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School of Chemical, Environmental and Mining Engineering

THE APPLICATION OF VIRTUAL REALITY TO THE SIMULATION OF MINE FIRES AND EXPLOSIONS

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Abstract

Despite significant improvements in mine safety, underground mine fires and explosions are responsible for a significant number of deaths world-wide each year. The training of personnel in safety procedures has had a significant impact on reducing the frequency of injuries and fatalities. This thesis presents an innovative virtual reality simulation, 'Fire-VR', designed to enhance the visualisation of a mine ventilation system. Fire-VR incorporates existing ventilation network analysis procedures with a graphical front-end and offers considerable potential for user interactivity in training scenarios.

The system, Fire-VR incorporates a suite of programs, created to model the mine infra-structure, ventilation system and environment of a typical mine. The key components include the ventilation modelling system (VentSim-VR) to simulate the flow of air through the mine network and an environment modelling system (EnvSim-VR) to simulate the effects of various external and internal influences on the quality of the ventilated air within the mine. The environmental system is able to model both pre-defined events (such as the liberation of firedamp from the strata) which can occur at certain times and also spontaneous events which occur when pre-determined criteria have been met.

The system has been created with two main interfaces for the user to interact with. Firstly, the 2D interface shows a plan view of the mine network with the primary function of displaying environmental and ventilation information. Secondly, the 3D interface, used as the main virtual reality graphical front-end to the simulation provides the user with a rich semi-immersive virtual environment. It is suggested that Fire-VR can potentially be applied in the training of personnel at a significantly reduced cost and in a safe environment. To demonstrate this a number of possible training examples have been presented to showcase the potential of the Fire-VR software.

Chapter One

Introduction

1.1 Introduction

Over recent years, the implementation of stricter legislation and developments in new technologies have helped to make the mining and minerals sector a safer place to work. However, work in this area is still amongst the most hazardous of all occupations. In many parts of the world, fires and explosions, roof collapses and general accidents still take an unacceptable human toll. Injuries and occupational diseases are not only costly to the industry, most especially in terms of human suffering, but also in their contribution to the rapid escalation of health care and compensation costs.

The Mining Community is committed to ensuring the opportunity for all workers to earn a living without unnecessary health and safety risks. The health and safety aspect in the minerals sector has improved, in part, as a result of health and safety legislation and subsequent enforcement of the regulations. In the UK the function of the Safety in Mines Research Advisory Board (SMRAB 1996) is to examine the current and future needs for non-medical health and safety research work in coal mines and in South Africa the Mine Ventilation Society has played a significant role in safety and health management (Wrigley 1995).

More rapid mineral extraction and the mining of a greater number of marginal mineral deposits are increasing the risk of geologically related incidents. Many issues remain unresolved and newly emerging health and safety concerns require additional work. However, the development of new technology, such as virtual reality (VR), is providing innovative opportunities for staff training and safety awareness.

Implementation of new safety procedures and low cost training systems coupled with the development of ways to better understand the environmental conditions in the modern coal mine can only improve the safety of the mining operations. For example, Wala (1997) describes a computer aided instruction system, developed for mining engineers and safety personnel, in order to convey the complex interrelationships between the mine ventilation system and a mine fire.

The overall aim of this project was to conduct objective scientific research related to the mining and minerals sector in the areas of explosion / fire prevention and management. By investigating the suitability of VR in the mining environment, this thesis aims to describe a unique prototype system created using existing tried and tested mining models combined with cutting edge three-dimensional computer graphics.

Justification for the research presented in this thesis can be demonstrated with examples of recent incidents that have occurred in coal mines. In an accident in China in 1998, 77 miners were killed in a large explosion at a coal mine in the Liaoning province (see Appendix 1a). A number of serious accidents have occurred in Chinese coal mines resulting in over 2000 fatalities in the year 1997 alone. The number of deaths was almost 30 percent greater than the previous year. Furthermore, the frequency of accidents claiming 10 or more lives, rose by more than 20 percent in 1997 to 102 (see Appendix 1a). Following the rise in the number of mining fatalities, the Chinese Ministry of Labour were prompted into action and called upon the coal mining industry to urgently review and improve their safety measures

In another recent incident in 1997, 25 coal miners were trapped 3000 ft below ground in a Russian coal mine following an explosion in which two of the workers were killed (Appendix 1b). The Itar-Tass news agency reported that the lack of strict safety standards and funding were to blame for many of the mining accidents in Russia.

Similar problems have occurred in the Ukraine where 63 miners were killed following a methane explosion in 1998. The accident at Donetsk was one of the Ukraine's worst mining disasters. Unfortunately, the original death toll was drastically increased due to the suffocation of a number of miners while they were awaiting rescue. According to a newspaper report, the *"high temperatures underground and the constant threat of a new collapse or explosion were hampering recovery efforts..."* (see Appendix 1c).

1.2 Research aims and methodology

The primary research aims of this thesis were to: -

1. Conduct objective research related to the mining and minerals sector in the areas of explosion / fire prevention and management.
2. Investigate extending traditional methods of analysis of mine networks using innovative VR technology.
3. Explore ways of representing mine environmental data using novel 3D graphics.
4. Create a prototype system on a standard desktop PC which could be applied to real world situations in the mining sector and used to produce example scenarios for training purposes / demonstrations.

A variety of literature was studied in order to obtain a better understanding of the subject matter. This included a general consideration of the current problems and issues with regard to mine disasters (such as fires and explosions) and a review of the suitability of using VR. The different available technologies currently used in accident prevention were then reviewed and considered for their appropriateness. Analysis and system design considerations were then investigated and a prototype system was created. This prototype system was used to examine certain case study situations including real world examples. Provision has also been made to examine potential future improvements to the system.

1.3 Structure of thesis

Chapter 1 Introduction.

This chapter presents the research aims, the research methodology and the structure of this thesis. Also included are a list of definitions and abbreviations.

Chapter 2 Mining engineering - The cause and prevention of underground fires and explosions.

This chapter covers a literature review of the causes of mine fires and explosions, the detection and prevention methods used in accident management and also a section on the techniques employed by the mining community during an accident. A detailed outline of the general nature of fires and explosions within the mining environment is also provided. Additionally, current research methods using computer based models for the analysis of ventilation systems are discussed.

Chapter 3 Computer graphics and virtual reality.

This chapter explores the various computer graphic and data visualisation methods that are currently available and also describes the application of virtual reality to the mining field.

Chapter 4 Design considerations and prototype research work.

This chapter discusses the exploration into CFD techniques visualised in VR using a spray paint workshop as an example application. Design flow diagrams are presented for VentSim-VR (see section 1.4.3 definitions). Data visualisation techniques used to describe ventilation flow and air status are also included.

Chapter 5 **Development of the VentSim-VR and EnvSim-VR Sub-Systems.**

This chapter describes the sub-systems produced which contribute to the Fire-VR research software. VentSim-VR is the ventilation network simulator and EnvSim-VR is the environmental modelling system. Both these are combined with either a 2D or 3D display system to provide the complete Fire-VR prototype system used in this research.

Chapter 6 **2D Interface and the mine description file editor software.**

This chapter explores the software created to support Fire-VR. A system has been created which displays the mine infrastructure in a familiar format similar to alternative ventilation programs. The 2D system is used primarily for testing purposes. Editing software and world building software was also designed and an account of this software is also included in this chapter.

Chapter 7 **3D VR based FIRE-VR simulator.**

The main interface design for Fire-VR is described in this chapter. 3D models are used to construct the mining environment based around the data created or edited within VentSim-VR. The environmental effects of fires and explosions are also modelled in 3D and these are also described.

Chapter 8 **Evaluation of the Fire-VR simulator**

In this chapter evaluation networks have been examined against data produced by the VnetPC™ for Windows™ package. Example scenarios have been selected to explore the possibility of using Fire-VR in mining situations such as ventilation control, the monitoring of fires and explosions and the control of the environment using an inert gas such as nitrogen.

Chapter 9	**Conclusions and recommendations for future work.** Conclusions arising from this research are presented in this chapter along with suggested improvements to Fire-VR. Recommendations for future work in the area of VR based mining simulations are also included.

1.4 Definitions and abbreviations for the thesis

In this thesis, many technical terms are used to describe features of the software system developed. Additionally, there are many mining terms that are also used. The following sub-sections list general mining and computing related definitions followed by general abbreviations used in this thesis. In section 1.4.3 the specific definitions adopted for the applications and processes developed for this research are listed: -

1.4.1 General Definitions

Collision Detection	The process of mimicking the real-world physics associated with objects interacting or colliding with each other in a virtual, computer generated world.
DirectX	DirectX provides strategies, technologies and tools to help programmers build multimedia applications. DirectX encompasses many sub-components. Direct Sound and Direct 3D are used in this application. The software written for this project uses DirectX version 5 SDK.
Direct3D	This is the component of the Direct X™ API which is used to program 3D graphics functionality into Fire-VR.

Direct Sound Direct sound is used to provide sound support within Fire-VR. Sound is used to provide aural cues such as explosions.

Flashpoint The flashpoint of a material is the lowest temperature at which there is sufficient vaporisation of the substance to produce a vapour which will flash momentarily when an ignition source is applied to it.

Ignition Temperature This is the lowest temperature at which heat from the combustion of the burning vapour is capable of producing sufficient vapour to enable combustion to continue. At this point, if the ignition source was removed then the material would continue to burn on its own.

Real-time No perceivable delay in the time taken to process signals or to update a simulation.

Roll-back The formation of a layer of hot gases, the product of a mine fire, which occur on the roof of the mine and which can spread in the opposing direction of the ventilating airflow.

Simulation In this thesis, simulation is a generic term used when referring to VentSim-VR and EnvSim-VR together (See section 1.4.3). Both are key parts to the modelling system in itself and for the sake of clarity it is often easier to refer to them as the simulation.

Texture Mapping The process of simulating detail by applying a texture or picture based graphic onto a face or the faces of an object.

Throttling The tendency for hot gases to expand against the prevailing ventilating airflow which causes a reduction in this airflow.

Ventilation System This refers to the typical methods that are employed by mining companies to pass fresh air through the mine to maintain working conditions suitable for humans. It is the real world equivalent of VentSim-VR. (See section 1.4.3)

1.4.2 Abbreviations

API Application Programming Interface. This is the library of computer functions and procedures that are used to allow the programmer to quickly program functionality into a software package. An API can be thought of as a set of standard tools and building blocks to help the programmer. In terms of this project, the API used was Microsoft® DirectX. DirectX is explained more thoroughly in section 5.2.

HMD Head Mounted Display. This is an electronic device capable of displaying independent left and right computer generated images to each eye in order to fool the brain into thinking it is in an alternative reality. It is currently one of the only ways of creating an immersive experience, primarily because the visual sensory information is so important in the way we construct information about our surroundings.

LEL The Lower Explosive Limit. This term is describes the lowest quantity of a gas or particulate such as coal dust by weight needed for an explosion to occur in the presence of an ignition source. For coal dust this limit is 60 g/m^3. The LEL of methane in air has been determined experimentally at 5 % methane and 95 % air (percentage volume). For gases it is common to consult an explosive diagram such as the Cowards diagram which represents the explosive limits for methane (see **Figure 2. 3**).

SDK Software Developers Kit. These are the core programming tools used by the programmer to construct applications in software. It includes the API, debugging facilities, help files and many other tools to help the programmer create software.

SHT Self-heating temperature is the lowest temperature that will produce a sustained exothermic reaction or thermal runaway.

VR The term Virtual Reality (VR) has been defined by a number of different people and hence, a plethora of possible definitions could be given. For example, in Isdale's paper (1993) "What is Virtual Reality?" the author discusses some of the different ideas people have about VR. This seems to be a 'reasonably' well accepted paper that considers many of the alternatives. In it the author states that :

"There are some people to whom VR is a specific collection of technologies, that is a head mounted display, glove input device and audio. Some other people stretch the term to include conventional books, movies or pure fantasy and imagination."

Most people, however, tend to think that VR relates to computer mediated systems. Hence the definition by Aukstakalnis (1992) is also appropriate; "Virtual Reality is a way for humans to visualise, manipulate and interact with computers and extremely complex data".

VE Virtual environment. A 3D data set describing an environment based upon real-world or abstract objects and data (Vince 1998)

VST Virgin Strata Temperature. VST is dependent upon the geothermal gradient prevalent in the area. If the VST is greater than that of the temperature of the mine air, heat is transferred from the rock strata to the ventilating air.

1.4.3 Application and thesis specific abbreviations and definitions

Cell A cell is a length of roadway or drivage within the mine when modelled by VentSim-VR. It is the smallest unit capable of holding environment information and is the fundamental unit used by VentSim-VR to model gas and environment changes. Each cell has two nodes associated with it and these are situated on each end of the cell.

EnvSim-VR The mine environment modelling system. This sub-system combines VentSim-VR with further data processing ability to cater for many aspects of modelling a mine environment such as: dimensions of the cells within the mine, levels of gases within cells, events within the mine, temperature within cells and many other factors which control the individual aspects of a section of roadway.

Event An event, in the context of Fire-VR, is a programmed task which is carried out when certain conditions are met e.g. a fire event is set when conditions in the Fire-triangle are met. (See section 1.3.5 Underground fire fighting). Events can either be pre-programmed to occur at specific times or be completely dependent upon other events.

Fire-VR Fire-VR refers to the complete computer software package which encompasses the sub component parts of VentSim-VR and EnvSim-VR into a system capable of displaying the simulated world in a 3D environment on screen. The software was written to realise the research carried out in this thesis.

MakeMine A pre-processing program which converts a mine description file into a fully 3D mine network model suitable for display by Fire-VR's 3D virtual reality interface.

Mine description file A text based file used to hold the data values of the simulation. This file is created with custom built editor software and is used as a form of describing the entire mine layout and the events which the user wishes to examine using the simulator.

NetEdit A program created as part of the suite of Fire-VR software. It was created to aid in the quick design and creation of mine description files for larger networks.

Node A node is a point defining a junction of pathways in a mine. In the case of the VentSim-VR, this refers to a point connecting cells together.

Path A path refers to a section of roadway which leads either away from or towards a node. A path could refer to either a single or multiple string of cells connected together.

VentSim-VR This is the name given to the underlying ventilation simulation which controls the ventilation model used by Fire-VR. VentSim-VR is a significant component of the Fire-VR software.

2D interface The computer generated display for the simulation, useful in displaying information about the mine description files created by the user for modelling. It is programmed using the Microsoft® foundation classes (MFC) and Visual C++™.

3D interface This is the main 3D computer generated display used to create the virtual reality graphical front end to Fire-VR. It is programmed using Microsoft's Direct X™ API.

Chapter Two

Mining engineering - The cause and prevention of underground fires and explosions

2.1 Introduction

A comprehensive exploration of available literature in the mining engineering field was conducted to provide a background to the proposed research. Various disciplines were studied in order to provide a clear review of the current engineering techniques and their relation to the proposed research. This chapter outlines the current problems and issues regarding current ventilation of a mine and methods for the prevention and management of mine fires and explosions. A review is also included of currently available computer based applications that are employed in the modelling of mine ventilation systems within subsurface mines.

2.2 Mine ventilation systems

The mine ventilation system is primarily concerned with maintaining a regular flow of safe, fresh air to the mine personnel. Careful planning is required in order that this system is not compromised in any way. This task is often made more complex by the fact that a mine is considered to be a dynamically changing environment. As well as providing an environment that is suitable for humans to work in, additionally, other factors have to be taken into account. Vitukuri (1986) and Rabia (1988) list essential requirements of a ventilation system: -

- To dilute the concentration of potentially explosive and toxic gases, fumes and radon to environmentally safe levels and to remove them from the mine.

- To dilute the concentration of the airborne dust to physiologically acceptable levels and to remove it from the mine.
- To provide a thermally acceptably environment in which persons can work without undue discomfort or danger of exhaustion from heat and to remove heat from the mine as may be necessary. Heat build up through the mine is a significant problem as heat can pass from the airway walls into the ventilation flow. Additionally, mine vehicles and personnel all contribute to the rise in temperature the further one gets into the mine. Attempts to mathematically model this transfer of heat have been carried out including research by Spirko (1991), Zhu et al (1991) and Wolski (1995).

Dry surface air typically consists of the following gases in the proportional amounts given below (Rabia 1986): -

- Nitrogen 78.09%
- Oxygen 20.95%
- Carbon Dioxide 0.03%
- Other gases such as helium, argon, neon, krypton and xenon 0.93%

Fresh air, in this form, is generally drawn through the mine via a main fan situated at the upcast shaft. The flow of air leading from one or more downcast shafts or smaller surface connectors is split at junctions throughout the mine in order to distribute the clean air to each face or other working area. The contaminated / spent air then continues to flow through the network of roadways and drivages where it is combined before being drawn through to the surface via a return upcast shaft by the main fan. To aid in this process and to maintain health and safety and governmental guidelines of acceptable limits to air pollution, regulators and booster fans are employed to carefully keep check of the airflow around particular sections of the mine. Additionally, ventilation doors and permanent and temporary stoppings also allow the mining engineers to change the distribution of air throughout the mine.

The human body has the ability to maintain life support functions even when levels of oxygen decrease to around 17%. This is achieved by automatically increasing the rate of breathing. Below 17% the brain starts to get confused as this automatic process is unable to cope and typically dizziness, headaches and rapid heart rate occur. At 7% volume of oxygen in air, a significant chance of fatality or brain damage could occur. Although oxygen levels within the mine are of prime concern, other components of the air are considered to be equally important.

Carbon monoxide levels are of significant concern as this gas is colourless, tasteless and odourless and highly dangerous to the human body. Carbon monoxide is quickly absorbed into the lungs where it has a strong affinity towards haemoglobin (part of the transport system used in the blood to carry oxygen to the body). This strong attraction locks out oxygen from the haemoglobin receptors hence, leading to severe breathing difficulties followed by death if not checked early.

Increases in carbon dioxide are also of concern primarily because they usually infer that either some form of combustion has occurred or that a significant quantity of CO_2 has been liberated from the strata e.g. from the surface oxidisation of coal. As the levels of CO_2 increase, the concentration of oxygen subsequently decreases resulting in a threat to human safety.

As well as the potential hazards associated with irregular levels of O_2, CO and CO_2, particulate contaminants within the air stream are also important. Hartman et al (1997) refer to these contaminants as dusts and mine aerosols. Coal dust and diesel particulate can cause serious long term breathing difficulties due to their respirable size and in the case of diesel, can have a potentially carcinogenic effect. These issues have been addressed by Watts and Waytulonis (1990) in their paper "Why is diesel particulate in mines an issue and how can it be controlled?". Wan et al (1995) present a method for modelling the generation and movement of diesel particulate matter in coal mines. A number of ventilation systems were also tested in order to control the emissions of diesel particulate.

The rest of this chapter will be concerned with the problems that occur when disaster situations such as a mine fire or explosion occurs.

2.3 Mine environment safety

2.3.1 Classification and causes of mine fires

There are many different types of combustible materials within a mine. For example, the mine infrastructure (in terms of the face, walls and roof of the mine) or the actual mining equipment itself e.g. conveyor belts (Verakis 1991), are both potentially combustible. The National Coal Board (1986) defines combustion as a chemical change or 'reaction' in which energy in the form of heat and light is produced. Oxidisation of a material can occur when there are sufficient quantities of oxygen and heat directly affecting the material or 'fuel'. Fuel, heat and oxygen are often referred to by using a 'triangle of combustion' diagram as seen in **Figure 2. 1**.

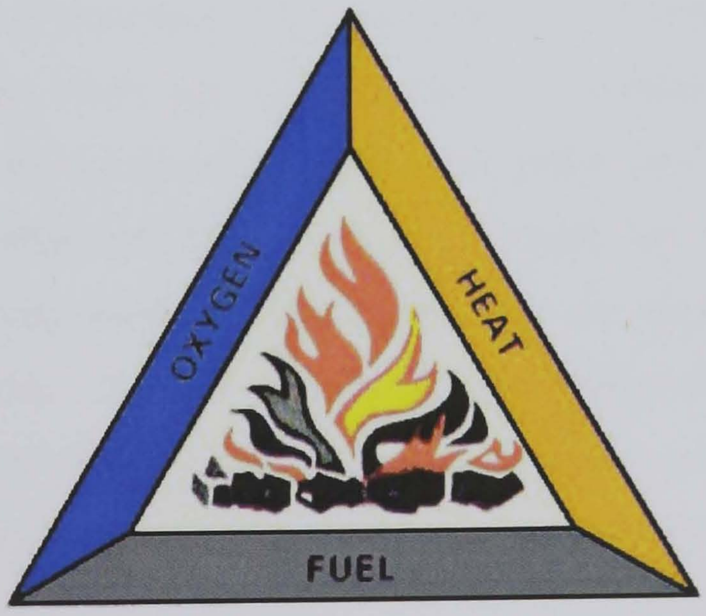

Figure 2. 1 Triangle of combustion- (Fire Fighting, National Coal Board 622.82 1986)

Without the presence of all three components of the triangle, then combustion will not occur. It is the responsibility of all personnel within the mine to minimise the possibility of these conditions being met. This can be difficult due to the dynamically changing environment of a mine and so it is vitally important to implement risk management procedures in order to try and reduce any potential fire hazard.

Underground mine fires have traditionally been classified into two main groups, open and concealed. In general, open fires occur in areas of the active ventilation system whereas concealed fires occur in areas with either limited access such as goaf or within the coal itself. Subsequently due to the greater availability of oxygen in open fires they tend to be accompanied by flaming combustion whereas concealed fires are primarily associated with the smouldering of combustible material due to lack of oxygen. Open fires are usually instigated by a discrete ignition source – the characteristics of which will directly affect the rate of propagation.

Most open fires are initially classified as 'oxygen rich' due to the supply of ventilating air enabling complete combustion. This situation can change as the burning process continues. For example, the fire may be extinguished by the removal of the heat side of the fire triangle due to the cooling effect of sufficient ventilation. Conversely, if the fire continues to burn and combustion products subsequently build up, a point may be reached where there is insufficient oxygen to completely combust the gases and vapours yet the temperature is still sufficiently high resulting in a 'fuel rich' fire. A fuel rich fire is considered to be even more hazardous than an open fire due to the potential explosion risk. These flammable gases at temperatures greater than their ignition point may build up to dangerous levels and explode when sufficient levels of oxygen return with the ventilating airflow.

Additionally, an open fire can cause disturbances in the ventilating airflow which significantly change the characteristics of airflow further within the mine. The sudden increase in temperature associated with an open fire can cause the air to expand significantly to the point that the only way to expand is along both directions of the roadway. This expansion provides an opposing force to the main airflow and produces a phenomenon known as the choke or throttle effect. McPherson (1993) suggests that this effect is analogous to the temporary increase in resistance of the airway. Another significant effect on the ventilation occurs with this sudden expansion of the air in the location of an open fire, namely that of *roll-back*. The lower density of the air surrounding a fire combined with the heat from the fire causes a buoyancy effect which results in hot gases, smoke and products of combustion moving towards the roof forming a layer. This layer then spreads out across the roof. If the roadway is slightly descending with the direction of the airflow or is near even level then this layer spreads across the roof behind the fire. This has significant implications because fire teams will generally try to put out the fire from this side. With the increase in combustion products and CO present in this layer, roll-back in this form presents a further risk for the fire crew.

Spontaneous combustion is the process where temperature of a material increases due to percolating airflow through the material. In a typical coal mine this phenomenon is apparent. Air seeps within the mine infrastructure and the temperature of the coal rises. The oxygen within the air creates the increase in temperature which in turn can create a smouldering combustion reaction within the coal. The ventilating airflow should ideally keep this temperature increase in check, however problems occur when the airflow is insufficient to reduce the increase in temperature and a point is reached when thermal runaway commences. Coal, like other combustible materials that are liable to spontaneous combustion, has a critical point when thermal runaway occurs called the self-heating temperature. After this temperature has been reached, the cooling ventilating airflow is insufficient to halt the combustion process and the positive feedback effect of the combustion process will escalate rapidly. Because of the restricted ventilation, a concealed, fuel rich fire then ensues which produces an abundance of products of combustion such as smoke, CO etc. and the associated risks such as the potential for explosive gases to build up.

The following sections present a breakdown of the components typically found in a mine fire in relation to the standard fire triangle (see **Figure 2. 1**).

a) Fuels

Fuel or combustible material is typically separated into 3 main classes (National Coal Board 1986): -

Solids. Examples of potentially combustible solid fuels include heavy wooden support beams or the coal itself. The rate of combustion depends significantly on the surface area of the combustible material as well as the density of the material. When heated sufficiently, solids give off a vapour or gas. The flame associated with combustion is due to the ignition of this vapour. In some cases, solid state burning occurs and this can be extremely dangerous due to the delay in the detection of the fire. Solid state burning takes place when minimal vapour is released, even though oxidisation is occurring. Because of the lack of vapour, a visible flame is not present and this is often the reason why some fires remain undetected for a while. With solid state burning, the oxidisation of the fuel leads to a charring of the surface of the material. Smouldering of the material and the release of odours during combustion may be further warning signals of an actual fire.

Another potential hazard exists from the occurrence of clouds of finely distributed solid particles in the air which could lead to an explosion. This is primarily due to the extremely large surface area to volume ratio of the combustible material which allows for oxidisation at a fierce rate if an ignition source is present.

Gases. Gases require only a spark from sources such as a vehicle, machine tool or small flame to create an explosion. In this scenario, the magnitude of the explosion is primarily dependant upon the concentration and type of gas vapour and the quantity of oxygen available in the environment.

Liquids. Inflammable liquids such as petroleum spirit vaporise at fairly low temperatures and consequently some of the hazardous conditions described above for gases can still apply. Even so, combustion will not happen, as an ignition source is still required. Diesel fuel is commonly used on mine vehicles due to its safer flashpoint temperature.

b) Heat

In order for a fuel to burn a heat source is required. When heated the fuel releases flammable vapours. The *flashpoint* of a substance is the lowest temperature at which the material gives of enough vapour such that if a flame is present then the released vapour would be in sufficient quantity to ignite. The *ignition temperature* of a substance is the temperature when the heated material is releasing enough vapour such that an ignition source is only needed to start the combustion reaction. If the ignition source is removed and the material is at its ignition temperature then the material would continue to combust on its own. An example of this could be a spark present only for a short amount of time in the presence of a material that was at its ignition temperature.

c) Oxygen, smoke and the by-products of combustion

Combustion with oxygen is the simplest form of oxidation (The National Coal Board 1986). The ratio of oxygen within the air directly affects the ferocity of the fire. If combustion of a material occurs freely (i.e. enough oxygen is present to fuel the combustion process completely), then the material oxidises and burns with little or no by-products being released. This process can be expressed using the following equation which describes the combustion of methane (CH_4) in the presence of sufficient oxygen: -

$$CH_4 + 2O_2 \rightarrow 2H_20 + CO_2 \qquad .....2.\,1$$

Smoke, tar and sooty products are released when incomplete or partial oxidisation of a material occurs. This is where, within certain zones of the flame, the heat given off is sufficient to decompose the carbon based material however the vapours and sooty products have not been ignited. This decomposition process produces carbon monoxide which can cause a significant threat to human life by asphyxiation (see section 2.2) as well as a reduction in visibility due to the occurrence of smoke.

Additionally, the most common causes of fire underground are described below by Rabia (1988): -

- **Conveyors**. Friction in drive belts against worn bearings / rollers lead to a dramatic heating of the conveyor equipment which can lead to fire.

- **Mechanical overheating**. Like conveyors, any equipment with moving parts that has become worn, or being used out of its original specification can suffer from overheating.

- **Combustible materials** such as oil / oily rags which are ill-placed.

- **Electrical**. Overloaded cables, faulty switches and damaged cables can all lead to electrical fires.

- **Spontaneous combustion** is the self-heating of coal by oxidation. This process can start at as low a temperature as 20° C. This process depends on the availability of oxygen and also the Virgin Strata Temperature of the rock.

Pomroy and Carigiet (1995) assessed the U.S. mining industries progress in preventing underground coal mine fires. They analysed 164 fires reported to the Mine Safety and Health Administration (MSHA) from 1978 to 1992. Several observations were made from their 15-year analysis which back up the information of mine fire causes shown above:-

The 164 fires investigated resulted in 30 fatalities and 43 injuries. A total of 10 injuries and 27 fatalities are attributed to just one event: the Wilberg fire of 1984. The last reported fatality occurred in 1987. Equipment was identified as the primary cause of these fires. In particular, increasing trends were observed for roof bolters, power centres, transformers, electrical equipment, conveyors, and conveyor drives as causes of fire. Incidents resulting in fire involving rubber hose, tyres, oil, and grease were reported to be declining. Diesel equipment was involved in only two fires.

Most fires were caused by electrical faults (such as a short circuit or insulation failure). In order of frequency, this was followed by fires due to friction (such as a conveyer belt rubbing on a pulley or stationary object), welding, flame cutting and spontaneous combustion.

Approximately 85% of the fires were first detected by mine personnel who saw smoke, smelled smoke, or saw the fire start.

About 45% of these incidents resulted in evacuating the entire mine. Another 15% required evacuation of nearby personnel only. Evacuations are far more likely to occur today than in earlier years of the study. The researchers noted that this trend might be due to management's increased awareness and caution concerning safety risks to personnel. The fires occurred in seven general locations. This implies that fire initiation is a mine-wide problem.

Concluding, it can clearly be seen from the above reported information that mine fires are a significant risk to personnel within the mine. Interestingly, with a reported figure of 85% of fires being detected by personnel, the need for concise, relevant training in the detection of fires seems of paramount importance. Training can play a significant part in increasing the awareness of mine personnel with regard to recognising the causes of mine fires. Training in the form of an immersive simulation of real life fire situations can therefore be of increased benefit.

2.3.2 Detection of mine fires

The most effective method to control combustion is by early detection (Sengupta, 1990). The easiest method for detecting heating is by monitoring combustion components and products such as carbon monoxide, carbon dioxide, hydrogen and oxygen. The graph in **Figure 2. 2** shows how concentrations of certain gases correlate with changes in the temperature of the coal. Hence, this can often give early warning to a potential fire breaking out within the mine. Statistics indicate that over 70% of fires detected during the first 15 minutes cause little or no damage to the mine (Pomroy, 1990).

Oxidisation of coal can occur at fairly low temperatures and this is often unnoticeable due to the lack of visible flame, consequently some form of early warning system is desirable. Frequently, a method of detection based around monitoring the ratio of carbon monoxide produced against a deficiency of oxygen has been used. Graham's ratio, as it is called, can be checked at the return airway of a mine or monitored at various points within the mine. A rising trend in the Graham ratio invariably indicates the onset of heating.

Graham's ratio (*I*) is defined by the following equation: -

$$I = CO_{\text{Produced}} / \%\, O_{2\ \text{Deficiency}} \qquad \text{.....2. 2}$$

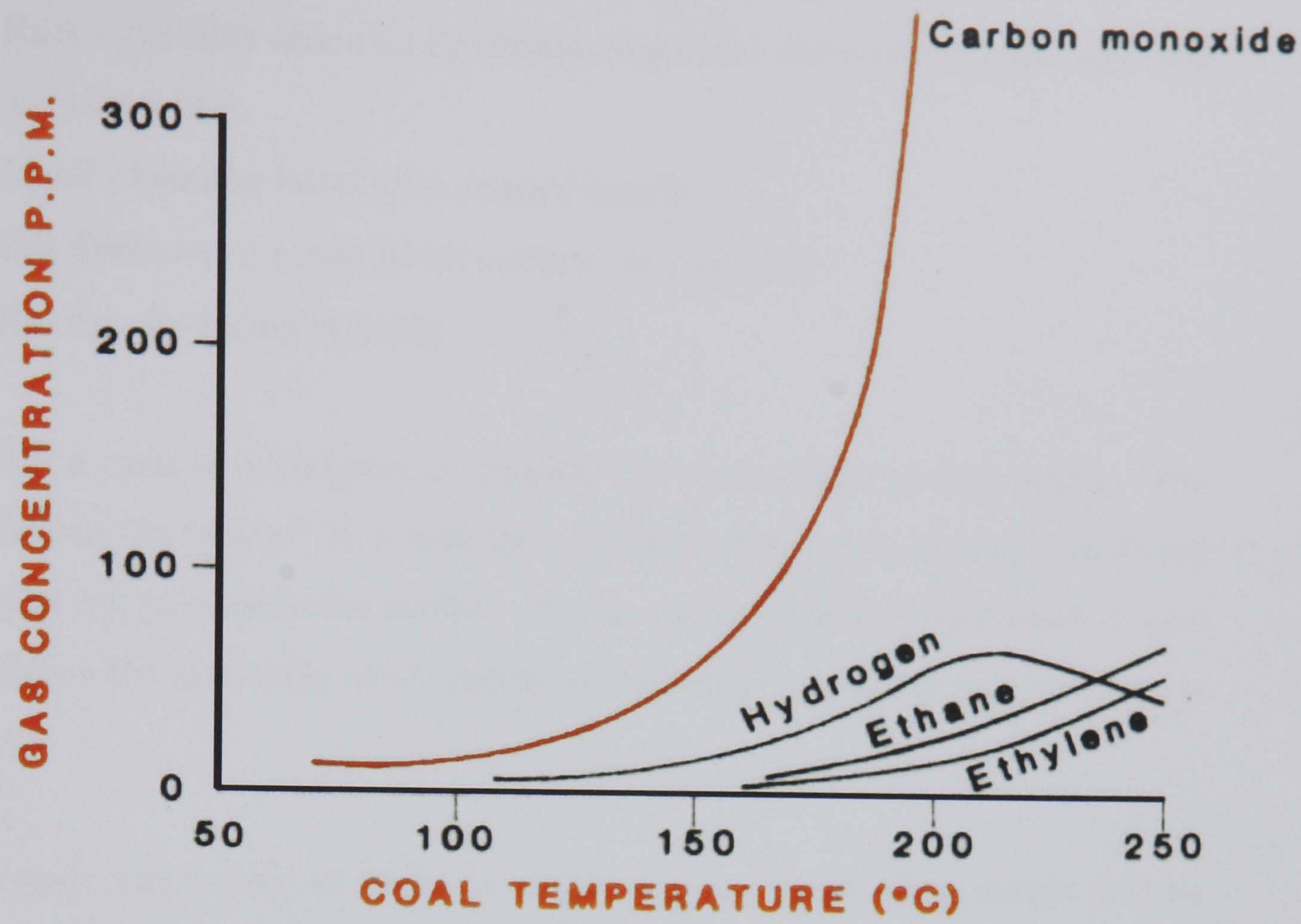

Figure 2. 2 Variations in gas concentrations with changes in temperature (Sengupta,1990)

Conti and Litton (1993) have researched various methods of improving the early detection of carbon monoxide levels by examining the effects of stratification of gas in the immediate vicinity of the fire. In general, the time to detect a developing fire is calculated assuming an average CO concentration that has mixed completely with the ventilated airflow. After experimenting with the variables of air velocity, sensor spacing and position their results conclude that CO sensors near the roof of an entry offer an advantage in detection due to buoyancy induced stratification of the combustion products of the fire. This effect was still true even during the low temperature smouldering stage of a fire prior to full combustion taking place and would only tail off gradually with an increase in ventilation flow, hence still providing significant improvements in early detection.

Additionally, common signs of spontaneous combustion can be detected by mine personnel observing the following characteristics (Rabia 1988) : -

- Sweating - more than usual presence of water on the rock.
- Haze - visibility obscured by shimmering of the atmosphere associated with additional heat.
- Smell - Familiar burning or unusual smells.
- Hot Surfaces - Unusually hot surfaces to the touch.
- Smoke - Reducing viability.

Within a mine it is common to monitor the environment at key points. The "Tube bundle system" is a collection of small bore-tubes through which air samples are pumped to the surface. At the surface, analysis equipment is used to display the gas levels which can be monitored by computer on a continuous basis.

If certain gases, such as methane, reach warning levels then alarms will be triggered and action can be taken. This information is recorded via computer and can be used as a quick method of determining a wide variety of potential hazards within the mine. The only limiting factor of the tube bundle system is that of slow recognition times of fast changing events such as explosions and fires. Because of the time taken to pump the sample up to the monitoring station such problems might already have occurred. McPherson (1993) suggests that tube bundle systems should have a maximum lead time of 1hr in order to increase the chance that significant changes will be noticed before an event occurs.

Detection equipment can be categorised into three main groups: -

- Handheld
- Portable
- Fixed point

Fixed point detection equipment is used for long term monitoring and usually has some form of transmission of its sensory data back to the surface. Portable detection equipment is used for providing a continuous indication during a shift while handheld units are used for spot checks by mine personnel.

Various chemical and electrical devices are available for the detection and the measurement of gases underground. Typically, thermisters are used to measure small changes in temperature. An electrochemical cell can be used to analyse the concentration of a particular gas by measuring the oxidisation rate of the electrochemical cell. Different gases can be determined by using appropriate electrochemical cells. Other analytical methods utilised include infra red cells and semiconductors.

Infrared (IR) sensors work by the fact that carbon monoxide absorbs Infra red light. A greater concentration of CO in the atmosphere will therefore correspond to a reduction in the amount of IR light being transmitted to the sensor. After calibration a reliable reading can be gained for the regular monitoring of CO.

A semiconductor's resistance can change when its surface is exposed to particular chemicals. Again after calibration a reliable reading of a particular gas can be taken.

2.3.3 Summary

By using various sensors most gases in the mine atmosphere can be detected. Varying thresholds of sensory equipment can cause limitations and inaccuracies in the readings that are detected, however these imperfections with the sensors or techniques can be modelled in the computer.

Whether it's a simply handheld methane display on the computer screen when the user is moving around the virtual environment or a complex "Tube Bundles System", ultimately, the end effect is that the above types of sensors can be simulated within the computer model thus providing a comprehensive simulated detection method.

2.3.4 Causes of mine explosions

There are two main types of underground explosion: -

Coal dust explosion. This occurs where coal dust dispersed within the air becomes ignited, probably due to an initial methane explosion. The coal dust itself is highly volatile and the explosion will continue to propagate though the mine.

Firedamp explosion. This occurs with the build up of methane gas or 'firedamp' as it is called in this situation. Methane combined with oxygen and an ignition source such as a spark is highly volatile. The Lower Explosive Limit (LEL) of methane in air has been determined experimentally at 5 % methane and 95 % air. Typically Cowards diagram (See **Figure 2. 3** below) is used to describe the explosive properties of methane.

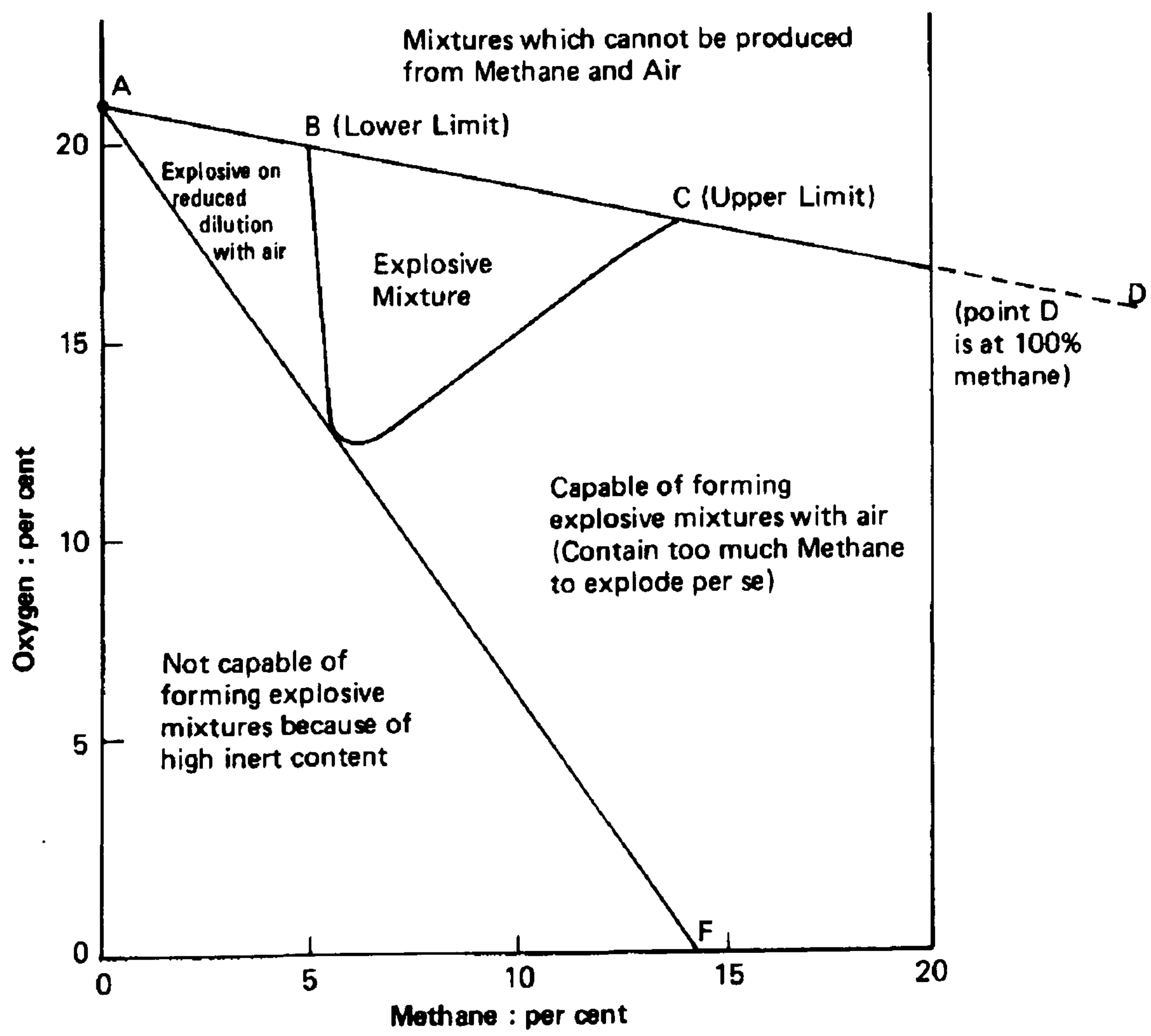

Figure 2. 3 Coward's diagram (Rabia 1988)

Kissell and Goodman (1991) discuss a strategy for preventing and reducing the chance of tunnel methane explosions by using various techniques such as better ventilation, better gas monitoring, reduced ignition sources and improved worker training. By applying a technique they describe as fault tree analysis they consulted 27 tunnelling experts and their responses to a questionnaire. By analysing their responses they were able to categorise the effectiveness of each safety element and its cost trade-off. Unsurprisingly, results indicated that the most effective solutions were provided when more than one element of the trial was used simultaneously.

2.3.5 Avoiding underground fires and explosions

Often, fires and explosions are caused either by human error or a code of safety violation. Almost all of these accidents could have been prevented. It is therefore necessary to develop a safe environment and to eliminate safety hazards. By reconstructing fires and explosions this enables the body of engineering knowledge to be expanded and hence may assist in the development of future prevention strategies.

Official accounts of mine fires and related injuries are the most important measure of progress in mine fire and explosion preparedness. Studying how miners use critical prevention, detection, and response systems offers important insight into the state of preparedness at any operation (Wiehagen, 1997).

It is important to understand the mechanisms by which underground fires and explosions propagate themselves. Mine fires, once started are fundamentally ventilation controlled. A good understanding of ventilation around the mine is of paramount importance for reducing the risk of mine fires and also for controlling fires should they occur.

2.3.6 Underground fire fighting

By managing the ventilation system and taking into account certain ventilation properties, fires can be controlled. The 'fire triangle' is a typical way of describing a fire. In order for a fire to occur, heat, oxygen and fuel are required. Hence by either cooling, smothering or starving the fire of fuel then the fire can be controlled as shown in **Figure 2. 4**.

