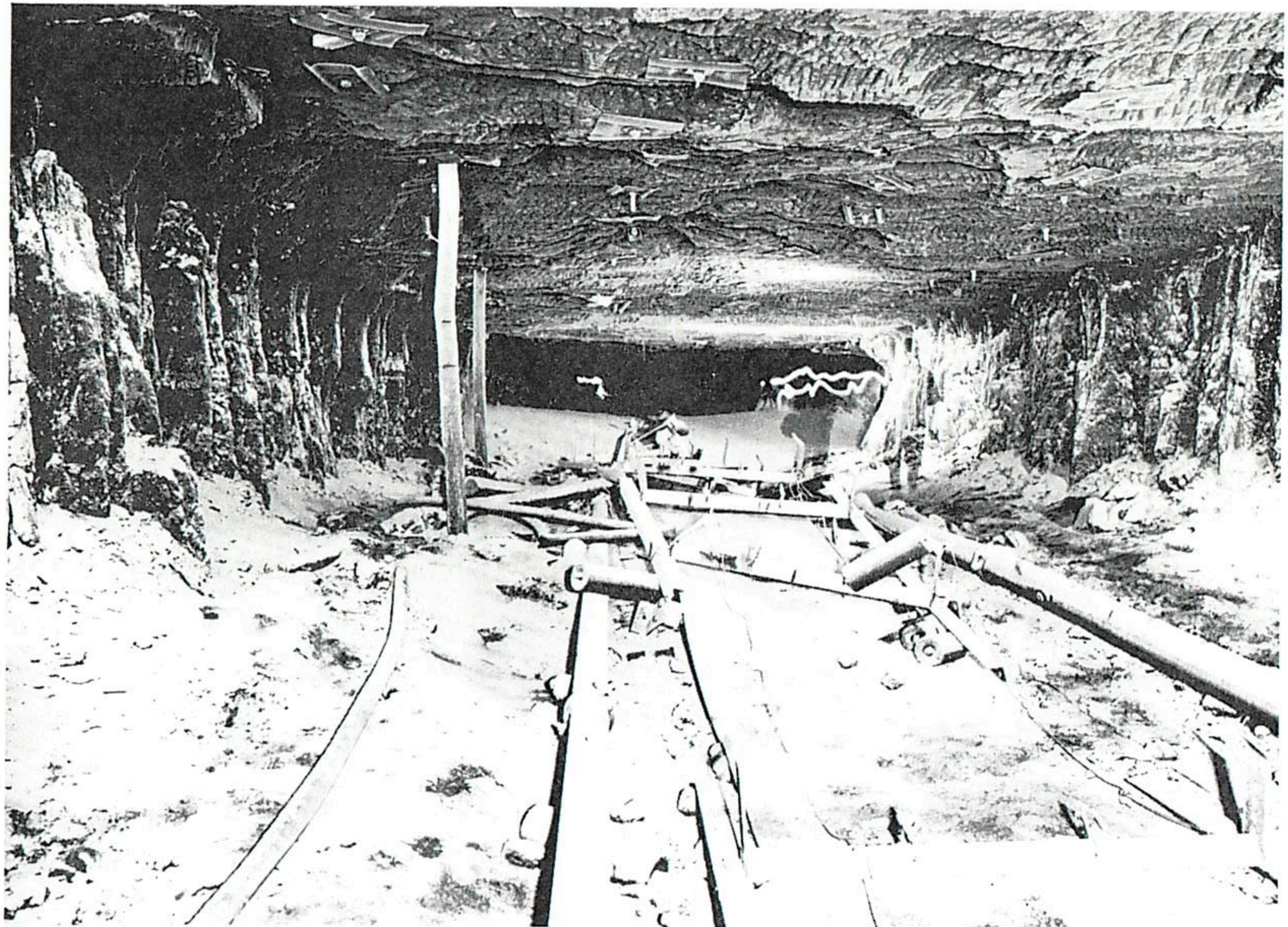


Plate 5

Belt conveyor in No. 3 Belt Roadway between 23 and 24 Cut-Throughs looking inbye. Top belt and rollers of conveyor removed by the force of the explosion. Light coloured deposit is fly ash used to suppress a fire.