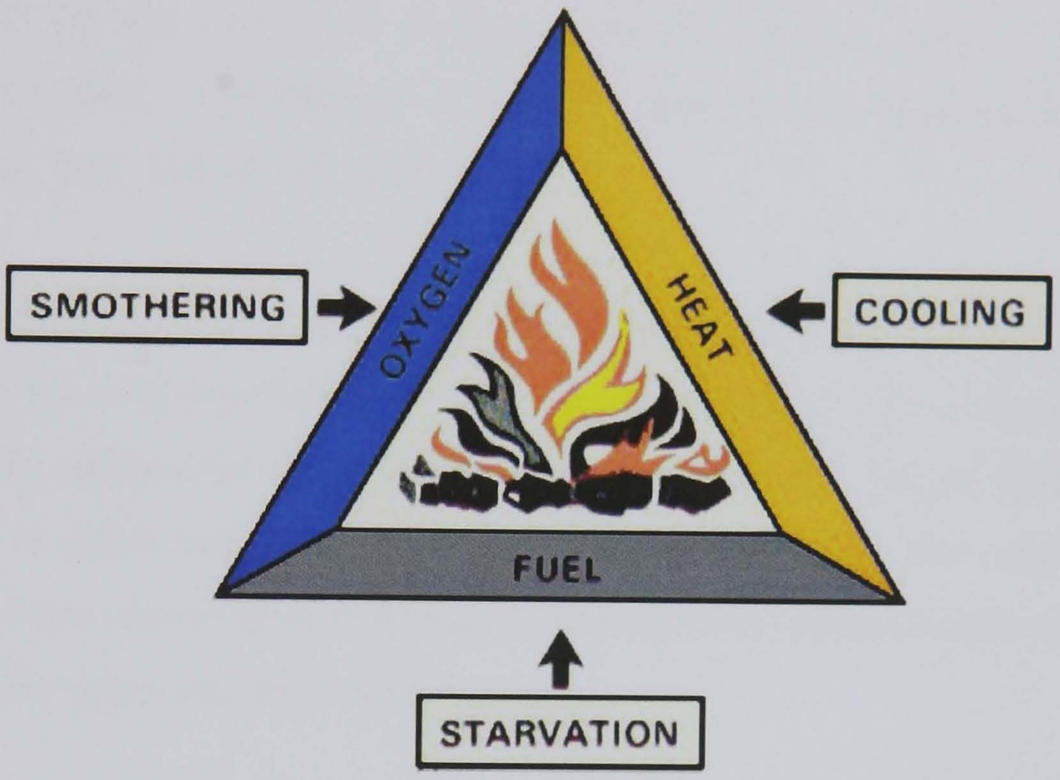

Figure 2. 4 Limiting combustion - (Fire Fighting, National Coal Board 622.82 1986)

It is not always possible or practical to remove the fuel, especially if the fuel is in the form of part of the rock face. However, fuel sources such as gases and tars can be significantly reduced by increasing cool airflow. The removal of heat from the strata causes a reduction in the liberation of potentially dangerous tar vapours and gases.

The cooling of the air around a fire is vital and often considered as the first step in controlling the fire. One method of achieving this cooling effect is to spray cool water as a mist into the path of the oncoming flames. This method can reduce the fuel 'side' of the 'fire triangle'. Analysis of the local vicinity of a mine fire shows nonsteady-state gas air flow as well as significant changes in temperature, oxygen and carbon monoxide levels. Stefanov (1989) has produced mathematical models and computer driven numerical solutions to describe the thermodynamic and gas dynamic processes that occur during a mine fire.

Secondly, the heat 'side' of the triangle can be reduced by cooling the area with a considerable quantity of fresh cooled air. If the airflow is strong and cool enough then it quickly removes the possibility of heat build up. It is the heat build up that can prove a major problem for fires starting or indeed spreading further. This method of providing cool air can therefore be used to reduce the 'heat' side of the 'fire triangle'.

In the situations described above, it is quite obvious that airflow is vitally important to combating fire within a closed environment. However, this is not necessarily appropriate when a large and extremely hot fire is burning vast amounts of solid fuel in the form of coal. In this case, the only possible method of fire control is by reducing the airflow to the point of suffocation thus significantly removing the available oxygen.

The smothering of fires is not frequently carried out as a control method because of additional problems that can occur such as fuel rich fires or explosions.

2.3.7 Ventilation control in fire fighting

Controlling the ventilation flow of air around the mine can have a significant impact on how quickly the fire can be eradicated. Good planning of the ventilation system in a fire situation is of paramount importance for the safety of the personnel who are fighting the fire. However, other factors need to be taken into account as well, not least the possibility that a change in the ventilation of the mine might lead to some significantly under-ventilated areas which could then be prone to the build up of explosive gases. This, of course, would be an extremely undesirable effect that could potentially compound the original problem.

Various methods of control of ventilation in fire fighting include (Vutukuri and Lama, 1986):-

- Regulation of air flow volume flow rates
- Short-circuiting
- Isolation of fire
- Reversal of mine ventilation

Making adjustments to the ventilation system can have far reaching effects on the whole mine and so different methods are used depending on the type and location of the fire and whether more than one method should be employed simultaneously.

Reducing the main airflow to a fire by reducing the main fan can be effective in decreasing the quantity of oxygen that the fire has available to it to consume. However, this obviously has a significant effect on the overall mine ventilation system.

If a fire is situated deep within the mine and the fumes from the mine are making access to the fire difficult then it might be appropriate to attempt to try and short circuit the ventilation flow so that any noxious fumes are re-directed to the return airflow. This enables improved fire fighting access to the fire itself and also prevents the smoke from spreading to other areas of the mine workings, which can aid rescue of personnel. However, a disadvantage to this procedure is that ventilation flow is reduced in other areas of the mine when a short circuit is being deployed and hence, will have a significant impact on available oxygen for the mine workers evacuating as well as the potential for a build up of explosive gases.

Complete isolation of a fire is possible in mines which are divided into special fire sections by means of ventilation doors and preparatory stoppings. (Vutukuri and Lama, 1986). Typically, potential danger areas can be managed in this way in the design stage of the mine and in the case of a fire, they can be quickly isolated until fire crews arrive. Grekov et al (1991) describe a method using an inert gas to fill an isolated section of a mine in order to prevent fires and explosions. Other references to ventilation control systems include Wala (1996) who presents a process designed to keep an escape route free from contaminating gases.

Reversal of the main fan is not usually advised as the fan works at a reduced efficiency; hence, it can take a significant amount of time for air flow to reverse which can lead to the formation and accumulation of dangerous gases. Furthermore, it is only really of practical use if the fire is near the downcast shaft entrance where fumes from a fire would be likely to spread throughout the whole mine. When reversing the main fan it is also important to have the appropriate design and number of ventilation doors installed. Most ventilation doors open one way and therefore a reversal of the airflow would cause the doors to burst open leading to the short circuiting of the ventilation flow. Latches are provided on ventilation doors to specifically stop this problem from occurring but it is a point of concern all the same.

The ventilation system is present for the safety of the mining personnel and consequently, before any of these adjustments are made, the mineworkers have to be withdrawn.

2.4 Mine network analysis

2.4.1 General theory

There have been many attempts to simulate the complex air-flow paths within a mine. The mine ventilation system, as it is called, has successfully been mathematically modelled at varying levels of complexity. Recently, computers have had an increasing role in producing these ventilation models. Some ventilation simulations even attempt to model the complex flows created when disturbances in the airflow are caused by fires.

Listed below are a number of the most common forms of mine ventilation analysis methods. They have been included as background information for the reader and more significantly they have played a part in determining a suitable model for this research. They range from simple equations to mathematically complex computer simulations and algorithms.

2.4.2 Atkinson's equation

Atkinson's equation,

$$P = RQ^2 \qquad .....2.3$$

Is analogous to Ohm's law used in calculating electrical circuits.[1]

Where, P = barometric pressure, N m^{-2}

R = resistance of airway, Ns^2/m^8

And Q = volume flow rate of air, $m^3\ s^{-1}$

The potential difference (V) of a circuit is analogous to the pressure differential in the mine circuit. Current flow (I) is analogous to the flow of air in a section of mine. Resistance refers to the resistance in the mine ventilation network in an analogous way to the way electricity is impeded in a copper wire. The square of **Q** is used while the equivalent part of the equation in Ohm's law, (I) is linear. This is to take into account the cross sectional area of a mine, a factor which is not relevant in a wire when using Ohm's law.

[1] Ohm's law, **V = IR** (Volts = Current * Resistance)

Because of the similarities of the two equations it is common to also apply Kirchhoff's laws to analyse mine ventilation networks. Kirchhoff's laws were originally used for analysing electrical networks and circuit behaviour. Typically, the equations which are used for electrical circuit behaviour, are inter-changeable, with little modification, in the analysis of mine ventilation circuits.

2.4.3 Kirchhoff's laws

Kirchhoff's first law states that 'the algebraic sum of all flow rates at any junction is zero.'

In **Figure 2. 5**, below it can be seen that for any given junction J1 or J2 that this applies i.e. the mass airflow is neither created nor destroyed.

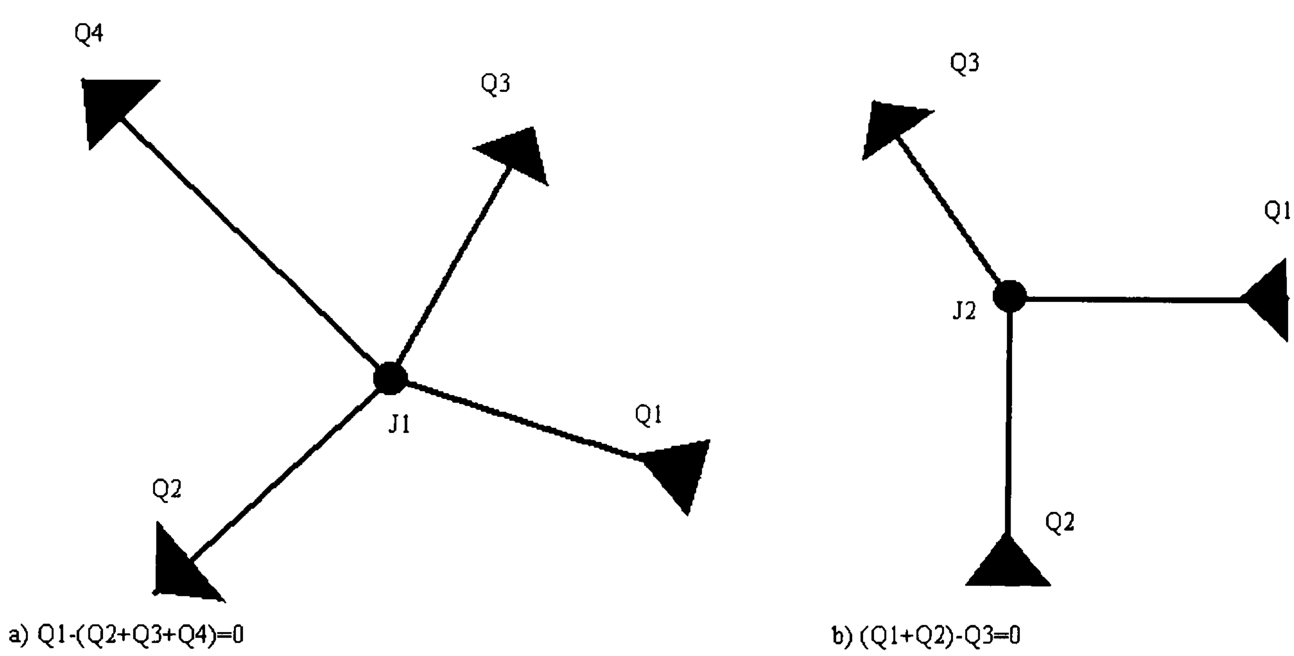

Figure 2. 5 Junctions at a node illustrating Kirchhoff's first law

This statement can be re-written as the equation : -

$$\Sigma Q_i = 0 \qquad .....2.\,4$$

Where **Q** refers to volume flow rate of air, $\mathbf{m^3\ s^{-1}}$ and $_i$ is a number from 1 to the number of paths at the junction.

Kirchhoff's second law (commonly called Kirchhoff's voltage law) states that the sum of the differences (voltage or pressure) around a closed path must be equal to zero. In terms of the mine ventilation model, the driving force of the fan creates a pressure difference equal to the sum of the incremental pressure differences across the system. Hence, the total headloss on a balanced network of paths equates to zero. This can be expressed as an equation: -

$$\Sigma P_{\text{total headloss}} = 0 \qquad \text{.....2. 5}$$

This is illustrated in **Figure 2. 6**. The main fan creates a driving force of 1500 Pa. Letters **a** to **j** refer to pressure drops across the relevant cell. In order for Kirchhoff's second law to be satisfied, the sum of the pressure drop across cells **a** to **j** must equal 1500 Pa in the example shown in **Figure 2. 6**.

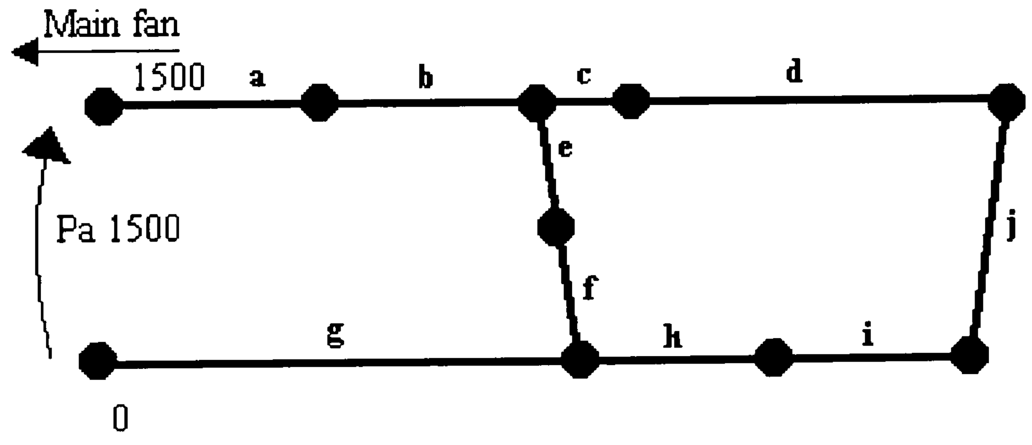

Figure 2. 6 Network illustrating Kirchhoff's second law

Series circuits

In a ventilation system, two basic combinations of airways are possible: series or parallel. Both types occur as well as various complex combinations. As discussed by Hartman et al (1997) a series circuit is defined as a circuit whose airways are arranged end to end so that the quantity of air flowing through each airway is the same

Because air can only flow down a single path, the resistance of all the sections of roadway can be summed to give a simple equivalent resistance.

It follows that for any simple part of the series circuit, say a section of roadway, there can be only one flow value, one resistance value and one pressure difference value (also referred to as Headloss in certain texts).

This transcribes to the following equation: -

$$Q_{\text{overall flow}} = Q_{\text{flow through section 1}} = Q_{\text{flow through section 2}} = Q_{\text{flow through section 3}} \cdots$$

Applying Kirchhoff's second law to this circuit results in the following : -

$$P_{\text{headloss 1}} + P_{\text{headloss 2}} + P_{\text{headloss 3} \ldots} - P_{\text{driving fan}} = 0$$

The driving fan head loss (or pressure difference) is equivalent to the total headloss across the system. (because it is the only driving force within a simple network).

The last equation equals zero because the driving fan creates the head loss and this is a closed system. The electrical analogy of the fan is that of the battery. Both provide a driving force which is equivalent to the difference dropped by each resistance in the series circuit.

The equation can be re-written to account for analysis of roadway sections without cancelling driving forces such as fans: -

$$P_{\text{total headloss}} = P_{\text{headloss 1}} + P_{\text{headloss 2}} + P_{\text{headloss 3}}$$

From the above simple series circuit, it can be seen that the quantity and direction of airflow through each airway are the same. Substituting the individual flows and resistances back into the equation, the equivalent resistance can be defined as follows: -

$$P_{\text{total headloss}} = R_1Q^2 + R_2Q^2 + R_3Q^2 + \ldots.$$

Factoring out $\mathbf{Q^2}$ gives the following : -

$$P_{\text{total headloss}} = (R_1 + R_2 + R_3 + \ldots.)\, Q^2 = R_{\text{equivalent}}\, Q^2$$

Re-arranging we get: -

$$R_{\text{equivalent}} = P_{\text{total headloss}} / Q^2 \qquad \text{.....2. 6}$$

Parallel circuits

In mine ventilation, the term used for parallel branches within the mine network is splitting. These splits generally form two major types; Natural Splitting and Controlled splitting.

The simplest, natural splitting refers to when the airflow is broken into more than one path. In this case the flow follows typical parallel path theory in a similar manner to how electrical current is divided down a parallel set of wires. The second form, that of Controlled splitting, is used when the mine requires a management of airflow to a precise quantity and this is achieved by the use of regulators or booster fans. This is common in mine networks because it is sometimes necessary to have a precise control over airflow so that it can be changed dynamically to the needs of the mine at that current time. This method of regulating fans can be quite useful in fire control and removing unwanted build up of potentially dangerous gases.

Fundamentally, in modelling terms, both behave in a similar way. Both methods exhibit the same principles, i.e. they adhere to Kirchhoff's laws. Interestingly, the analogy to an electrical circuit still stands; in the case of a parallel circuit with one path containing a regulator, this is analogous to a similar circuit with one path having a variable resistor.

The path without the fan is called the free split. The regulator effectively controls the amount of air flowing through the roadway which gives it a variable range. In general, a regulator is an orifice, usually situated in a ventilation door that can be opened and closed to varying amounts.

The pressure drop across a parallel set of paths applies to all paths. If the resistance of each path is known then this information, combined with the pressure difference across the parallel circuit, can be used to calculate the individual flows through each path.

$$Q_i = \sqrt{(P_{total\ headloss} / R_i)} \qquad .....2.7$$

Where $_i$ = number of the path in the split.

Again, in a similar manner to series circuits, the network can be simplified to an equivalent airway. Calculation of these air flows within complex mines is the key to modelling a ventilation simulation.

Improvements to these modelling methods are continuously being designed. By making changes to an original model, then there is the opportunity to achieve either a greater degree of accuracy or for methods which produce a similar result more quickly. Hu and Longson (1990) have extended upon the basic theories above and have established a new method for calculating the optimal airflow distribution in a ventilated mine network when the air flow in certain branches is known whilst Sudhakar et al (1991) has suggested that Atkinson's equation is only suitable in an ideal case and has improved on this by proposing a constitutive law which provides a more general description of air flow characteristics in mine ventilation.

2.4.4 Hardy Cross iterative method

Additionally, an iterative method such as 'Hardy Cross' can be used to calculate larger more complex mine networks. This technique can be computationally intensive to perform so it is usually necessary to use a computer program. The process is fairly straightforward in itself though and is described below: -

The Hardy Cross method is based upon the principle that for any given arrangement of airway resistances and driving forces (such as main fans, booster fans or natural ventilation), there is only one possible distribution of the air mass throughout the mine network.

Any given mine network can be broken up into a series of nodes or junctions combined with connecting roadways between the nodes. These junctions can have 1 to n number of roadway segments adjoining them.

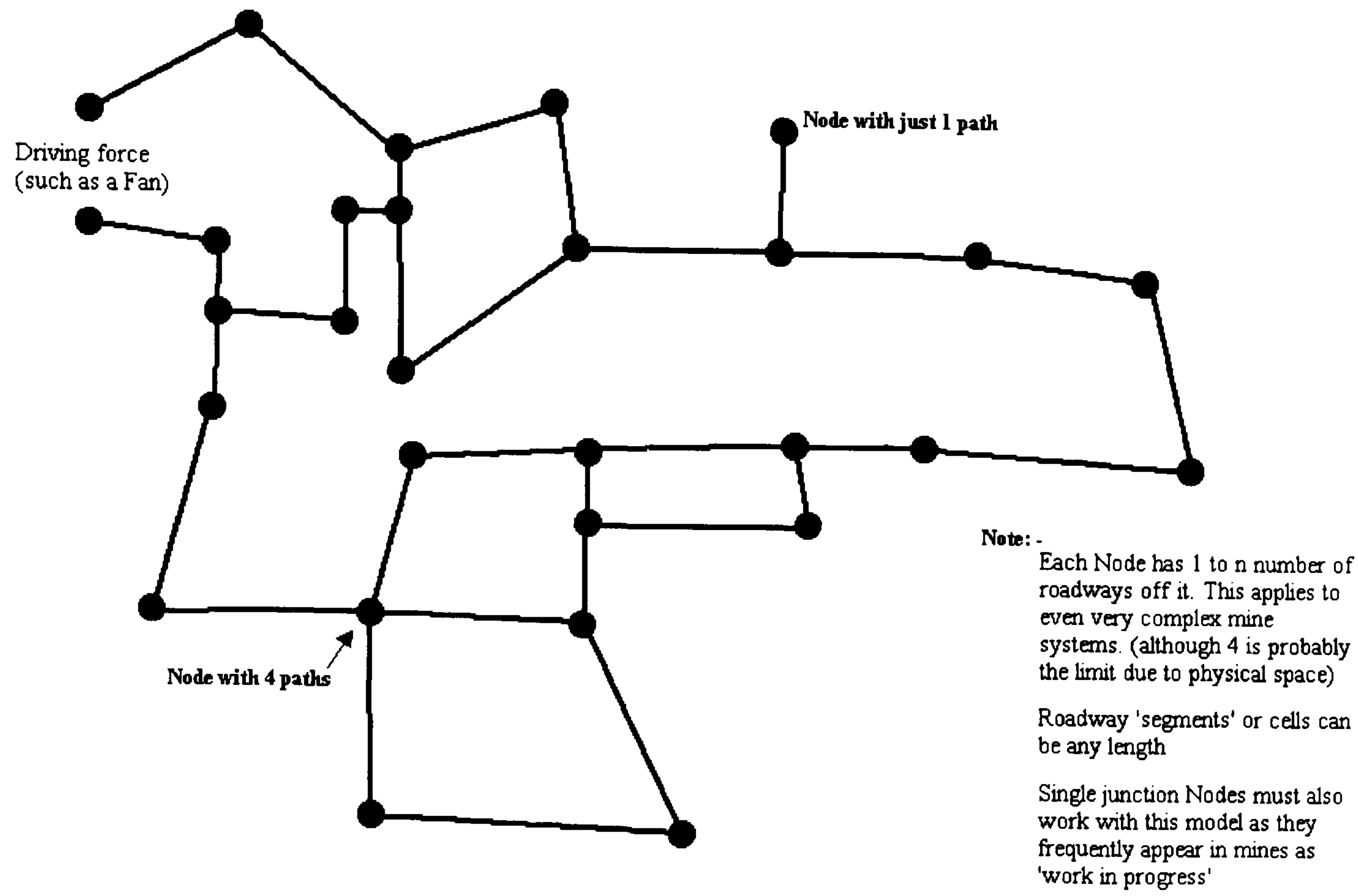

Figure 2. 7 Complex mesh of interconnecting paths

This simple method can be used to model even very complex mine networks (note the above network **Figure 2. 7** is not supposed to be indicative of a realistic mine scenario. Instead it has been used to test theories of complexity).

At each node a pressure value (**P**) at that point can be stored. These values of P are unknowns at first and have to be estimated.

An error value of (**Q**) is then calculated for each node mesh within the network, applying Kirchhoff's law (stating that sum flow in = sum flow out). This error is then removed from the node values and has the effect of reducing the error on each node, via negative feedback, so that the network balances out.

Effectively, because this method is an iterative solution, then an approximate solution is successfully improved until the error is acceptably small. The number of iterations needed depends upon how complex the network is, whether high resistances are used in conjunction with very low ones and also how accurate the starting estimates of node pressures were.

2.4.5 Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) is the numerical solution of fluid motion equations on a digital computer and has evolved over the last 40 years to become a well established discipline within a number of science and engineering branches. High performance computers have allowed CFD to become accepted as a cost effective and predictive design tool.

CFD is a method of modelling flows (of any type) in a very accurate way. This method is particularly computationally intensive because it calculates flows by using specialised algorithms, based on mathematically accurate equations to a high resolution. Lea (1994) describes a computational model using multi-dimensional CFD in order to examine flow patterns around a mine fire.

The most fundamental equations of motion for an incompressible fluid are the Navier-Stokes (N-S) equations. These equations are partial differential equations and comprise of combinations of the flow variables, such as the velocity components, the fluid pressure, and the derivatives of these variables. The solution of the complete Navier-Stokes and relevant conservation equations together with associated boundary conditions represents a formidable task (Edwards et al 1995). This method is a complex system which requires sometimes days just to calculate a snapshot of the flow in a particular roadway.

Although desirable due to its high level of accuracy, it was discounted for use in this simulation due to the current limitations of computing power and that the primary design consideration of this work should be a real-time based virtual reality application.

However, CFD based work was utilised in this project as a method of visualisation (see Chapter 4). Although a real-time VR based CFD simulation was impossible due to computing constraints, the possibility of visualising CFD generated data in a non real-time environment using a VR front end was explored. In this example use of pre-calculated CFD generated data, it is possible to visually display information in full 3D allowing the user to experience a high level of detail. This is appropriate if the user does not require a real-time element or if the user has sufficient time to enable a batch job of CFD data to be generated. Of course the latter option prevents real-time interaction.

FLUENT is a general-purpose computer program for modelling fluid flow. It allows the engineer/designer to quickly analyse complex flow problems. It incorporates a number of different modelling techniques based on fundamental principles, for simulating a range of flow patterns. FLUENT uses a finite difference numerical procedure to solve the fundamental equations governing fluid flow (the Navier-Stokes equations). Additional equations are solved for the conservation of the parameters of the k-e turbulence model, chemical species and enthalpy. Its high accuracy at modelling flows means that it is often considered as the simulation system for modelling flows of gases.

2.5 Ventilation and mine fire simulation packages

2.5.1 Introduction

A number of computer applications and prototype software packages have been developed in order to simulate the complex ventilation flows created within a mine system. Most of these systems use derivatives of the Hardy Cross iteration method for balancing out closed network systems such that the resulting pressure loss across the whole network is equal to zero (Kirchhoff's laws).

Some of the original ventilation network analysis programs ran on mainframe computers. However, in 1989 the U.S. Bureau of Mines / Michigan Technological University mine ventilation mainframe program was successfully transferred over to the PC platform, hence enabling the ventilation network analysis program to reach a wider audience (Ng 1989). Their version ran on a modest PC specification whilst allowing a reasonably complex network analysis to be produced. Accuracy of the PC version of the software was consistent with its mainframe parent and the software itself was only different in the fact that it took longer to arrive at the final result.

VnetPC™ (Mine Ventilation Services) for Windows is a Microsoft® windows based application that is designed to aid mine environmental engineers in the planning of subsurface ventilation layouts. Given information that describes the geometry of a ventilation network, airway resistance or dimensions, and the locations and characteristic curves of fans, the code will produce listings and visual graphics of (Mine Ventilation Services 1996): -

- Branch airflow
- Frictional pressure drops
- Airway resistance
- Air power losses in airways
- Ventilation cost of each airway
- Fan operating points (pressures and airflow)
- Duties of required regulators and booster fans
- Gas flows and concentrations in branches

WIPPVENT (McDaniel and Wallace 1997) have used the same air flow distribution sub-routines and included most of the same functionality as VnetPC™ but increased the user-friendliness of the software by re-writing the user interface using Windows® (Microsoft Corporation) based graphics.

More recently produced packages offer the additional functionality of being able to model the complex flows and eddies created when disturbances in the airflow are caused by fires; PCVENT (Wolski 1991), MFIRE (Chang et al

1990) and FIRES (Zhongli and Husheng 1993) are popular examples whilst others such as Abbas and Scheck, (1991) and Hardcastle (1995) and have focused on providing more user friendly interfacing to standard network analysis techniques. Another extension to the basic ventilation simulation has been developed by Lilic et al (1997) in the form of coupled expert system which incorporates procedural and declarative knowledge to provide extended functionality to the basic ventilation software.

MFIRE developed by the US Bureau of Mines is a computer simulation program that performs normal ventilation network planning calculations, and dynamic transient state simulation of ventilation networks under a variety of conditions (Chang et al 1990). The program is useful for the analysis of ventilation networks under thermal influences such as temperature and internal influences such as fires. Extensive output enables detailed quantitative analysis of the effects of the proposed alteration to the ventilation system.'

MFIRE was applied by Laage and Yang (1991) using in-mine experiments in order to validate the temperature distribution and heat exchange functions in the program. More recently, Laage and Yang (1995) performed a series of experiments to obtain temperature profiles as a function of time and distance from a fire and compared the results with simulations using MFIRE.

Miclea (1991) has also applied the MFIRE and SES (Subway Environment Simulation - version 3.0 developed by Associated Engineers) computer programs for tunnel fire modelling and formed a comparative study. In the study, an example scenario was created which models the buoyancy effect of hot gases which may produce a backlayering against the main fan thus resulting in restricting the safe evacuation of mine personnel.

Gallery tests have been carried out as a means of experimentally examining the effects of mine fires and explosions when they occur underground. Institutions such as the U.S Bureau of Mines at Pittsburgh (now known as the National Institute of Occupational Safety and Health) and the Polish Academy of Sciences Strata Mechanics Research Institute (Cracow) have been performing these tests since the early 1980's. Data has been obtained for a variety of different materials such as oil and wood etc (each with a range of calorific values) to determine information such as the rate of oxygen and fuel consumption, CO production and temperature profile etc. These tests have enabled Dziurzynski et al (1993) to produce POZAR as part of the VENTGRAPH® mine simulation package. POZAR is a sub-program for simulating the effects occurring in the mine ventilation network after a fire has commenced based on the incorporation of real data regarding flow distribution of mine gases into a mathematical model.

2.6 Summary

This chapter has explained the current problems associated with properly ventilating the working areas of mine personnel. The problems associated with harmful pollutants and gases have been discussed with regard to their effect on the workforce. An introduction to the mining engineering principles needed to provide adequate ventilation has been described. The chapter continues to explain the procedures implemented to maintain mine environment safety in the form of methods used to protect the work force and the mine infrastructure from fires and explosions. The processes of combustion and the skills and techniques required to keep combustion of materials in check have also been examined.

The techniques used to mathematically model mine networks have been discussed. Finally, the software applications which are currently in use or which are currently being researched are outlined, thus concluding the chapter.

Chapter Three

Computer graphics and virtual reality

3.1 Introduction

VR can be thought of as a logical extension to 3D graphics. The creation of a virtual world utilises computer 3D graphics as a way of displaying this virtual environment. A basic overview of 3D computer graphics is described in section 3.2 followed by a discussion of the additional functionality that a VR system utilises in section 3.3. There is now a substantial amount of published work available on the subject of VR in the minerals sector not least work carried out by the AIMS[1] research unit based at the University of Nottingham (Denby et al 1998, Squelch 1998, Williams et al 1998, Schofield et al 1997 and McClarnon 1996). In this chapter, the emphasis is on areas of research and technologies that have been utilised for FIRE-VR.

3.2 Computer Graphics

3.2.1 The display medium and current technology

Computer graphics and in particular 3D computer graphics are the power house behind VR and VE systems. Computer power has increased significantly over the last few years which has now allowed even low cost computer systems the ability to produce quality computer graphics. The ultimate goal of the community, who specialise in producing 3D computer graphics has to be the production of photo-realistic computer rendered images. For the virtual reality community this goal extends to producing 3D photo-realistic computer rendered images in *real-time.*

[1] Artificial Intelligence in the Minerals Sector

Photo-realism has been achievable for a number of years even on home PC's in the form of still frames - that is, pre-scanned pictures or frames created with other electronic devices such as a digital camera. Monitor displays on even a modest desktop PC can display resolutions of up to 1280 x 1024 pixels. Additionally, colour depth perception of these computers can easily reach real world integrity in the form of 'true-colour' displays.

This is fine when dealing with the process of producing images that have been converted from an original 2D source via a digital camera or scanner. However, it is not so straight forward to reach this final rendering stage when the image is generated in 3D, by the computer, based on a model created by a programmer or artist.

3.2.2 The generation of 3D computer generated images

The production of an image which is based on a simulation output or that which is created from a non-real world source is significantly harder to achieve. The hardware to display these potentially imaginative images is available, however the methods are in need of refinement. Software companies specialising in 3D computer graphics have evolved to fill this gap. Many software packages are now available which allow engineers and designers to produce 3D computer images of their work. e.g. An architect may design his creation with 3D CAD software which can produce both a 3D image and rolling film of a design. 3D Studio MAX® from the Kinetix® software group is one such program developed to aid the production of 3D computer generated graphics.

3D Studio MAX® and others in their genre are significant in their ability to tackle the tasks of producing realistic effects to the existing basic geometry modelling techniques.

Perrie (1997) defines a basic overview of the process involved in creating a 3D computer generated image as separated into two distinct processes: -

Modelling (see section 3.2.3) is the creation of the geometry of the object to be rendered. The geometric primitives might be polygons or surface patches. The primitives might be created by brute force by defining the 3D co-ordinates of the vertices of the polygons or might be created via interaction with a computer program such as a Computer-Aided Design program or a simple program which allows a user to create surfaces of revolution.

Rendering (see section 3.2.4) is the process of displaying the image of the object on the screen of a video display monitor, i.e. determining which pixels will be displayed and what the shade (i.e. colour) of each pixel will be. Rendering might be accomplished via hidden-surface techniques, ray-tracing techniques, radiosity techniques or some combination of these methods.

3.2.3 3D Modelling and world building

World building is the term given to the process of constructing a 3D virtual environment using basic building blocks. These building blocks, referred to commonly as objects by Pimentel & Teixeira (1993), Foley et al (1990) and Hearn (1994) are combined together to form the world.

Objects can be simple cubes or tetrahedrons that can be combined to form more complicated objects or they can be complete objects in themselves. Objects can have environmental effects applied to them individually such as gravity or they might have functional effects such as the ability to rotate or move in a pre-programmed path. Additionally, objects can be assembled into hierarchical groups. An example of this are the wheels on a vehicle. Each wheel can rotate around its own axis, however the position of the wheel in space is dictated by the position of its hierarchical parent, the vehicle chassis, as well as its own orientation and position. Another example of this idea would be the finger bones on a human skeleton. Each finger would be connected to a hand which itself would be connected to a wrist etc. Moving the wrist has the effect of moving all of the hand components in space even if the individual finger did not move on its own.

In **Figure 3. 1** below an example view from a 3D model and world building editor package can be seen. The isometric view shows a number of individual models which have been constructed and placed within a scene. The package allows for the quick production of 3D models and objects as well as being able to specify lighting conditions, object materials, camera animation view points and a variety of environmental effects such as fogging. Typically, to display the objects in real-time, so as to allow easy manipulation of the objects for editing purposes, the objects are reduced to their most basic display which is that of a 'wire frame' model. Once the objects dimensions and co-ordinates are stored in memory, mathematical transformations can be applied to control their position, orientation and size within the generated scene (Hearn 1994, Angel 1990 and Angell 1984).

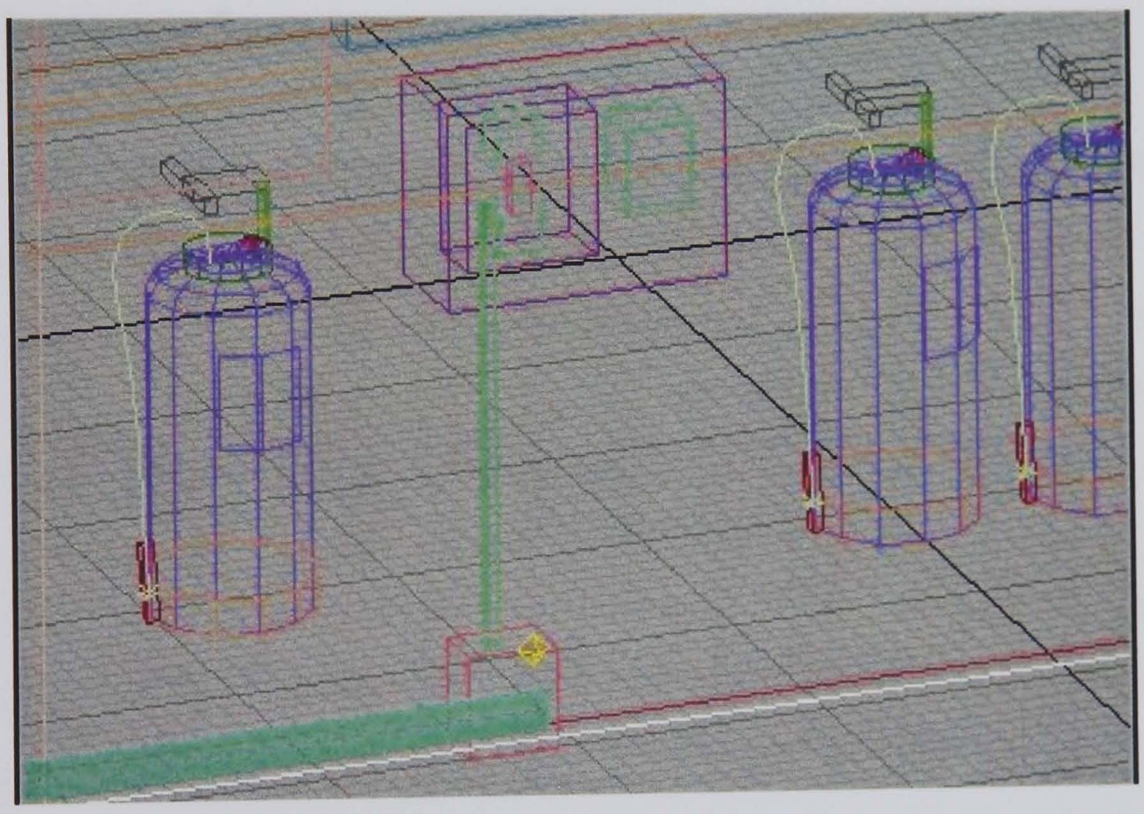

Figure 3. 1 Wire frame model of fire point scene constructed with 3D Studio Max® Software from Kinetix®.

Pimentel & Teixeira (1993) describe two main types of objects within a virtual world. Static objects are objects that either do not move until interacted with or are objects that make up the scenery of the world which the user is viewing. Dynamic objects are those which either move or change under simulation control. An example of a dynamic object would be that of a smoke cloud object whose appearance would change depending on the state of the simulation.

3.2.4 Rendering of a 3D scene

Arguably, this area is where a significant amount of the most recent research work has been carried out in computer graphics. Furthermore, it is where most work is still required in order that the idealised photo-realistic image can be generated.

Even if the 3D models in the virtual world are detailed and accurate, the way they are rendered has a significant impact on whether the scene is realistic. Various mathematical algorithms and techniques have been developed in order that this issue can be addressed. An example of some of the most frequently used rendering techniques are discussed in sections a) to f) below.

a) Clipping and back-face removal

The time taken to render each frame to the display can vary significantly primarily because as the user moves through the VE the quantity of visible objects changes. If the user is facing a wall and is very close to it then the scene might be rendered at a significantly reduced time frame than that of a scene that contains many complex objects. In a VE, some objects can be obscured from view by others in which case there is no need to actually render the hidden object at all hence saving on rendering time. Many algorithms and processes have been developed to aid in the recognition of redundant objects within a scene. Clipping is a technique where calculations are used to determine whether an object is visible. One such algorithm works by tracing back a line of site from the object in question back to the user position (Hearn, 1994).

Back-face removal and hidden surface removal (Angel 1997 and Harrington 1987) are techniques where each face of an object is checked for orientation and position within the scene and if its normal is pointing away from the user or it lies behind a closer, obscuring object, then it can effectively be cut from the rendering pipeline, again saving in rendering time for each frame.

These techniques have most effect when polygon counts are high and when binocular views are being calculated (primarily because they have to calculate a different view for each eye).

b) Lighting the scene

Simple scenes can be generated by assigning colours to each object within the world. This very basic approach to lighting assumes a uniform ambient light exists across the whole scene. This method is very inflexible and difficult to adjust because each face, of each object, has to be pre-programmed to the desired colour and brightness level based on the type of material. The disadvantages of this method are that the scene looks very sterile and that objects look the same even when they move around within the world.

A significant improvement to this situation is that of dynamic lighting which, in the following forms, is used to calculate a brightness intensity level for each face of each object within the world. By calculating these intensity levels for each face a more accurate lighting model of the objects is gained. Vince (1995), Angel (1997) and Harrington (1987) examine different types of dynamic lighting: -

A **Point light source** is a way of defining the lighting requirements of a scene by only specifying a location and intensity of light. This is analogous to the way a light bulb on the ceiling might illuminate a room.

A Directional light source is assumed to be located so far away that all of the incident light rays are parallel. This means that if the fall-off in intensity during the light's journey is ignored, the intensity of the light hitting a surface is based upon the angle of which the rays hit the surface and the original intensity of the light source. This is analogous to the way objects are lit by a near infinitely far away object such as the sun.

A **Spot light source** is analogous to the way a spot lamp functions in that it will have intensity, position, direction and also an angle of illumination. The angle of illumination refers to the diameter of the light cone.

Ambient lighting refers to an overall level of light associated with the whole scene. It is used to provide a background lighting effect which can be used to fine tune the overall brightness of the objects in the world.

Provision for using these lighting techniques is installed into the rendering pipeline as part of the rasterising process.

c) Flat Shading model

Flat shading is used as a 'quick and dirty' method of displaying 3D models within a scene. Each face is rendered at a uniform colour intensity and brightness. This intensity value is calculated by averaging the intensities of light at each corner of the triangle or face which is then used by the rasteriser to uniformly colour each pixel as it is displayed on the screen. The end result of this is that each face has a uniquely rendered brightness intensity based on the average intensity across the whole face.

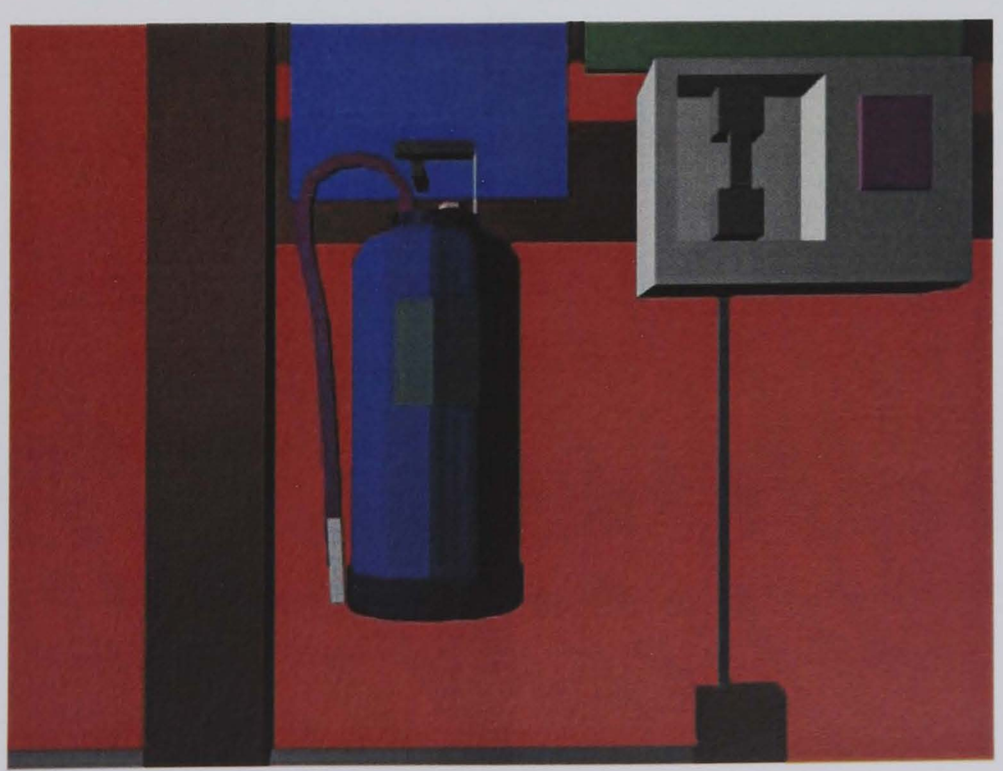

Figure 3. 2 Flat Shading model of fire point scene

This provides a fast rendering pipeline for the graphical display, but it lacks any real detail and noticeable boundaries between faces can be seen (See fire extinguisher in **Figure 3. 2**). This now primitive type of shading is shown above in **Figure 3. 2** and is typical of the early computer generated images which were in widespread use in the 1980's.

d) Gouraud shading model

In **Figure 3. 3**, below the computer generated scene of a fire point using Gouraud shading is shown. The scene has reasonable clarity because the objects are smooth shaded to provide a graduated colour change uniformly across face boundaries which enhances curved surfaces. The image quality, however, is not highly detailed due to the simple objects used within the world.

Figure 3. 3 Computer generated mine fire point scene using Gouraud smooth shading techniques to render the world objects

e) Phong Shading and Radiosity

Phong shading, described by Angel (1997), is a more advanced form of shading that is used to take account of specular reflections emitted from each surface of a polygon eg as shown on the fire extinguishers casing in **Figure 3. 4**. Radiosity can be described as a global illumination model which allows for complex diffuse reflections to occur between reflective surfaces within the scene. Even simple computer VE can contain complex lighting conditions. In the real world, light bounces around objects in a near infinite way creating very delicate distortions in each objects colour and brightness. Radiosity can model the subtle lighting effects created when one objects reflective colour affects the colour of another close object. This technique is performed by an algorithm which holds reflective and emitted energy levels for each mesh within the generated scene. Radiosity is a measure of the sum of emitted energy and reflected energy of an object and has to be calculated simultaneously in relation to every other object present. Because of this, radiosity is no mean calculating feat.

Both Phong shading and Radiosity are mathematically complex and require a significant amount of processing time on a desktop PC rendering platform. At the time of writing, these techniques are available for rendering non real-time scenes in software packages such as 3D Studio Max® but are not practical for real-time VR based applications due to the large rendering time overheads. At the time of writing the Software API used in this research, version 5 of DirectX® does not support Radiosity or Phong Shading.

When we perceive the world though our eyes we see the world as a whole; constructed from the images of the objects that are present and the knowledge that we have learned, combined with these images, to form our understanding of the environment. Within our field of view, our eyes perceive the light intensity of the objects, their hues, their textures and their distance from us. Although the precise details of this process goes beyond the scope of this thesis it is important to recognise some of the processes that are occurring. The ability for the brain to recognise depth cues is important. Vince (1998) uses an example of a Boeing 767 flying overhead and states that because of its small size our brains assume that it is far away.

Other significant effects happen to the visual perception of objects that are far away. Some of these factors are addressed by current 3D graphics and VR systems to aid in the process of increasing realism. Many of these effects actually destroy detail which in effect results in a more realistic image.
Haze created from depth needs to be introduced along side adjustments of hue due to depth.

Vince (1998), Rogers & Earnshaw (1990) and Hearn (1994) describe some of the more common techniques in detail and brief outlines of these are below: -

f) Texture Mapping

Texture Mapping is a method of applying a picture or texture to an object such that it appears to have more detail. This technique is frequently used in order to give a simple object more detail. Vince (1998) gives an example of the use of texture maps in the form of a bookcase model. By applying a texture of wood grain, his model of a bookcase takes form and appears to have significantly more detail than would be visible if the bookcase was drawn in flat shaded colours. Texture mapping in this example has given more detail to an object which was primarily based on a simple design and because of its simple design the model is quicker to render.

In **Figure 3. 4** the same scene (as in **Figures 3. 1** to **3.3**) is rendered using textures which have been applied to various objects surfaces. The result of this is that more perceptible detail is gained at no great loss in speed to the rendering process. This occurs because the actual polygon count for rendering the scene has not increased. In the scene, the floor, roof, walls and signs including the fire extinguishers all have textures applied to increase detail.

Figure 3. 4 Computer generated fire point scene using textures to provide more detail to the scene.

Another commonly used technique is that of texture decals. Instead of wrapping a texture around an objects surface, a texture is automatically rendered face-on towards the camera at all times. These textures in this format are also referred to as 'sprites' and were frequently used in the home computer games industry because they required less processing power than that of fully rendered 3D objects. Decals can be used in place of simple 3D objects and an example of a texture decal would be the display of a sphere within a 3D world. A sphere looks the same whichever angle it is viewed. A decal texture of a sphere can be created using a simple bitmap and placed within the scene. This has a huge speed increase over creating a 3D sphere model which might have hundreds of faces. The down side of using decals in this manner is that the decal is fundamentally a flat object and therefore lightning conditions within the world will not look correct when compared to using a true 3D model.

Fogging is a technique first introduced to provide flight simulators with the impression of haze as the view tails off into the distance. The atmosphere present in the real world has a significant effect on the visual quality of the modelled objects as the depth from the view point is extended. This effect is calculated mathematically on the depth of the view and attenuates the saturation of the objects colour by increasing the white component. As well as being a visual enhancement to the generated scene, fogging has a significant impact on reducing processing time of the image as sometimes the rear clipping plane in the viewing frustum can be moved closer to the view point thus allowing more redundant objects to be removed from the rendering pipeline. Although the technique is called fogging, by using other colours to devise the hue of objects, other effects are achieved. By using black, for instance, a false darkness effect can be achieved i.e. the further away the object, the darker it becomes which can be used in an underground scene.

Figure 3. 5 Underground fire point clearly showing detail into the distance

Figure 3. 6 Same underground fire point this time with black 'fog' impeding the view along the z axis (into the distance)

The scene shown in **Figure 3. 5** does not use fogging. By including fogging into this underground scene, as in **Figure 3. 6** the effect has two benefits; firstly that the scene is more representative of a dark working area such as a mine by introducing a false, yet effective dynamic lighting effect and secondly, that the rear clipping frame can be brought closer towards the camera (user position) thus reducing on rendering time (see section 3.3.1 Visualisation and rendering of an image).

Transparency is a technique required if objects within the scene are translucent or transparent. Examples of transparency (sometimes referred to as opacity or translucency) are that of modelling glass or water and an example of partial transparency could be that of smoke. In **Figure 3. 7**, example translucent objects are shown with varying levels of translucency.

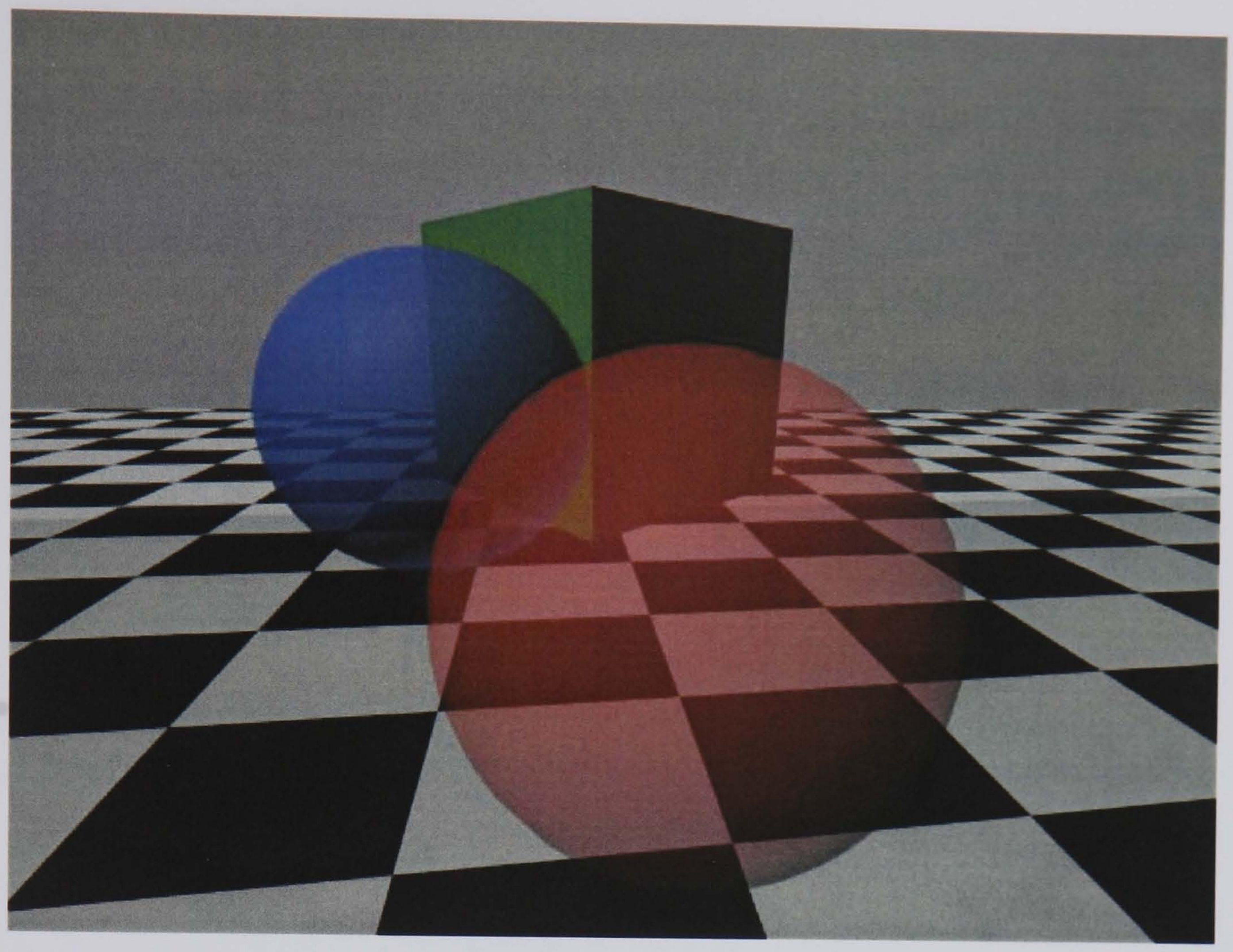

Figure 3. 7 Simple objects demonstrating (from far to near) 100 %, 70 % and 40 % opacity levels.

3.3 Virtual reality

Virtual Reality has been around for longer than people imagine. As early as 1965, in his paper, 'The ultimate display', Sutherland discusses the artificial creation of environments that a person could interact with. In this paper, Sutherland also discusses various accepted VR principles such as immersion, tactile response and visual perception. (Sutherland, 1965)

Additionally, the military was quick to accept the technology not only as an additional way of training in the form of flight simulators, but also in terms of providing additional flight information in the form of Head Up Displays (HUD).

The term Virtual Reality, by definition, refers to the forced construction of sensory information such that the recipient's awareness is fooled into thinking that they are experiencing a pre-programmed artificially constructed reality. In practice, however, this notion of completely reconstructing a reality for the user to experience such that he forgets about the real world and is immersed into a virtual, computer constructed reality is rarely, if ever, achieved.

That said, the recent advances within the computer graphics industry combined with the continually reducing electronics and computer hardware costs have progressed the virtual reality experience from its cumbersome infancy into at least the equivalent of a bad tempered teenager...

Matsuba and Roehl (1996) define VR as: -
"Virtual reality is a computer-generated simulation of a three-dimensional environment, in which the user is able to both view and manipulate the contents of that environment". They go on to define the key points which a system should consist of in order that it can be defined as VR.

The System should be able to: -

- keep track of every object in the virtual world
- store and update information about each object's location and appearance
- simulate the behaviour of the objects
- render the world in three dimensions
- generate sounds for the virtual objects
- allow the user to navigate through the virtual environment
- provide the user with some means of interacting with objects in the environment

Each virtual world consists of a collection of 3D objects, environmental factors such as light sources and a viewpoint or viewport. Additionally, a virtual reality system has to also consist of the actual physical computer hardware which the software is running on. It also has to take into account the hardware equipment with which the user interacts with the system such as Head mounted displays (HMD) or a joystick.

3.3.1 Visualisation and rendering of an image

In VR, in order to obtain a realistic computer generated interpretation of a world, high frame rates are needed. Ideally, VR simulations need to be updated at least 24 frames per second to give a smooth interpretation of movement. This is an accepted standard used in the film industry and a frame rate which we can strive for in a typical VR application.

Frame rate in a VR based simulation is based on two major points: -

Firstly, how much rendering the computer has to do in the scene. Each frame that the computer has to generate is time consuming. The amount of time taken to draw a frame depends directly on the complexity of the scene which is to be rendered. e.g. There will be a significant difference in frame time between rendering a complex large 3D object with lots of specula highlights and a small-uncomplicated object with flat shading.

Secondly, the actually calculations needed to be performed by the simulation (assuming the rendering pipeline is a part of the same simulation system). In this case, both VentSim-VR and EnvSim-VR take up a significant amount of processing time per frame.

Clipping is a method of reducing processing time while performing these calculations. By reducing the processing time taken by rendering the scene, for instance, faster frame rates can be gained. This can be achieved by removing redundant objects from the rendering loop. Redundant objects are those which are not necessary to render in the current frame. An example of this is an object that is behind another object or one which is behind the camera or even one which is so far away from the camera that it is out of view. In all of these cases, the end result of rendering would be that of a frame drawn without the redundant objects being visible on screen. This clipping technique is useful in reducing the time taken to draw each frame but it has disadvantages as well. Sometimes it is difficult to calculate quickly whether objects are able to be clipped from the scene. If a large amount of calculations are required then the time taken for this clipping calculation can outweigh the advantages brought about by the actual clipping of the object.

For the majority of rendered frames, however, this technique is very useful. **Figure 3. 8** below shows the technique of using front and back clipping planes that reduces the amount of objects directly in the scene. Because it is easy to define a plane in terms of distance from the camera point of view, a large amount of redundant objects can be removed from the rendering loop every frame.

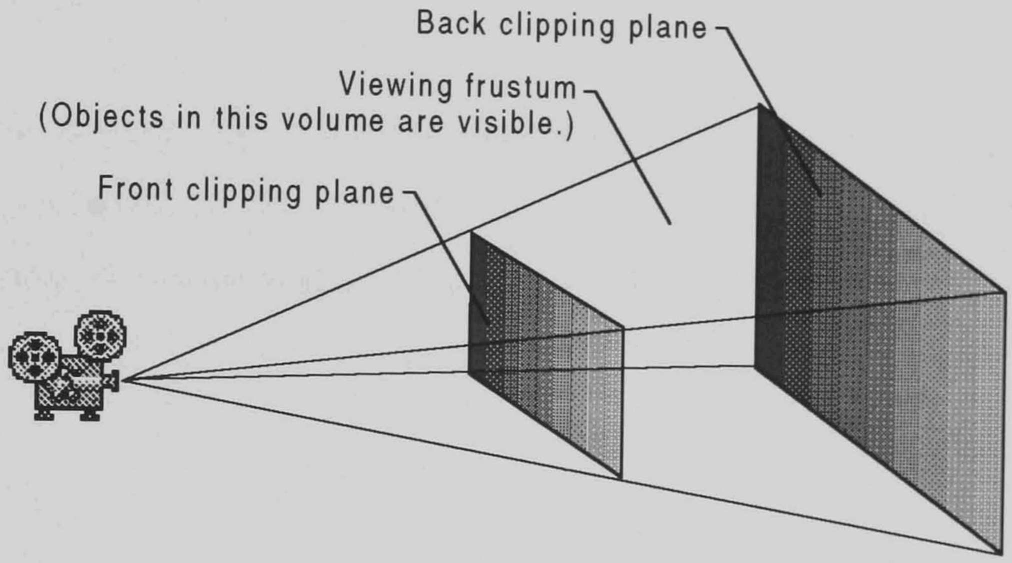

Figure 3. 8 The viewing frustum showing front and back clipping frames. Microsoft® (1995)

3.3.2 Graphical improvements to the visualisation

Various graphical algorithms and techniques are employed to achieve a greater realism in the virtual world. In the past, when VR was in its early inception, worlds tended to look very plastic in nature and they had an essence of clinical sterility about them. This was primarily because of computing power limitations that were imposed by the limited hardware at the time. Objects that were modelled within the world were simple cubes or combinations of simple polygons. As well as actually having a very simple structure, colour was also kept to simple flat shaded hues. Curved and smooth graduated shaded objects were just not possible and this had a significant impact because obviously the world we live in is very different.

As computing power has increased, so too has the ability to introduce more realistic modelling techniques into the world and many of the techniques discussed in the section 3.2.4 (Rendering of a 3D scene), can now be employed within the real-time VR simulation fields.

3.3.3 Interaction with the environment

All virtual reality systems require provision for the user to interact with the created world. Pimentel and Teixeira (1993) describe a simple model that is at the heart of all VR systems.

In this example, the participant or user experiences the VR world through the output sensors or devices. In VR terms, these would typically be a HMD or projection system as well as positional sound through headphones on the HMD or speakers.

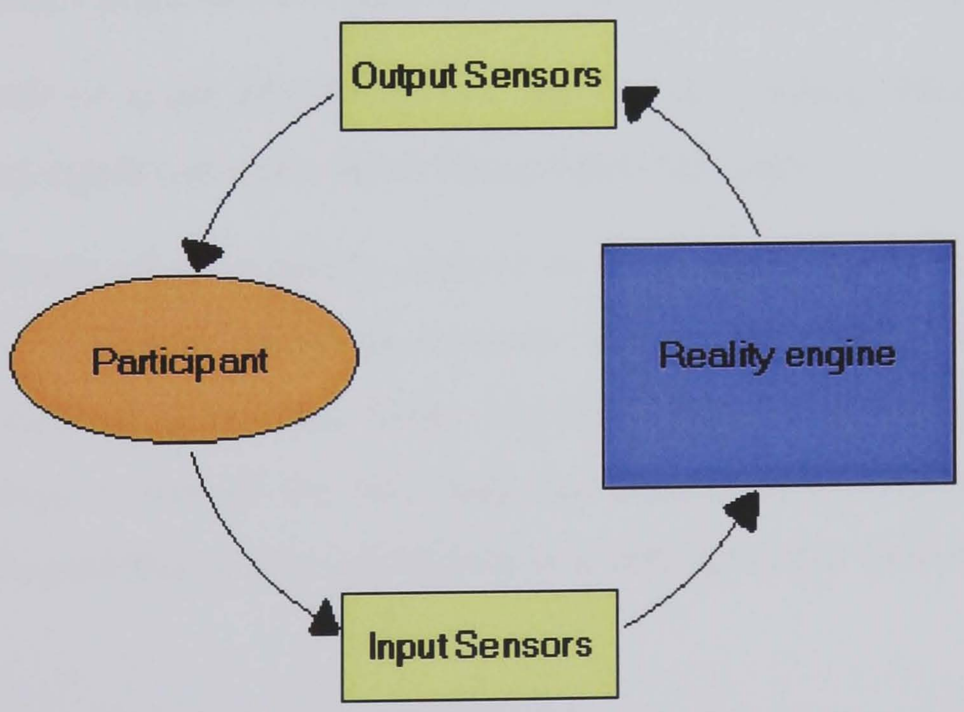

Figure 3. 9 Block diagram of VR sensory feedback loop (Pimentel and Teixeira 1993)

The feedback cycle begins when the user reacts to this output information by actuating the input sensors which would be typically a joystick or motion detectors in the HMD.

The reality engine itself is a broadly defined component of this system which controls many functions including: -

- The rendering engine including the geometry processor to output the users view.
- Positional and orientational processing of the input sensors.
- Simulation.

There are now a number of specialised input sensors and output devices which have either been developed for or are used by VR systems. MacDonald and Vince (1994), Angel (1997) and Artwick (1984) discuss some of the commonly used options available. Examples of input devices are: -

- Two Dimensional devices such as the mouse, trackballs and joysticks.
- Spaceball or space orb that give 6 degrees of freedom which allows for complex combinational control through true 3D space.
- Data gloves which typically behave in the simplest form as a positional tracker. Advanced versions contain many sensors allowing for the monitoring of individual finger bends as input. An extension to this technology is that of the full body suit although for obvious reasons of encumbrance this is only appropriate in a very specialist field of simulation.

More recently, in the affordable market range, a new element to input control has arrived in the form of force feedback joysticks, steering wheels and handsets. These systems, although fundamentally input devices, also allow for an additional output of information from the reality engine. Vision aside, one of the major forms of human sensory formation of his environment is that of touch.

By providing tactile information through the feedback loop, more immersion is achieved. Lag or latency problems occur when user input in the form of movement sensors within a HMD or a joystick move at a faster rate than that at which the computer can update the display. The usual feedback loop between display of the VE and the user navigational input is corrupted with a lag. This can have severe consequences for the user within the virtual world in the form of over compensation of control movements. There are two main reasons for the breakdown of this feedback loop; lag associated with a slow rendering pipeline and lag associated with slowly updating input mediums such as magnetically controlled head tracking units. Ideally the control systems overall update rate should operate at least at standard video refresh rates of 25 Hz (UK) to avoid this problem (Vince 1995).

Kyger and Maybeck (1998) have explored a multiple model estimation system which reduces lag in virtual displays by predicting in advance and pre-calculating the desired scene based on the possible angular orientation and position that the head could move to. By making the system adaptive, their system out-performs similar non-adaptive predictor systems.

3.3.4 Collision detection and real world physics

Objects within the virtual world are rendered to the screen to make up the current view of the user. These objects are simply collections of polygons which have been sorted and processed in the correct order and then displayed. Because of the very nature of virtual reality and the fact that we are constructing something that isn't real, each object within this world has no real-world physical attributes such as weight, inertia and balance. In addition to this, each basic object within the scene has no appreciation of other objects within the scene. A moving object could quite easily pass through the airspace of another object which in the example of a flight simulator would have a significant impact on the realism of the simulation if a plane was to fly through a tower block without addressing the issues of collision detection!

Collision detection and real world physics are both examples of applying characteristics to objects to aid realism. They can be viewed as a way of providing each object within the scene with a form of intelligence as to their surroundings.

In order to maintain these features a significant amount of processing time can be used, all of which have a significant impact on the rendering loop of the VR system.

3.3.5 Immersive and non-immersive systems

Some people say that without immersion, in the form of Head Mounted Displays (HMD), there is no true virtual reality. This is perhaps true in the pure sense of the expression but more frequently than not, large screen computer graphic displays or simple computer monitors are being used as a method of displaying three-dimensional computer graphics to the user with the aim of creating a virtual world.

There are many reasons, but probably the main reason for this acceptance of a non-immersive system such as a flat display is that large LCD projection based systems and monitors are becoming inexpensive. Furthermore, the technology of HMD's in the form of goggles and helmets, are still quite cumbersome to use and are not becoming vastly improved in visual resolution and clarity.

One of the benefits of using an immersive HMD is that depth perception can be recreated by separately calculating and rendering the view for each eye resulting in binocular or stereoscopic vision. This effect although useful when viewing close up objects is redundant when objects move further away than approximately 30 metres (Vince 1995). The fact that the users eyes experience less irritation by using a projector has also played a significant role in turning people away from using full HMD's.

Additionally, in terms of training, more than one person can experience the simulation simultaneously if a projection or monitor system is used.

An emerging technology and a compromise between single user immersion and mass-user non-imersive systems utilises shutter glasses along with a projector based display. Shutter glasses are reasonably light weight and when used in combination with a large LCD based projector system, multiple users can experience the VE. Binocular vision can be experienced by the user(s) because the projector display alternates between left and right eye views. The users eyes receive the correct image by blacking out each eye's view of the screen alternatively in time with the display showing the opposite eyes view. Simple LCD based 'shutters' on the lenses of the glasses can be quickly turned on or off as appropriate to give a similar binocular effect that would be seen using a HMD yet with a greater resolution and mass audience appeal of a projector based system.

3.4 Literature review conclusions

A wide range of technologies have been explored in Chapters 2 and 3 with the aim of influencing and defining the fields of research for this thesis. Until now, mine ventilation and environment simulations have been completely schematic in nature; that is, their displays have consisted of a 2D representation of a 3D world model. The purpose of these simulators has been to focus on the modelling of the environmental data and ventilation airflow. However, in this research, an attempt has been made to expand on this concept by including VR as a tool to open up this field of mine ventilation with increased user interactivity and improvements in methods of data visualisation.

It was decided that the modelling and controlling of the ventilation and environment should be handled by bespoke software. VentSim-VR, described in the following chapters, consists of similar techniques used by VNetPC, however it concentrates on certain relevant areas only. Tried and tested techniques are used in VentSim-VR to produce a simulation which can model ventilation flows without incurring large overheads created by processing less relevant aspects of a typical mine ventilation simulation. One of the main problems with using an 'off the shelf' package such as VNetPC is that it is difficult to integrate additional functionality such as a 3D front end. In creating this innovative propriety code (VentSim-VR) these restrictions are therefore not encountered.

EnvSim-VR described in the following chapters was created to work in conjunction with VentSim-VR as a method of modelling environmental factors associated with a mine ventilation system. EnvSim-VR was developed in order to be able to model fires, explosions and the associated environmental effects that these events produce. This system offers the advantages of smaller overheads in terms of computational time for the real-time VR simulation and the ability to integrate the simulation data with a 3D display in real-time.

The following chapter outlines some of the preliminary research and designs created to explore the research goals.

Chapter Four

Design considerations and prototype research work

4.1 Introduction

This chapter describes a prototype system, created to test whether or not the application of a CFD based VR simulator was possible for modelling underground fires and explosions. Other systems were then investigated and found to be more suitable given the constrains of the current technology. A Hardy Cross based network ventilation model has been discussed previously (see section 2.4.4) and forms the core method used in the Fire-VR research. This method has been utilised in conjunction with a computer graphical front-end which combines both 2D and 3D models useful in realising the final VR system. Design considerations regarding graphical display and software structured programming techniques used to realise the prototype system have are also described in this chapter.

4.2 CFD based prototype application

The ability to model gases in a full ventilation system is of paramount importance as only then can the effects of fires and explosions be accurately modelled. Although it was obvious from the onset that the intensive processing required to model the gases in a mine using CFD would be too great a burden for a simple desktop PC when combined with a VR system, a small application was created in order to test possibilities of including some of the methods such as pre-calculated data sets and whether or not they could be incorporated into the VR simulation in some capacity. This would, of course, only be relevant to those examples which did not require user interactivity as the time taken to re-calculate environmental data would not be possible in real-time.

One of the main goals of this research was to produce a more immersive modelling system using VR and computer graphics as the main information display unit. Consequently, due to computer processing limitations, design consideration had to focus on Network analysis theory such as the Hardy Cross iterative technique and Kirchhoff's laws as these methods are less computationally intensive. The design of the ventilation model based on these techniques combined with a method of displaying the information was considered.

Graphical features were also considered by experimenting with different forms of information display. In particular, factors such as how the display would graphically portray invisible information such as airflow, polluting particulate and gas components required attention.

4.2.1 The FLUENT spray paint workshop test application

It was postulated that simplified models could be used to maintain the high frame rates required by the VR Simulation, whilst those areas required to display more detail could utilise the CFD data for greater accuracy. Based on this, it was proposed that certain areas of interest could be pre-calculated and hence merged seamlessly into the simulation. An example was created in order to test the ability to import FLUENT® CFD data into a virtual environment.

In the following example, CFD data was computed from a test model which simulates the movement of air particles in a paint spraying workshop. This model was selected due to the similarities existing between the modelling of particulate in the spray workshop model and the modelling of gas flow in a restricted ventilation system underground.

In this example, a spraying machine, with four jets, is situated on a table in the centre of the room. The room itself has an inlet vent and also two extractor fans to draw away the polluted air from the room. FLUENT® version 4.3 was used in this application as shown in **Figure 4. 1**. A sample environment was set-up (Ren 1997) involving both extractor fans (Vent 1 and Vent 2) and the inlet vent (Intake). After processing the fluid dynamics of the model, the data from FLUENT® was recorded to a text based file and then imported into a VR environment using specially coded C++ routines to interpret the position and orientation of each finite element in the model.

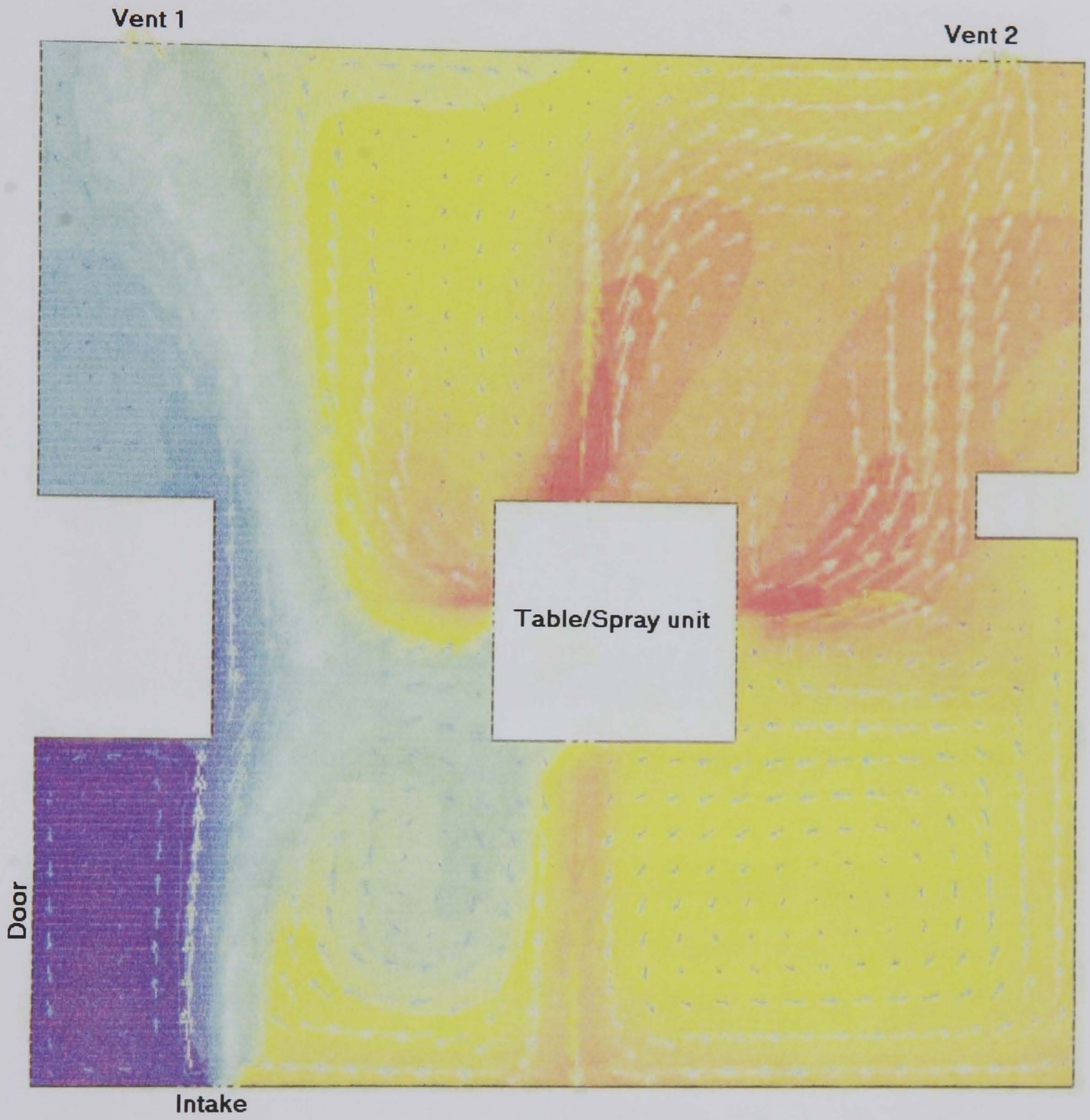

Figure 4. 1 Spray workshop 2D representation from FLUENT®.

In **Figure 4. 1** above, a sample planar output of the spraying room from FLUENT® is shown. This output clearly shows the complex airflow that has been pre-calculated from FLUENT® in the form of vector based arrows. In the example, the length of the arrows corresponds to the magnitude of the flow of air. The colours of each finite element correspond to the quantity of particulate in relation to fresh, clean air represented in **Figure 4. 1** as light blue.

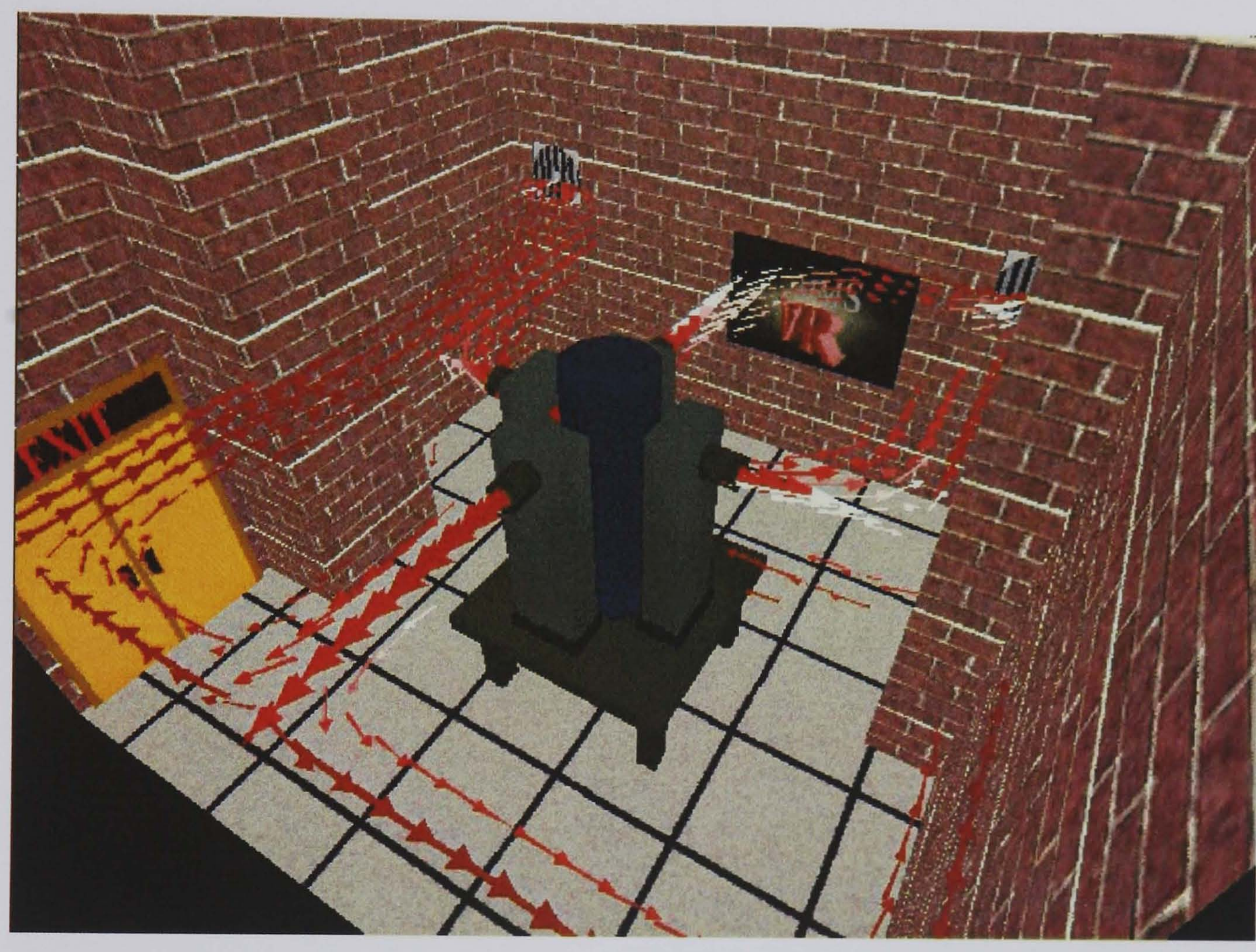

Figure 4. 2 Spray workshop modelled in VR showing imported data from FLUENT®.

The next stage involved importing the data from FLUENT® into a VR test application. The room, the spray unit and the doors and vents were built using 3D studio version 4 by Kinetix® (Pre 3D studio Max) and then converted and imported into a purpose developed VR simulator. This example enabled important design decisions to be made, showing that it was possible to visualise the pre-calculated 3D data within the virtual representation of the 'real' environment. The user is able to walk around the room and observe different areas of interest. In the above diagram (**Figure 4. 2**) only a single horizontal plane of the air-flow data is being displayed.

Vector based arrow objects were created to show the direction and magnitude of the airflow. The original matrix of data was grouped into 4 units and the mean determined by a separate pre-processing program to reduce computational time, so as to allow real-time display. The ability to focus on certain areas of interest, such as the plane of information shown in **Figure 4. 2** is an example of where VR can be integrated to display information as and when required.

Information overload is a common problem encountered when attempting to display complex data in a meaningful way. The arrows are used to give the impression of the airflow within the room and are analogous to isobars used in weather reports. The colour, length and width of the arrows are variables that can be set accordingly in order to give information to the user. An example of this are the different colours of the arrows which were chosen to show the concentration of pollutants given off by the spray guns at that particular location.

Figure 4. 3 Close up showing the spray unit, ventilation flows and the air vents within the room

This method was found to be quite effective, with high accuracy due to the pre-calculation of data using the CFD FLUENT® package. However, the method in itself would not be easily merged into a 3D VR simulation such as Fire-VR for modelling the information in a mine situation due the inability to update dynamically changes in the air-flow in real time. It was always the prime goal of this research to be able to create a semi-immersive VR system that would allow dynamic changes to be made to the simulation as it was executed. This would allow the possibility of real-time training sessions with personnel to be developed, enabling the trainees to learn about the implications of fires and explosions and to carry out preventative safety procedures accordingly.

Although this aspect of the work was not considered to be appropriate with respect to the Fire-VR research, it was extremely useful in that it helped to define the boundaries of what could and could not be achieved. The need to display information of the air flows in a meaningful manner is obviously an important factor. The method used in this example to display polluting particles within a ventilated room was shown to be quite effective. This subsequently helped to define practical ways of displaying flow information in the main Fire-VR program. Some of these techniques are explored further in section 4.4.3.

4.3 Fire-VR proposed features

4.3.1 Basic overview of Fire-VR system on PC

The Intel® based desktop PC was selected as the proposed platform for the Fire-VR system due to its wide availability and cost effectiveness. **Figure 4. 4** shows a representation of the component parts of the proposed system. This diagram is based upon a generalised VR system with specific Fire-VR sub-systems.

It was proposed that Fire-VR would incorporate the following components: -

- VentSim-VR — Network analysis modelling.
- EnvSim-VR — Environmental modelling.

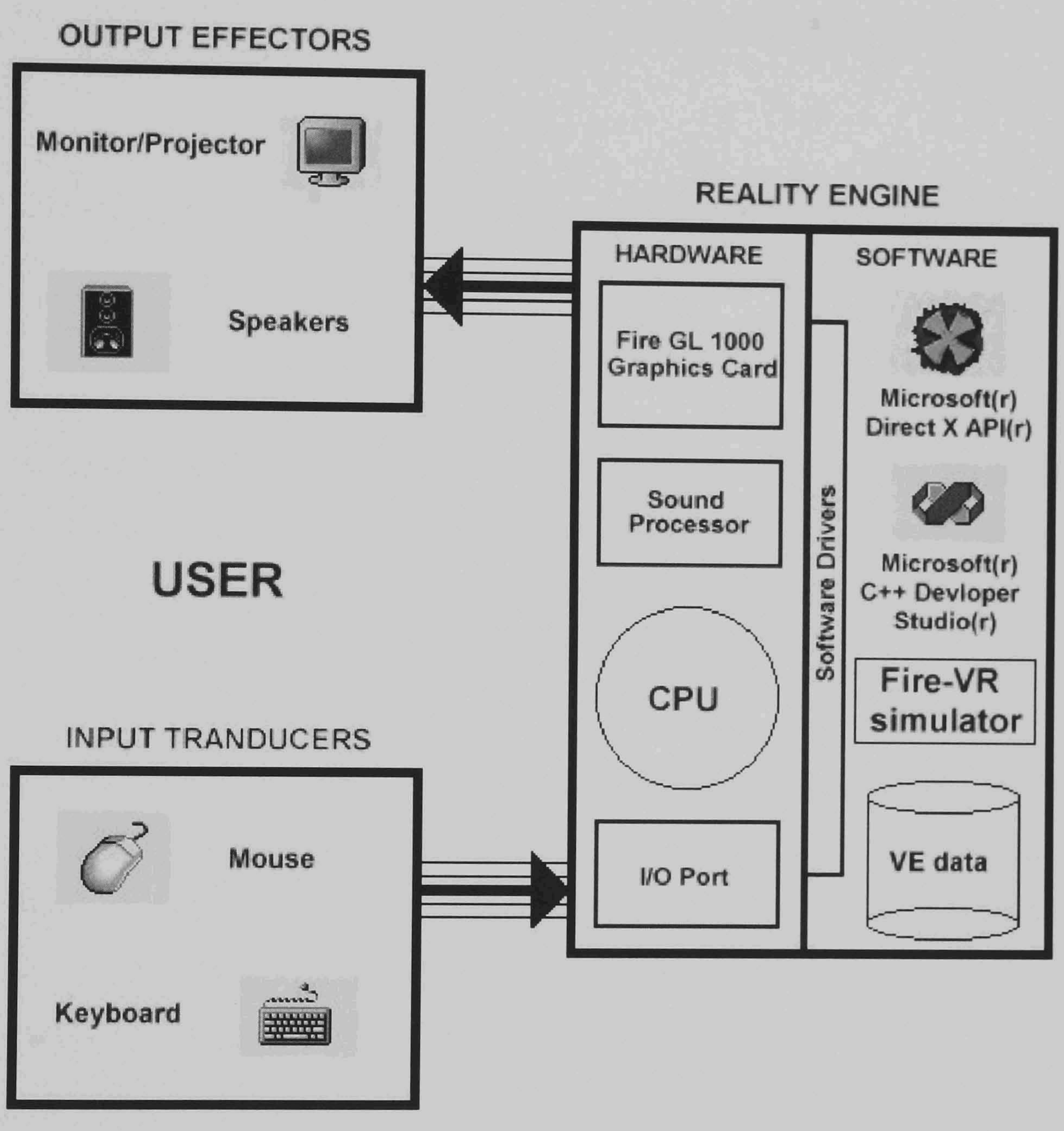

Figure 4. 4 Diagram of VR system design for Fire-VR showing specific hardware and software components.

The main ventilation system (VentSim-VR) performs the iterative process for balancing out a network of inter-segment nodes and calculates the pressure levels which ultimately describe the mine ventilation in terms of volumetric flow rates. Each segment in the network has a variable that holds the volumetric flow rate for that entire length of segment or roadway.

All environmental data and variables such gas concentrations and the programming of spontaneous events are stored and processed in the EnvSim-VR sub-system. Fire-VR subsequently provides the 3D interfaces to the VentSim-VR and EnvSim-VR sub-systems. Hence the integration of these separate components forms the complete simulation model.

In the development stage, two interfaces to the Fire-VR simulation were proposed: -

- **2D Interface**: Used primarily for testing due to its ability to clearly display information from a plan view. It will also be familiar in design to many existing simulation models.

- **3D Interface**: Used to provide the full 3Dimensional view for the Fire-VR system. In this mode, graphics are displayed as real-world objects and as such they have been designed to model their real-world equivalents where computing power constraints have allowed.

Basic input transducers and output effectors were proposed for this prototype research. User interaction is based upon input from a typical mouse and keyboard configuration whilst visual and aural perception of the VE are based around a simple monitor/projector and speaker set-up. Sound processing within the simulation is via a Creative Labs Sound Blaster 16® sound card.

These methods provide a semi-immersive VR situation which is very useable for a prototype system. Other forms of input and output devices are easily interchangeable with little or no software re-write and hence, were considered to be of low importance for a prototype system.

The main computer system is based around an Intel Pentium® microprocessor running at 166MHz with at least 32 Mb of RAM. Software used in the system is based around the Microsoft® visual C++ version 5 programming language which was proposed because of its good integration with the PC platform, its high-level language style and its ability to operate at high speed similar to low-level languages.

The Microsoft® DirectX and specifically the Microsoft® Direct3D API were` proposed as the additional graphical library of functions used to provide 3D graphical support to the Fire-VR simulation. Microsoft® Direct3D API adds additional high level graphical functionality which is used in conjunction with the C++ programming language. DirectX also provides a transparent layer of abstraction across a wide variety of hardware platforms. This means that a variety of different PC platforms can be used, all with different hardware set-ups, without having to re-compiled the software simulation specifically for an individual PC.

4.3.2 Software design of Fire-VR using JSP

The programming of the Fire-VR simulation was structured around the Jackson Structured Programming (JSP) and design methodology (King and Pardoe 1985). Programming, using this method, is based around a tree structure whereby the execution flow of the program travels from the top to bottom and left to right. Iterations are marked with an Asterisk (*) and Conditional paths are marked with an 'O'.

A broad initial representation of the proposed simulation in JSP can be seen in **Figure 4. 5**.