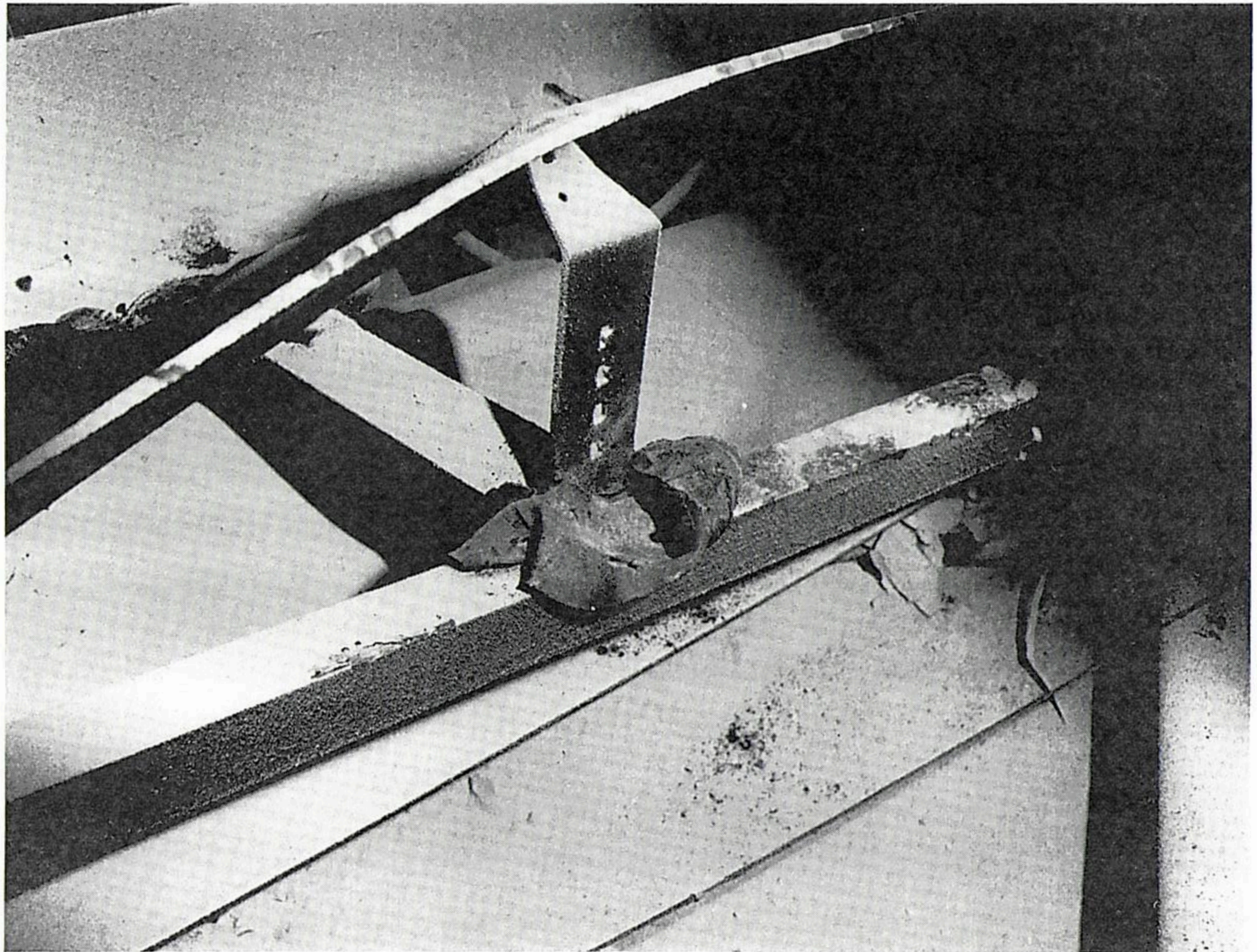


Plate 6

Safety Helmet softened by heat and projected by explosion to a position on the conveyor in No. 3 Belt Road 13m outbye of 25 Cut-Through.