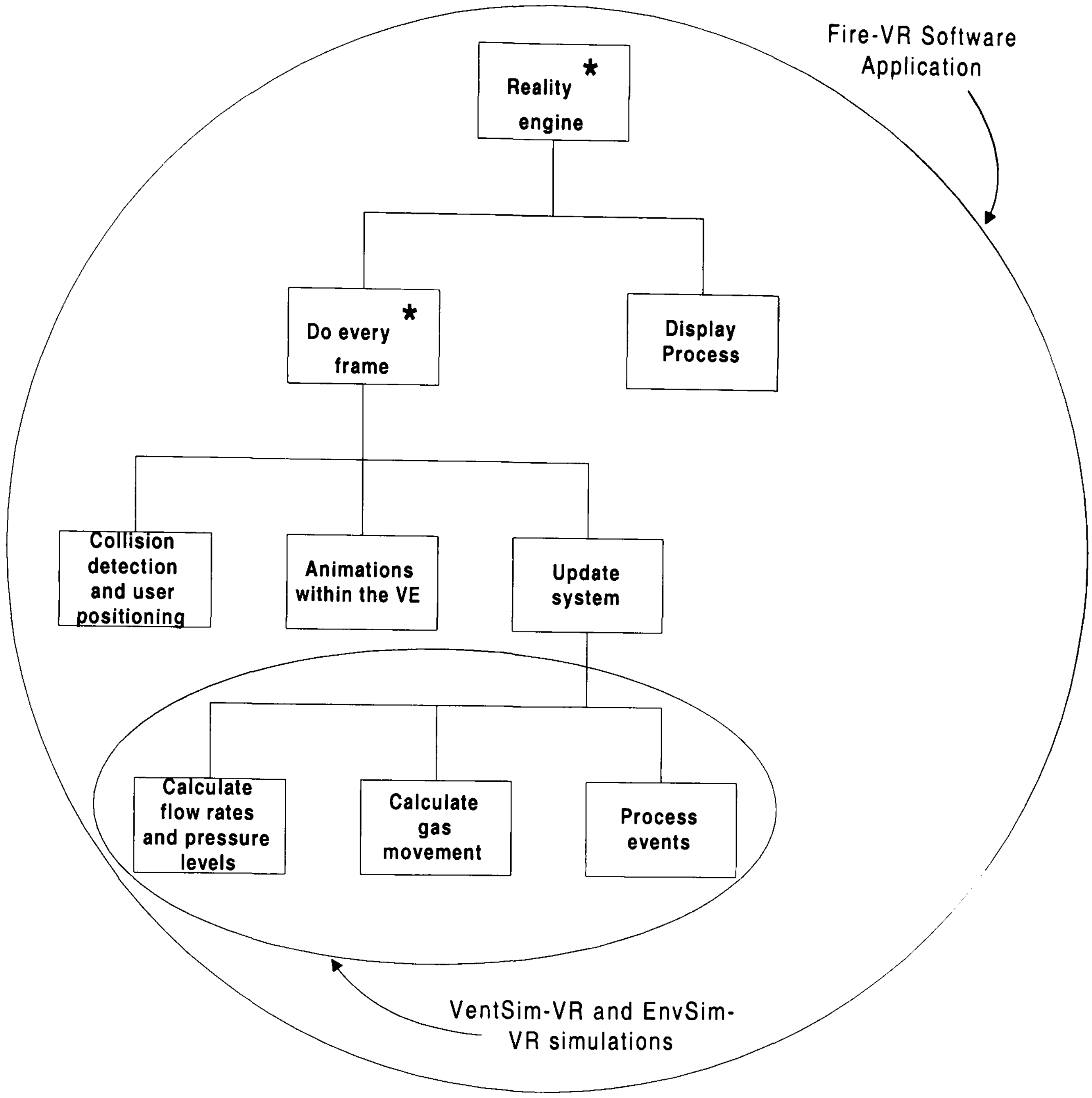

Figure 4. 5 JSP Diagram of Fire-VR (pre-prototype)

In the diagram, the main simulation in the form of VentSim-VR is shown under the process of Update system. Update system is run every frame along with 3D animations such as smoke displays and calculations for user positioning and fault correction techniques such as collision detection. The main program process (Reality engine) is iteratively run with two sub-processes; Do every frame and Display.

4.3.3 VentSim-VR and Fire-VR graphical considerations

Careful consideration was given to analysis the most effective techniques of creating a useful graphical display for the user. Various different techniques were examined and some initial proposals are discussed below.

Different objects were initially considered as a means of displaying flows within the mine networks. In the Fire-VR simulation, translucent arrows were selected as they could be animated to give the impression of flow and also show its direction. An example of this could be the representation of the flow of air within a roadway by the display of an arrow moving at the same rate as the calculated flow rate for that roadway. Other possibilities were considered for displaying variables within the simulation. It was proposed to use transparency as a method of graphically showing smoke which may be translucent and also for the mine and data visuals such as air-flows which are mathematically determined and that would not necessarily be visible in the real world.

Decals were selected as a means of displaying on screen information to the user in a similar form to the head up displays (HUD's) of flight simulators. The application of fogging techniques was also considered in order to increase visual realism as well as its associated benefits from reducing the rear clipping frame (see **Figure 3. 8**).

4.3.4 Editor software for easy construction of case study mine situations

In order to enable the system to be easily adapted for different mining scenarios, an editor program was proposed to be incorporated as part of the research goals. The functions required of this editor were to allow the following to be performed: -

- The creation of mine infra-structure including dimensions of roadways in full 3D space.
- The ability to populate cells of the mine network with objects including vehicles, ventilation doors, fans etc.
- The specification of gaseous levels within each cell at the simulation start time.

- The programming of events based on time intervals.
- The specification of mine ventilation characteristics such as fans, regulators and ventilation doors.

4.4 Summary

A pre-prototype research model using pre-calculated CFD based data for its main input was designed and built. However, it was discounted as unsuitable for application in the main system due to its inflexibility with current desktop PC technology.

A basic overview of the proposed VR system has been described in this chapter based upon the use of the Hardy-Cross iterative network model. The system has been partitioned into 3 main sub-systems. The VentSim-VR system enables the modelling of ventilation flows in an underground mining situation whereas the ability to simulate the effects that fire and explosions would have on the environment is achieved using the separate EnvSim-VR sub-system. Finally, Fire-VR is defined as the surrounding component which encompasses VentSim-VR and EnvSim-VR and provides the graphical capability to provide a 3D output.

Design factors have been taken into account regarding user interface and platform for the software. Different graphical techniques were considered along with their associated benefits.

Finally as an additional design feature, an editor program was proposed as a means of inputting the complex mine structures and data sets.

Chapter Five

Development of Fire-VR; the VentSim-VR and EnvSim-VR Sub-Systems

5.1 Introduction

In the previous chapter, the design of the Fire-VR system was discussed along with pre-prototype research in the form of an example application. This chapter discusses the implementation of the proposed design for Fire-VR.

During the design of the system, many factors had to be considered, not least the computing power that was available at the time of development. Simulations are notoriously computer intensive - this fact, combined with the need to display the simulation with a VR front-end (which generally in itself is mathematically intensive) meant that it was necessary to make a compromise between accuracy and speed. The introduction of additional thermodynamic analysis would subsequently have prevented a near interactive transfer of data into the visualisation engine. Therefore, a simpler modelling approach was adopted which would be representative but not exact of the real process. The Hardy Cross iterative method was selected for use in the simulation in conjunction with a fast 3D rendering engine for the 3D visual aspect of Fire-VR, the aim being to model a complete ventilation system with 3D visuals. The decision to use a desktop PC to model these aspects of the simulation was based on a trade-off between realistic speed and visual realism.

Although suitable in terms of their ability to accurately model ventilation and in some cases also fires, some of the software based packages discussed in section 2.5, were found to be inappropriate for this particular application due to the following reasons: -

- Complexity, where not required, will lead to speed constraints subsequently affecting the ability to achieve a 3D real-time system on one desktop PC.

- Limited ability for user interaction with the ventilation simulation in real-time.
- Inability to output the data and information on a real-time basis for display in a separate 3D sub-system.

The following sections in this chapter describe the component sub-systems of Fire-VR including the VentSim-VR and EnvSim-VR as outlined in **Figure 4. 5**. The way in which real world objects and concepts such as ventilation doors and fans etc. are programmed within the simulation are then discussed. Lastly, key concepts of the simulation are discussed in terms of how aspects of fires and explosions have been designed and programmed into Fire-VR.

5.2 Fire-VR

The main ventilation system, VentSim-VR, performs the iterative process for balancing out the pressure levels in a network of inter-node cells and ultimately describes the mine in terms of volumetric flow rates. Each segment in the network has a variable that holds the volumetric flow rate data for that entire length of segment or roadway (cell). All environmental data and variables are stored in the EnvSim-VR sub-system. Fire-VR provides the 3D interfaces to the VentSim-VR and EnvSim-VR sub-systems.

Fire-VR incorporates both 2D and 3D interfaces: -

1. **2D Interface**: This program was developed primarily for testing due to its ability to display information from a plan view. This Interface is discussed in detail in chapter 6.

2. **3D Interface**: This interface was developed to provide the full 3D view for the Fire-VR system. In this mode, graphics are displayed as objects within a 3D VE. They have been designed to model their real-world equivalents where computing power constraints have allowed. The main interface to Fire-VR is discussed in chapter 7.

5.3 VentSim-VR - modelling ventilation flows

The ventilation system, VentSim-VR, was designed using a combination of Hardy Cross iterative methods and Kirchhoff's laws. These mathematical methods form the basis of the network analysis component of the software and are used to generate an accurate model of a mine network in terms of pressure level gradients, air flow rates and direction of flow within a roadway of pre-defined resistance.

The system was designed so that each segment of roadway could be variable in terms of length and also in total resistance. These features allow a complex network of mine paths to be constructed with varying levels of resolution at specific points. I.e. where detail is not required the network model can be simplified, therefore freeing up computational resources for other areas.

One of the limiting factors of this approach is that this model, on its own, is only able to calculate values for a steady-state network. Transient changes within the ventilation model can be recalculated, however due to the fact that the calculation time to reach each steady-state can vary, this model can lead to non-representative airflows during the determination of flow rates and other environmental characteristics based on these flow rates. Furthermore, in the event of a fire breaking out, it was considered to be computationally impractical to model localised disturbances in the ventilation model such as roll-back (see section 2.3.1) due to the dynamically changing environment. As the growth of a fire is a dynamic process, then a steady-state will only be achieved once the fire has been extinguished or contained. However, VentSim-VR does offer the facility to specify user definable fire profiles which can be programmed according to requirements.

To model the airflow distribution system within the mine ventilation network it was decided to adopt an incompressible Hardy Cross analysis, as commonly employed within many commercial computer programs for ventilation planning. This ventilation model is based around pressure gradients through the mine network and performs a volume flow balance at junctions and pressure drop closure around the meshes of the network. Localised temperature increases, such as those caused by a heating, can also act as a driving force in changing the airflow paths, however these are unaccounted for in this simplified model. In order to take into account these thermodynamic changes then a mass-flow balance based system would have to be incorporated (as opposed to the volumetric model which assumes a constant air density).

These simplifications have had to be incorporated due to the trade off between complexity and computing power available and the need for Fire-VR to be able to produce real-time 3D graphics.

5.3.1 Node and Cell based network

A simple example mine is shown below in **Figure 5. 1**. This mine uses the node and cell based approach outlined in chapter 2 : -

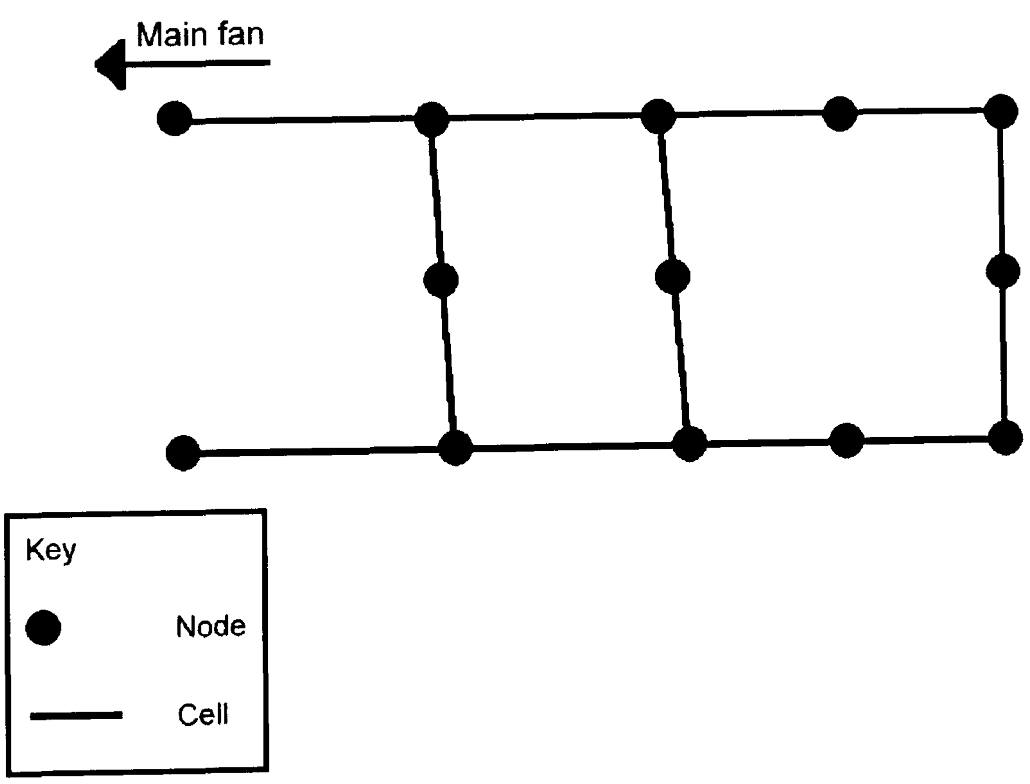

Figure 5. 1 A test network using nodes and cells.

Nodes (see section 1.4.3) of the network are used as calculation points for the pressure levels and each node is connected to its neighbours by one or more cells.

As defined in section 1.4.3, a cell refers to a computer modelled segment of roadway or drivage within the mine when modelled by VentSim-VR with an input node and output node on each end. It is the smallest unit capable of holding environment information and is the fundamental unit used by VentSim-VR to model gas flow and environment changes. The nodes and cells are combined to form the basis of the network.

This method of using a network of interconnected cells is typical of other ventilation systems such as VNetPC®. Each segment of the network can have a specific length and resistance value assigned to it in the form of a data variable.

5.3.2 Data Structures used in the node and cell network

The mine network in VentSim-VR is constructed out of an iteratrion of nodes combined with an iteration of cells as shown in the JSP data structure diagram in **Figure 5. 2** below. [2]

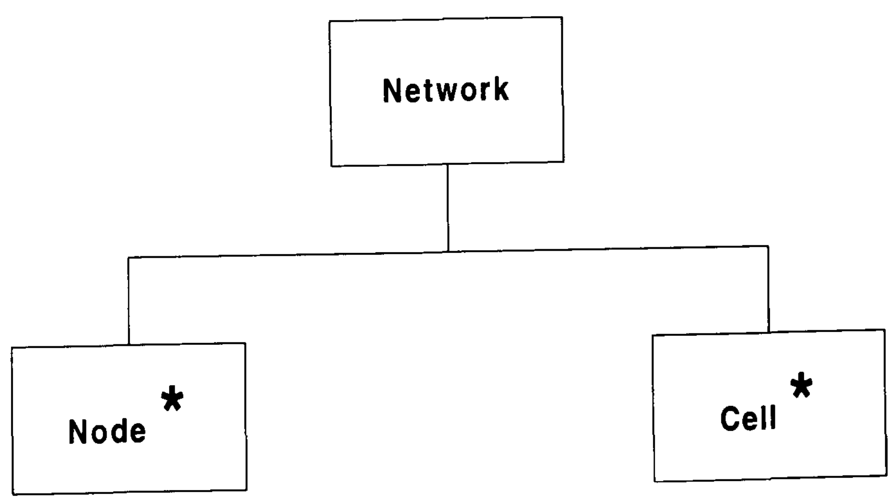

Figure 5. 2 Network data structure for VentSim-VR

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[2] Figures 5.2, 5.3, 5.4 and 5.6 use '*' to define a iteration and 'O' to show a condition.

An easily adaptable data structure was defined to enable environmental information in the form of variable data to be stored and managed within the Fire-VR application. In **Figure 5. 3** this data structure diagram has been expanded in order to show the additional variables that were defined to hold the information required to describe all aspects of the nodes position within world. Screen co-ordinate data and information needed to describe the number of surrounding pathways and the actual cell number for every cell surrounding the node are also held within the data structure. This information was provided to allow the simulation to easily traverse through the network by cross referencing neighbouring cells and nodes.

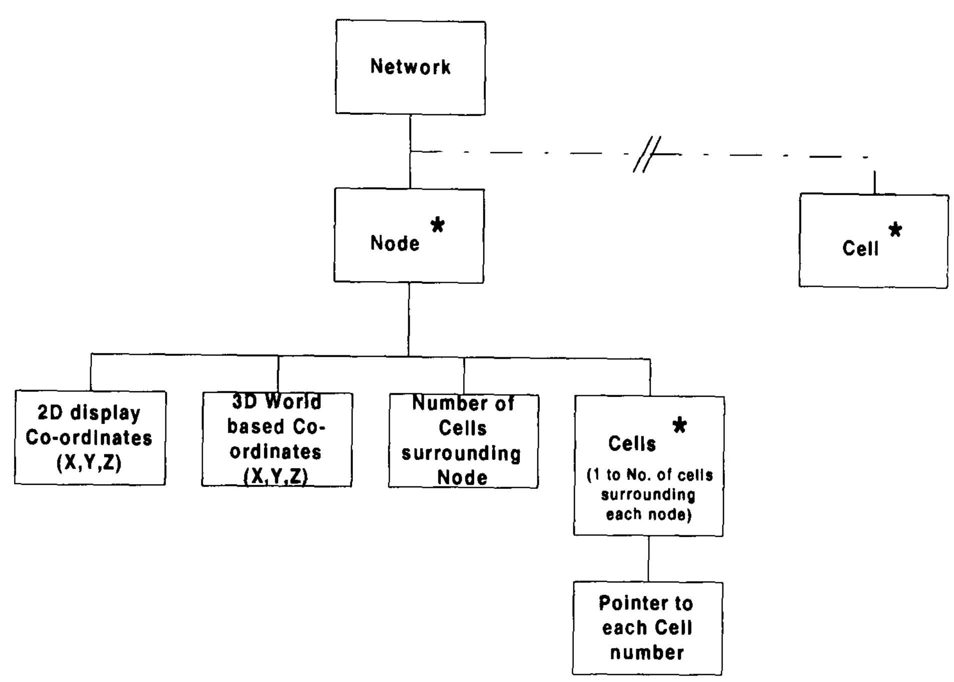


Figure 5. 3 Outline of Node data structure in VentSim-VR

The iterative 'cells' data structure, shown above in **Figure 5. 3**, is used as a method of storing the unique cell number for each of the cells surrounding the node. This enables each node to be specified in terms of its position in relation to other nodes and hence subsequently allows mathematical calculation of traversal paths through the network to be performed.

The data structure of the cells is more complex because they not only have to store their own position in relation to each node within the network, but also environmental variables within each roadway. The data structure for the cells and their relationship to the nodes is shown in **Figure 5. 4** below: -

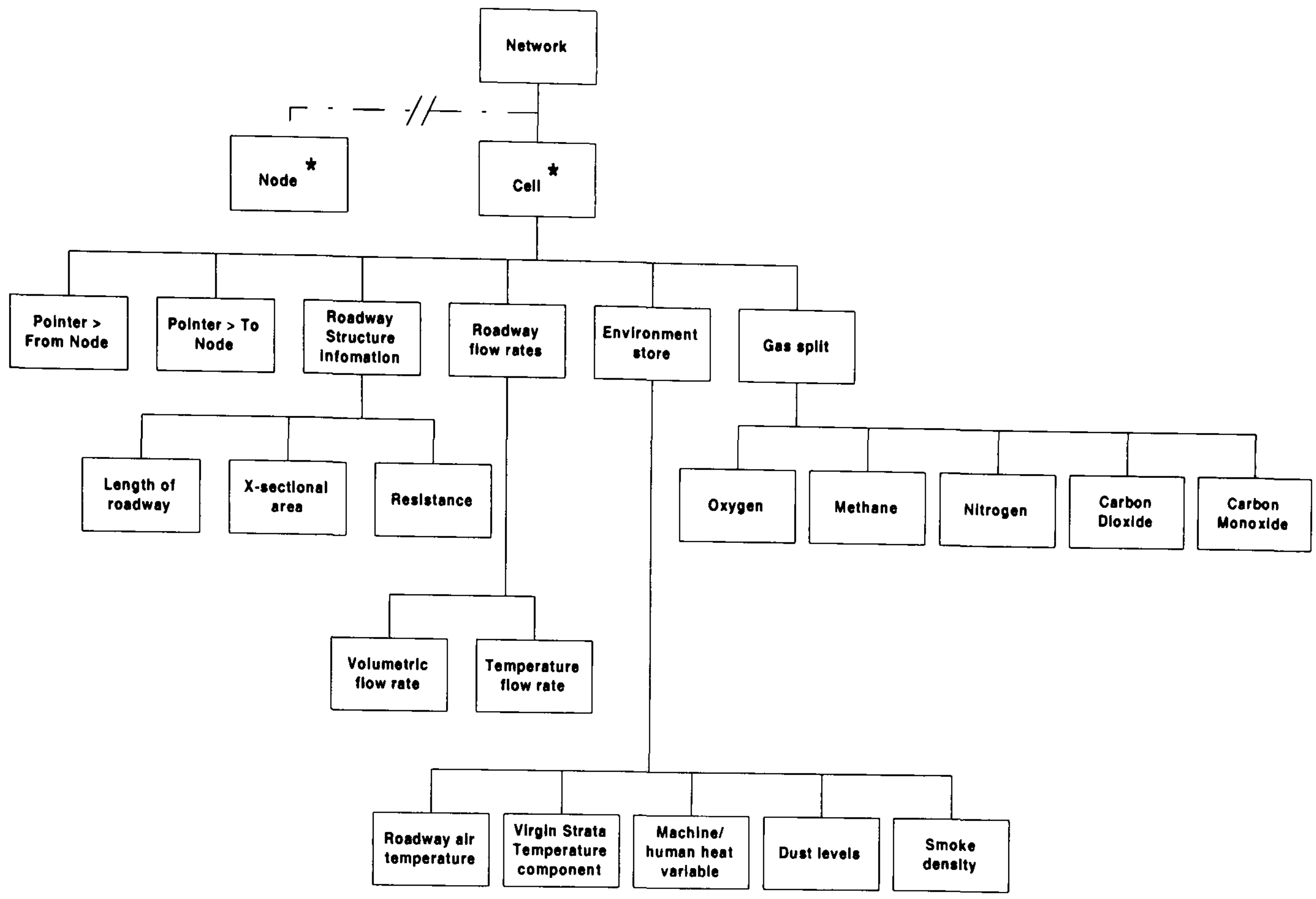


Figure 5. 4 Outline of Cell data structure in VentSim-VR

Additionally, the cell and node data structures are listed in code form in Appendix 2.

5.3.3 VentSim-VR mine network description file

The data structure described in section 5.3.2 above is used to construct the main application mine network description file. This file, which is used by VentSim-VR, consists of three main sections and is a way of defining complex mine network models which can be stored on disk for future use. The first section defines the nodes in the network of roadways in terms of their position and the starting conditions. Initially, the pressure values at each node can be set to zero and the driving force of the main fan can then be used to balance the system out by iterative mathematical network analysis.

The second section consists of the cells or roadway segments that connect across 2 nodes within the network. Again, start-up information is stored such as the percentage quantity of different gases, VST, smoke and dust levels within the cell. It is also necessary to identify which type of cell is being defined i.e. whether it is a simple cell or whether it has specific features such as a fan or a door as discussed later in this chapter.

Finally, the third section of the data file is used to define events which occur within the simulation scope of the model. This area has been set aside to describe driving forces such as fans as well as allowing for events such as fires, explosions, gas liberations etc to be programmed as events for the simulator to process.

Both VentSim-VR 2D schematics and network description files for the mine examples created while researching the Fire-VR program are shown in Appendix 3.

5.3.4 Pressure and flow calculation algorithms

Kirchhoff's second law states that on a closed network, the algebraic sum of all the pressure differences between nodes must equal zero. Although Kirchhoff's laws were originally defined in relation to electrical circuits, they can be considered to be analogous to the air flow within a simple mine network as shown in **Figure 5. 5** below: -

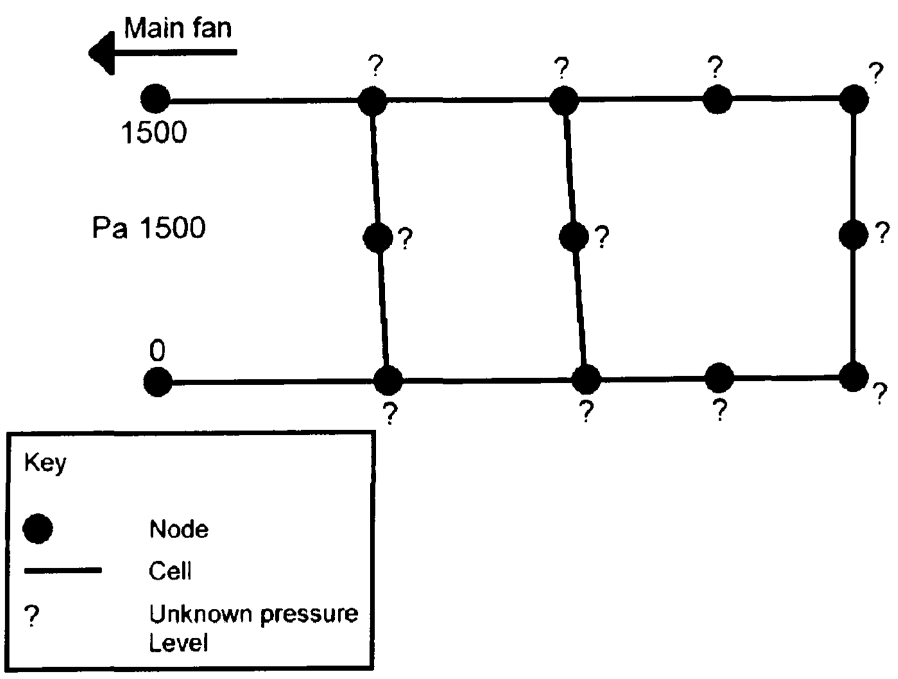


Figure 5. 5 Network showing fan pressure of 1500 Pa

Applying Kirchhoff's second law to the network in **Figure 5. 5**, it can be stated that the nodes with unknown pressure levels (shown as question marks in the diagram) will have pressure drops which upon summation will be equal to the pressure difference created by the main fan, in this case 1500 Pa. The values of the unknown pressure levels across each cell in the network are initially approximated and then iteratively calculated to reduce the error with each pass. By combining Kirchhoff's first law with the iterative process, the network balances out giving a network with pressure values at each node which are analogous to the pressure values that would be present in a real mine.

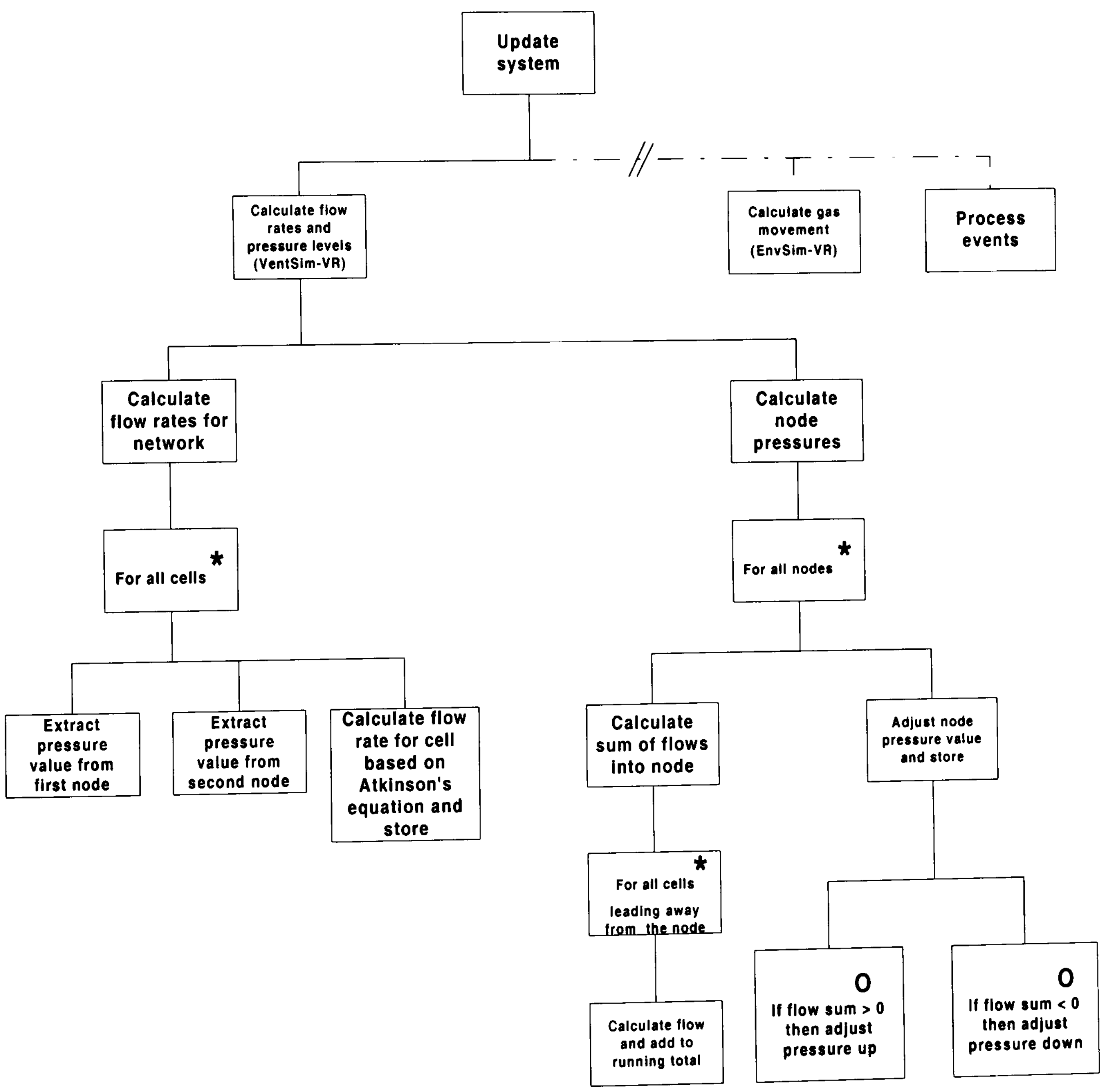


Figure 5. 6 JSP flow diagram for VentSim-VR's flow and pressure calculation procedures based around the Hardy Cross method

Figure 5. 6 above shows the JSP flow diagram for the routines which VentSim-VR uses in order to determine the mine ventilation data in terms of flow rates. There are two main processes involved: -

1. Firstly, the flow rate of air is calculated in each cell using Atkinson's equation (See equation 2.3). This is achieved by initially determining the pressure difference across each cell by calculating the difference in pressure levels of the two nodes. Atkinson's equation is then applied in order to derive the flow rate for that particular cell using a pre-defined resistance value. This process is displayed in the diagram as 'for all cells *'.

2. Secondly, the nodes pressure values are calculated based on a corrective error algorithm. The sum of the flow at each node is first calculated and the value is stored. Depending whether the error of the sum of flows into the node is positive or negative, the pressure value of the individual node is raised or lowered accordingly. At this stage one iteration has occurred. Upon the next iteration a negative feedback loop exists which continuously reduces the error value associated with pressure values at each node.

Balancing of the network occurs because as the error approaches zero on each node then the pressure and flow values for the entire network of nodes and cells are considered to have satisfied Kirchhoff's second law. This process of convergence, however, does take a finite time to complete which is proportional to the change in the pressure values stored in each node. This ventilation model is accurate for a static system, but may have limitations when modelling dynamic changes in ventilation flow. With enhanced computing power and improved algorithms it might become possible to address this issue, however at present, whilst modelling a VR front-end and a ventilation and environment simulation, a simplified model had to be accepted along with the subsequent time delay associated with the balancing routine.

The above methods can be applied to provide a very good approximation of how the pressure levels and flows will behave within the network. Because the simulation needs to model fairly large and complex mine systems the following facility (below in section 5.3.5) was included in order to achieve the necessary detail.

5.3.5 Variable sized roadway lengths using cells (preliminary testing of variable resolution methods)

In order to optimise the system, a multi-resolution feature was necessary. This would enable valuable computing time and resources to be allocated to particular areas according to the level of detail required.

To achieve this, the pressure balancing algorithms need to able to process both high and low resolution pathways. In areas of low interest within the mine network, large segments of roadway can be modelled in one long cell because detail is not needed in that area.

Figure 5. 7 below shows an example network with three pathways for the airflow.

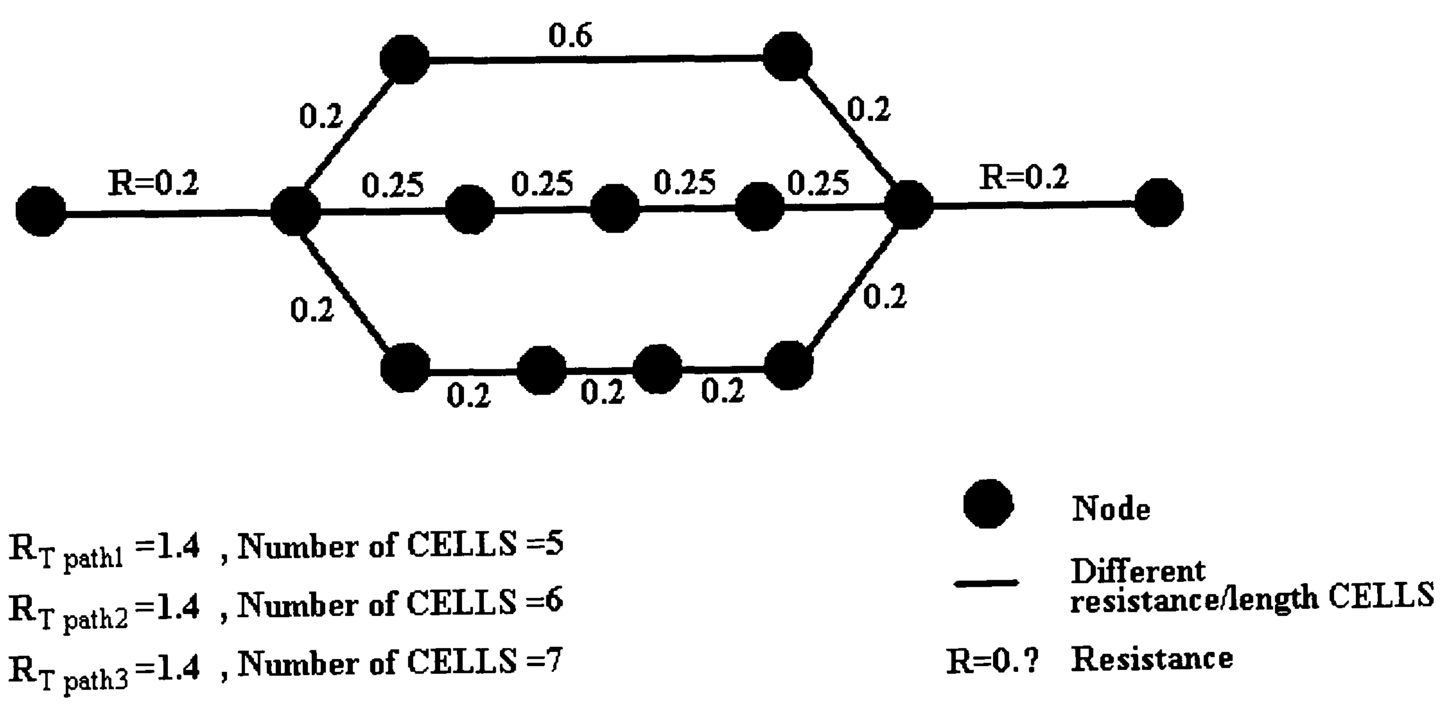


Figure 5. 7 Network showing split flows and differing resolution by varying the cell numbers in each path.

In this example it can be seen that although path 3 contains more cells within the path, it has an equal resistance for the entire path to that of paths 1 and 2 (each path has a total resistance of 1.4, arbitrary units).

Path 3 is an example of an area where the simulation is known to have a lot of detail and therefore a greater number of nodes and cells are used to provide this detail in the form of additional resolution. Path 1 is an example of an area with little detail. In a real-life situation this could be a long section of roadway which is not frequently used but is still within the ventilation system. For a greater number of cells / nodes within the simulation then a finer resolution of information will be possible. Hence, this gives the opportunity for greater detail discussed previously.

By using the above example with 3 paths all with the same resistance, it was straight forward to test that the ventilation algorithms were working correctly.

The above example was tested with a fan providing the driving force for the air-flow and allowed to balance out. If the algorithms were working correctly then the relative pressure levels throughout the network would be equal which would lead to equal quantities of gas being driven through each path of the network.

Effectively this means that volumetric flow rates through all three paths would be equal, however path 3 would have a greater resolution of detail, along with the most computational overheads whilst the opposite would apply to path 1.

The pressure difference across each cell can be simply checked by applying the equations specified in section 2.1.

$$P_{\text{pressure difference across cell}} = Q^2 R_{\text{cell}}$$

The flow rate (Q) is assumed to be equal because each path has equal resistance i.e. the same Head-loss occurs over the entire split. Using a known resistance for each cell and a known flow, the pressure drop across the cell can be determined: -

If flow (Q) across the split is defined as 10 m^3 s^{-1} then the pressure drop across the cell with a resistance of 0.6 (path 1) will be : -

$10^2 * 0.6 = 60$

So there is 60 N m^{-2} pressure difference across the cell.

By calculating the pressure drop across each cell and summing for each path it is found that the total pressure drop in each path is equal. This concludes that using a cell based approach to refining resolution within differing paths is possible and shall be used as a method of providing various detail levels within a mine network.

5.4 EnvSim-VR - Modelling the environment

The main ventilation system, VentSim-VR, provides the iterative process for balancing out a network of inter-cell nodes and calculates the pressure levels which are then converted into volumetric flow rates using Atkinson's equation. Each cell in the network has a variable which contains the volumetric flow rate for that entire length of roadway. EnvSim-VR is the sub system which is concerned with other environmental components of the simulation.

Three parts to EnvSim-VR were created; when combined they provide a comprehensive system able to model most environmental aspects of a mine.

- Firstly EnvSim-VR creates objects within the world which are present that have a direct effect on the ventilation model. Section 5.4.1 describes the methods that have been programmed to deal with ventilation doors, regulators and fans etc.

- Section 5.4.2 describes the algorithms used by EnvSim-VR to monitor gaseous movement throughout the mine. VentSim-VR provides the programmed functionality which calculates mass-air flow through the mine. EnvSim-VR calculates the individual gas component movement throughout the mine in terms of the gas-split percentage composition of the air-flow. A 'packet' based air-flow split algorithm is described in this section which maintains conservation of energy laws while simulating the movement of the gases through the mine using data obtained from VentSim-VR.

- Finally in section 5.4.3, the third part to EnvSim-VR is concerned with tracking events which occur throughout the mine simulation. Two types of events have been programmed; events which are built inherently into the system as part of the original mine description file including events such as the release of CH_4 into a particular cell, simulating a build-up of fire damp or a fire. Active components such as fans or pre-programmed explosions set to occur at specific time intervals are also included. Secondly, spontaneously occurring events have been programmed in a linked-list format that allows events which are the direct result of pre-determined criteria to be dealt with. Examples of these type of events could be an explosion occurring when a cell's condition matches a pre-programmed specification based around Cowards diagram (see **Figure 2. 3**).

The following environmental factors were considered, based around knowledge amounted from researching the causes of mine fires and explosions documented in chapter 2 : -

- Temperature of the segment of roadway air
- Cell strata heat or VST
- Machine heat
- Potential energy of strata
- Coal dust

- Resistance of roadway

These environmental variables are described in relation to other data structures within the simulation in **Figure 5. 4**.

The above variables were stored for each cell within the network. Additionally, the following variables were stored for each cell which describe the current environmental factors which exist within a cell segment of roadway. These include: -

- Smoke levels within the cell
- Gas levels of oxygen, methane, nitrogen, carbon dioxide and carbon monoxide levels within a cell

The gas and smoke levels are stored in each cell and hence, provide information of particular gases (O_2, CO_2 etc) or smoke in a particular area of the mine. The breakdown of gases is displayed on a real-time basis thus providing not only a ventilation system within a mine environment but also a realistic view of the environmental factors within the system.

The data variables stored in each cell combined with the ventilation flow system provide a method of simulating the actual flow of constituent gases around the mine which is more useful information than simply modelling the general ventilation flow of air.

For the actual movement of gases around the mine, an algorithm was developed which adjusts the quantity of each gaseous component by a proportional amount relative to the flow rate at the particular cell. This is updated on a per-cell basis and occurs every frame. A scaling factor variable was used so as to make it possible to either adjust the flow rates to suit realistic conditions or to have a scaling factor to speed up the simulation.

By creating a solid environment system in conjunction with the VentSim-VR sub-system a provision for modelling explosions and fires has been created.

5.4.1 Simulating the world objects within EnvSim-VR

Provision was made within the cell data structure so that certain characteristics could be associated with a cell, allowing the system to model various world objects such as doors, fans etc. These features are modelled by programming special functionality into the cells and are activated by the use of an event processing sub-system (see section 5.4.4).

The network description file was programmed to allow this additional functionality of cells. The size of each of these special cells needs to be considered when the user is programming the features into the simulation. E.g a ventilation door cell should not be very large in size as typically a ventilation door might only by a few inches thick whilst a cell designated to be a fan could be considerably thicker.

a) World cell

The world cell was implemented within the system to create the continuous path which defines a closed network. This important component has been labelled as the world cell because it is synonymous with the outside world part of a mine. Each mine has one or more intake entrances and one or more upcast shafts. They are connected via the outside 'world' and consequently this is modelled within the system via a connecting path within the network.

Each mine has at least one driving force (fan) behind it. Pressure values across the fan can be held at a rating that dictates the operating conditions within the mine. E.g this head force could typically be 1500Pa. The pressure distribution levels are balanced out across the nodes within the network with the iterative process defined in section 5.3.

The world cell has been programmed with the assumption that it would have negligible resistance. This approximation is appropriate because the world air space can be considered as near infinite – by substituting a large air space with that of a very low resistance this condition can be successfully approximated in the simulation.

Two additional factors have been utilised by using the world cell approach.

Firstly by having a world cell, a method for 'cleaning' became available. As fresh air is drawn into the cell, it can be normalised against set pre-programmed values of oxygen, heat etc. This effect was programmed into EnvSim-VR to maintain the continuous loop of the closed network via a method of direct substitution of the existing environmental data values returning to the surface with standard values for fresh air based on a user definable pre-calculated ratio.

Secondly a simulated surface mounted gas monitoring station was programmed. With the world cell it is possible to monitor the environment within the mine in a similar way to how real mines are monitored for environmental changes. By comparing upcast and downcast environmental factors (i.e. recording input and output cells gas levels) information can be quickly generated about how the mine ventilation system is behaving. For example, Grahams Ratio (see section 2.3.2) compares the proportion of CO/O_2 deficiency with values which enter the mine and therefore this ratio can be used to show a heating.

A number of assumptions were made in this simulation model : -

1. The normal composition of return air of a mine district was as follows : -

- Oxygen O_2 19.95%
- Nitrogen N_2 78.83%
- Methane CH_4 0.64%

- Carbon Monoxide CO 0.005%
- Carbon Dioxide CO_2 0.58%

2. That the nodes to and from the world cell are set at zero Pa (or N/m^2). This is used to set the relative pressure levels around the mine system. Any fluctuations in air pressure that might occur due to atmospheric pressure changes are neglected.

b) Fan Cells

For simulation purposes there are two major types of fans which need to be modelled – Main fans and Booster fans. They hold a pressure difference between the two nodes each side of the fan. Fan characteristics have been omitted for simple networks and a steady driving force was used instead for simplicity. Fan characteristic curves are used to describe how the fans driving force is changed under load conditions – provision for inserting real fan characteristics was included in the prototype system.

The main fan and booster fan sub-routines have been programmed with slightly different functionality.

Main fan

By holding one of the nodes of the main fan at zero Pa (or N/m^2) a working main fan can be simulated. Zero Pa was used as a reference to the pressure at ground level and all other pressure values are also relative to this value. The other node of the main fan cell can then be artificially driven up to a set value (which is usually the fan rating) over a period of time, taking the load into account in order that fan characteristics are modelled. This provides a pressure difference across the fan cell in a similar way to a battery generating a potential difference. This in turn provides a driving force for air-flow within the network.

Booster fan

Booster / auxiliary fans, although essentially just smaller versions of the main fan, are generally placed deep within the mine to provide a boost to the air-flow and to aid in air-flow management. They differ in terms of programming in this simulation because the node on one side of the fan cell cannot be set to zero Pa. (Because the booster fans are additional to the main air-flow driving force, which is normalised to zero Pa, a relative source of additional air-flow must be provided). In the main fan example, the pressure at one side of the fan cell could be set because the position of the main fan is at the surface and pressure values on a closed network have to be normalised to a reference value. (In this case the reference can be set because the outside pressure fluctuation is assumed to be negligible).

The problem of being able to model booster / auxiliary fans within the ventilation simulation was overcome by introducing a method of creating a pressure difference across the booster fan cell (thus providing the driving force for the fan), as well as being a relative pressure source to the main fan. The booster fan was programmed by adjusting both nodes, each side of the booster fan cell, by a relative amount (as opposed to simply setting one relative to zero Pa as in the main fan example, as shown in **Figure 5. 8** below.

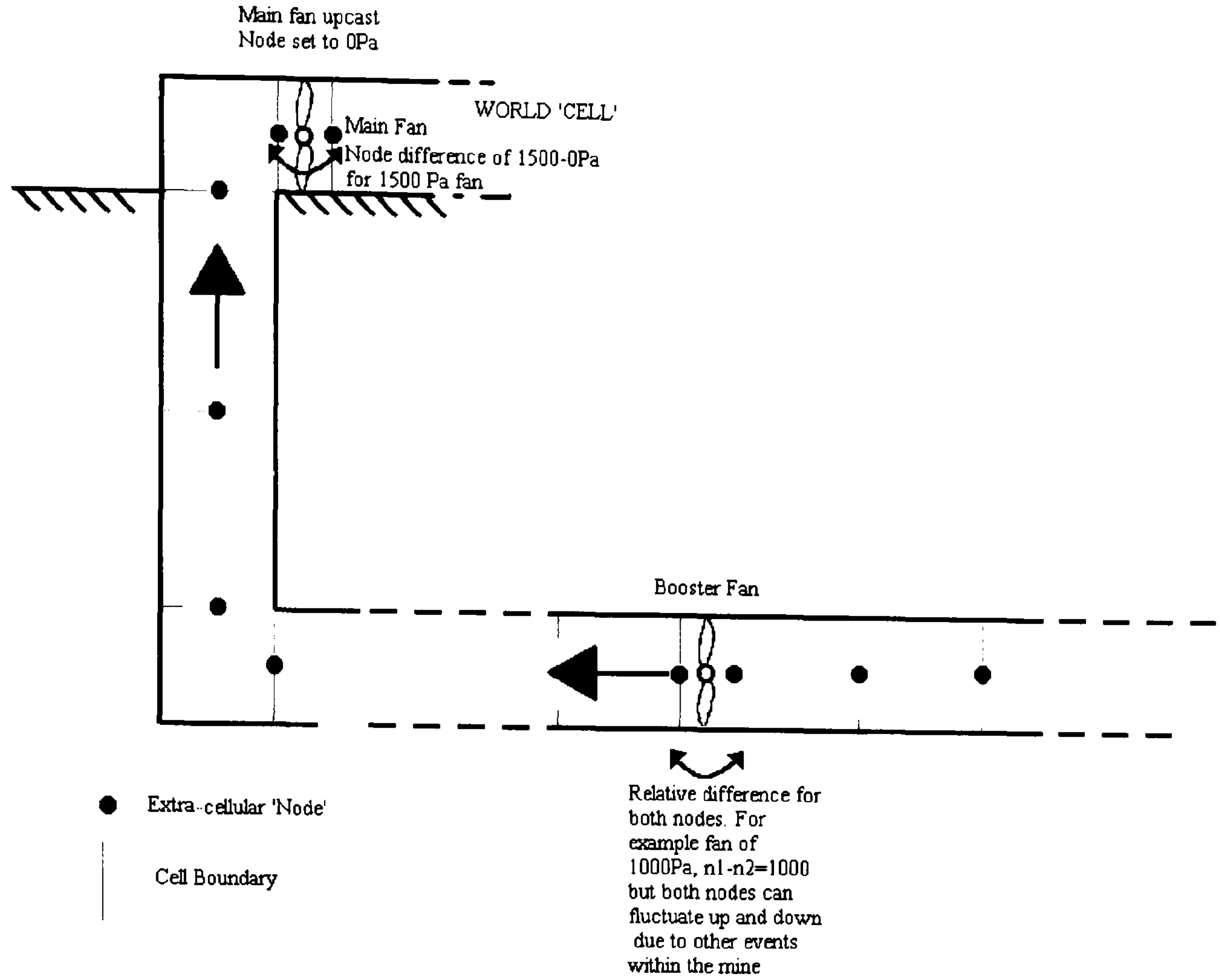


Figure 5. 8 Example of Main and Booster fan simulation techniques

The force of the booster fan will produce a different pressure drop across the cell depending on various effects such as load, back pressure etc. The pressure levels of the nodes either side of the booster fan cells can move relative to the pressure levels in adjacent cells. This allows the correct operation of the booster fan under various conditions which might occur elsewhere in the mine system. An example of this might be an explosion event further back in the mine which has affected the pressure values of the whole mine ventilation system, however the booster fan will still produce its driving force which is in addition to the pressure levels generated by the main fan and any significant event that has recently occurred.

Booster fans can be seen as a relative additional component to the main fan pressure. In terms of programming, this can be achieved by 2 steps: -

- Create the pressure difference across the booster fan.

- Allow the fan to be included in the iterative pressure balancing algorithm as an entity in itself (this stops the pressure difference across the fan from being smoothed out).

Another important consideration, and also a way of justifying using this complex way of simulating the booster fans, is that of what happens when an explosion further back within the mine occurs which has the effect of producing such a large amount of back pressure (due to the effects of implosion after the initial explosion). Or alternatively, what happens when an explosion occurs, resulting in a blast of air (a driving force it itself) which should theoretically add to the driving force produced by the fan cell?

The method described copes with of both these of these situations completely because the booster fan is working relative to all of the pressure values that already exist within the mine network. E.g. If the blast of an explosion is travelling down a section of roadway towards a fan cell which is operating in an opposed direction then the fan will provide a certain amount of dampening to the explosion as long as the characteristics of the fan are still within specification.

The same applies to the situation where the fan direction is in line with the air-flow produced by the blast. In this case, however, the fan pressure driving force is added to the blast driving force as long as the fan characteristics are still within specification. Fan characteristics are important because fans can become overloaded and they can also stall if there is a lack of air between the blades. In the case of explosions, which often cause very severe changes in pressure levels, it is quite feasible that the fans which are in the near vicinity might be effected albeit temporarily.

c) Ventilation door cells

Doors within the mine are frequently used to control ventilation. By careful manipulation of the ventilation by the opening and shutting of doors, drastic effects on ventilation can be achieved.

With careful planning, the opening of short circuiting doors can have the effect of restricting air-flow to certain areas of the mine and increasing flow to other areas. This is an extremely valuable option for use in mine evacuation practices i.e. the air flow can be re-directed according to the situation.

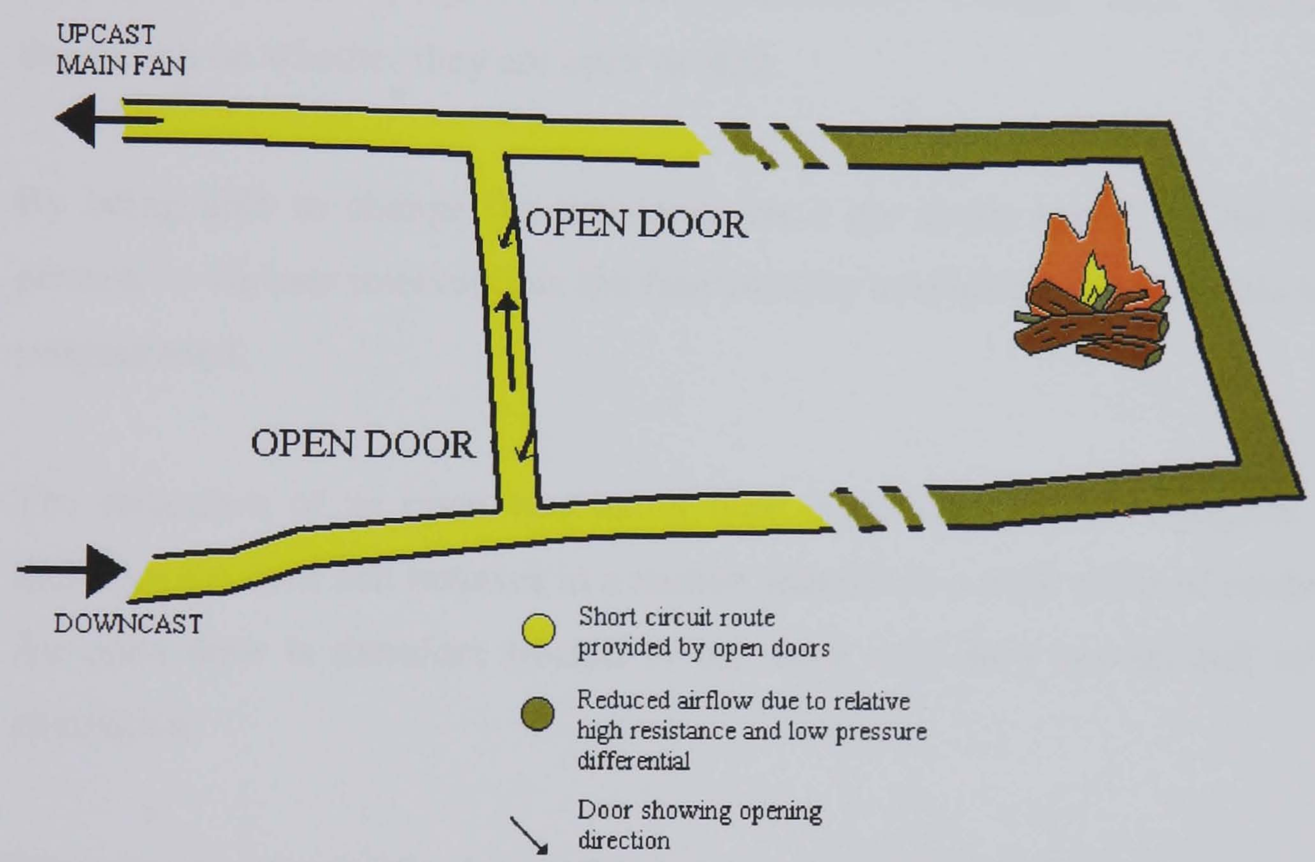


Figure 5. 9 Ventilation being drastically altered by opening ventilation doors

In a real-life situation, it may seem logical to prevent the flow of air to a fire because the oxygen component of the fire-triangle is being removed. However, this can generally not be achieved because of two reasons: -

- It is usually impossible to reduce the oxygen content to a sufficiently low level in order to inhibit combustion, primarily because natural ventilation is still present.

- The cooling effect of air flowing through the mine is of great importance in preventing the spread of fire. By reducing the flow of air using ventilation doors, heat could build up very quickly in certain areas which are now insufficiently ventilated, thus potentially causing further hazards.

Doors are used within a mine in order to restrict air-flow. The pressure difference across an open door will create an air-flow through the door. This can be also applied to that of a door cell in the simulation by creating a special case cell for a door within EnvSim-VR. These cells have all of the characteristics of normal cells including length, cross sectional area, variables for gas, other environmental factors such as smoke etc, but an additional facility has been programmed to dynamically change their resistance depending on whether they are open or shut.

By being able to change the resistance on a per event basis, via the inject process or via user intervention, the functionality to model mine doors has been programmed.

The resistance of an open ventilation door is assumed to be negligible and therefore the door cell behaves in a similar manner to a short piece of roadway. An open door is therefore treated in the same way as a normal cell in the simulation.

When the resistance of a door cell is increased, compared to the resistance of a typical section of roadway, then the door behaves like it is closed. In this situation, the ventilation system quickly adjusts the nodes each side of the door cell to achieve near-zero pressure difference and in turn this provides near-zero airflow.

Programming the facility of the system to enable user interaction to open and closed doors is extremely powerful as this has a direct use in the training of staff to manage mine ventilation systems.

d) Regulator cells

Regulators are also frequently used to control ventilation. Regulators are panels set in ventilation doors which can be opened accordingly to variable levels thus allowing adjustments to the ventilation paths to be made. By installing regulators in a mine, the effects of resistance of each path can subsequently be set and controlled. This is useful if the flow in one path of the network is constantly changing due to heavy mining activity. By changing the resistance of a path, the flow through that path can be controlled accordingly. The net result of this is that a variable resistance to air is achievable within the path.

The function of regulator cells was modelled by VentSim-VR because the C++ code to change the resistance in the doors was already programmed as part of the mine loading up routines. For the regulators, the resistance of the door is graduated from fully closed to partially open in order to model the effect of the regulator being adjusted.

e) Permanent and temporary stoppings

Stoppings, both permanent and temporary, can be modelled in EnvSim-VR by increasing the resistance of a cell to near infinite. In practice, raising the cells resistance by a factor of between 20 and 50 times the usual amount gives a realistic stopping effect to the air flow through the cells path. Stoppings can be pre-programmed by adjusting the mine description file via the appropriate cells resistance data value.

f) Firedamp and gaseous liberation from the strata

The simulation of a methane build up can quickly be achieved using EnvSim-VR. Any cell within the network has the ability to have an event assigned to it so that certain gases are liberated into the cell. Typically, methane may be released into the roadway and if there is insufficient ventilation, a build up of gas can occur. Hence, this is an example of where Fire-VR can be used to demonstrate the importance of maintaining good ventilation practices.

EnvSim-VR can model this effect of gaseous build up very well. E.g for methane, an event can be programmed and the ventilation process initiated. If the production of methane liberated into the section of roadway is greater than that removed by the ventilating air-flow then a build up of methane occurs. After the methane source is removed or it naturally reduces, EnvSim-VR can model the dispersion of the gas as it mixes with fresh air provided by the ventilation system modelled by VentSim-VR.

g) Modelling Fires

As discussed earlier in section 2.3.1, the causes of fires within the mining environment can typically be attributed to one of the following categories: -

- Conveyor belts.
- Mechanical overheating.
- Combustible materials.
- Electrical faults.
- Spontaneous combustion.

The system was programmed to be able to cope with a variety of generic and specialised fire situations, which were achievable within the boundaries enforced by computing power restrictions. Within the cell based structure of the mine network, two methods of creating fires were programmed, each of which has the ability to induce further fires in a chain type reaction.

Fires can either be started using the 'inject' method detailed in section 5.4.4 part a. or by a spontaneous event which occurs because the environmental conditions are sufficient for combustion to occur (see section on Spontaneous Events in 5.4.4 part b).

This gives the flexibility of producing a series of events which are defined prior to the running of the simulation and also the ability to model the ever changing environmental system which is dynamic in nature in terms of spontaneous events.

The first of these options, the 'injection' method, enables events to be precisely tracked because they are set up by the user before the simulation is started i.e. they are a known quantity in terms of burn rate, length of burn and position etc.

The second of these options, that of spontaneous events, have been programmed to occur, as in a real situation, when certain conditions are fulfilled. These parallel the 'injection' events, differing only in the fact that they are dynamic in nature. Events such as these are created and destroyed when needed by the simulation and managed by a separate event processing routine outlined in section 5.4.4.

A typical example (shown in **Figure 5. 10**) utilising both of these methods in a mine network was set-up to model the progression of a mine fire through a ventilated section of roadway. [3]

Figure 5. 10 VentSim-VR modelling a strata fire with the 2D Interface

In the above diagrammatic representation of a section of roadway, split into cells, the starting strata fire can clearly be seen. In the example shown, the fire has been modelled using the 'Injection' method. This allows the fire to be started in a position specified by the user.

[3] Figures 5.10,11,12,13 are generated from the 2D interface discussed in Chapter 6.

To assist readability of the diagram, a limited number of environmental factors are shown namely: -

- Oxygen content of the cell (set at approximately 20.0% to represent the normal concentration of oxygen in air)
- Heat within each cell (measured in relative units at present)
- Heat developed from the strata (set as 10.0 arbitrary units in the above example)
- Smoke in the form of progressively darkening grey circles
- Relative heat shown with progressively darkening orange arrows

Once the 'Injection' fire has been started (denoted by the far right strata fire cell), it can clearly be seen that certain environmental events are occurring.

Differences in ventilation, the availability and sources of fuel and the fact that fire is a chaotic phenomenon meant that the simulation had to be designed with the ability to be easily configured.

The provision to insert different fire profiles has been programmed which gives the facility of modelling different types of fires within the simulation. Each profile can specify the amount of particular gases which are produced and consumed during the combustion process. It is beyond the scope of this research to define profiles for individual fire scenarios, but this ability to profile events allows flexibility in creating specific case studies for future work.

In the simulation, a number of environmental effects have been programmed when the 'Injection' fire starts. These are : -

- Fuel within the cell is consumed until the fuel supply is diminished. This implements the 'fuel' side of the 'fire triangle'. (See section 1.3.5 Underground fire fighting.)

- Oxygen is consumed from the burning cell. This implements the 'oxygen' side of the 'fire triangle'.
- Smoke is produced from the burning cell at a configurable rate.
- Various gases are produced as a by-product to the burning process, in particular carbon dioxide and carbon monoxide. The quantities released are again configurable.
- Heat is also produced in significant quantities.

With the above conditional rules programmed into the event processing routines, spontaneous events can be modelled. In the example below, the cells adjacent to the primary injection cell can be seen to be burning and hence are event based fires. That is to say they have been created dynamically by the simulation based on the conditions and rules described above. The fires are initiated when heat within the cells reaches a pre-defined temperature. Because heat is being forced along the roadway in the direction of the ventilation airflow, the fire subsequently propagates along the roadway, as shown in **Figure 5. 11** below.

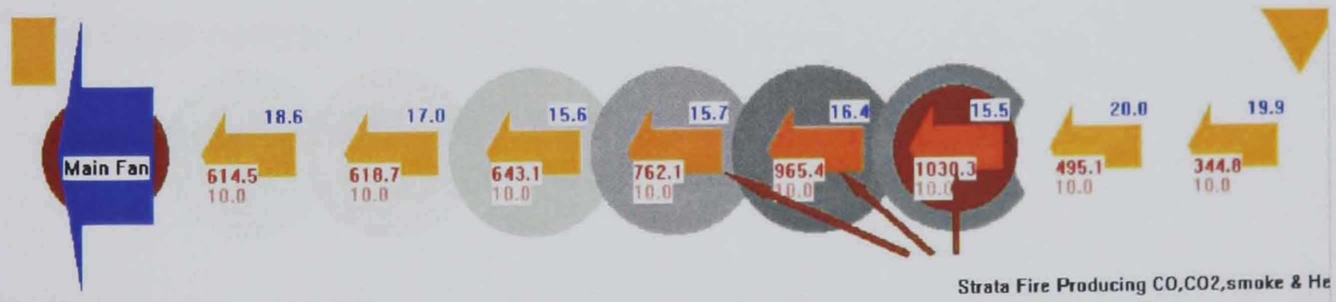


Figure 5. 11 Strata fire after progression down roadway

By programming the rules for various spontaneous events, many different situations can be modelled. The reaction of user interactivity can also be tested in training sessions to assess how they would manage a pending situation.

h) Modelling Explosions

Similar conditions and rules were specified and programmed for the modelling of explosion events within the simulation.

By using a combination of the following techniques and defined processing systems a representative model of explosion events was produced.

Firstly, the event processing system can be used to spark off new events such as explosions when the right conditions are met. These conditions are directly computed from the event processing system using virtual sensor information from the event processing procedure.

A simple example of an explosion event was programmed by setting off the explosion event processing routine when the following conditions were met : -

- Methane content is greater than 5% in air.
- Oxygen content is greater than 10% in air.
- Methane content is less than 14% in air.
- Oxygen content is less than 20% in air.

These simple conditions allow for spontaneous explosion events to be modelled. It can be seen that the above linear conditions create a rectangular 'window' of explositivity whose lower boundaries are similar to that of 'Coward's triangle' (see **Figure 2. 3**).

This simplified model was considered sufficient for testing purposes because in a real mining situation there is likely to be more concern about the lower levels of explositivity rather than the upper levels. This is because in a well ventilated mine, the conditions needed to cause an explosion are likely to be met from the lower end as methane builds up to dangerous levels, rather than reducing to explosive levels from high levels of methane.

The system had to be able to cope with a variety of generic and specialised explosion situations, but remain within the boundaries specified by the restrictions of computing power.

In a similar manner to the fire processing system, the explosion processing system has been designed with both the 'injection' method (events provided at the network design time) and the 'event' method (that which is truly spontaneous and dynamic at run-time).

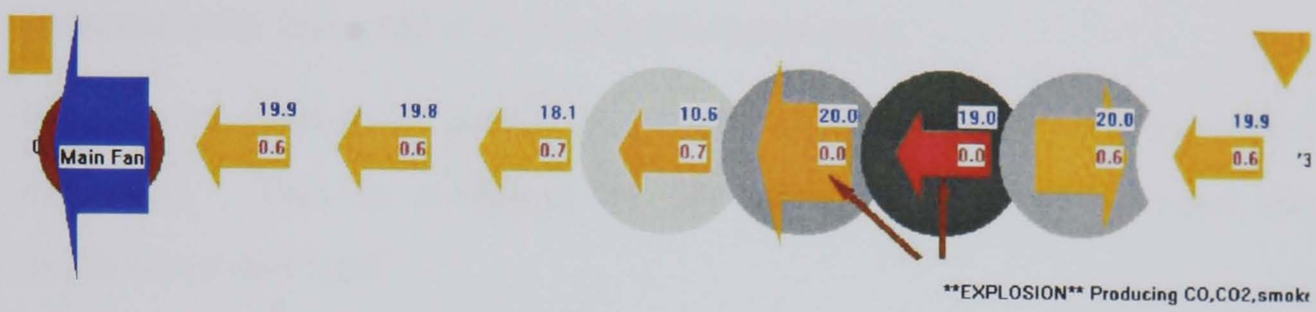


Figure 5. 12 VentSim-VR modelling an explosion with the 2D Interface

In the diagram above (**Figure 5. 12**), the 'injection' explosion can clearly be seen. The phenomenal heat produced is indicated by the red arrow. The arrow directions of each cell either side of the explosion cell are opposing, thus demonstrating the blast effect which is caused by the sudden increase in pressure at the point of the explosion. The diagram also shows that the methane in the cell has been consumed, indicated by the red digits; which in the case of the explosion cell have been reduced to zero.

In the simulation a number of environmental effects have been programmed when the 'Injection' explosion occurs. These are : -

- Any explosive gas mix is consumed at a rate which is configurable.
- Pressure around the 'cell' increases to simulate the expanding gases caused by the explosion.
- Fuel within the cell is consumed at a configurable rate.
- Oxygen is consumed from the cell which is classed as burning.

- Smoke is produced from the burning gas at a rate which is configurable.
- Various gases are produced as a by-product of the combustion process, in particular carbon dioxide and carbon monoxide. The quantities released are configurable.
- Heat is also produced in significant amounts. The heat from this part of the event / injection will cause a chain reaction transferring heat to the neighbouring 'cells'. Additionally, conditions may be met for new fire events to occur. (This is why, in some of the diagrams, fires have spontaneously occurred after the initial explosion.)
- Finally, an implosion occurs due to a vacuum created by the initial explosion. This is modelled by decreasing the pressure around the explosion event 'cell'.

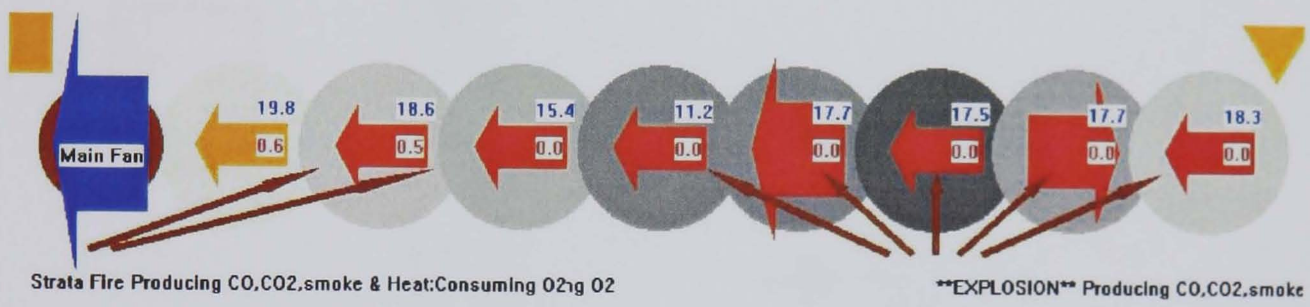


Figure 5. 13 Chain reaction effect of an explosion with the 2D Interface

In the above diagram (**Figure 5. 13**), the propagating effect of one 'injection' explosion creates a chain reaction of events along the roadway. The initial explosion has occurred causing extreme temperature changes which leads to the ignition of the methane in the surrounding cells. Because the proportion of methane to oxygen satisfies the conditions specified above in the approximate Cowards 'triangle' the effect is that the explosion sweeps through the entire roadway, combusting the available methane creating pressure waves as each cell explodes.

5.4.2 Air packet movement and proportion based gas-split algorithm

In addition to simulating the ventilation system in terms of flow, resistance and pressure, it is also necessary to simulate the movement of actual gas constituent components within each cell, i.e. how they flow around the mine in relation to the general airflow and how they mix. Gases within a cell are stored as variable amounts within the cell data structure.

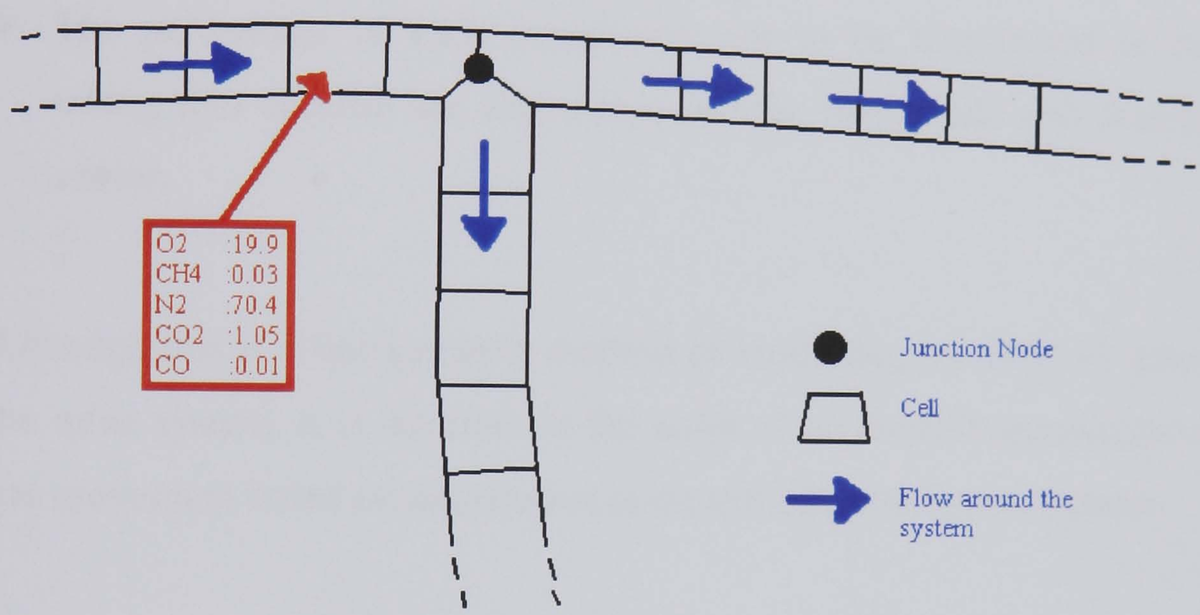


Figure 5. 14 Gas constituents moved around the mine using VentSim-VR flow rates

A method of modelling the movement of gases around the mine in proportion to the pre-calculated airflow was needed. By taken into account the percentage values of each gas, a method of 'air-packet' movement was devised as shown in **Figure 5. 14**. This is where a 'packet' of air (a snapshot of the constituent gases) is moved into the next cell in its flow path based on the flow rates for that particular cell. In other words, a cell with a high flow rate will transfer a larger mass of gas per time cycle than a cell which has a lower flow rate.

Because this method takes into account the flow rate in each cell, and also the percentage of different gases in the cell on a time cycle basis, an accurate method of modelling gas flow around the mine was developed. In this system, the following algorithm applies, per frame or cycle of time.

For all cells (cycled through in a loop, one at a time)

- The direction of flow for the cell is noted. (The direction is used to actually transfer the relevant data from one cell into the cell in which the gas is flowing as dictated by the ventilation algorithms).
- The appropriate quantity of gas to transfer per cycle of time is calculated. (This is based on flow rates calculated by the VentSim-VR.)
- The percentage of each constituent gas to be transferred is calculated, taking into account the above two factors, magnitude and direction i.e. a vector.

Although this is a fairly simple method of modelling the flow of gases around the mine system, it is accurate to the point of an overall representation of the gas movement based on an iterative node and cell ventilation system.

The gases in a real mine would obviously suffer from turbulence (locally within the cell), different tolerances to heat amongst a multitude of other phenomenon. The modelling of all of these factors is beyond the scope of a desktop VR system based upon current technology.

The gases are represented in the 2D system, on screen, as percentage constituents breakdown of the air within that cell. There are two main reasons for this method: -

- Due to the variable length and resistance of the cells it would not be very informative to display information of the gases in terms of the number of molecules per cell. I.e. for different sized cells it would be difficult to compare the quantity of gas present if it was described in terms of molecules.

- The flow-based algorithms used in the airflow simulation already have to take into account the length / width of the roadway and also the flow rate developed within it. At this point, in order to avoid unnecessary re-calculation which would be needed if the algorithm was defined on a per molecule basis, the proportion using percentages was considered to be more appropriate.

Junctions

The simulation has been programmed to model the gas movement of packets of air around the mine system in conjunction with the airflow system as described above. However, the programming of junctions required additional consideration.

The ability to cope with a multitude of different junction scenarios was of paramount importance. In a typical mining environment any junction can have up to 5 roadway paths off a single 'node', although it is more likely to have a maximum of four offshoots.

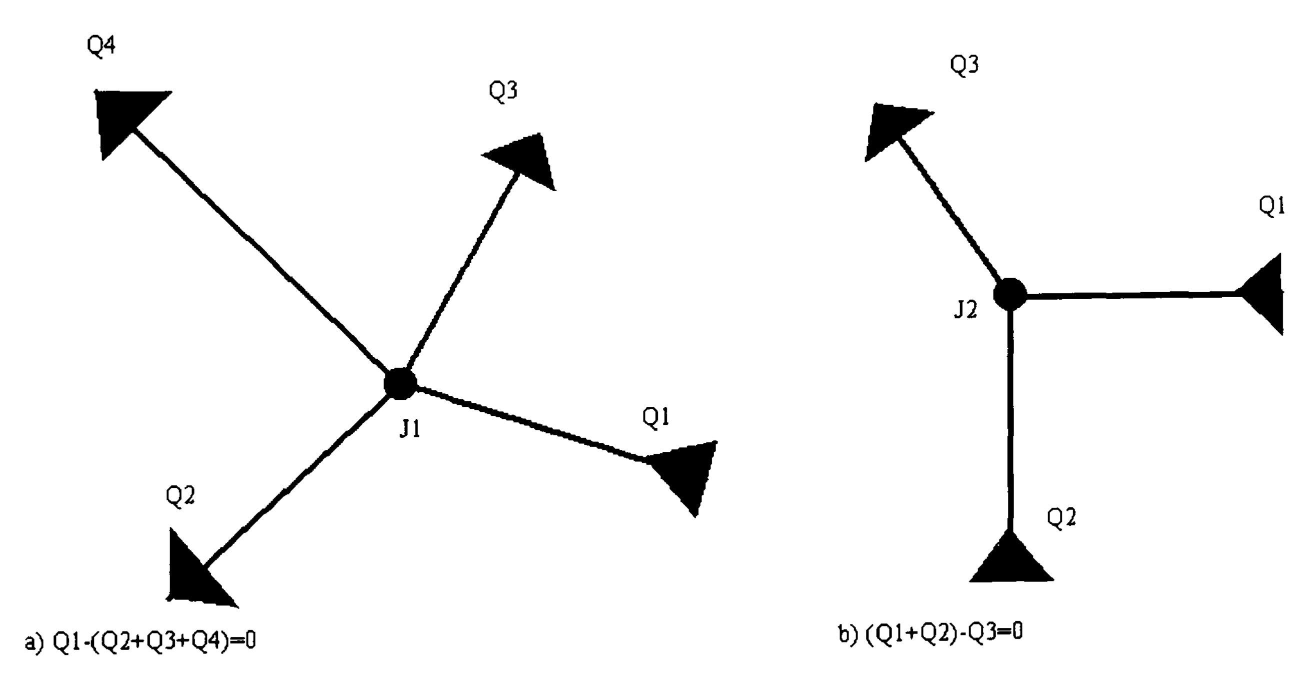


Figure 5. 15 Typical junctions within a mine showing paths of airflow

From the above diagram (**Figure 5. 15**) it can be seen that for any situation, the node can be described as having: -

Outflow paths n	Where n is a number from 0 to number of output paths.
Inflow paths m	Where m is a number from 0 to number of input paths.

The algorithms used in coping with the movement of gases, based on the ventilation system are as follows : -

For all nodes (cycled through in a loop, one at a time)

Step 1. Pre-calculation

- Working round a node, the number of output paths from that node is determined.
- The flow rates are then calculated for each output path assigned to the node
- The number of input paths to the node is determined.
- The flow rates for each input path are then calculated.

Conservation of energy laws state that the output mass flow of gases will be equal to the input mass flow of gases to that node (assuming that no pressure changes, or liberation of gases from the strata or machinery has occurred).

Step 2. Calibration of gas movement based on typical flows

The simulation calculates the appropriate amount of gas to move per cycle of time (this is based on a pre-defined, user configurable flow rate, that would be calculated to model flows found in a typical mine situation).

Step 3. Movement of gases into proportional amounts

For each path leading off the node: -

- If the path off the node is an input, that is to say mass air flow is currently heading towards the node in question, then the mass of gas is firstly calculated in the cell, based on current flow rates in that cell, in order to determine the amount of gas to transfer to the next frame.

- This amount of gas, in the input path, then needs to be moved to all of the output paths (which are defined by the fact that mass airflow is currently heading away from the current node).

- To achieve this, the number of output nodes are initially counted i.e. paths heading away from the node in question.

- The quantity of gas to be moved from the input path (calculated above) is then allocated accordingly to all output paths from this current node. The proportion of the gases to be transferred to the output paths (cells) is based on a split calculated by applying the following formula: -

For all output cells/paths away from the current NODE: -

Quantity of gas to be transferred into output cell = *Quantity of gas to be transferred * (current mass air-flow rate in the output cell in question / Sum of flows out*

Where ;

Quantity of gas to be transferred = Current Input Cell / scaling factor

Sum of flows out = the combined mass air-flows of all the outputs

And ;

The scaling factor is derived to calibrate the quantity of gas to be moved with the volumetric flow rate.

This algorithm is applied to all environmental measurements within the system; oxygen, methane, nitrogen, carbon dioxide, carbon monoxide and also smoke and dust.

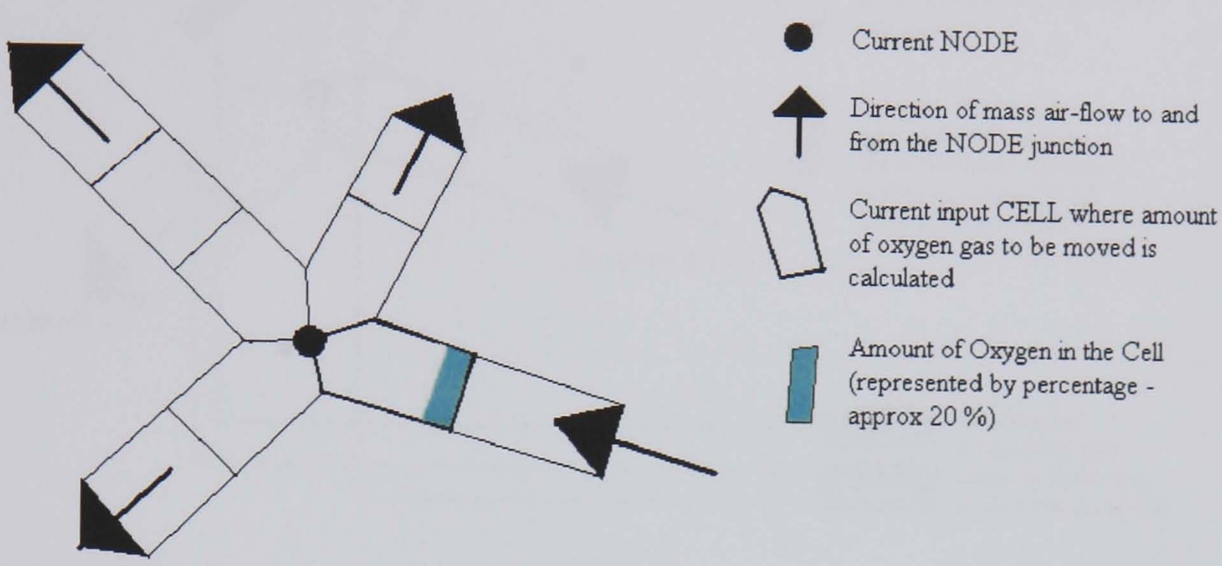


Figure 5. 16 ***Stage 1***. Oxygen (used in this example) at the input cell

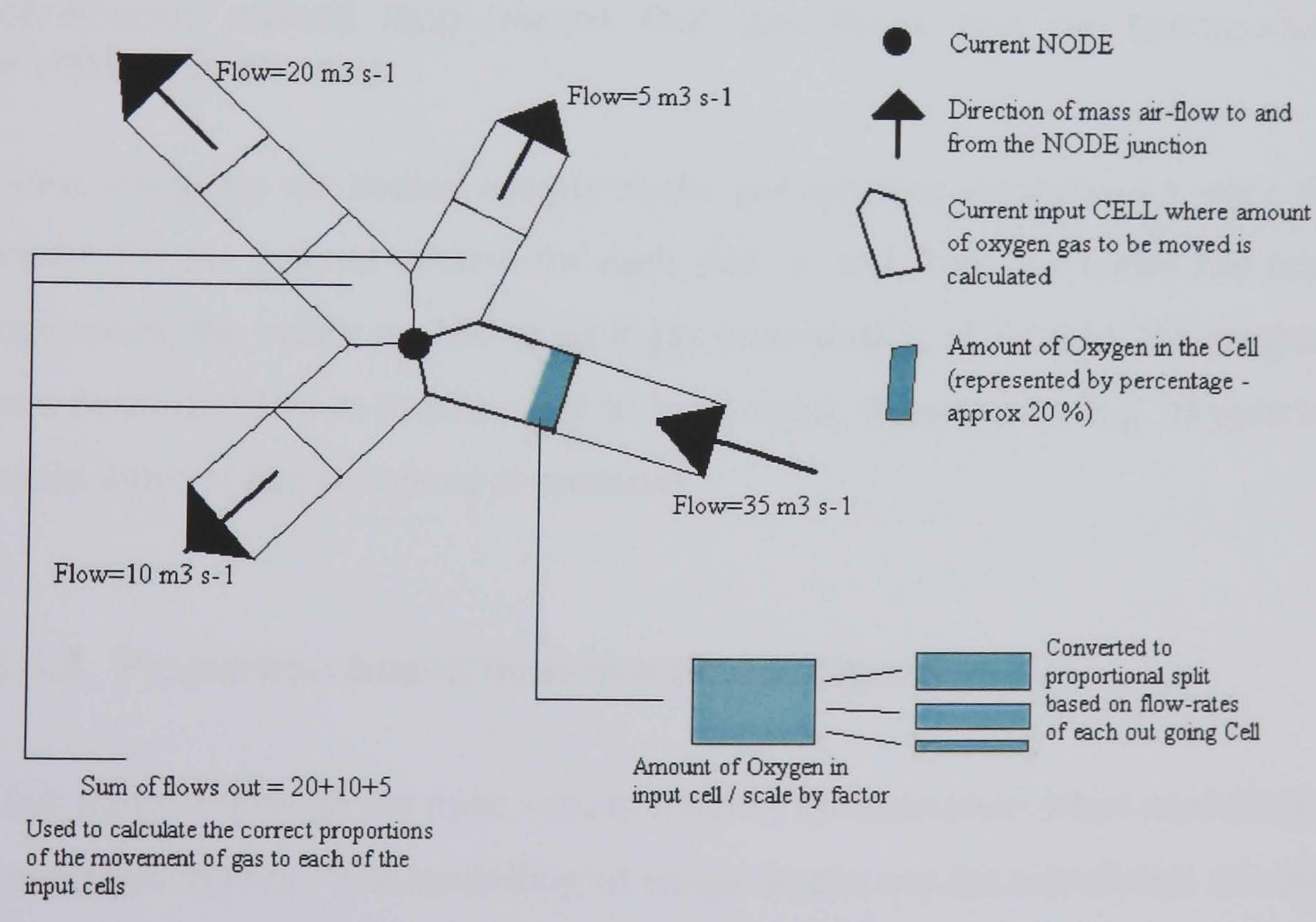


Figure 5. 17 ***Stage 2.*** One input, three output junction. Showing amount of oxygen to be moved to corresponding output cells based on flow rates within those output cells.

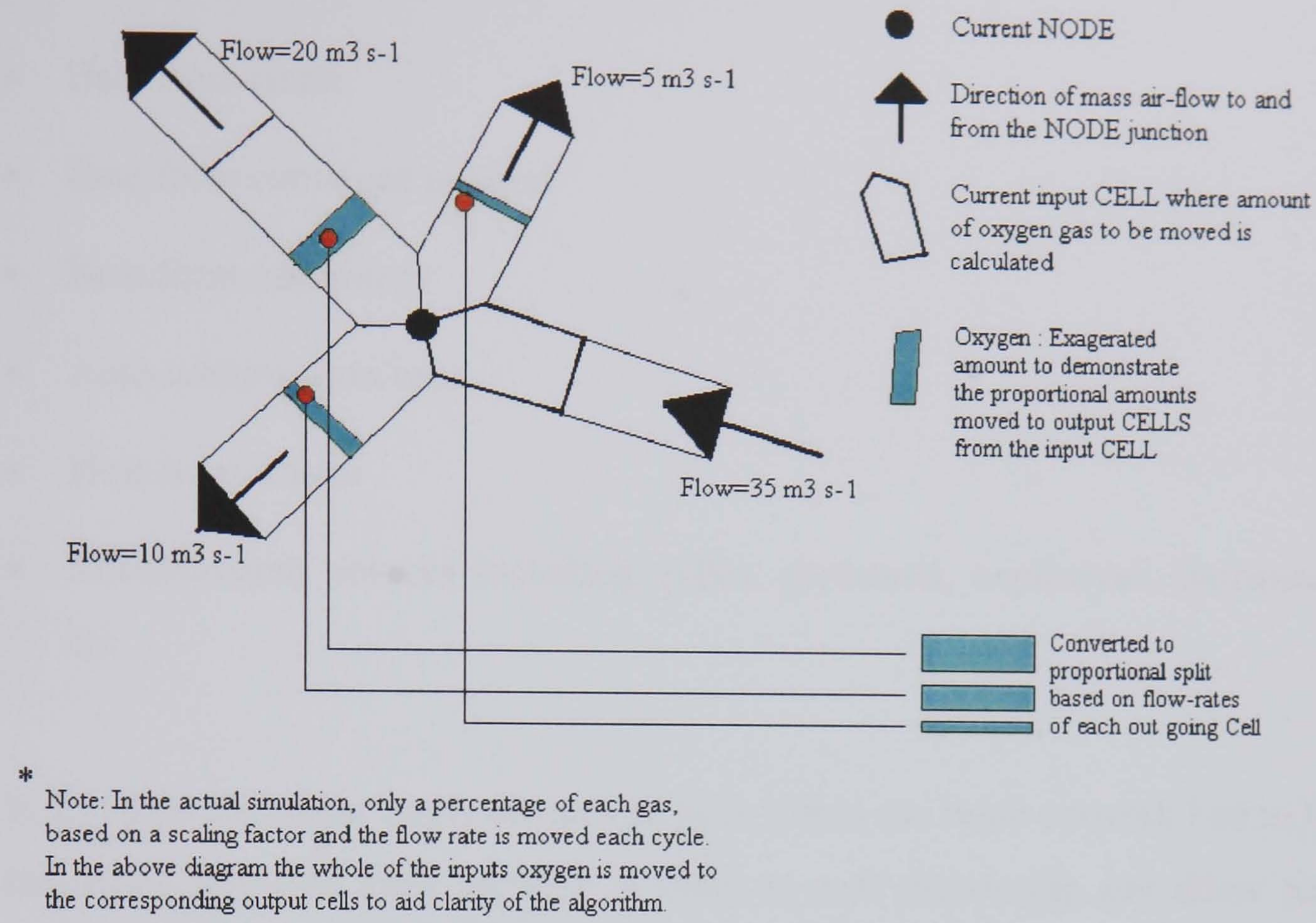


Figure 5. 18 ***Stage 3***. Finally the amount_to_move value of oxygen is moved to the corresponding output cells. At this point the algorithm moves onto the next node in the list. The fact that the network is a continuous closed loop means that gas flows can be successfully modelled in this way.