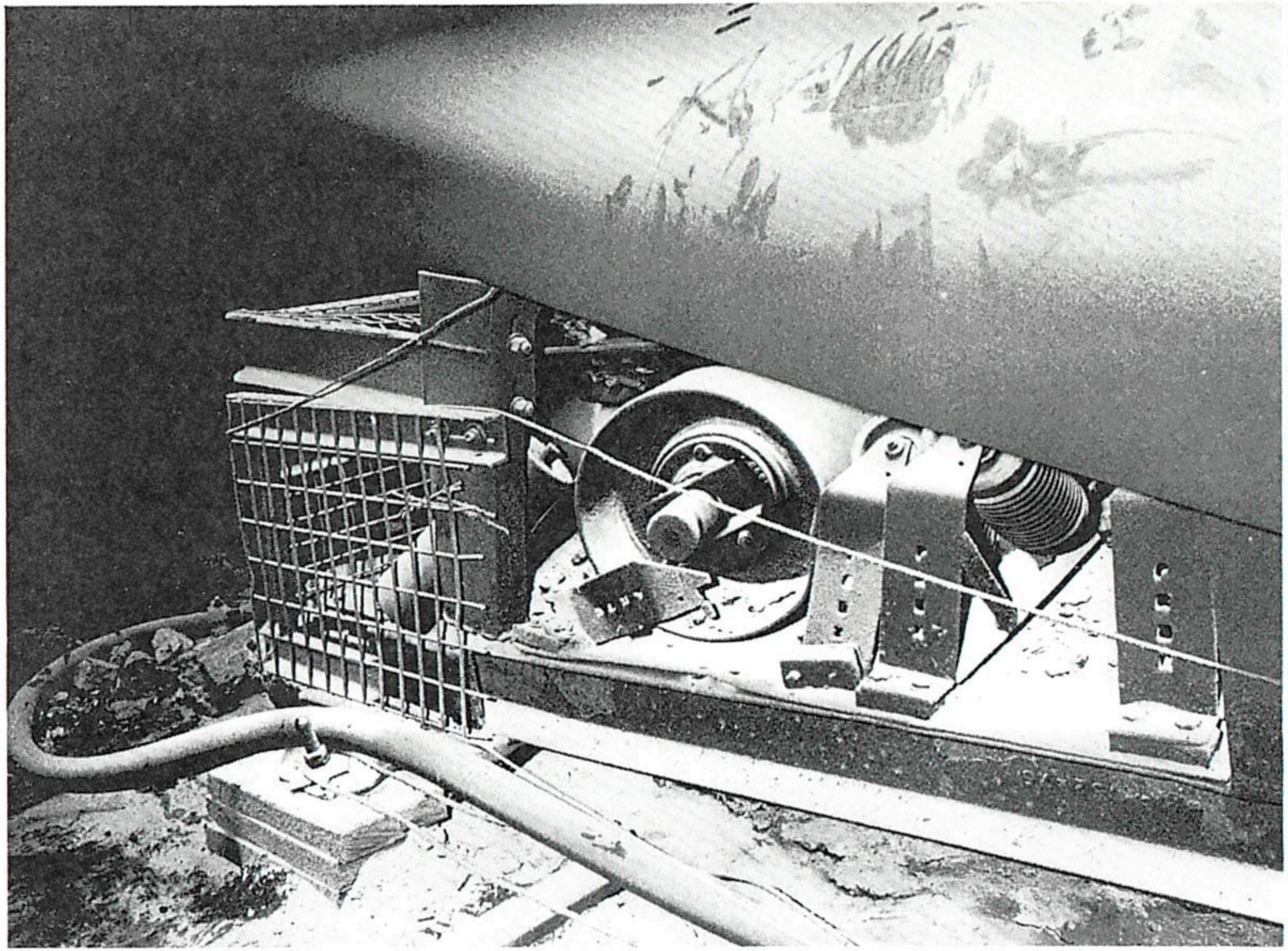


Plate 7

Tail end of belt conveyor and return drum moved outbye during the explosion.

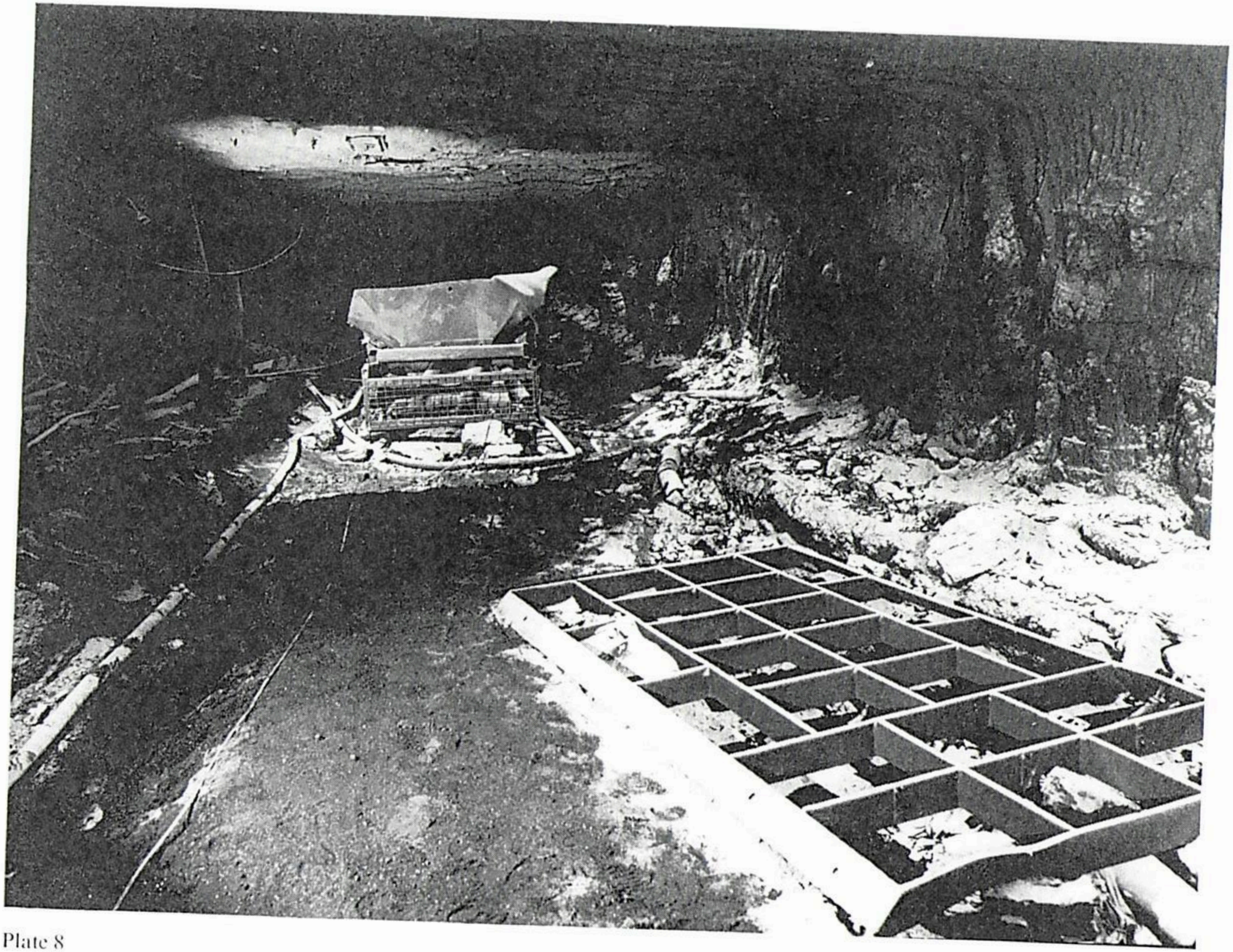


Plate 8

Grizzly (0.[illegible]t mass) moved inbye from normal position at return end of No. 3 belt conveyor during the explosion.

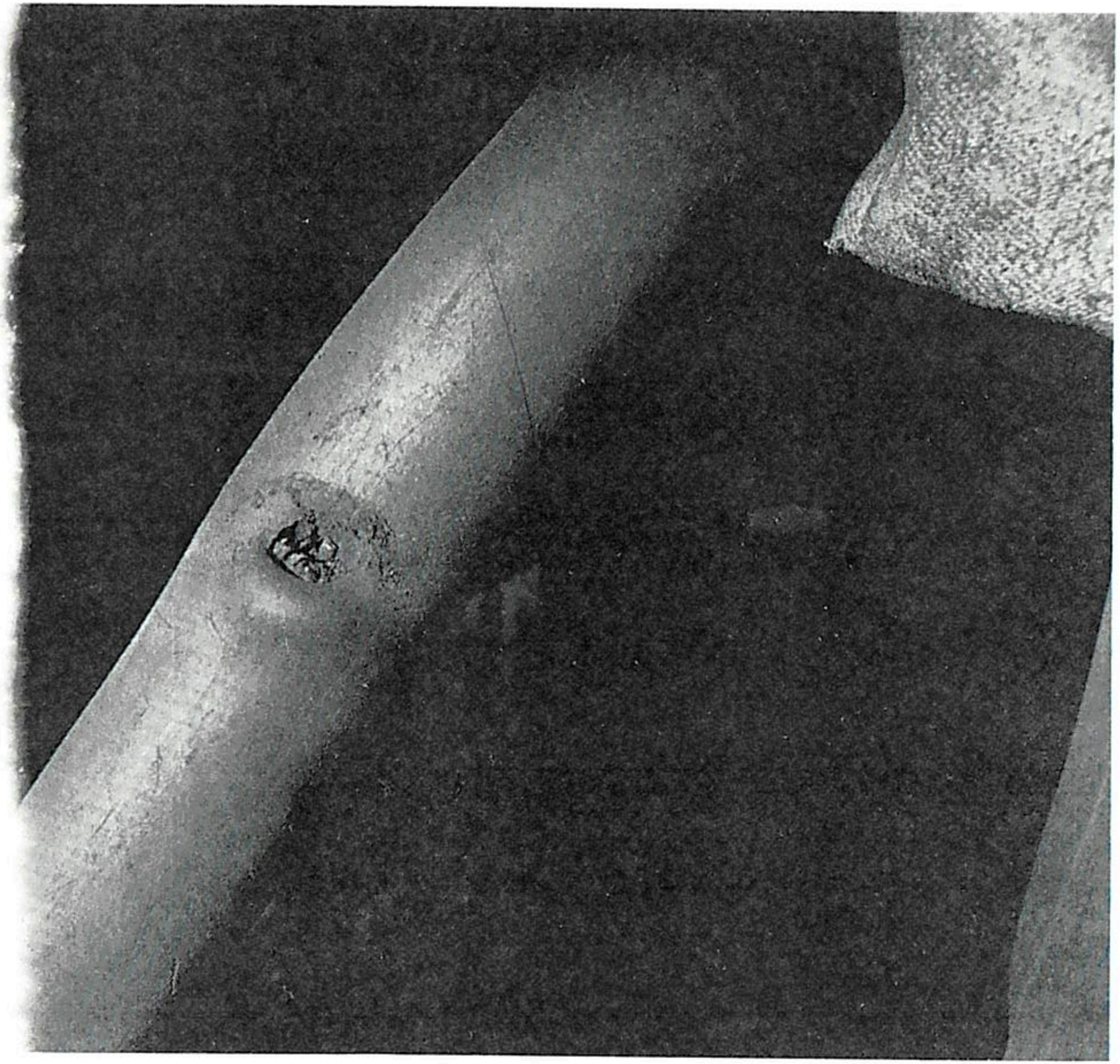


Plate 9

Damaged power cable in 26 Cut-Through showing penetration of cable by a piece of wood.