Note: All gases are treated equally in the gas splitting algorithm i.e. once the vector for the general airflow for each path to and from the nodes has been calculated, the vector applies to each gas individually. That said, the program was constructed so as to allow this to be changed if necessary. E.g. oxygen set could move at half the speed of methane.

5.4.3 Proportion based heat-movement algorithm

Heat transfer through the mine system requires consideration when modelling a ventilation system. The modelling of temperatures and the calculation of other climatic variables such as humidity and the rate of transfer of moisture through mine roadways and working faces are complex problems. Difficulties may also arise when attempting to continually assess and monitor the specific moisture and thermal properties of rock in underground airways.

The major sources of heat in mines have been identified as (Rabia 1988) : -

- Heat from strata
- Heat from conveyed mineral
- Heat from machinery
- Auto-compression heat
- Heat from wastes
- Miscellaneous sources including: pipes, personnel, explosives, oxidation, etc

In EnvSim-VR, these many sources of heat within the mine network had to be simplified into two main sections in order to ease processing and allow real time interaction. It can be seen from the list above that, in general speaking, heat can arise from the environment which includes: -

- Strata heat emissions / pipes etc.
- And also dynamically moving / changing objects such as machinery, personnel etc.

Strata heat emissions

For any given cell within the mine network: - If the VST is greater than the temperature of the air flowing through that particular cell then a proportion of heat energy from the rock / face will be transferred to the air (in keeping with the second law of thermodynamics).

Cooling of the strata, which would normally occur over a period of time within a real world scenario, has not been modelled in the simulation because after an initial rapid decline in temperature the VST soon reaches a point where it is near ventilation air temperature. Provision has been set a side for implementing this effect if required. Each cell can have a unique VST value.

This value could be reduced on a per cycle basis, calibrated against known VST cooling data to provide a good simulation of this effect.

At this point, the effect of cooling of the strata due to heat transfer into the mine air is assumed to be negligible. This, combined with a variable to hold the temperature of air within the cell, means that by applying a similar algorithm to the air packet movement algorithm; heat can be modelled. Unlike the proportion based gas movement algorithm, the proportion based heat movement algorithm has two parts: -

- Modelling of air-temperature and its movement around the mine system with regard to mass airflow.
- Modelling of heat exchange between strata and air.

The modelling of the movement of heat through the mine uses the same algorithm applied for modelling the gas movement through the mine except that the flow rates have been adjusted; effectively the principles used are the same. For this system a fairly simple mathematical model of heat movement was considered to be adequate. It is assumed that the temperature of the air of a particular cell is fixed i.e. there is no dispersion between cells.

The modelling of heat exchange between the strata and air uses a simple formula which adds a certain proportion of energy to each cell at every frame. This quantity added is based upon the size of the roadway (cell size), VST of the cell and air temperature of the cell. The net result of this is a simple, yet reasonably accurate way of modelling key areas of temperature based aspects of mine ventilation and safety planning. With further development, it may be possible to include a more accurate thermodynamic model.

The above methods provide ways of modelling various scenarios including: -

- Heating of a face
- Heating of air-flow due to VST emissions
- Heating of air-flow due to machinery
- Heating of air-flow due to a mine fire
- Heating of air-flow due to an explosion

5.4.4 Event Processing Systems

a) Configuring the system for different events

The balancing algorithms used for adjusting the pressure combined with the mixing algorithms used for logging gaseous and particulate movement around the mine system are acceptable for a known mine layout and with no user or environmental interference the mine quickly balances out to a steady state. However, by introducing user configurable factors into the simulation, an additional facility is created to generate environmental changes which could produce typical events within the mine: -

- The 'injection' or liberation of gases into a particular cell or length of roadway
- The production of excessive heat from machinery or a fire
- Spontaneous combustion of strata
- The production of coal dust from operational equipment

These events were labelled within the data file as 'injections' because they were originally concerned with setting up a source of an environmental change, typically acting upon a cell within the network and assigning conditions such as: -

4	6	0.040	10000	25000	METHANE

In the above example,

4	=	The index number of the injection to be processed
6	=	The cell number within the mine which the inject will affect.
0.040	=	The numeric value of the inject which is occurring. (In this example it refers to the amount of methane liberated from the strata per unit frame rate).
10000	=	The number of cycles completed when the injection is to commence.
25000	=	The number of cycles completed when the injection is to end.
METHANE	=	The type of injection.

See section 6.3 for more details of the mine description file.

This feature enables gases such as methane, oxygen, nitrogen, CO, CO_2 to be created within a cell at certain times of the simulation. The effects can then be tracked by following their progress through the mine system. With the facility of gaseous injections (providing a simple form of managing changes within the mine ventilation system) it is possible to simulate situations which model real world possibilities such as the excess production of heat from machinery and how this heat then travels through the mine.

Below is a complete list of the injection types that were originally supported: -

- OXYGEN
- NITROGEN

- METHANE
- CO
- CO2
- DUST
- SMOKE
- FAN1ON
- DOOROPEN
- DOORCLOSE
- MACHINEHEAT
- STRATAFIRE

FAN1ON command was programmed as a method of turning the main fan either on or off. The EnvSim-VR program checks the inject commands per cycle and in the case of FAN1ON, simulates a fan. The numeric value of the injection was used in this case to signify the pressure levels induced by the fan. (The numeric value can be assigned to any value and it is this variable which can be used to specify the magnitude of the inject.)

In a similar manner, DOOROPEN and DOORCLOSED were used to provide a way of operating the doors within the mine. When the simulation encounters a DOOROPEN injection, the program executes the necessary adjustments to the resistance of the cell containing the door. DOOROPEN and DOORCLOSE are performed only once and the simulation ignores open/shut injects when the door is already in the requested state.

The doors can be closed to block the short cut return of air to the surface and they can also be used as an example of testing the effect on the airflow when a door is opened or closed. By providing a series of doors and having the ability to change the airflow through the mine it is possible to starve fires of oxygen which is useful in fire fighting techniques.

The doors within the mine usually open one way and are held shut by the pressure difference due to the fact that one side of the door is on the upcast or downcast. An example application of ventilation doors is shown in **Figure 5. 19** below demonstrating the effect of closing doors on the air flow.

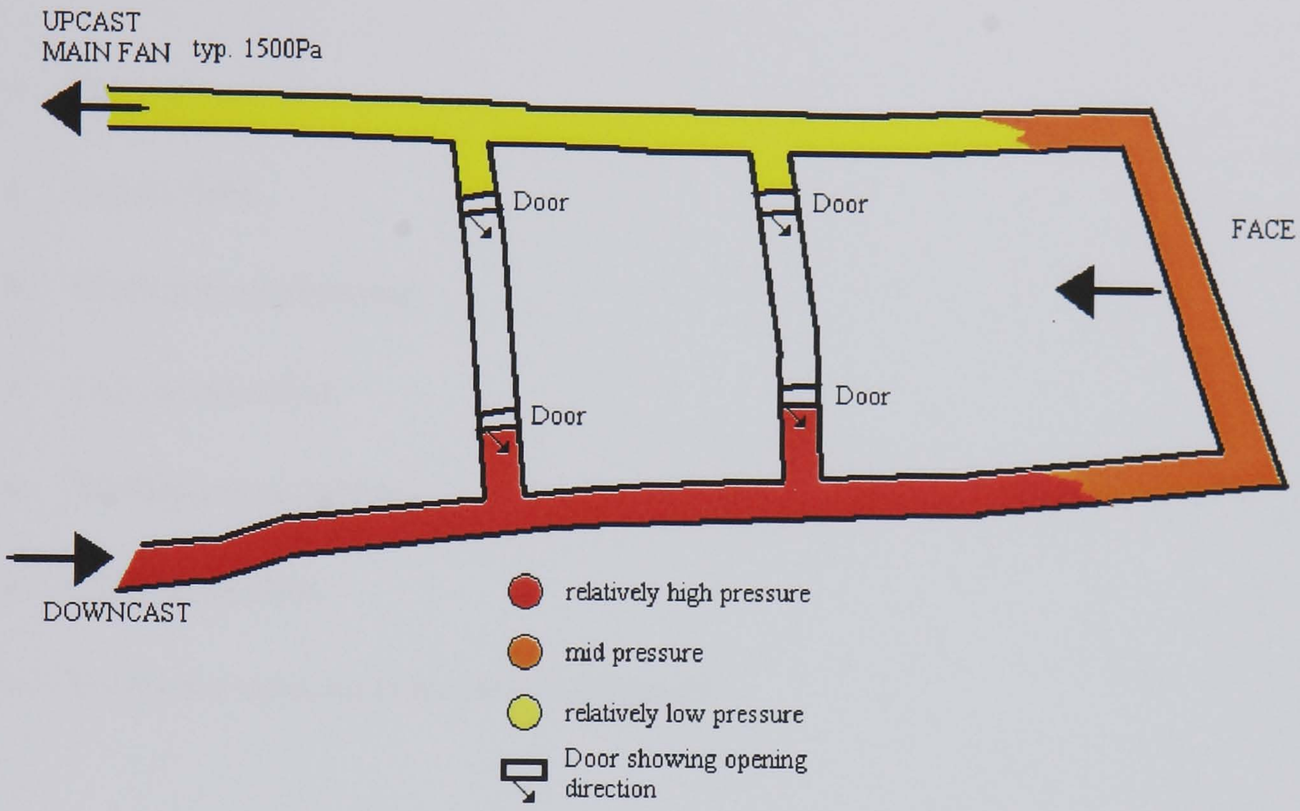


Figure 5. 19 Example showing typical application of ventilation doors within a mine

b) Spontaneous events and Cowards diagram

Spontaneous events can be defined in a similar way to 'inject' type events. Spontaneous events are those which occur when pre-defined conditions are met. In the case of an explosion, a model of Cowards triangle (**Figure 2. 3**) can be used as the conditional factor for triggering explosive events.

Events within the EnvSim-VR program are checked each cycle of the computer program. Each event has a series of conditions which have to be met before the event can occur. Explosions occur according to the Cowards diagram boundaries and need an additional ignition source, whilst fires follow the 'fire-triangle' set of conditions. Some of the other events occur as by products of other events such as the production of carbon monoxide etc, whilst other events such as explosions and fires, by their very nature can be self propagating (i.e. the event produces conditions in surrounding cells that are conducive of starting new events).

Events modelled by EnvSim-VR are: -

- Open fires
- Strata fires
- Methane explosions
- CO_2 production
- Methane production
- CO production
- Ignition event such as electrical spark

Other events are possible due to the modular way that EnvSim-VR has been programmed. For example, coal dust explosions.

The programming of the event processing routine was achieved by creating a linked list. Each event, as it happens is placed in a list. The event list (as it is called) is processed by the simulation every cycle. Each event in the event list is processed in turn one at a time. In the case of a fire event, every cycle the fire is burning a certain proportion of CO and CO_2 will be produced as well as oxygen being consumed.

Because the conditions for each event are processed every computer cycle, when the conditions fail to be met, the event effectively dies. In the above fire example, when one of the components of the fire triangle is at a level outside of pre-defined boundaries, the event will be removed from the event list (the event is said to have been destroyed).

This method is dynamic in nature; the event list changes in size in a dynamic way dependent upon how many events are currently being processed. Many possibilities exist with this method including the propagating effects of events causing other events to occur e.g. an ignition event may cause an explosion event to occur which in turn leads to a fire event.

The event processing system was not designed to be interactive with the user. However, the 'Inject' system can be controlled by the user to set-up different scenarios by means of editing the mine description file (see section 6.3). The event system creates a volatile, potentially chaotic environment which can help to create events similar to those which might occur in a real mine.

5.5 Conclusions

This chapter has outlined the techniques and algorithms used to construct the simulation. It has aimed to provide a concise description of the fundamental sub-systems which have been programmed to produce this research. The chapter started by describing the relationships of the three main parts of the simulation; Fire-VR, VentSim-VR and EnvSim-VR. Data structures used in the simulation to store the required environmental variables and the network description file, used in holding this information, have been discussed. The main algorithms programmed to simulate mass air flow through the mine by the VentSim-VR sub-system have been shown.

EnvSim-VR, which is the sub-system programmed to monitor environmental fluctuations within the simulation, has been described including the three main tasks of this sub-system; additional objects required to model complex mine situations, gas movement through the mine and the ability to model pre-programmed and dynamically activated events.

The following two chapters explain the techniques used in displaying the simulation data to the user and the additional programming which has been implemented to allow user interactivity. Chapter 6 describes the original prototype display, programmed in 2D, which aimed to allow an easy diagnostic error-checking capability whilst the simulation was being programmed. Chapter 7 then describes the additional functionality utilised to port the simulation over to a full 3D virtual reality based interface. This chapter also describes the models which were designed in order to create a realistic VE.

Chapter Six

2D interface and the mine description file editor software

6.1 Introduction

In the previous chapter the algorithms which are used in the core simulation were discussed. This chapter is the first of two which describe the user interfaces to the simulation. In this chapter, the features of the 2D interface are discussed. The interface was deliberately kept isolated as a separate component to the main simulation so that changes to the user interface could be programmed with no software re-compile of the core simulation. This allows for constant update of the interface whilst allowing the fundamental simulation and the testing which was performed on this sub-system to remain unbroken by potential bugs which can occur in any complex software system when changes are made elsewhere. The separation of the simulation and its display device is clearly shown in the JSP diagram in **Figure 4. 5.**

This chapter is separated into 2 main parts; firstly the 2D interface to VentSim-VR and EnvSim-VR are detailed including the ways in which the common data structures are displayed for the user. Secondly, the editor software created to allow the user to input mine networks and the environmental conditions of the mine into the simulation is outlined. The editor software has been included in this chapter because of its relevance in the input side of the user interface.

6.2 2D interface to VentSim-VR and EnvSim-VR

6.2.1 Programming language and utilities used in the 2D interface

The 2D graphical representation of the system was implemented using the Microsoft® Visual C++ and the Microsoft® Foundation Classes (MFC). The

MFC provides the additional classes used for allowing easy programming of commonly required functions which are not typically supplied by the visual C++ language on its own. The 2D interface utilises various graphical enhancements to Visual C++ in the form of simple drawing routines. Typically, the MFC has been used to draw circles, squares, lines etc as well as providing easy access to the windowing system commonly used in Windows® applications.

The System was programmed on a Pentium™ class 166 MHz machine with 2-MB diamond FIRE- GL™ graphics card and 128-MB main memory.

6.2.2 Colour key notation used in Fire-VR

Throughout all sub-systems and programs written for this research a standard colour key was adopted in order to enable the identification of the various data structures, gases and particulate used in the simulation displays. The following table (see **Figure 6. 1**) maps these objects with the particular colour used. Both the 2D interface and the 3D interface (see chapter 7) use these colours.

Gases	
Oxygen	*Blue*
Nitrogen	*Green*
Methane	*Red*
Carbon monoxide	*Black / yellow (2D / 3D interfaces)*
Carbon dioxide	*Magenta*
Environmental	
Air flow	*Red*
Smoke desity	*Various levels of grey*
Cell air temperature	*Shades of orange to red*
Cell VST	*Pink*
Potential Energy	*Light purple*

Figure 6. 1 Colour key diagram showing representations used in Fire-VR

6.2.3 Graphical representation of the data structures

To provide the 2D interface to the simulation, a clear graphical display was constructed (using the MFC) that the user could interact with. This interface consists of the actual physical display of the current network calculated from the mine description file and the additional software components needed to provide the interaction between the simulation and the user.

Functionality of the software included the following display criteria: -

- Graphical display of information.
- Textual display of numerical data

a) Graphical display of information

Data which is calculated by the simulation is displayed in the 2D interface by means of simple geometric shapes. All of the following data structures in the display can be switched on or off so that the user can configure the system to provide only the information which is desired. This is needed so as to reduce information overload in the display. There are many ways of showing information in this type of display. The system has been created to maximise the information that the user can view without the display becoming cluttered. Objects are used to display magnitude, length, concentration levels etc.

The following list describes each of the elements of the simulation which are graphically displayed: -

- Nodes (shown in **Figure 6. 2, part a**) are displayed as purple squares, their size dependant upon the relative pressure level that is present at that particular node. This provides an easily recognisable visual cue as to the pressure gradients occurring throughout the mine network without the user have to examine specific figures.

- Cells (shown **Figure 6. 2, part b and c**) are displayed by using an arrow which points in the direction of the air flow. The user can instantly observe the pattern of the overall flow paths through the mine because of this. Other variables are also displayed with the arrows in terms of their width and colour etc and these different methods of data display are described in section 6.2.3.
- Smoke levels are displayed on screen by a grey circle which surrounds the cell. The circle's grey intensity is proportional to the quantity of smoke present within the cell and provides the user with a quick way of interpreting the effects of a fire within the mine. (See **Figure 6. 2, part d)**
- Additionally, any data which is displayed is coloured with a standard convention (see **Figure 6. 1**) used throughout this research. Examples of this are red for methane, blue for oxygen, green for nitrogen etc. (see **Figure 6. 3**).

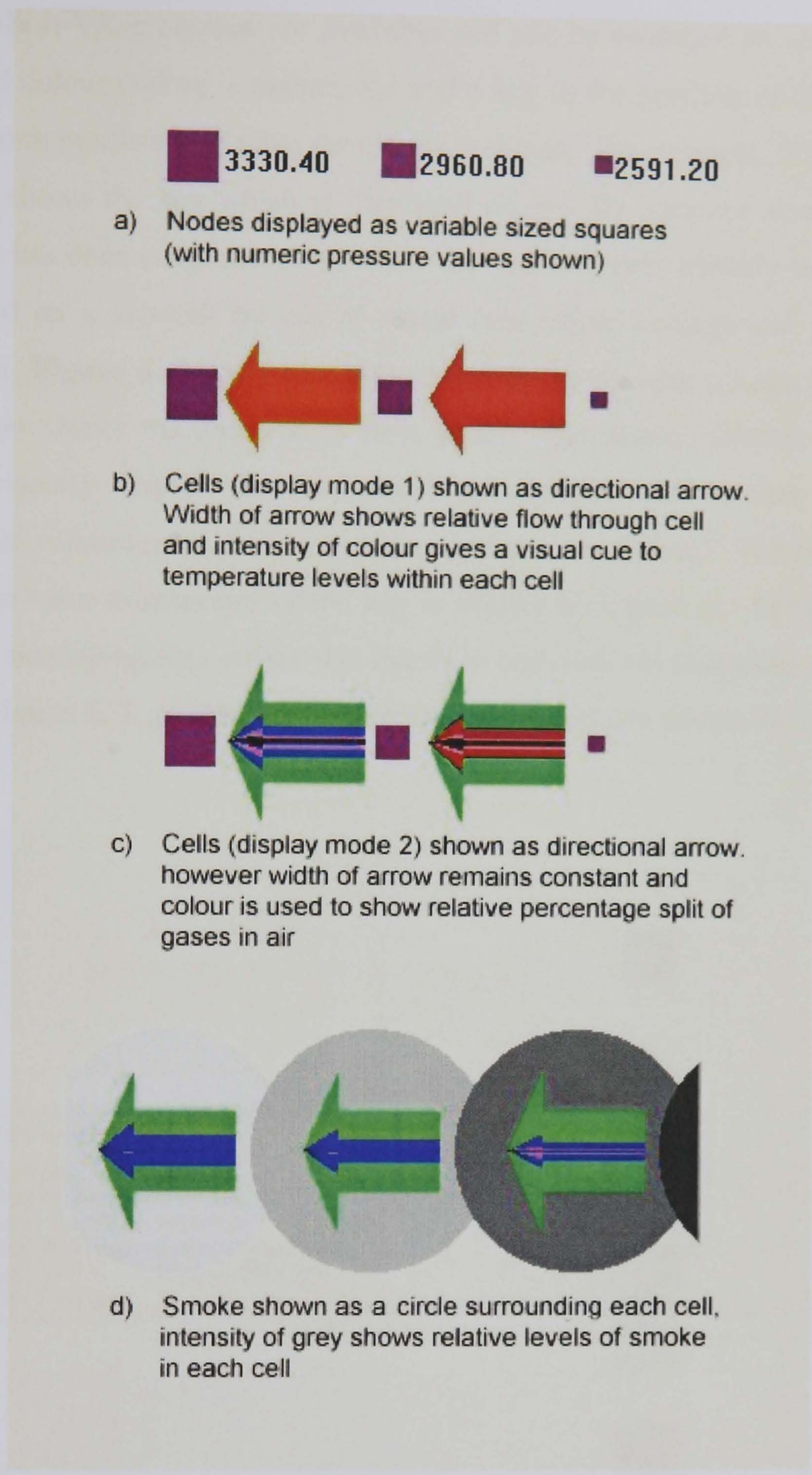
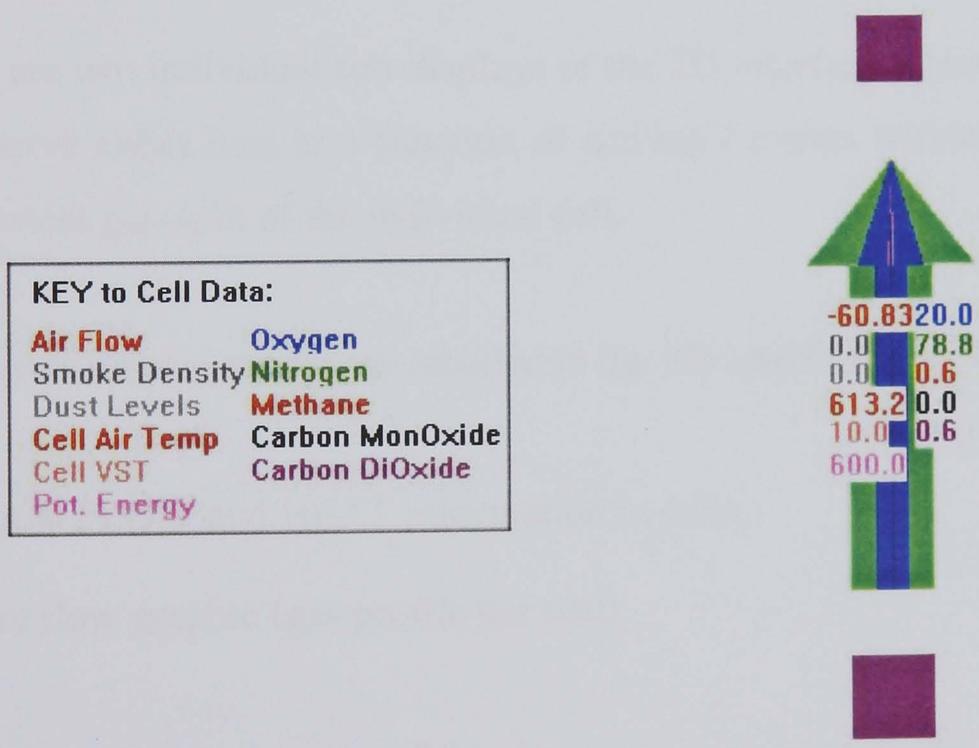


Figure 6. 2 Key to graphical representation of data structures used in the 2D interface.

b) Textual display of numerical data

Numerical data derived from the simulation is converted to two decimal places and then displayed in the 2D interface. Data values for all of the VentSim-VR and EnvSim-VR processes are available and can be switched on as required. Standard colour coding is maintained and a key to the position of the data on the diagram in relation to other data items is shown. For example, **Figure 6. 3, part a)** shows the key which is displayed on the 2D interface screen. This diagram has been programmed to allow the user to easily identify data values displayed on a network by use of visual (via colour coding) and positional cues. In **Figure 6. 3, part b)** a typical cell is shown with a node each side. The arrow shows the direction of flow of air. The colours used to draw the arrow visually display the component gas split of the air-flow and the numerical values represent the environmental data in that cell. The position of each data value mirrors that of the key in **Figure 6. 3, part a**). There are two ways of displaying data within this interface and both are discussed in section 6.2.4. **Figure 6. 3, part b)** has been set to show the gases within the cell.



a) Key to cell data used in the 2D interface shows colour of data and relative position on each cell.

b) Typical cell with all data values shown. Position of data matched to key.

Figure 6. 3 Key to colours used to represent objects within Fire-VR

Examples of the type of data which can be displayed to the user include: -

- Node pressure levels
- Cell volumetric flow rates
- Percentage volume of particular gases such as oxygen, methane etc.
- Smoke and dust levels within each cell in numerical form
- Cell air temperature and VST
- Potential energy available in each cell

With these different display methods, the user is able to configure the 2D interface to match specific requirements.

6.2.4 2D Interface display modes -

There are two individual sub-displays of the 2D interface which enable the user to observe either heat as a function of activity / events within the mine or the component gas-split of the individual cell.

These two display modes are labelled in the 2D interface as: -

- Show FLOW and HEAT information in cells.
- Arc flow graphic (gas profile per cell).

In both displays, arrows are used to show the direction of the air flow. After calculating adjustments to change centring information and scaling, the arrow's orientations and positions are calculated from the mine description file using basic trigonometric functions which are then drawn using the MFC.

Additionally, when the display is configured for 'show FLOW and HEAT information in cells' the width of the arrow is programmed to be proportional to the mass airflow in that cell. This provides an easily distinguishable reference for the user to observe the relative flows rates in each path. This visual cue to flow within a cell, shown notably by the decreased width of the arrows furthest away from the main flow paths, is easily recognisable in the test mine which is displayed below by the 2D interface in **Figure 6. 4.**

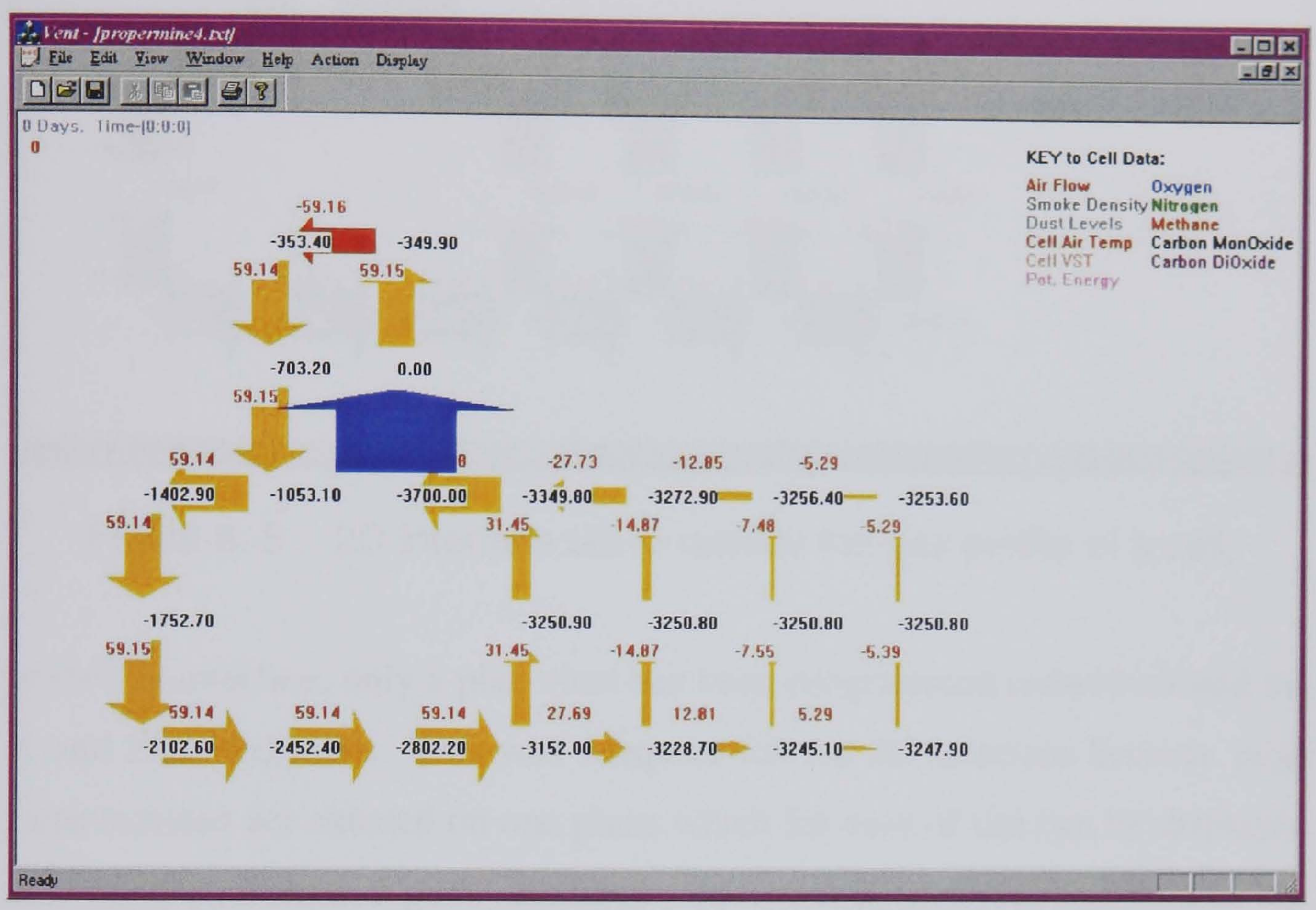


Figure 6. 4 2D interface set to display heat and flow information.

The secondary display has a fixed width arrow which is proportionally coloured to show the percentage breakdown of gases within the cell. This option is useful if the user wishes to observe a particular event which might be producing a distinct change in the environment within the mine such as a methane build up. This display mode is shown in **Figure 6. 5**. Note that the width of the arrow in this display mode does not change. This option is enabled by selecting 'Arc flow graphic (gas profile per cell)' from the menu bar. Menu commands for the 2D interface are outlined in section 6.25.

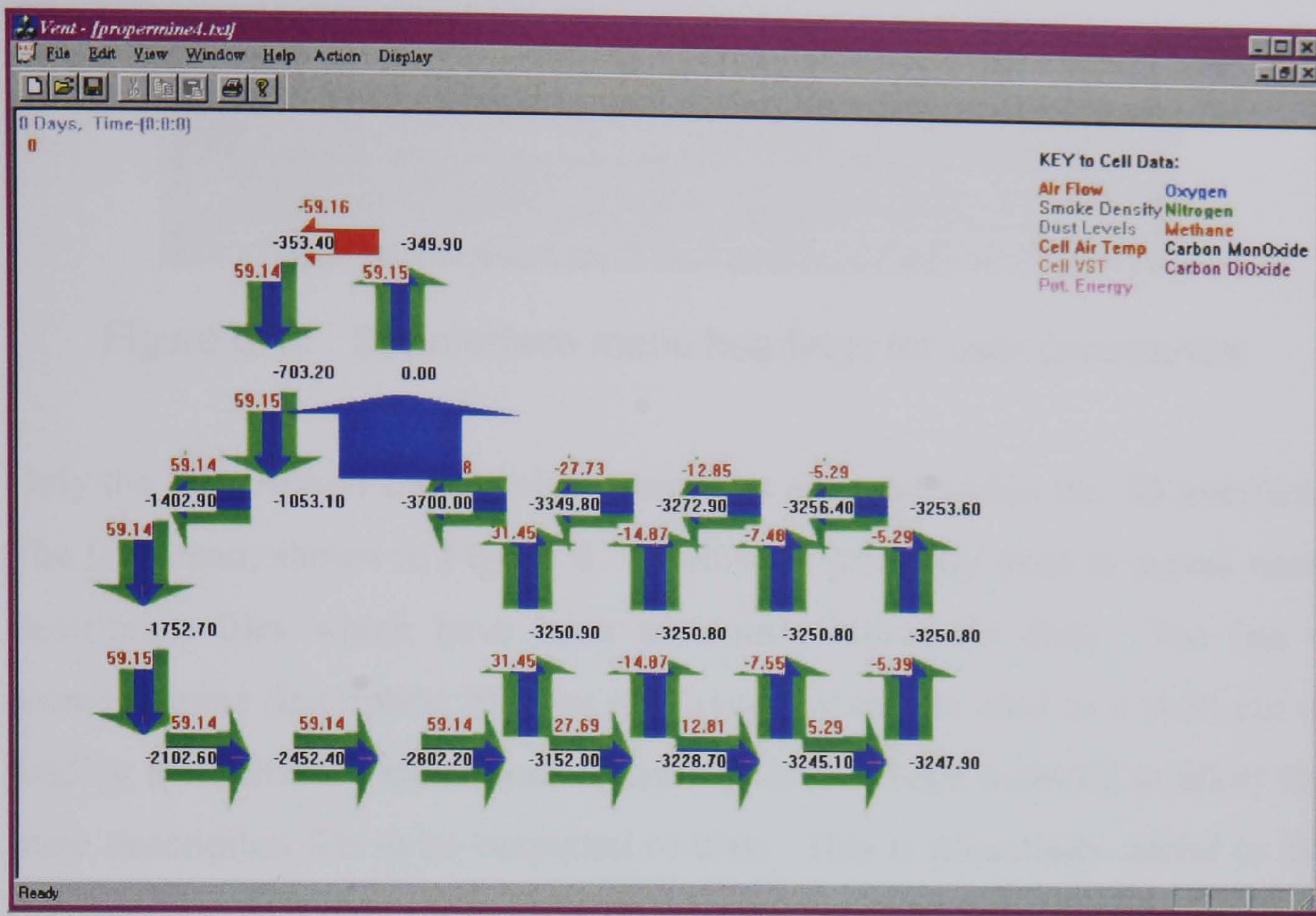


Figure 6. 5 2D interface set to display the gas profile of a cell.

In the 2D interface, only a plan view has been programmed centred around the X and Z co-ordinates. This was adequate for the 2D interface because most mine sections are situated on one plane which for ease of use can be displayed well from an overhead plan. However, the full VR application, Fire-VR, has the ability to model mines in full 3D including inclines and multiple level sections. Additionally, the mine description file editor application created to supplement the Fire-VR application, obviously needs to be able to allow the user to create mines in all three dimensions. The features of this editor are described in section 6.3.

6.2.5 User driven menu commands for the simulation

As well as the two main display modes discussed in the above section, there are other important menu commands that allow the user to adjust particular aspects of the simulation.

All commands in the 2D interface are accessed via the menu bar at the top of the application screen as shown in **Figure 6. 6** below : -

Figure 6. 6 2D interface menu headings for user commands

Only the File, Action and Display commands are used within the 2D interface. The file menu, shown in **Figure 6. 7**, below, is primarily used to access mine description files which have been previously stored on disk. The last 4 accessed mine description files are displayed and can be used as a short cut to loading them into the simulator. A save option has been included to allow the mine description file to be outputted to disk. This is potentially useful in the development of training exercises where the simulation has been running and the user wishes to save the network out either when a particular event is occurring or when the network has balanced in order to observe the effects on the ventilation system.

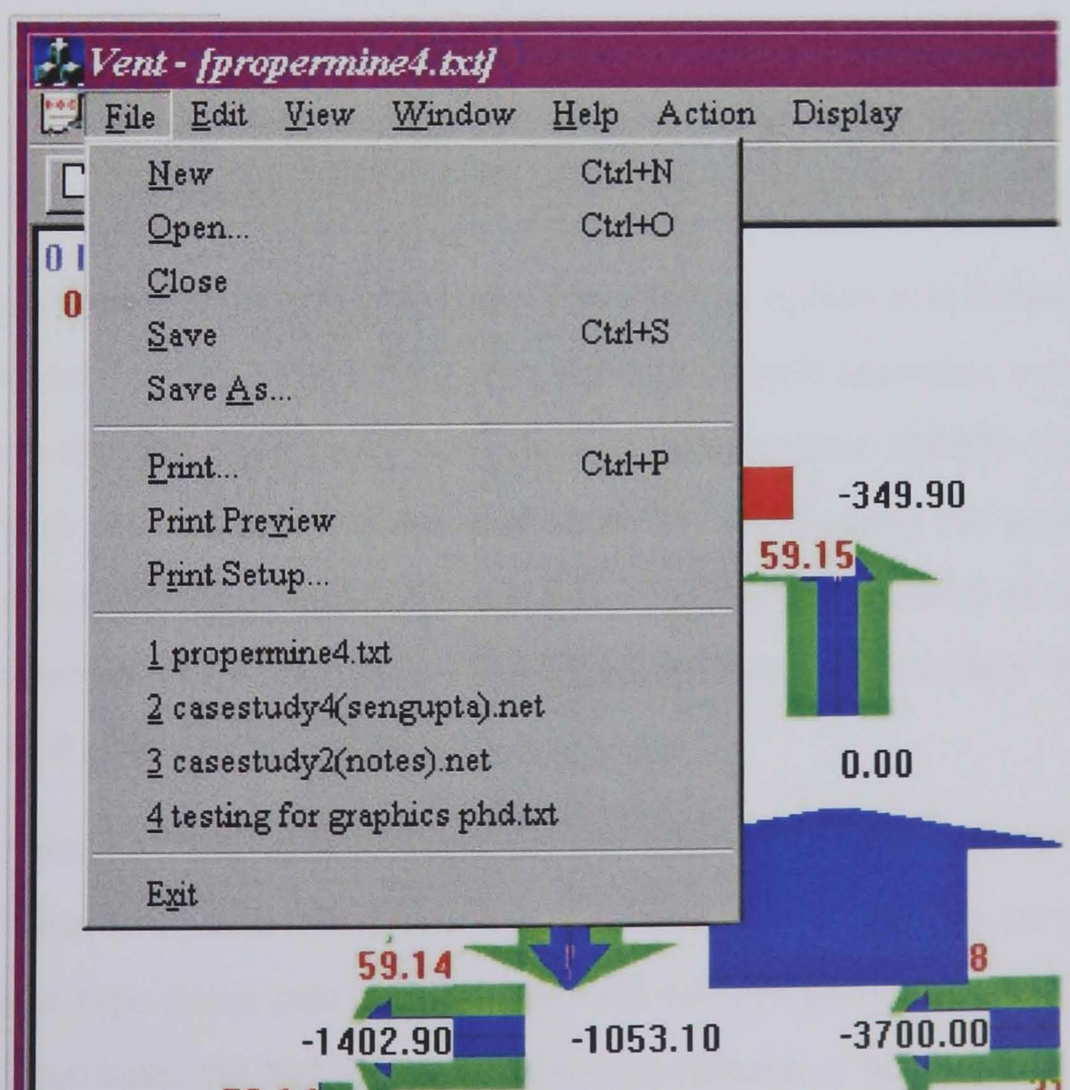


Figure 6. 7 File menu displayed from the menu bar in the 2D interface

The action menu is the main command section which allows the user to control various aspects of the simulation. From this menu, shown in **Figure 6. 8**, the user is able to stop and start the simulation by clicking on 'Go'. Additionally, the user can stop the simulation at any time by clicking within the main window. Other commands in the Action menu are outlined below: -

- **Gas movement off.** When this feature is selected (√) the simulation does not calculate the air packet movement algorithms outlined in section 5.4.2. This allows the user to pre-balance a mine so as to determine the pressure levels for all of the nodes prior to running the simulation. This enables the user to input a mine into the editor (described in the following section) without the need to pre-calculate the pressure levels within the mine. Instead, the user can let the simulation balance out the network assuming a fan is described within the mine description file.
- **Adjust Node off.** If the simulation is balanced and no environmental effects are desired and the fan is to maintain the same output conditions then there is no need to calculate pressure levels every cycle. This has the effect of saving valuable computer processing time and can therefore speed up pre-balancing of the simulation. Obviously, a limitation of this feature is that this is only valid if dynamically changing events are not occurring.
- **Time Looping over 300000 cycles off.** If this option is selected (√) then the counter which stores the cycle number (which increases every cycle through the simulation) will continue to increment after 300000 cycles have occurred. This is useful if the user wants to continuously run a simulation which has the inject form of event pre-programmed to occur at a specific time interval. If this option is not selected then the cycle counter will revert back to 0 after reaching 300000.
- **Time on.** This option needs to be selected if the user wishes the simulation to update the main cycle counter. If the user has programmed an inject type event into the network with the aim that it should occur at a particular time, yet the user wishes to pre-balance a network beforehand,

then the user can stop time while the network balances and then re-start time ready for the event to occur.

- **Time x10 and x100 factors.** These two options allow the user to increase the multiplication factor in the way the simulation counts time. As well as increasing the incremental factor of the time counter they also directly multiply the amount of air packets which are moved during the processing of the air packet movement algorithm (see section 5.4.2). The very nature of these commands can introduce inaccuracies in both the air packet movement algorithm and the node balancing algorithms and so should not normally be used. However it is useful in some circumstances where the user wishes to accelerate through cycles to quickly reach an event.