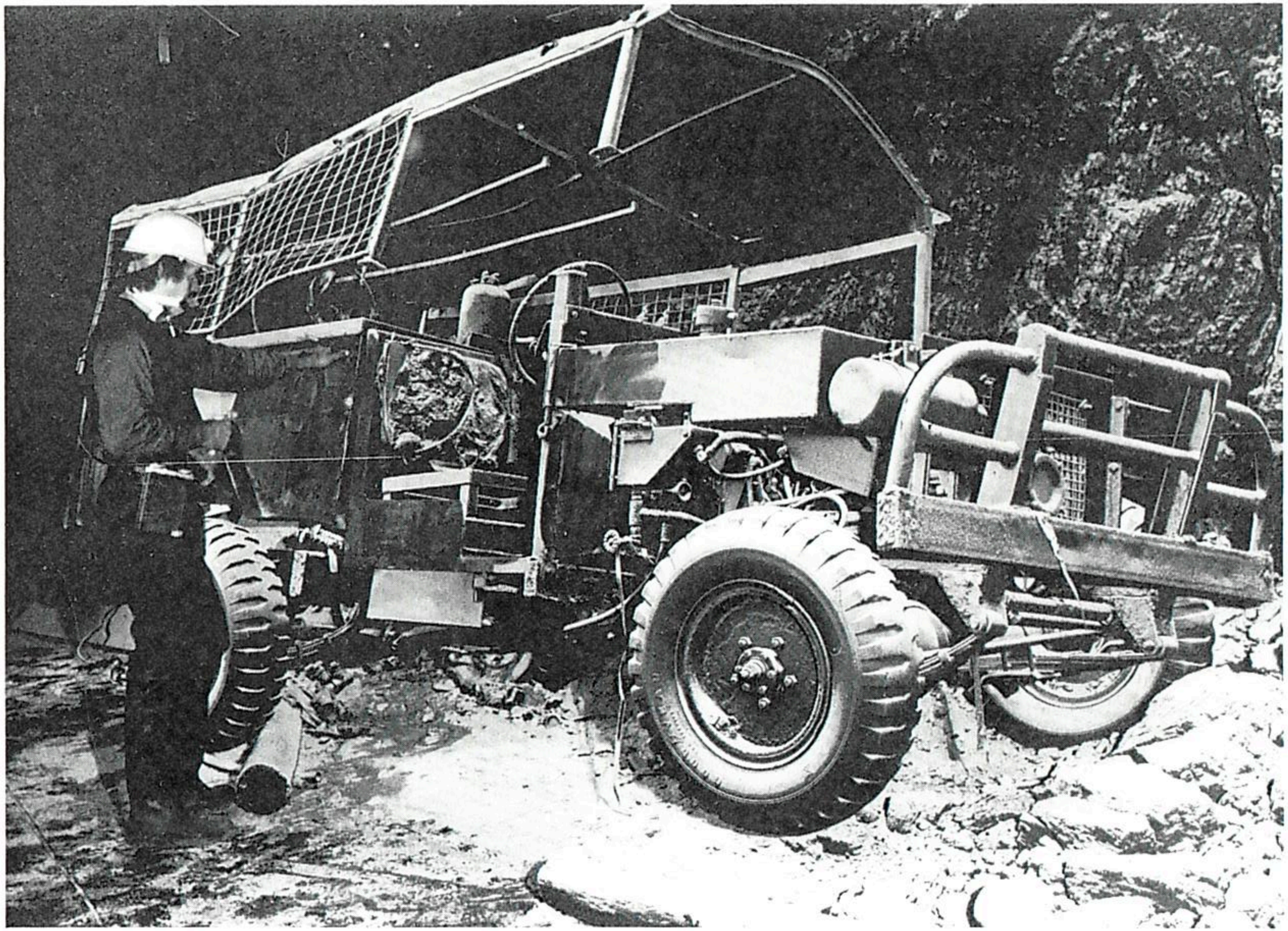


Plate 10
Mine Rover in No. 4 Supply Road inbye of 26 Cut-Through. Canopy of vehicle held by roof bolt plate and fabric on seat burnt.

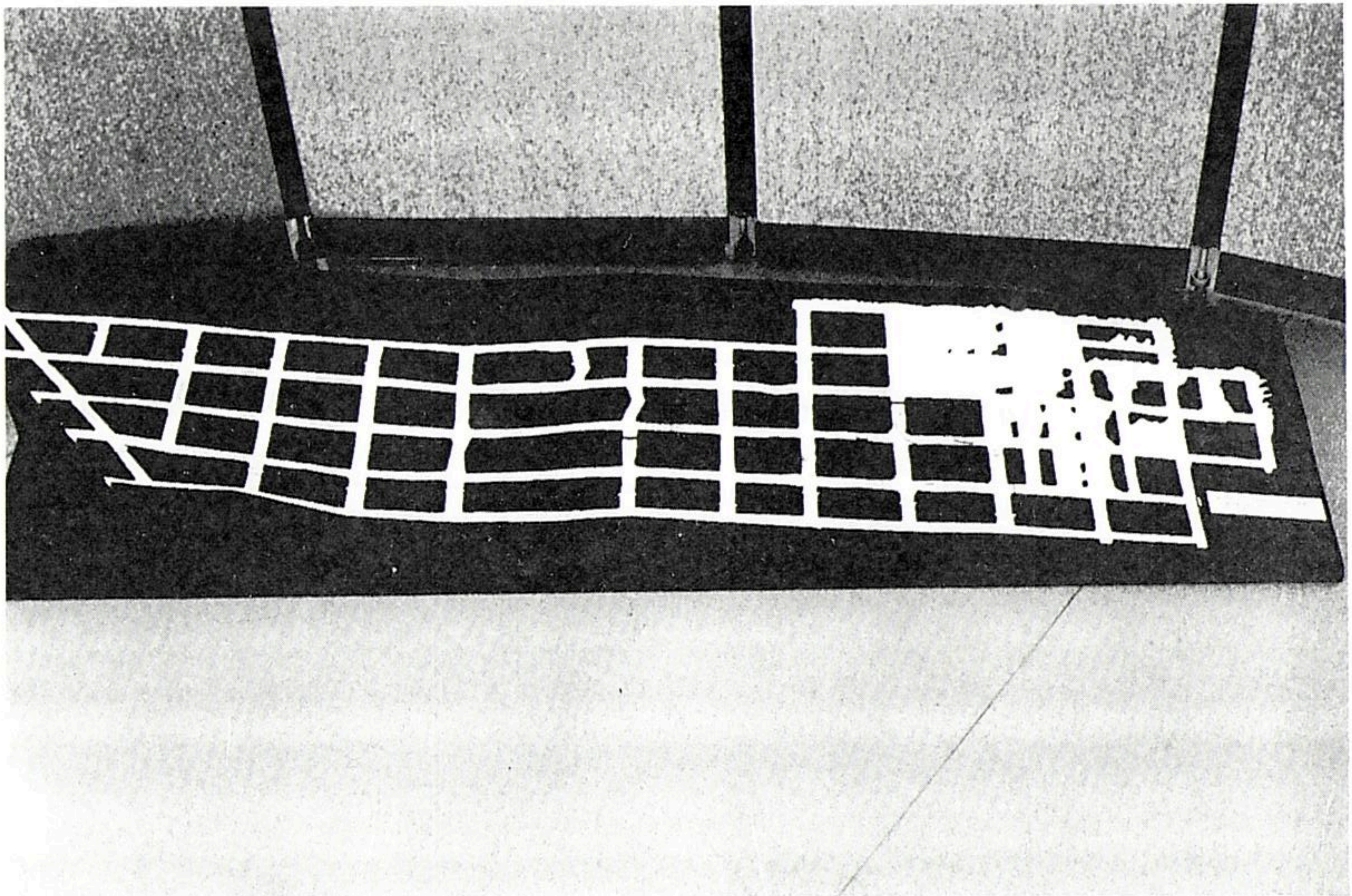


Plate 11

Model of Dip Workings of Moura No. 4 Underground Mine (Scale 1:300).

APPENDIX K

Consultants Who Gave Assistance to the Project

<u>In the United Kingdom</u>

Health and Safety Executive, Mines Inspectorate

Dr M. Jones	HM Chief Inspector of Mines
Mr P. Williams	HM Deputy Chief Inspectof of Mines

Health and Safety Executive, Research and Laboratory Division

Dr J. McQuaid	Director of the Division
Dr B. Thomson	Director RLSD, Buxton
Dr J. Barton	Deputy Director RLSD, Buxton
Dr G. Lunn	Fire and Explosion Research, Buxton
Dr D. Pritchard	Incident Investigation, Buxton
Mr F. Powell	Retired (Formerly Frictional Ignition Investigation, Buxton)
Mr R. Brookes	Retired (Formerly Incident and Investigations, Buxton)
Dr H. Phillips	Explosion Modelling, Buxton

Harwell Laboratories, Atomic Energy Research Establishment

Dr I.P. Jones	Computational Systems Group

Building Research Centre, Borchamwood

Dr G. Cox	Computational Fire Group

Transputer Technology Solutions

Mr C. Scott	Manager

Department of Health and Social Security

Dr R. Maynard

University of London

Dr B. Sims	Forensic Pathologist

Dr J.H. Bourgoyne & Partners, Consulting Scientists and Engineers

Dr J. Bourgoyne
Dr R. Watt

Scientific Research and Development Branch, Home Office, London

Dr J. Stealey
Dr G. Carr-Hill

Guy's Hospital Medical School, London

Dr I. West	Forensic Pathologist

Janus Consultancy

Emeritus Professor D.H. Desti

Research Consultants, Forensix Scientists and Explosion Experts

Mr L. Payne	Research Consultant
Dr T. Hayes	Consultant Forensic Scientist
Mr P. Gurney	Cannon Row Police Station

In the USA

US Bureau of Mines, Pittsburgh Research Centre and Lake Lynn Laboratory

Mr J. Murphy	Director
Dr N. Greninger	Chemical Engineer (Fires and Explosions)
Dr W. Courtney	Supervisory Research Chemist
Dr M. Hertzberg	Research Chemist
Dr J. Edwards	Research Physicist
Dr Cohen	Research Physicist
Mr K. Cashdollar	Research Physicist
Mr A. Furno	Supervisory Physical Scientist (Retired)
Mrs L. Snyder	Physicist

Mine Safety and Health Administration, Bruceton Safety Technology Centre

C.R. Stephan	Senior Mining Engineer

University of California, Los Angeles

esident Pathologists

In the Federal Republic of Germany

Experimental Mine Tremonia, Dortmund

Dr Ing. J. Michelis	Head of Department of Explosion and Shotfiring
Mr G. Muller	Physicist
Mr B. Margenburg	Physicist