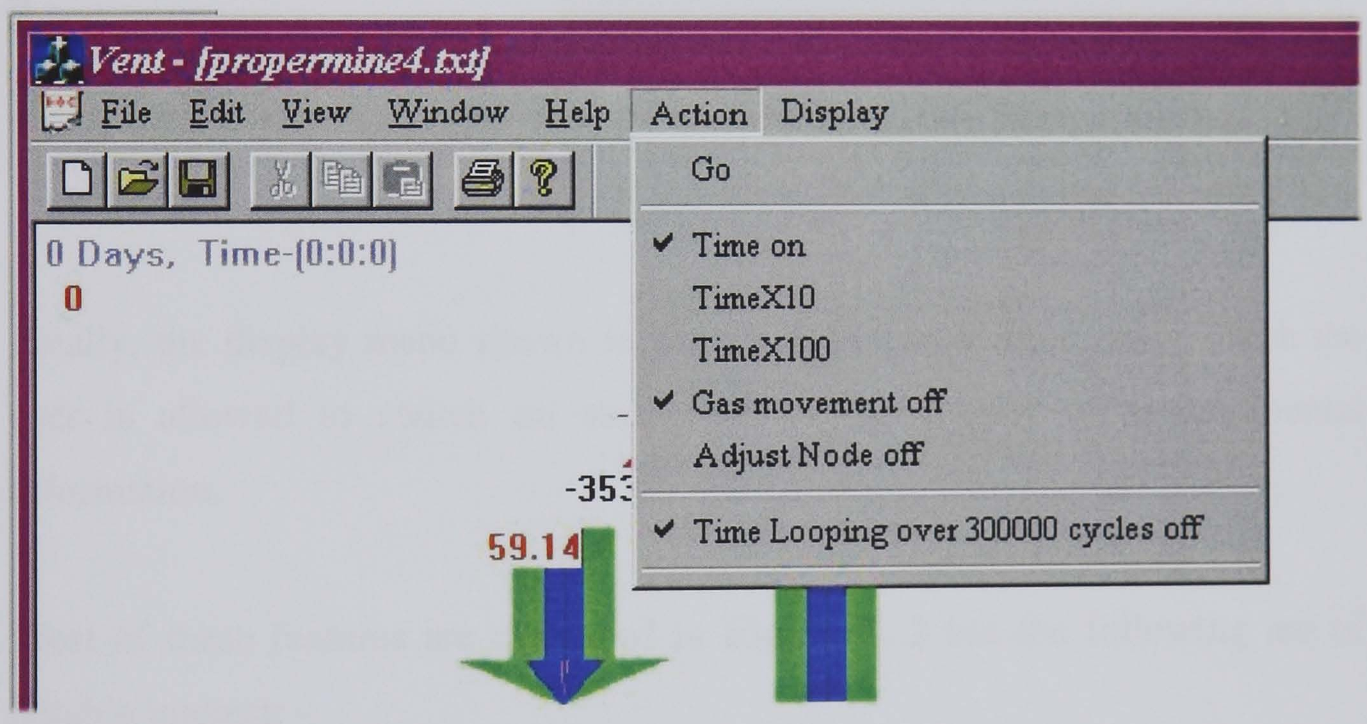


Figure 6. 8 Action menu displayed from the menu bar in the 2D interface

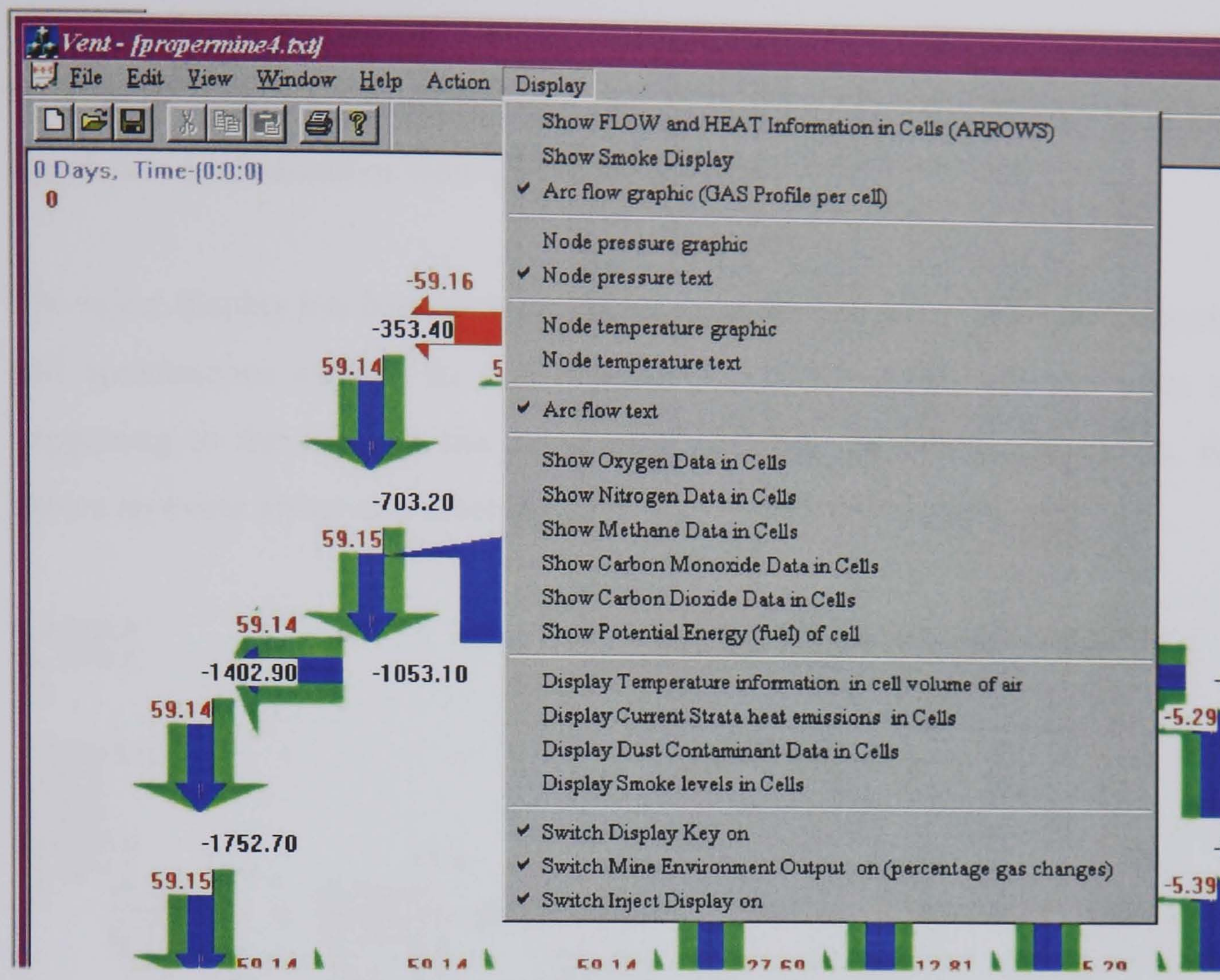


Figure 6. 9 Display menu from the main menu bar in the 2D interface

Finally, the display menu shown in **Figure 6. 9** shows the options which the user is allowed to switch on and off with the display of environmental information.

Most of these features are displayed in **Figure 6. 2** but the following are of notable interest: -

- Arc flow text
- Node pressure text
- Switch display key on
- Switch inject display on
- Switch mine environment output on

'Arc flow text' and 'Node pressure text' show the data outputted from VentSim-VR in terms of the description of the mine.

The 'Switch display key on' refers to the key described in **Figure 6. 3, part a)**. This facility can be removed if the user is familiar with the display or if the simulation is cluttered or slow due to its presence.

The inject display has been programmed to display various events (both injects and spontaneous events) so that the user can dynamically observe what is happening to the mine in the event of a situation occurring. **Figure 6. 10** shows an event arrow and label showing where the event is occurring.

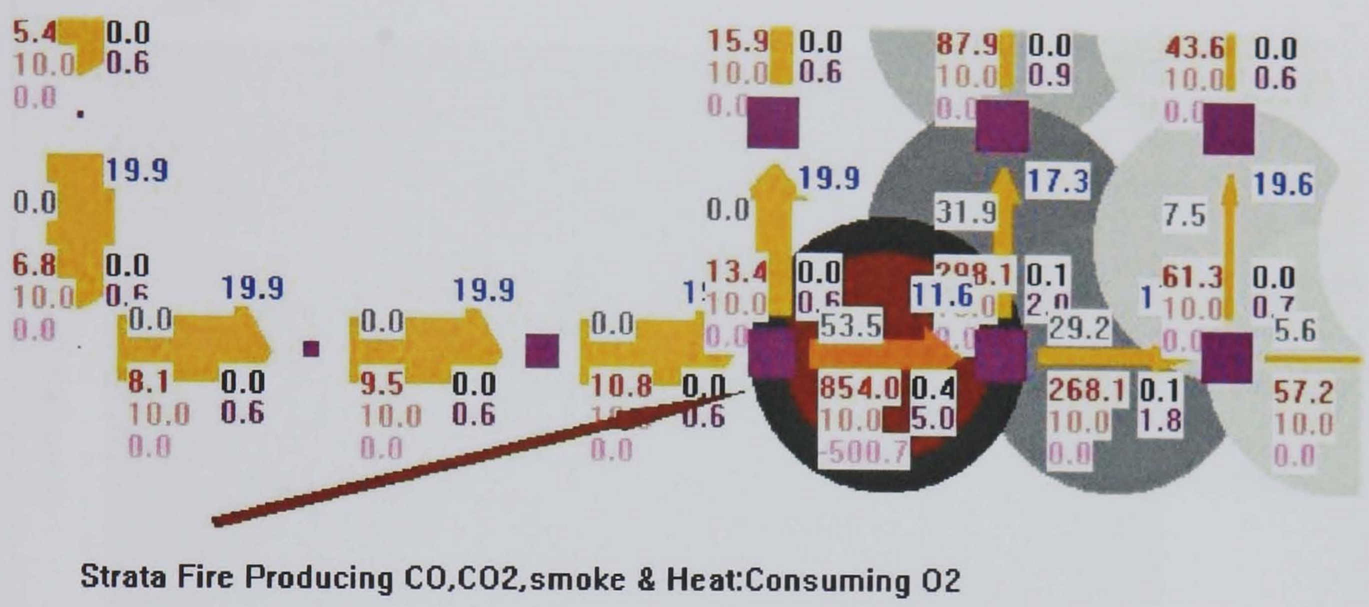


Figure 6. 10 Inject display. Clearly showing an event occurring via a pointer arrow

The labelling of events / injects only occurs if this option is selected (√).

Finally the option 'Switch mine environment output on' can be used to show the gaseous output from the mine as a function of the percentage increase from intake. This information is typical of that used in the Graham Ratio calculations discussed in section 2.3.2 except that all of the gases are displayed, not just CO and O_2.

The example mine shown in **Figure 6. 4** onwards, was also used in the example shown below. The TestNetworks.net data file (See Appendix 4) was designed to be a simple example of the ability of the simulation to demonstrate the Grahams Ratio principle (i.e. of checking input conditions against output conditions). The test network used was a closed loop mine with a single production face and a number of cross cuts that could later be used for testing ventilation doors. Two events / injects were added to the data file, namely : -

A fan with 1500 Pa was created as a main fan and this was used to create an airflow around the test mine. Secondly, a strata fire was to occur at cycle 5000 and burn until cycle 90000. The output from a typical simulated fire in the test mine is shown below: -

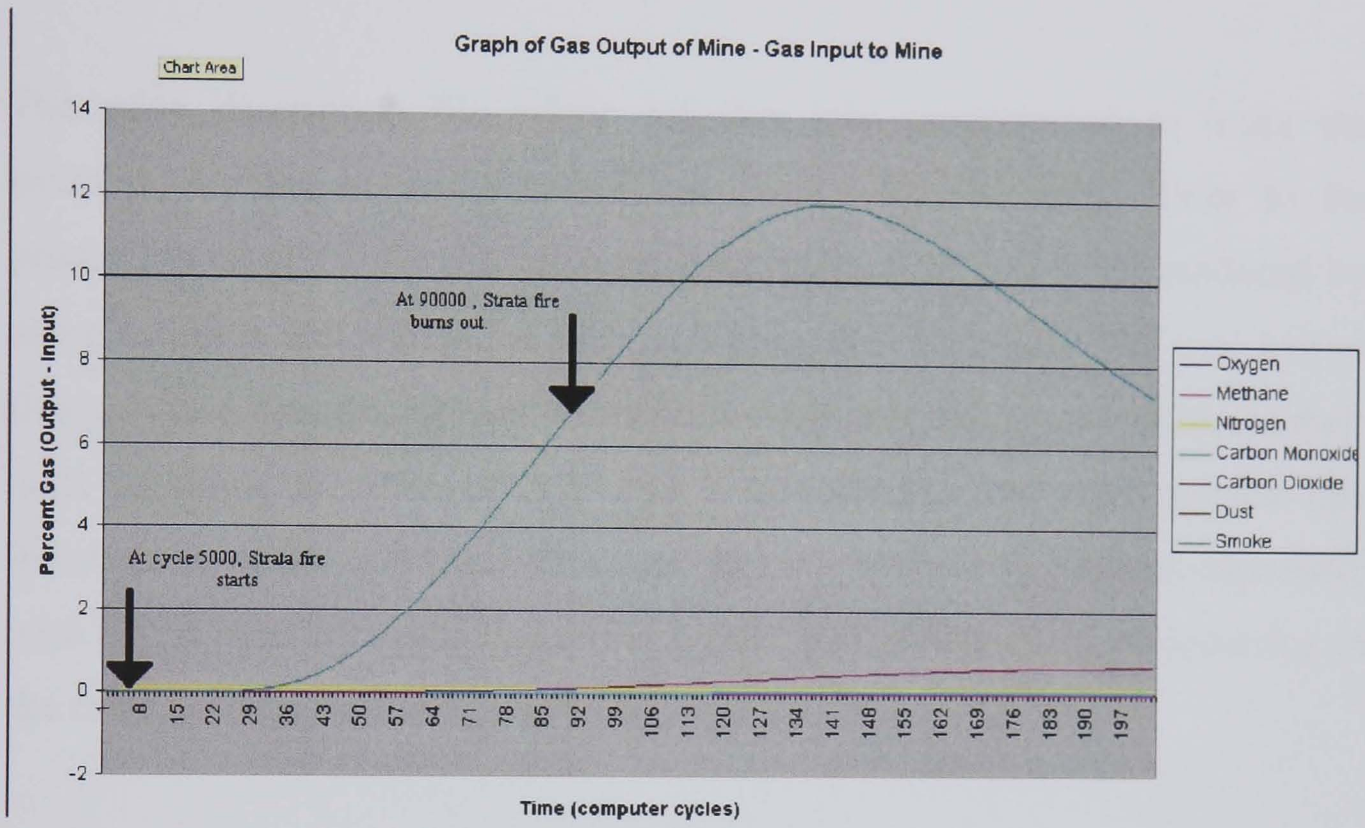


Figure 6. 11 Gas output in relation to gas input (percentage increase)

In **Figure 6. 11**, above, it can be seen that after the fire event has started, the level of smoke in the airflow increases rapidly. There is a short lag before the smoke is noticeable because the fire occurs deep within the mine, whereas the gas component virtual sensors (switched on by selecting 'Switch mine environment output on') are placed at the upcast exit from the mine shaft. The percentage output to input of gases are also shown on the diagram. There is an increase in carbon dioxide and carbon monoxide (although the CO increase is difficult to read on the diagram due to the scale used).

At cycle 90,000, the point where the fire burns out, the position has been marked. This is the point where fresh air starts to dilute the smoke that is deeper within the mine. Again the delay between smoke source and output means that the curve continues to display large amounts of smoke until about cycle 139,000 when the level of smoke in the air starts to reduce again due to being mixed with fresh ventilation air.

6.3 NetEdit - the mine description file editor software

6.3.1 Introduction

The mine description file editor software was programmed to make the creation of mine networks easier and quicker for the user. Prior to the production of this software, all mine description files had to be produced by using a simple text file editor such as Microsoft® Notepad. The user had to firstly draw a network by hand using nodes and cells, calculate and record their node locations in terms of X,Y and Z co-ordinates and then transfer this information to the text file. This soon became a troublesome task especially with larger mine networks due to the greater probability of errors occurring in the mine description file.

A quicker, more accurate way of inputting mine data was required. This challenge was met by the production of a bespoke editor package which could allow the user to quickly design networks of nodes and cells, automatically calculate their co-ordinates from screen co-ordinates and also diminish the possibilities of errors occurring in the file. (In the earlier stages of design of Fire-VR, when mine description files were being hand built using a text editor, frequent errors would result where the number of cells or nodes within the mine did not equal the appropriate number of data segments that were in the file.)

The editor software created allows the user to draw nodes and then connect them together using 'rubber-banding' techniques frequently used in computer drawing and paint packages (Hearn and Baker 1986). In **Figure 6. 13**, this rubber-banding technique is demonstrated.

6.3.2 Toolbar used by NetEdit

NetEdit was programmed to provide the user with easier tools to create a mine description file rather than using a text editor alone. A selection of toolbar buttons which allow the user to define the nodes and cells as well as various environmental events and characteristics of the mine were programmed. The tools that the user can use to create a mine network description file are shown in **Figure 6. 12**.

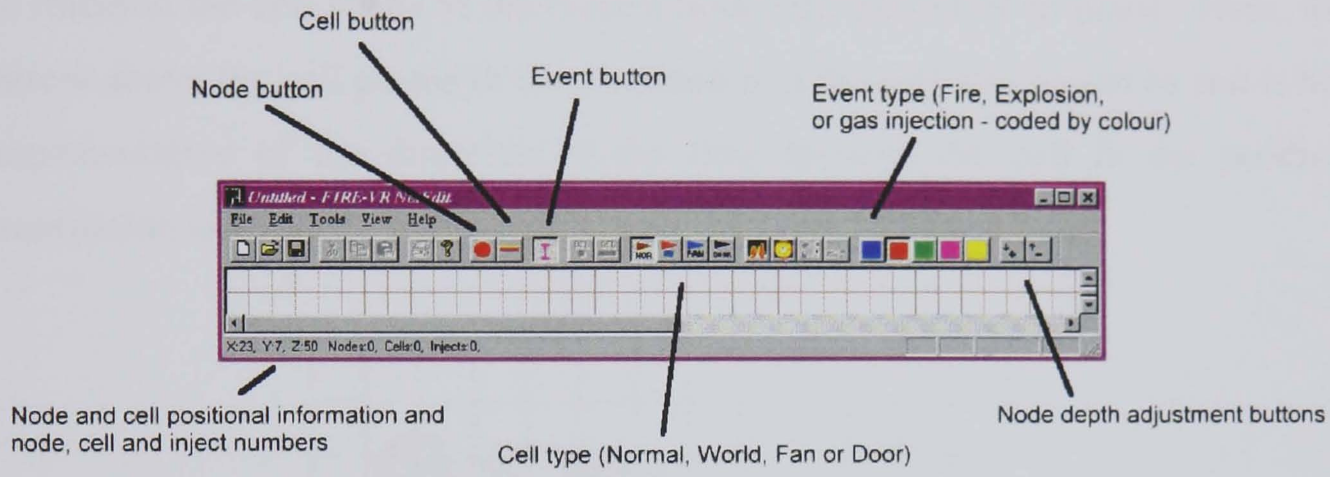


Figure 6. 12 Key to the toolbar commands used when creating a network file using NetEdit

6.3.3 Creating a mine network description file using NetEdit

The following example shows a number of aspects of the editor software. The process of designing a viable network is based around the three tasks outlined below: -

- Node and cell placement
- Placement of special cells
- Defining events

a) Node and cell placement

Firstly, the user positions the nodes of the network by selecting the node button and then clicking on the main editor area where the nodes need to be located. An incremental number is drawn automatically over the node which shows the user which node they are currently on. Secondly, the user then clicks on the cell button, signifying that they require to attach the nodes. This is done by first clicking on the first node and then dragging out a rubber-banded pair of lines until the user is hovering over the second node. When the mouse button is released the cell snaps to the closest node and the cell is in place. Note, the arrow above the cell points in the direction that the cell was drawn in and is not representative of the direction of the flow through the cell in the pending ventilation simulation which of course is variable in nature.

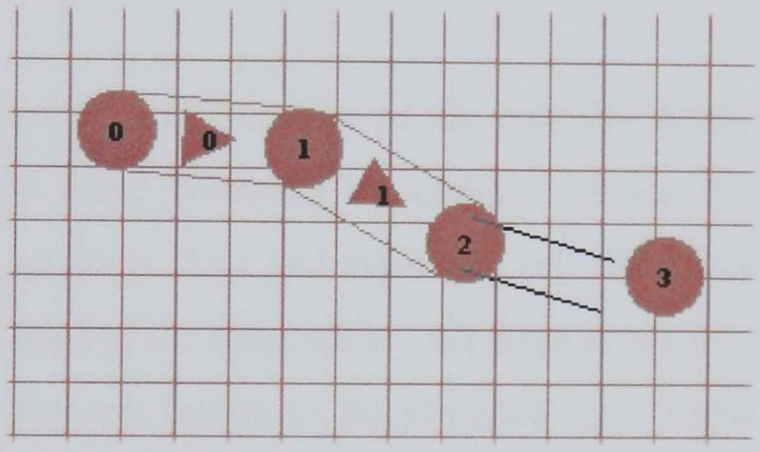


Figure 6. 13 User 'drawing' a cell from one node to another using the cell command with 'rubber banding'

The mine description editor software is able to view the mine which the user is creating from two angles. Firstly, the mine can be viewed from above in a plan view format whilst secondly the mine can be viewed from the side. This allows full 3D mine networks to be created in the editor and thus enables 3D mines to be transferred into the 3D interface much more easily. In order to cope with this 3D aspect of the mine, nodes can be positioned into and out of the screen whilst in plan view. By raising or lowering the current node, variable levels within the mine can be achieved. This is diagrammatically shown on the screen of the editor by reducing and increasing the node size to give the impression of height. This is shown in **Figure 6. 14**, below.

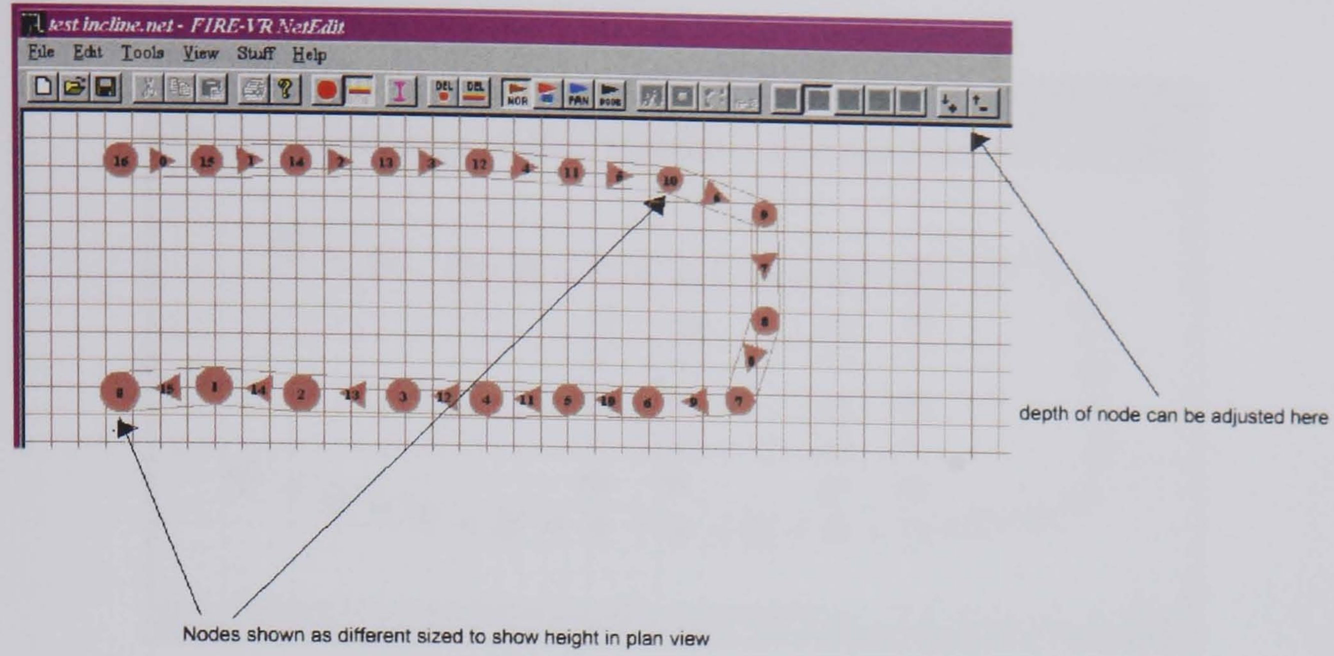
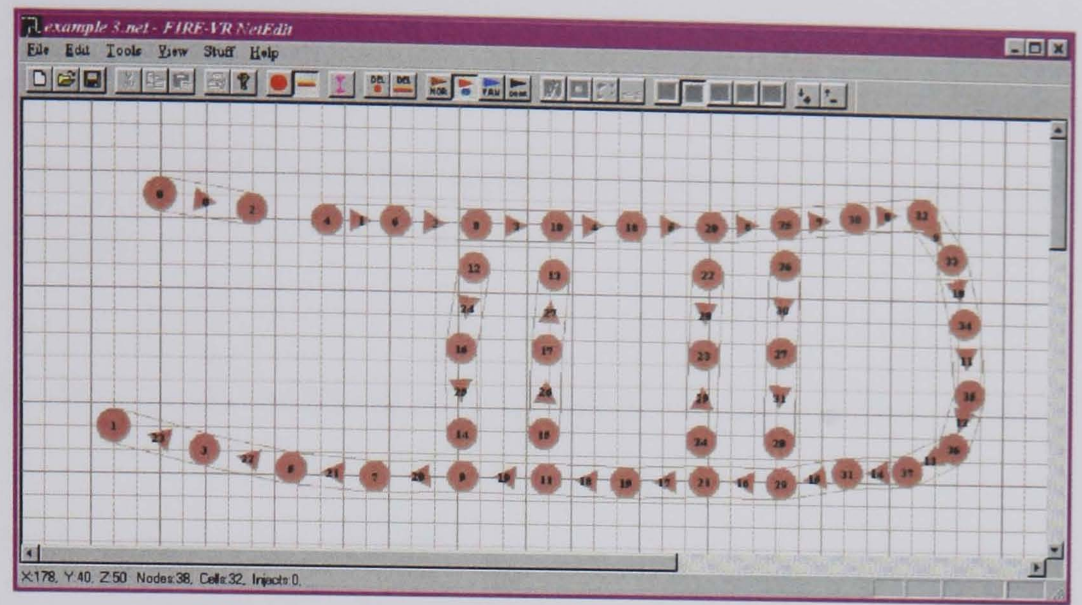


Figure 6. 14 Placement of nodes and adjustment of their depth within the world

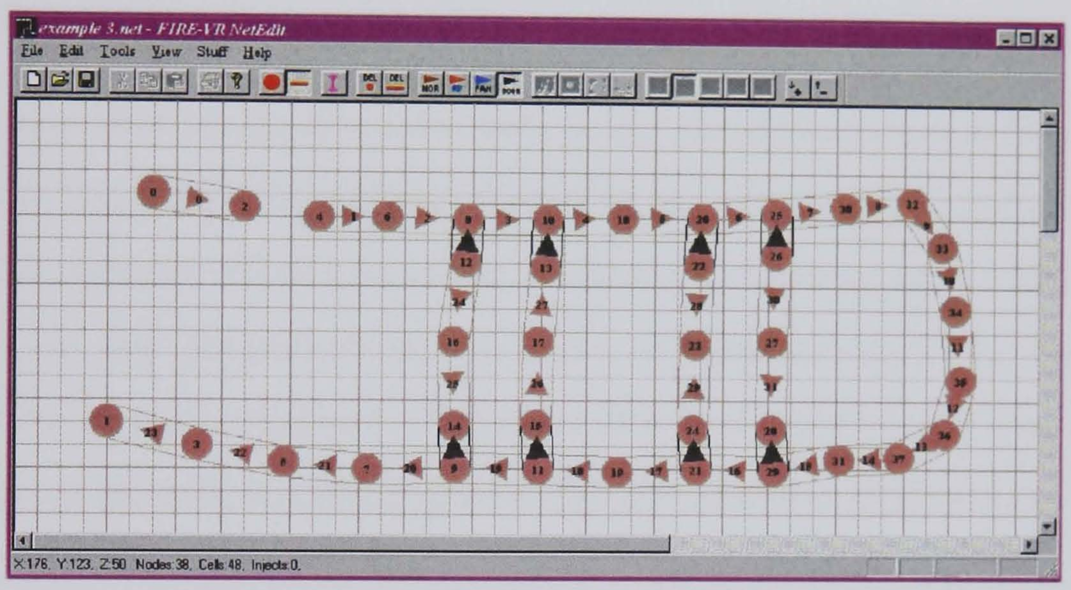
b) Placement of special cells; including world cell, doors and fans

After the normal cells (which consist of the majority of the defined roadway sections within the mine network) are created the user can then insert the special cells such as doors, fans and the world cell which ultimately create the ventilation model used in the simulation. All three of the following special cell functions require the cell button to be switched on. These special cells are shown in **Figure 6. 15**.

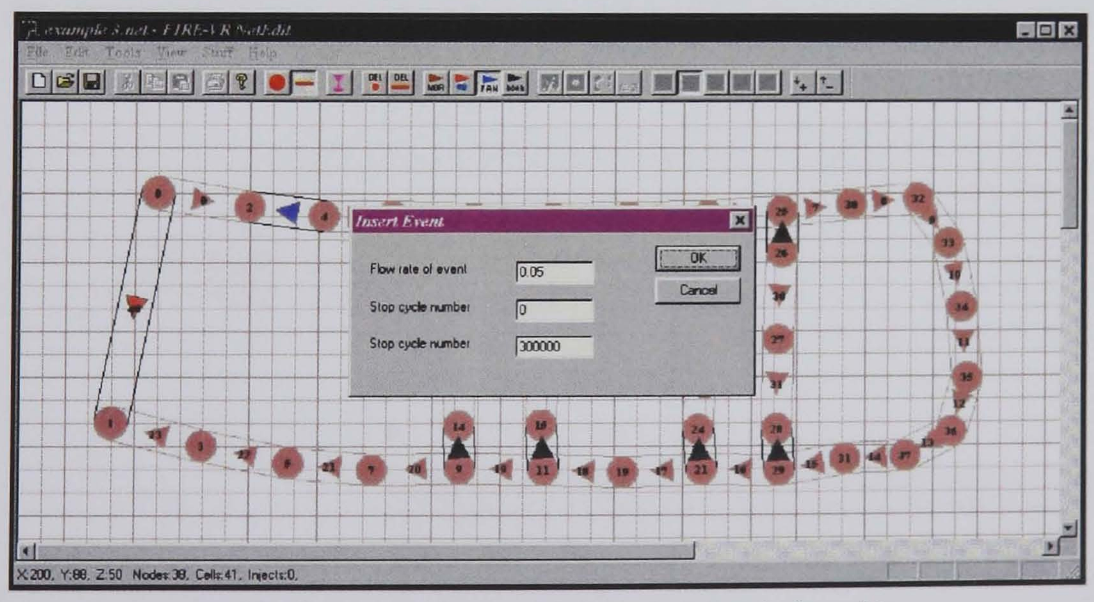
- **World cell.** A world cell can be created by switching on the world cell button and then drawing a cell as one would with a normal cell. World cells are displayed in red on the screen.
- **Ventilation door cell.** Ventilation doors are created by switching on the ventilation door button. Doors are marked in black on the NetEdit screen.
- **Fan cells.** Fan cells are shown in blue and are drawn by firstly switching on the fan button. A dialogue window appears so the user can define fan characteristics such as desired flow rate and operating window.



a) Basic node and cell network created with NetEdit without world cell, ventilation doors and fans



b) Ventilation doors are then added by clicking on the ventilation door button on the menu bar



c) Finally a world cell is created (shown in red) and a fan cell is described via a pop up window

Figure 6. 15 Creating ventilation doors, fans and the world cell using NetEdit

c) Defining events

When the user switches on the event button, the user configurable event buttons are accessible allowing various events to be inputted into the mine description file.

Available options for events closely model those described in section 5.4.4. e.g.

Events such as liberation of methane from the strata at a user specified rate or the defining of a inject type fire event which is designed to occur at a particular time within the simulation.

The user can click on the desired event. In the example shown in **Figure 6. 16** a fire event has been selected from the menu bar. The appropriate cell, where the desired injection event is required, is chosen by clicking on it. The user can then type in any parameters of the event, if appropriate, using the pop-up window shown in the diagram. The event is then displayed as a large circle in the middle of the cell, its colour is set to those outlined in **Figure 6. 1**.

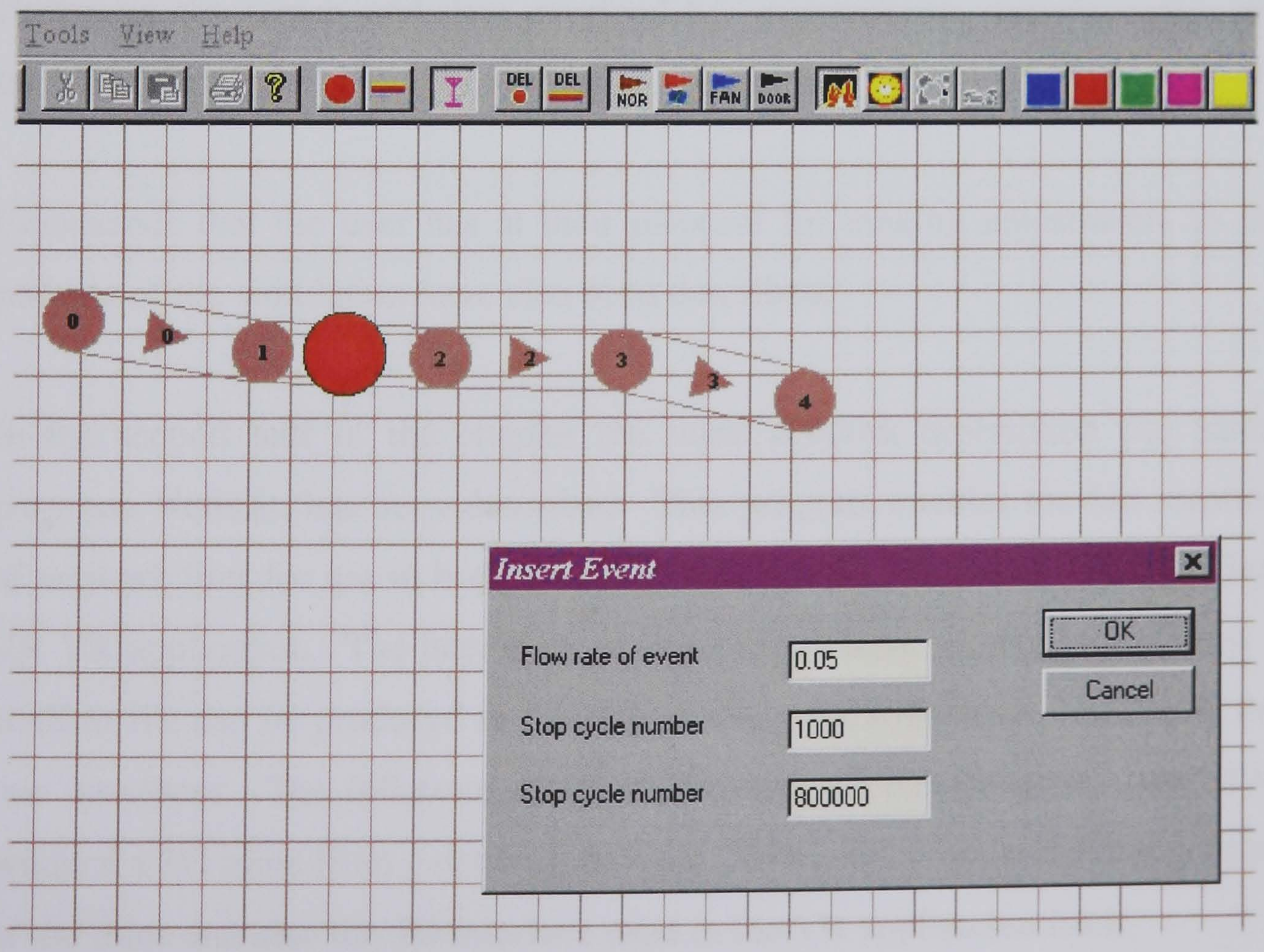


Figure 6. 16 Programming events using the event button in NetEdit

Finally, the file is then ready for exporting out of the NetEdit editor program and importing into either the 2D interface program or via 'makemine', a pre-processing 3D mine creation program (see section 7.2), and then into Fire-VR itself.

6.4 Summary

This chapter has described the 2D interface to VentSim-VR and EnvSim-VR which was programmed to allow the user of the software to view mine networks created for simulating. The programming tools used to produce the interface have been discussed. The interface itself has been designed with a standard colour coding (used throughout this research for consistency).

Because of the large quantities of data which the simulation can potentially model, data structures used in the display have been defined and listed for the reader. Both graphical and textual information have been discussed and their relation to the overall display which produces the main display for the simulation. Two methods of displaying the data in the cells were used and these have been discussed along with the benefits of being able to reduce clutter on the screen and data overload by programming options within the interface to switch on and off various data variables.

Commands that the user has at their disposal for making adjustments to the running of the simulation have also been described.

In the second half of the chapter the mine network description file editor program, NetEdit, has been described. This program enables the fast creation of network files for use in both the 2D interface sub-system and the main Fire-VR VR application. The later parts of this chapter have shown, briefly, how a NetEdit file can be produced in three steps ready for simulation in either of the two interfaces. The following chapter describes the sub-programs created to produce a 3D mine from a network file, the 3D models produced to aid realism of the mine and also the 3D interface used in the VR application itself.

Chapter Seven

Fire-VR, 3D Interface

7.1 Overview

The 2D interface, discussed in chapter 6, was initially developed as a viewing tool for mine networks created for modelling in the simulation. In this chapter, a prototype graphics engine created for the simulation is examined. This chapter covers all aspects of research which were carried out to produce a VR system that was then integrated into the main simulation program. Different approaches for generating the 3D world are discussed including ways of building the VE and world objects (which had to comply with the limiting factors discussed in chapter 4 regarding current computer limitations).

In order that the mine networks created for the simulation could be transformed into a 3D world, various world objects and graphical techniques were examined. Firstly, a separate world creation program, called MakeMine, was programmed to extract the mine infrastructure information from a typical mine description text file, and then output the geometry of a 3D model of the world. This program pre-parses through the network description file examining the nodes and cells and constructs a 3D mine model in 3D world space of the mine.

Secondly, the data structures, described in chapter 6, which model gases and flows within the mine were translated to 3D to provide the user with the same information. Thought was needed as to a suitable method of display of these data structures so as maximise the information displayed to the user whilst remaining unobtrusive.

Thirdly, objects needed as visual cues to the user were constructed which could be placed within the mine and used as interaction points. Examples of these objects would be telephones, doors and fire extinguishes.

7.2 Construction of the mine infrastructure using MakeMine

The VE that the user views has to be constructed around the original network of nodes and cells. In **Figure 7. 1** below, an example of a section of a network is shown in node and cell format.

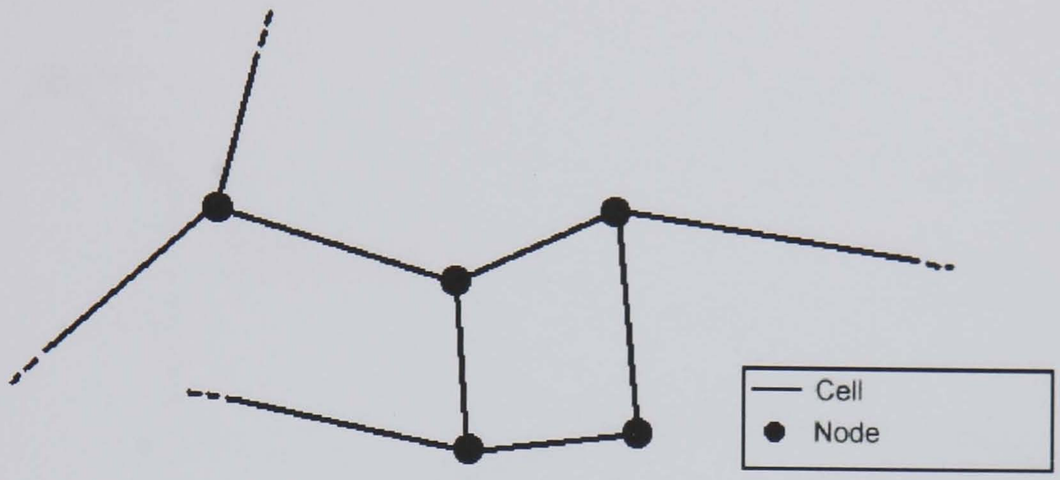


Figure 7. 1 Example network of nodes and cells prior to constructing the mine infrastructure using MakeMine

Environmental data structures discussed in **Figures 5. 3 and 5. 4** are held within the main data structure component of the simulation. A separate pre-processing program called MakeMine, was programmed, in order to construct the 3D mine infrastructure based upon the node and cell information.

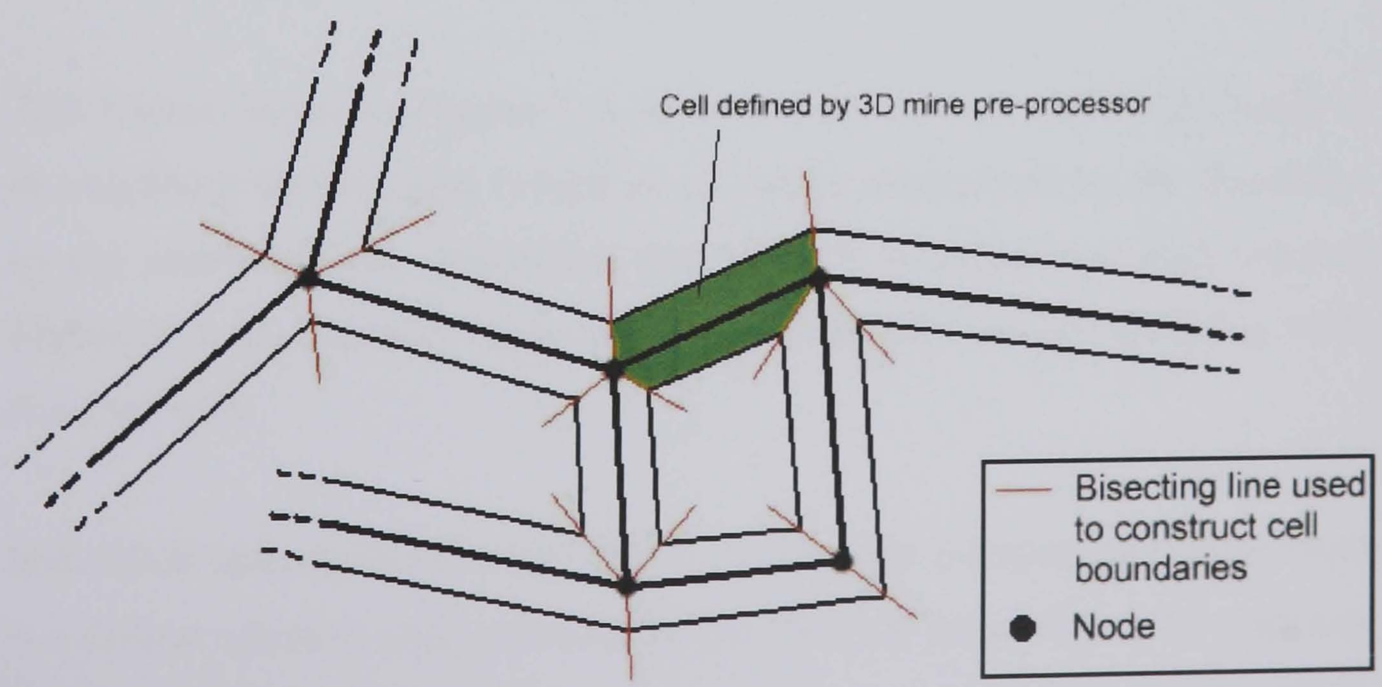


Figure 7. 2 Example network of nodes and cells after MakeMine has constructed the surrounding walls.

Using MakeMine, each length of roadway is partitioned into a discrete cell whose boundaries meet exactly with each neighbouring cell. This is achieved by defining all cells as six sided objects which are calculated to tessellate with the adjacent cells (see **Figure 7. 2**). The information used to produce the co-ordinates of these six sided cells is calculated by various trigonometric functions derived from the angle of each cell in relation to others surrounding it, and the position of the nodes themselves.