University of Munster, Department of Medical Physics

Dr Erdmann

Bochum Hospital, Bochum

Prof Dr Machtens	Superintendent
Dr Hartung	Pathologist

In New Zealand

Auckland Medical School

)r T. Koelmeyer	Forensic Pathologist
Dr I. Smeaten	Forensic Pathologist

In Norway

Telemark Institute of Technology, Porsgrunn

Dr B.H. Hjertager

APPENDIX L

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APPENDIX M

CURRICULUM VITAE

DR ANTHONY GREEN

QUALIFICATIONS:

- BSc. with Honours in Chemistry - Edinburgh University 1972 Ph.D Edinburgh University, 1976

PROFESSIONAL AFFILIATIONS:

- Chartered Chemist
- Member - Combustion Institute
- Member - Combustion Panel, Institution of Engineers, Australia

EXPERIENCE:

- Health & Safety Executive, UK - Scientific Officer
- Health & Safety Executive, UK - Higher Scientific Officer
- Londonderry Occupational Safety Centre, NSW - Senior Projects Officer, Combustion
- Londonderry Occupational Safety Centre, NSW - Manager Research

DR PETER GOLLEDGE

QUALIFICATIONS:

- B.Sc. (Hons) Mining Engineering, Dip.Met.Min., Wales 1959
- M.Sc. , Wales 1960
- Ph.D, Wales 1963

PROFESSIONAL AFFILIATIONS:

- Fellow Australasian Institue Mining and Metallurgy
- Fellow Australian Institute of Energy
- Member Canadian Institute Mining and Metallurgy

:XPERIENCE:

- 1st Class Mine Managers Certificate
- National Coal Board, UK - 4 years as a coal miner Rhondda Area, South Wales
- Canada and West Africa - 10 years experience as a Mining Engineer
- Australia - 18 years experience as:
  - Queensland Department of Resource Industries-Inspector of Mines
  - Queensland Department of Resource Industries-Chief Engineer
  - Queensland Department of Resource Industries (SIMTARS) - Manager, Research and Technical Services

MR IEUAN ROBERTS

QUALIFICATIONS:

- Chartered Engineer

PROFESSIONAL AFFILIATIONS:

- Fellow Australian Institute of Mining and Metallurgy
- Member Institution of Mining Engineers

EXPERIENCE:

- British 1st Class Coal Mine Managers Certificate of Competency, endorsed for Queensland
- Britain, India, Australia - 11 years as manager of underground coal mines -
- 2 years deep mine planning
- 5 years Chief Inspector of Coal Mines, Department of Resource Industries, Queensland
- Past President of Coal Mine Managers' Association, NSW
- Previously Vice President and Managing Director of Curragh Queensland Mining Limited; Director and Vice President Anaconda Australia Inc.
- Served on a number of committees dealing with mine safety, mine rescue, education and research
- Author of papers on mine safety, industrial relations and technology presented to various international conferences
- Currently,

  - Consultant in Coal Mining
  - Chairman, Mines Safety Research Advisory Committee
  - Director, South Blackwater Mines Ltd

DR KORNEL ROMANIUK

QUALIFICATIONS:

- B.D.S., University of New Zealand, December, 1961
- M.D.S., University of Otago, New Zealand, December, 1963
- Fellow Royal Australian College of Dental Surgeons, Australia, 1967
- Dr.med.dent., University of Munster, Germany, August 1972
- Ph.D., University of Queensland, Brisbane, August 1977

PROFESSIONAL AFFILIATIONS:

- Member of International Association for Dental Research

EXPERIENCE:

- University of Otago Dental School and Dunedin Public Hospital, 1962-1963 - Resident Dental Surgeon
- Medical Research Council of New Zealand, University of Otago Dental School, 1964-1965 - Research Officer
- Department of Dentistry, University of Queensland, 1965-1972 - Lecturer in Oral Biology
- Department of Health, 1969-current - Consultant in Forensic Odontology
- Department of Civil Aviation, Melbourne - Consultant in Forensic Odontology
- University of Queensland, 1973-current - Senior Lecturer in Oral Biology

DR ROBERT BARNES

NOT AVAILABLE FOR REPORT

DR SALLY LEIVESLEY

QUALIFICATIONS: BSocWk, BA (Hons), MSPD Qld, PhD Lond., MACE

PROFESSIONAL AFFILIATIONS: NOT AVAILABLE FOR REPORT

EXPERIENCE:

APPENDIX N

CURRICULUM VITAE

PROFESSOR DAVID ROWLANDS

QUALIFICATIONS:

- B.Sc.(Hons.) Mining Engineering, Dip.Met.Min., Wales, 1953
- M.E., New South Wales, 1969
- Ph.D., Queensland 1974

PROFESSIONAL AFFILIATIONS:

- Chartered Engineer (U.K.)
- First Class Mine Managers Certificate 1956 (UK)
- Fellow Institute of Mining Engineers (London)
- Fellow Institute of Engineers (Australia)
- Fellow Australasian Institute of Mining and Metallurgy
- Member of Board of Professional Engineers, Queensland
- Member of International Bureau of Strata Mechanics

EXPERIENCE:

- Nine years experience in underground coal mining with the National Coal Board, Rhondda Area, South Wales
- Twenty seven years of university teaching and research in New South Wales and Queensland
- Member of the Boards of Inquiry into Box Flat and Kianga Disasters
- Member of Technical Standing Committee No. 2 of NERDDC

APPENDIX O

Listing of Review Committee Members

NAME	ORGANISATION	PHONE NO/FAX	ADDRESS	REPRESENTING/ ROLE
PJ Dent	Director SIMTARS	07 288 2788 07 288 2874 FAX 818 1402	2 Smith Street REDBANK Q 4301	SIMTARS
Dr P Golledge	SIMTARS	07 288 2788 07 288 2874 FAX 818 1402	2 Smith Street REDBANK Q 4301	SIMTARS Project Manager
I Roberts	Chairman Mine Safety Research Advisory Committee	374 1082	499 Brookfield Road BROOKFIELD Q 4069	Independent Member - Industry
G Duncan	Occupational Health & Safety Officer QCA	07 221 8366 FAX 07 229 7730	GPO Box 908 BRISBANE Q 4001	Queensland Coal Association
J Sleeman	QCA/Utah-Bth	07 226 0600 FAX 07 229 2575	BHP-Utah Coal Ltd GPO Box 1389 BRISBANE Q 4001	Queensland Coal Association
B Allison & M Best	District Union Inspectorate	07 202 3099 FAX 07 281 9483 A/H 818 1932	16 East Street Ipswich Q 4305	Queensland Colliery Employees' Union
J Torlach	Program Manager Department of Resource Industries	07 224 2954 FAX 07 229 7770	Queensland Minerals Energy Centre 61 Mary Street BRISBANE Q 4000	Department of Resource Industries
B Lyne	Chief Inspector of Coal Mines	07 237 1585 FAX 07 229 7770	Qld Minerals Energy Centre 61 Mary Street BRISBANE Q 4000	Department of Resource Industries
R Bancroft	Snr Inspector of Mines	07 282 1077	Inspectors Office PO Box 15 BOOVAL Q 4304	

SUPPORT CONSULTANTS

NAME	ORGANISATION	PHONE NO/FAX	ADDRESS	REPRESENTING/ ROLE
Dr S Leivesley & Associates		07 221 2625 FAX 07 221 5780 A/H 878 1001	11th Floor T&G Bld 141 Queen Street BRISBANE Q 4000	Consultant
Dr K Romaniuk		07 377 3699 A/H 378 2529	Dental Faculty University of Qld ST. LUCIA Q 4069	Consultant

Dr A Green		047 774 261	Londonderry Occupational Safety Centre 132 Londonderry Rd LONDONDERRY NSW 2753	Consultant
Dr R Barnes	Assistant Director	03 450 3444 FAX 03 450 3590	State Forensic Lab Forensic Drive MACLEAD VIC 3085	State Forensic Science Lab
Insp N Sprenger	Qld Police	07 364 6464	Police Headquarters Roma Street BRISBANE Q 4000	Police Liaison

APPENDIX P

Distribution of Report

1. Review Committee Members

	P.J. Dent Dr P. Golledge	SIMTARS
*	I. Roberts	Independent Member - Industry
*	G. Duncan	Queensland Coal Association
*	J. Sleeman	Queensland Coal Association
*	B. Allison M. Best	Queensland Colliery Employees' Union
	J. Torlach B. Lyne R. Bancroft	Department of Resource Industries

2. Support Consultants

*	Dr S. Leivesley	Consultant
*	Dr K. Romaniuk	Consultant
*	Dr A. Green	Consultant
*	Dr R. Barnes	State Forensic Science Laboratory
*	Insp N. Sprenger	Police Liaison

3. Distribution Elsewhere

Mining Industry - interstate

* . Hon. N. Pickard MLA
Minister for Minerals & Energy
4th Floor Minerals & Energy House
P.O. Box 536
ST. LEONARDS N.S.W. 2065

* . Hon. G. Carr MLA
Minister for Mines Fuel & Energy
10th Floor
London House
214 St George Tce
PERTH W.A. 6000

* . Hon. M. Weldon MLA
Minister for Resource & Energy
10 Murray Street
HOBART TAS 7000

4. **Overseas Consultants**

* Dr B. Thomson
Health & Safety Executive
Explosion and Flame Laboratory
Harpur Hill
Buxton
Derbyshire SK179JN
ENGLAND

* Mr J. Murphy
Director
Pittsburgh Research Centre
PO Box 18070
Pittsburgh
Pennseylvania 15236-0070
USA

* Dr Ing. J. Michelis
Head of Department of
Explosions and Shotfiring
Versiichsgrubengesellschaft MBH
Tremoniastrasse 13
4600 Dortmund 1
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5. **Other**

* Professor D. Rowlands — Reviewer

* Department of Resource Industries Library

Note: * Abridged Versions

For other addresses not given here, please see Appendix O.