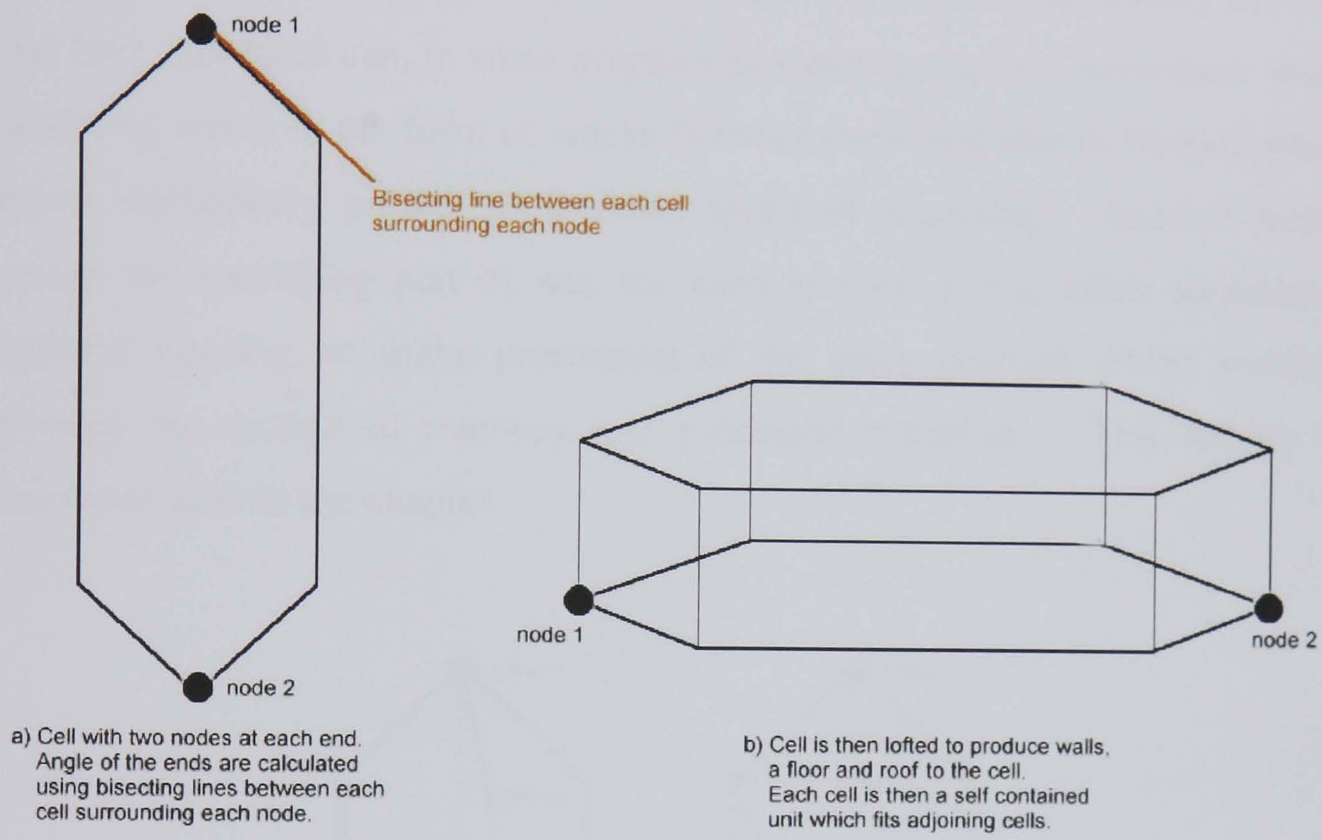
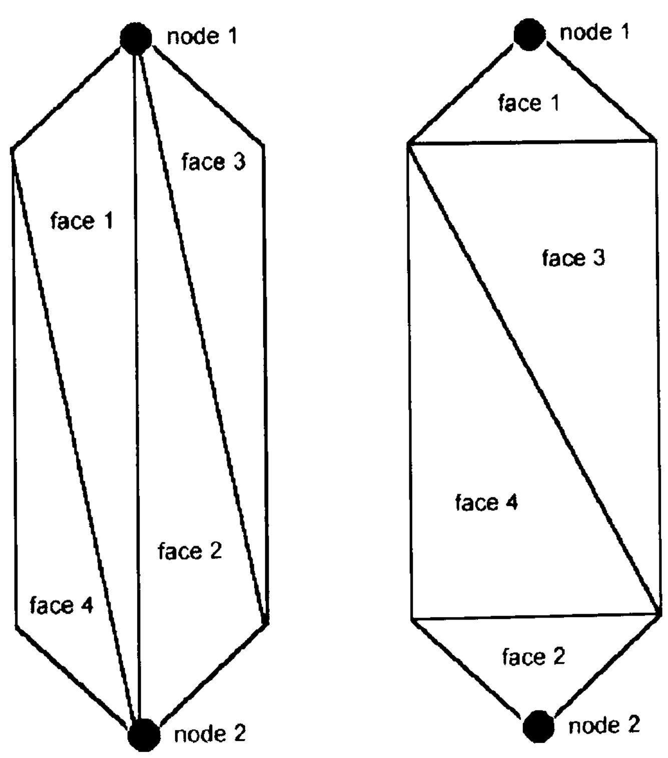


Figure 7. 3 Construction of 3D cell after pre-processing using MakeMine

This format, shown in **Figure 7. 3, a)** above, allows each cell to fit closely to its neighbour without gaps (which would not be represented by the simulation by any data structure). MakeMine then lofts the information of each cell (see **Figure 7. 3, b)**) into a 3D representation of a mine for the cell including walls floor and roof.

MakeMine outputs data to a text file to describe the infrastructure of the mine in a format which is easily readable by the Fire-VR simulation. Two options for the visual format of this data file are shown in diagram **Figure 7. 4** below. Although both designs for mapping triangular faces provide a covering of the cell using the same number of faces, the second mapping, shown in **Figure 7.**

4, b), was deemed to be the most appropriate because a pivot point naturally exists at the end of each cell which allows for the possibility of elevated roadway sections within the mine models. This pivot point allows the incline of a cell (defined using Pythagorous's theorem and the 3D co-ordinates of nodes 1 and 2 in world space) to be easily produced. This is not possible with part a) where faces on the floor and roof of the cell would become very distorted when the incline of adjacent cells was steep leading to an uneven roadway floor. Other potential problems exist with method a), namely the fact that long thin faces can, in some graphics processing engines, sometimes show rendering errors in the form of cracks between each face due to floating point errors deliberately present to increase speed of rendering. Another major reason for specifying part b) was the need to have a flat, albeit sometimes inclined flooring, to make processing of the users position whilst walking through the section of roadway less processor intensive. This facility is discussed later in the chapter.



a) Possible configuration of cell using triangles

b) Alternative solution to mapping a cell with triangular faces

Figure 7. 4 Different solutions for representing a cell using triangular faces

If **Figure 7. 4, b)** is considered to represent the floor of a particular cell then the roof can be constructed as a lofted version of the floor (here lofting refers to extrapolation of the desired co-ordinates for the roof faces based on the displaced co-ordinates for the floor and a pre-programmed specified height constant). Walls of the cell can likewise be constructed from the co-ordinates already calculated.

Information of the floor, roof and walls is then outputted from the MakeMine program in a format that is then readable by the main application of Fire-VR. Construction of the actual faces and their texturing is processed by Fire-VR.

7.3 Fire-VR, 3D interface

7.3.1 Programming considerations.

The 3D programming of virtual worlds within a virtual environment has features in common with object oriented programming techniques. This is different to the 2D Interface (see chapter 6) where graphical information is unique to the current frame and hence graphics must be re-displayed to the screen each cycle of the simulation. However, in the 3D environment 3D objects are re-drawn every cycle via the rendering pipeline (which is heavily dependant on the graphic hardware) and so the programmer only needs to concern himself with deciding where he wants objects to move to and how they should change in colour or orientation (for instance). This is in line with object oriented methodology.

The 3D objects in a VE world are constructed with real dimensions in a similar way to real world objects. Each object within the world has its own dimensions constructed from sets of co-ordinates in 3D space. These objects can also be programmed to contain behavioural information which can provide additional realism to match real world objects e.g. a fan might be spinning, or a wall might hold collision detection information in order to prevent other objects from passing through it (see section 7.3.7 a)). This allows a certain degree of intelligence to be built into individual objects and is very different to the approach of display used in the 2D interface, where the display is discarded after every screen refresh.

In the 2D interface, throwaway information such as the labels that describe events can easily be added. Sometimes this information might only be needed for a single frame and is 2D in nature. In 3D, due to the object-orientated approach to the display, the object has to be created even if it only exists for 1 frame. The construction of a flat object, such as text, is achieved by using a texture decal. 2D text information can be added to the 3D display in a similar form to the methods used in the 2D interface but text in this form is only available for use via a HUD type arrangement and consequently is not appropriate for displaying text with depth co-ordinates (i.e. text being scaled correctly as it moves towards and away from the user). Both the 2D interface and 3D interface have their benefits, but inevitably development has progressed down slightly different routes.

The 2D interface was designed primarily for the purpose of testing the complex algorithms associated with EnvSim-VR and VentSim-VR. Its large array of configurations and its colourful, informative display allow the user to quickly model a mine network and then to check particular events and phenomena. The very fact that it is a plan view, constructed in 2D, reduces confusion which may be caused by the display of too much information.

The 3D Interface, designed to be the main interface of the Fire-VR simulator, is concerned primarily with displaying the mine network in a way that can be easily identified with the real mine equivalent. Although the detail of the models is restricted to what can be achieved with the current computer technology, an attempt has been made to simulate real mine conditions and objects within the mine. Fire-VR was designed to be a VR mine simulator and not just a 3D display of data from a mine.

By definition, VR refers to a method of modelling the subject matter in a way that makes the user feel that they are immersed within the computer-generated world. In the case of Fire-VR, the simulation has been designed to provide an environment for the user with an approximation of the conditions that a real mine may have. For this reason, data displays are kept to a minimum leaving visual cues to give the desired effect. A relevant example of this is the modelling of smoke around the mine after a mine fire has occurred. In Fire-VR this is achieved by visually rendering smoke within the mine. Constituent gaseous components of the air flowing around the mine are displayed on screen in the format of a hand held display unit i.e. in a similar manner to the actual hand held detection units used by personnel.

The Microsoft Direct X® API was chosen as the API of choice because it provided the following benefits:-

- Strong, hardware independent support by most modern PC's. Direct X® is available as a free set of platform independent drivers that can quickly be installed on most modern PCs.
- Integration of the software to work with a variety of hardware accelerated graphics cards. This ability for Direct X® to be compatible with a variety of PC platforms, regardless of exact specification, allows Fire-VR to be transferable to a high proportion of different PC platforms, whilst maintaining a maximum throughput of speed for the 3D display.
- Large amount of written documentation. Because Microsoft's Direct X® and Direct 3D® have largely been applied in the entertainment domain, there has been a tremendous amount of support for programming with this API. This support is in abundance on the World Wide Web.

Both the development SDK and the Direct X® runtime libraries are free software. This is useful because it means that no royalty charge needs to be made to any third party when showcasing software written with Direct X®.

7.3.2 Direct 3D®

Direct 3D® is an applications programming interface used to provide an efficient programming of 3D graphics independent of the host hardware. The Windows® operating system was traditionally not concerned with speed. The display routines used by Windows® were primarily designed for business applications which required a generic image such that training from one software application to the next was as straightforward as possible. The screen refresh rate per second for a business application is rarely required to be particularly fast as the information on the screen, from applications such as an Excel™ spreadsheet, is not changing at a high rate. Users still require their spreadsheets to run fast and calculate all of the adjustments as quickly as possible. However, the screen update for this type of application does not need to be very fast. In this example, it is more appropriate that the majority of processing time is utilised actually calculating any changes that have been made in the spreadsheet's formulae. In contrast, in a VR computer application, fast frame rates are required because objects, information and user input are changing rapidly.

Furthermore, in VR, in order to produce a realistic computer generated interpretation of a world, high frame rates are needed. Ideally, VR simulations need to be updated at least 24 frames per second to give a smooth interpretation of movement.

When calculating the 3D display of a VE, clipping becomes increasingly important as a method of reducing processing time whilst producing the display (see **Figure 3. 8**). The use of Direct 3D® has allowed the programming of 3D objects and worlds in Fire-VR and provided high level programming routines to allow these types of calculation saving methods to be performed.

Microsoft developed DirectX® so that the performance of applications running in the Microsoft Windows® operating system could rival or exceed the performance of applications running in the MS-DOS® operating system. This allowed the ever more popular Windows operating system to release the speed constraints it inherently had and hence, has enabled the programming of VR systems on a PC system.

7.3.3 Colour key notation used in Fire-VR

The coloration of data structures visualised in the 3D world was defined in a similar way to the colour key discussed in section 6.2.2. This key was selected so as to maintain consistency across the research interests of the simulation.

7.3.4 Graphical considerations.

One of the major considerations during the development of Fire-VR was that of how the representation of real world objects and environmental conditions could be achieved in computer graphics. The environmental modelling system, EnvSim-VR, and the pressure based flow calculation system, VentSim-VR, are primarily concerned with modelling environmental changes within the mine network. To model these objects, some compromises had to be made and graphical techniques had to be tweaked to optimise performance, whilst giving a general representation of the object to the user.

The following observations were made: -

- Physical objects within the world would have to be modelled with a level of detail which was recognisable by the user whilst not creating such a performance hit that the simulation or frame rate display for the 3D VR system would suffer.
- Environmental effects would create additional problems. Visible effects such as rendering smoke would need a simplified yet identifiable model. The modelling of smoke within Fire-VR was deemed necessary as a visual cue for the presence of a fire event. Other such environmental effects such

as methane build-up posed a problem. Naturally occurring gases, found within a mine, are of course invisible. The method selected to graphically display these environmental attributes is described in section 7.3.5.

7.3.5 Graphical representation of environmental information

The Fire-VR application consists of a VE world created from the environmental data present in a mine description file (produced with the NetEdit program) and the mine infrastructure (created using the MakeMine program described in section 7.2). Additionally, other aesthetic objects are imported into the VE to enhance the display. Furthermore, Fire-VR has additional programming to allow user interaction with the VE via mouse and keyboard commands listed in section 7.3.8.

a) Graphical display of the world

Structural information regarding the mine environment is loaded into the 3D interface via the pre-processed text files discussed in section 7.2. Appropriate textures are then applied to the surfaces in order to generate a more realistic image via techniques discussed in Chapter 3. The textures used in this research are defined in Appendix 5.

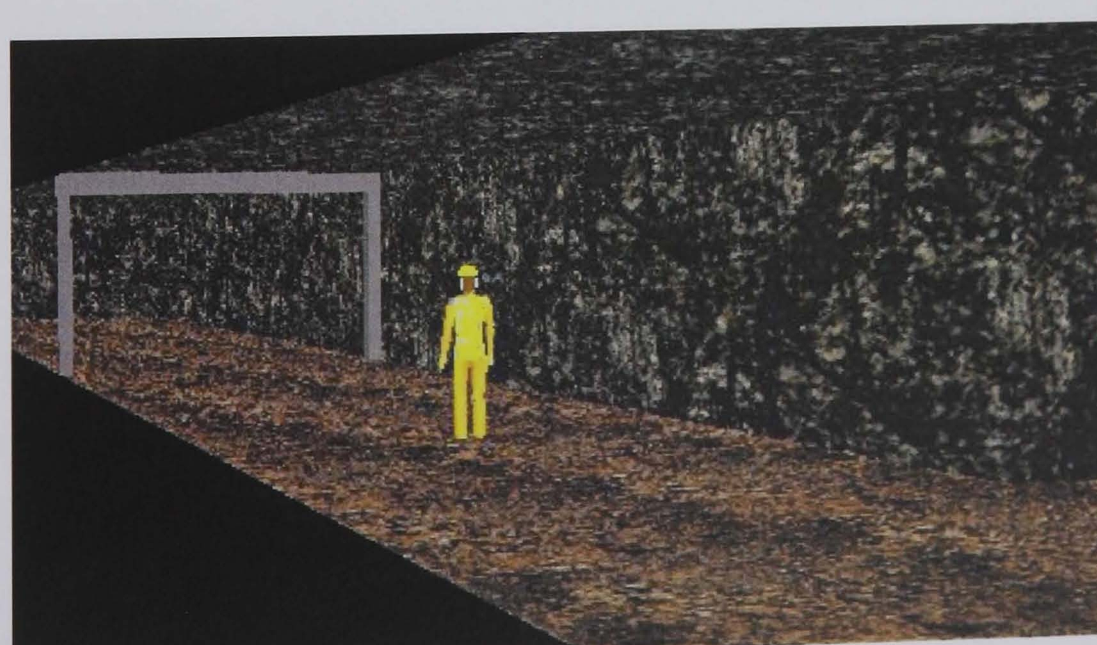


Figure 7. 5 Mapping of textures onto 3D cell geometry defined by MakeMine

Figure 7. 5 shows a length of roadway constructed from 3 adjacent cells with the geometry displayed in the 3D interface using texture maps on the walls, floor and roof. In this instance, the figure has been added to enable the scale to be judged more easily.

A roof support object was also defined and this was loaded into the geometry as part of the mine infrastructure in order to increase visual detail within the mine. Further enhancements to the visual detail of the mine infrastructure, in terms of additional objects, are possible if required. For this prototype work, however, the basic structure above was deemed to be suitable for the desired purpose of displaying a mine network.

b) Graphical display of information

Different techniques were considered in order to model the environmental changes within the 3D interface. In the following two sub-sections, the techniques used in the 3D interface to display the environmental information created by the simulation are described. Particle and fluid based objects are notoriously difficult to model in computer graphics even when all processing power is contributing towards the display process. Fire-VR uses the following methods to display the information in a way that is recognisable to the user but is not too computationally intensive. By implementing the cell structure discussed in section 7.2, a variety of environmental modelling effects were able to be introduced.

Visual modelling of smoke

Fire-VR models smoke by applying a wrap of translucent material over each cell within the mine network. The information gained from the constructed cells provides the dimensions and positional information for the cell wraps. The level of translucency and the colour of the wrap are then varied depending upon the level of smoke currently in that cell. This method can give a very convincing representation of smoke levels in the mine.

Figure 7. 6 Smoke modelled by using varying levels of opacity to colour the cells

In the above diagram (**Figure 7. 6**) the smoke wrap around each cell can clearly be seen. The ventilation path, of this example, is split into 4 (including the face at the end) and smoke is carried along by the air-flow. The more dense the smoke, the more opaque the roadway section becomes. This diagram was constructed from a fire event created by the user in the bottom left hand corner. After the event has died (due to there being a lack of combustible material in this example) the smoke gets cleared from the mine by the fresh ventilated air-flow. As more oxygen is drawn in, the smoke levels decrease; this is shown graphically by increasing the transparency accordingly. Eventually, smoke is cleared from the roadway and the cell wraps are completely transparent again.

This technique is applied while the user of Fire-VR is in third person perspective mode. Another technique is required when the user is in first person perspective mode due to the fact that any wrapping texture used for modelling smoke is only visible from a position external to the mine infrastructure. (These different types of display mode are discussed in section 7.3.6).

Smoke, in this case, is generated by using the fogging techniques previously described in section 3.2.4. Fogging effectively reduces the visible amount of detail that is viewable from the camera point of view. Simple linear based fogging is achieved by specifying a start and end point for the fog effect. The fog effect begins at the specified starting point and increases linearly until it reaches its maximum density at the specified end point.

The start point, for the fogging effect, is defined a small way in front of the camera, whilst the end point is defined at the back clipping plane of the viewing frustum. **Figure 7. 7, part a),** below, shows how this method has been implemented.

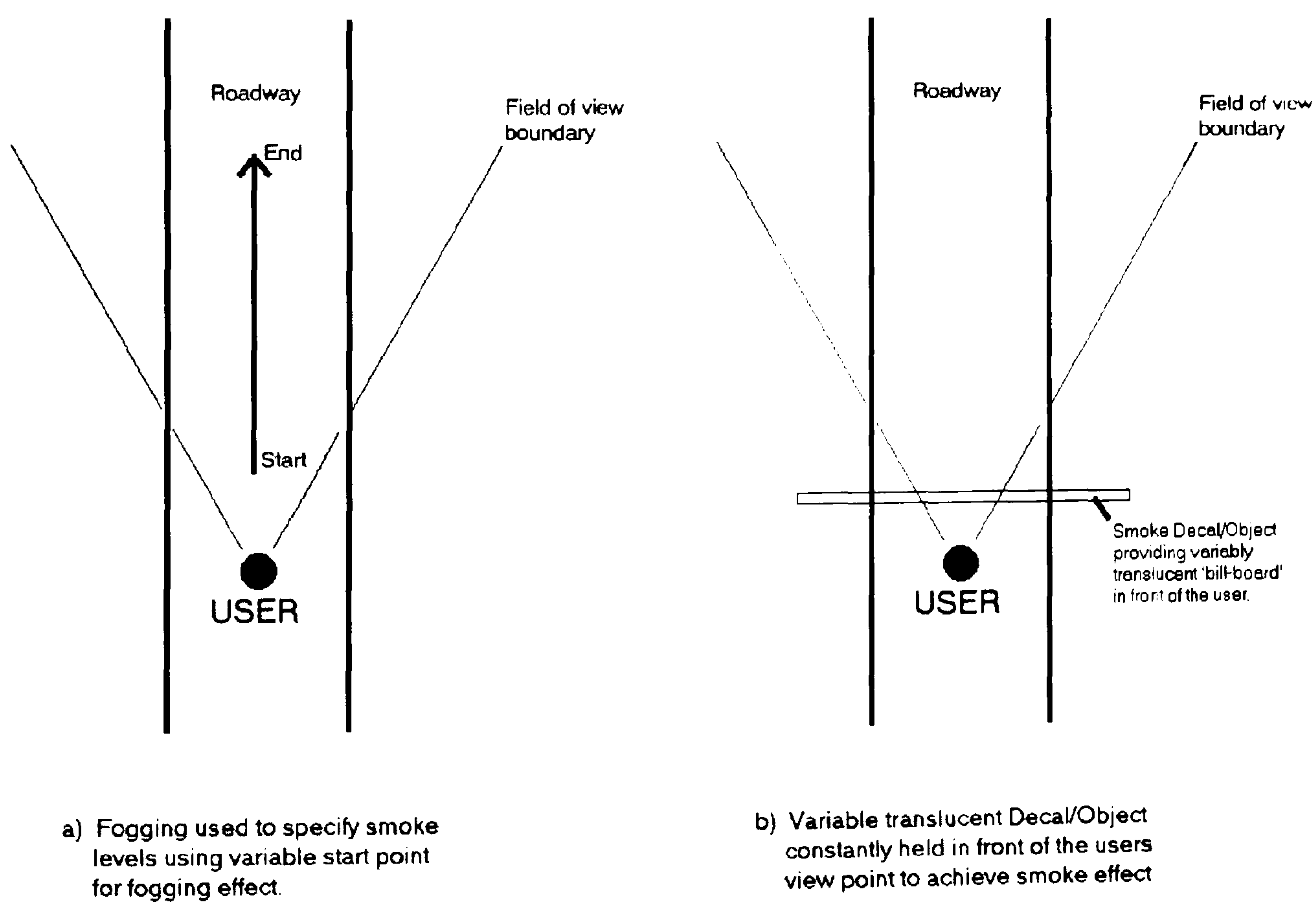


Figure 7. 7 Two methods of displaying smoke in first person perspective mode

The varying levels of smoke which EnvSim-VR computes each frame can be translated to a variable used in creating the fogging effect. By shifting the fog start point backwards and forwards from the camera point of view, a variable density of fog (smoke) can be achieved i.e. when the fogging start point is moved closer to the camera, more smoke appears to be present thus restricting visibility (see **Figure 7. 7, part a)**).

Additionally, other techniques were tested to assist in the visual effectiveness of producing a smoke effect in a first person perspective view, namely, that of a variable shaded decal texture (see section 3.2.4) which was automatically placed permanently in front of the camera (see **Figure 7. 7, part b)**). By varying the shade and translucency of this decal, the effect of smoke within each cell as the user walks through the mine can be achieved. Decal textures combined with alpha transparency techniques (needed to provide the varying levels of translucency) were found to be incompatible with each other, in the version of Direct3D® used for this research, rendering the implementation for this method impossible. A solution was found by creating a flat object, wrapping an alpha transparent enabled texture around the object and providing the necessary positional and orientational adjustments to ensure that the 'bill-board' was maintained at a permanent position in front and perpendicular to the user even when moving. (With decal textures this orientational adjustment is automatically provided by definition i.e. it being a texture which is placed as part of a simpler 2D flat rendering technique, giving its position in front and always facing the user, as opposed to a full 3D rendered technique).

This alpha blended transparency implementation for smoke from a first person perspective point of view is shown in **Figure 7. 8** below: -

a) No fogging or Alpha blended textures used

b) Variable translucent Decal/Object constantly held in front of the users view point to achieve smoke effect

Figure 7. 8 Smoke generated using a flat object positioned and orientated to be in front of the user using a variable alpha transparent texture

Together, both of these techniques for creating fog in the first person perspective view mode were found to give a very good visual cue as to the presence of smoke within a mine.

Visual modelling of gases

Oxygen, methane, nitrogen, carbon dioxide and carbon monoxide are all modelled using vector type arrows in a similar manner to that used in the 2D interface. The only major difference between the two Interfaces is that the arrows in the 3D interface are made translucent in order to prevent the obscuring of the roadway.

In Fire-VR with the user in third person perspective mode, the arrows that are drawn can be changed to display only one of the gases at a time. Again, as in the 2D interface, oxygen is represented by blue, nitrogen-green, methane-red, carbon dioxide-purple and carbon monoxide-yellow. For example, **Figure 7. 9** below shows a section of roadway with methane flow represented by the red arrows.

Figure 7. 9 Section of roadway with information about flow represented as a semi-transparent arrow on the floor

During development, this implementation was removed and an alternative procedure was installed which was found to perform more satisfactorily in the 3D interface as discussed later.

The main flow of air is represented by white arrows which move through the mine in the direction of the air flow and at a flow rate actually representative of the flow rate of gases at each particular roadway segment or cell. Prior to this, static arrows were used with the arrow's direction representing the flow direction of the air. With the implementation of moving arrows (shown in **Figure 7. 10, parts a) and b).),** which actually travel along the same vector as the cell (including inclines), the implementation of the 3D interface became more representative of the actual airflow within the mine.

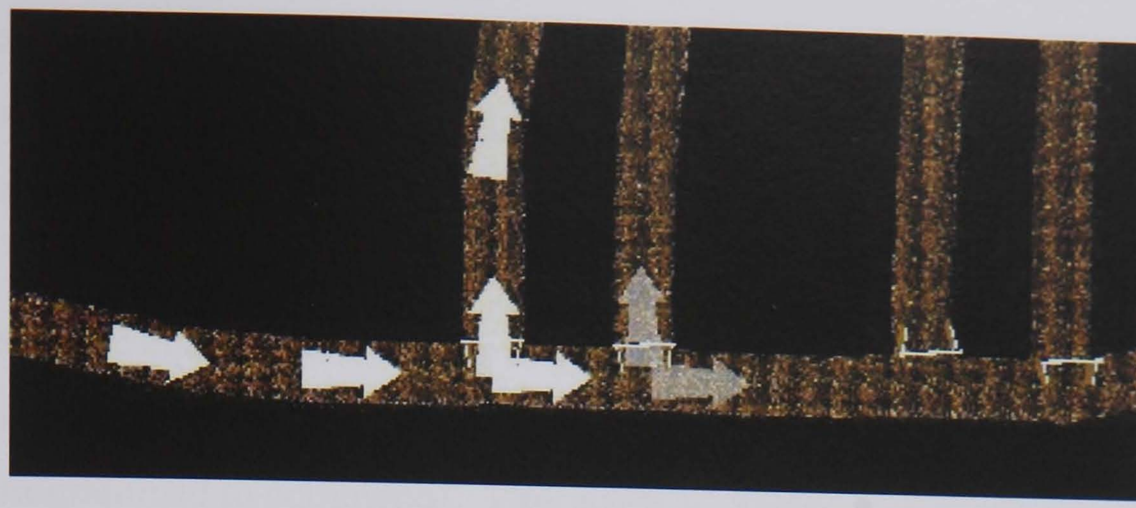


Figure 7. 10 Part a). Moving arrows which travel through the cells in direction of airflow. Opacity levels used to show relative speed.

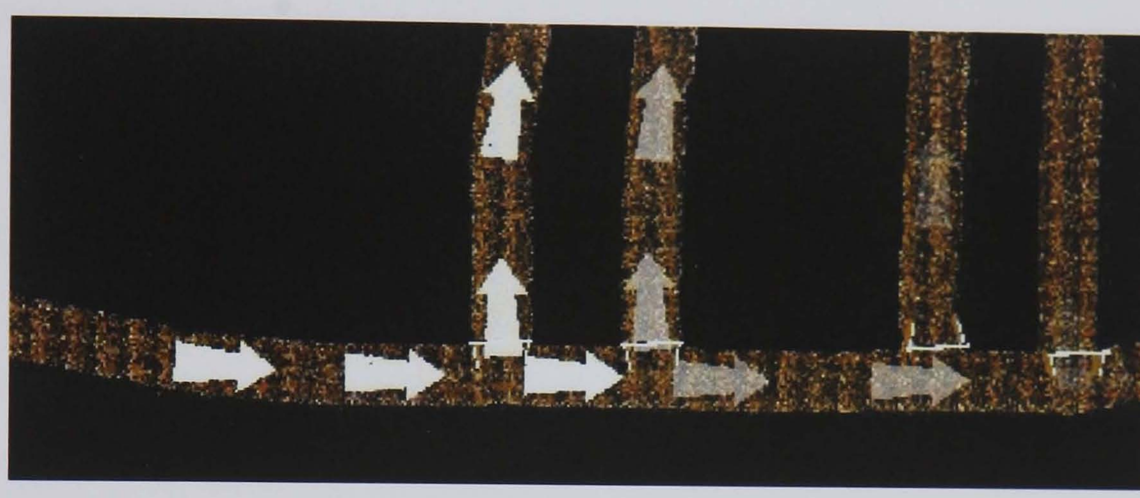


Figure 7. 10 Part b). Showing movement of arrows after progression of simulation.

The arrows were created by defining an arrow object class and loading up a copy of this class for every cell within the network. The arrows are initially loaded up at the 1st node[2] and are orientated to point along the cell's vector in 3D space. Each frame of the simulation, the arrows are moved along the cell in proportion to the flow rate calculated for that cell by EnvSim-VR. If the flow rate is the reverse of the direction of the arrow then the arrow is rotated through 180 degrees so as to account for this. The arrow travels through the length of the cell until it reaches the end (unless a reversal of the airflow has occurred which means the arrow's direction and orientation is also reversed). At the end of this path, when the arrow reaches the node, a process is started which initiates the movement of arrows within the surrounding cells of this node. This process is analogous to the 'firing' of a neurone cell with the brain. The movement of arrows within the Fire-VR 3D interface was designed in this

[2] Each cell has a node either side of it. The 1st node can be considered to be the node which was set in place first, by the creator of the mine description file using the NetEdit software.

manner so as to keep the movement of the arrows smooth in relation to the airflow that they represent. Each cell only displays its arrow when an arrow from an adjacent cell has passed into it. Once an arrow reaches the end of the cell's length it is destroyed (after initiating the creation of the adjacent cells arrows). The entrance to the mine is considered to be the starting point for the airflow and it is here where the 'pulsing' action of creating the first arrow has been programmed to commence. This arrow is created at a steady time interval (assuming this part of the display is switched on – see section 7.3.8 b)) and when it reaches the end of its path it is destroyed whilst creating a new arrow to take over its path through the rest of the mine network. This process allows the smooth animation of arrows passing from cell to cell.

This method of producing animated arrows for modelling the airflow is able to cope with junctions. The same process as above occurs, except that all outward flowing cells have an arrow created within them when an inward coming arrow arrives at the node junction in question.

Additionally, arrows are displayed with varying amounts of alpha blended transparency to show the relative flow rates of air passing through each cell. The faster the airflow, the less transparent the arrow is rendered.

Because this model was concerned with representing flow rates primarily, another display medium had to be provided to show information regarding gases within the cells.

Numerical representation of gas levels within a cell, when in the first person perspective mode of Fire-VR was catered for by providing a hand held display unit for the user (see sub-section c below).

In third person perspective mode, where data representation can be more intrusive to the main display, a new method of displaying gaseous information was devised.

The cell 'wraps' which were designed to be used in displaying smoke information in each cell were doubled up to provide a useful display which could provide information about the air constituents in each cell in terms of the percentage gas split of the modelled gases. In **Figure 7. 11** an example mine is shown. In this mine, an unusually high liberation of methane from the strata has occurred thus causing a build-up of methane gas which has not been dispersed adequately by the ventilating airflow.

Figure 7. 11 Methane build-up within area of mine shown using alpha transparent cell 'wraps'

The Fire-VR display has been set to show methane gas and the methane component, calculated by EnvSim-VR, is then displayed using varying opacity levels which are applied to the wraps of each cell.

This allows the user to quickly distinguish problems areas within the mine ventilation network. An intensity variable (activated by pressing the U and I keys (see section 7.3.8 b)) for increasing and decreasing intensity of the display respectively) has been included. This facility has potential in being used as a training feature because the user can interact with an example mine scenario. Hence, different methods of action can be explored to eradicate potential dangers such as a build-up of fire damp (methane + other gases). The display can be changed to highlight each gas in turn ranging from methane to oxygen levels etc. Coloration of the cell wraps were defined in accordance with the key shown in sections 6.2.2 and 7.3.3.

c) Numerical display of data

Numerical data calculated by the simulation is displayed to the user, when in first person perspective mode (see section 7.3.6), by means of a hand held display unit in the lower right portion of the main 3D interface screen. This hand-held unit represents a portable monitoring rig which a miner could typically carry into a mine in order to check various environmental conditions.

Figure 7. 12 Handheld data monitor in bottom right-hand corner of display

The display is representative of an LCD based hand-held unit which reports to the user levels of gas including oxygen, nitrogen, methane, carbon dioxide and carbon monoxide as well as present levels of smoke and dust. Gases are displayed as their percentage constituents within the air whilst smoke levels and dust levels are defined, at present, only in terms of relative amounts in this prototype system.

Obtaining information from within a section of roadway

As the user walks through the mine and passes from cell to cell, the information reported to the user via the hand-held unit is updated. A routine to report back the current cell identification number that the user is within was programmed and with this information, data can then be extrapolated from the EnvSim-VR sub-system and displayed on screen. The programming routine for returning the current cell number is gained as a by-product of information returned via the collision detection processes which are discussed later in this chapter in section 7.3.7.

7.3.6 Differing perspective views of Fire-VR

Fundamentally, Fire-VR is a virtual reality system that allows the user to walk around a mine system and interact with the surroundings. As well as modelling the world in an accurate a form as possible, a decision was made to increase the usability of the system by the provision to include information that cannot necessarily be seen in real life. An example of this is the display of carbon monoxide levels within the mine, even though in real life this gas is invisible.

Options were created within Fire-VR to allow two main modes of operation: -

1. **Modelling of the mine from a first person perspective**. This mode models only real world objects and therefore the physical representation of invisible components such as methane gas is not included. However, information of the gas levels is fed back to the user via the hand held display unit discussed in the previous section. This view is primarily designed to provide a VE that the user can move within and interact with which is a natural model of the world from a miners perspective.

2. **Modelling of the mine from a third person perspective**. This mode allows the user to see a view of the mine from above or any other angle, and also enables the user to view data which would otherwise be invisible. Gases, in this interpretation of the world, are modelled as data structures which are representative of the data within each cell. The gases are displayed in a method that is visually easy to identify but physically unrepresentative of the real world.

Part a) below describes the first person display mode used in the 3D interface sub-system of Fire-VR whilst parts b) and c) describe additional third person perspective modes that have been programmed to allow the user extended access to the data that is represented by the simulation.

a) Main VR view of the mine

The first person perspective mode is the main view that Fire-VR uses. It consists of a window into the virtual world that allows the user to view the mine environment as if through his own eyes as shown in **Figure 7. 13**. Graphical detail has been defined to a level that is recognisable by the user by providing graphical cues to the environmental features within a mine, whilst not being so complex that the frame rate or simulation suffers. Graphical representation of data structures used by EnvSim-VR are not catered for in this view except for the display of impeded visibility due to smoke caused by fires. This feature was included so as to maintain a visually realistic environment for a person being present within the mine. The hand held display showing the user environmental information such as air quality is present in this mode. The user is able to 'walk' around the VE interacting with the environment and observing pre-conceived scenarios set-up as example mine networks. Objects within the mine can be interacted with by use of simply control functions such as the clicking of a mouse button. These control methods are discussed later in section 7.3.8.

Figure 7. 13 Typical view along a section of roadway – seen from first person perspective.

b) 3D Plan view of the mine

A plan view of the mine network can also be displayed by the user by pressing the 'M' key on the keyboard. This view provides a third person perspective view of the entire mine, scaled to fit on the screen in its entirety. Because this view is based upon repositioning the camera only, it conveniently shows all aspects of the mine at once including objects such as ventilation doors, fire extinguishers and any additional objects which have been programmed. Additionally, because this view is from a third person perspective point of view, it is appropriate to show environmental information such as gases and smoke. In order that this information can be seen from a positional view which is essentially within the rock, the walls of the mine infrastructure have been made one way. This allows the walls to have a texture applied to one side of the mine wall infrastructure only thus giving the impression of a solid wall from one side (first person perspective mode) whilst allowing the user to view into the mine roadway when outside of the tunnel structure (when the user is in any of the other main view modes).

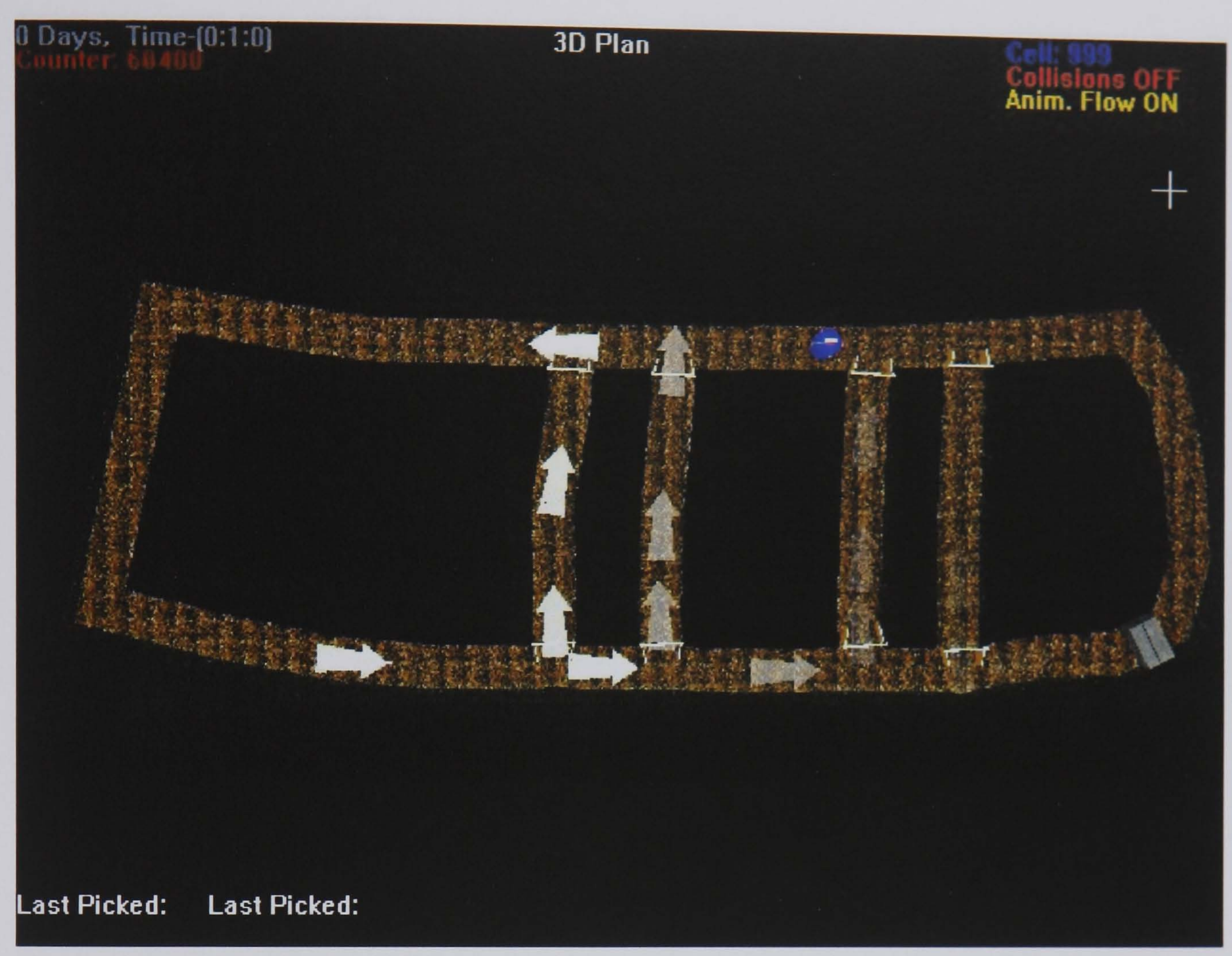


Figure 7. 14 Main plan view of example mine in Fire-VR

Figure 7. 14 above shows this plan view of the example mine network. The handheld display for this mode is disabled and the floor of the mine can easily be seen through the roof allowing the user to view the environmental data within the mine network.

c) Additional views available to the user

The option to observe other views has been programmed for the user to enable creative ways of examining the data created by the simulation and to allow further training possibilities.

Third person perspective view

The third person perspective view refers to the ability to view the mine network from any angle, including those which would be impossible to view in real life. This gives the user access to sections of the mine network which he wants to see in its entirety and to view the simulation in segments or as a whole depending upon what is required. Positioning of the camera can be achieved by disabling collision detection (see section 7.3.8 below) and moving outside of the boundary infrastructural walls. A typical example of a third person perspective viewpoint on the VE is shown in **Figure 7. 15** below.

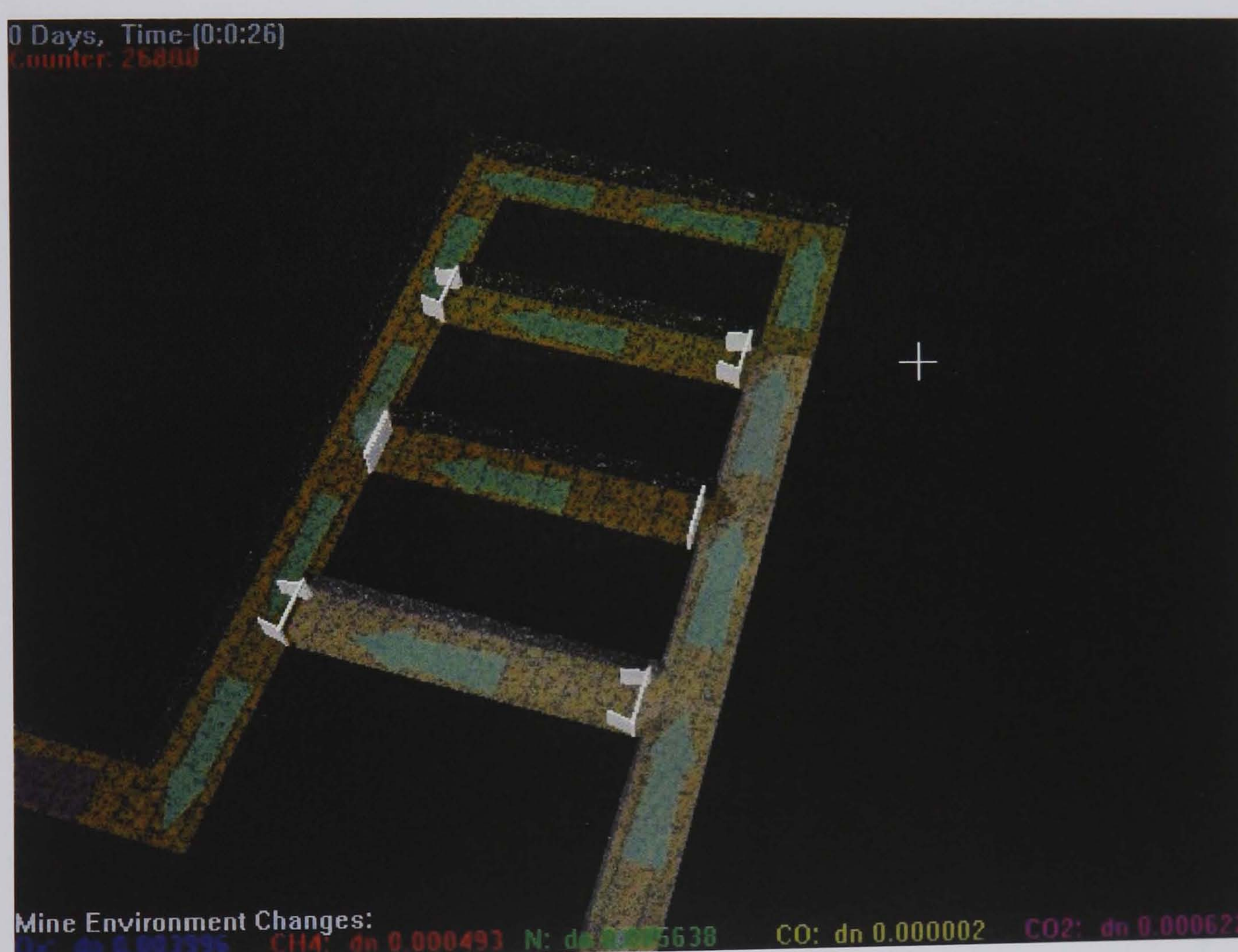


Figure 7. 15 Third person perspective view showing gaseous flow of oxygen

Map views

Additional map views were programmed in order to provide information to the user about the structure of the mine network when still in the main VR, first person perspective view. This provides the user with additional information which can help in locating which part of the mine the user is currently in. It has been designed to reflect the possibility that maps of the mine would be available to a miner when moving through a mine. This facility is optional because disorientation of the user might be a key part in training when dealing with low visibility situations created when a mine fire is occurring.

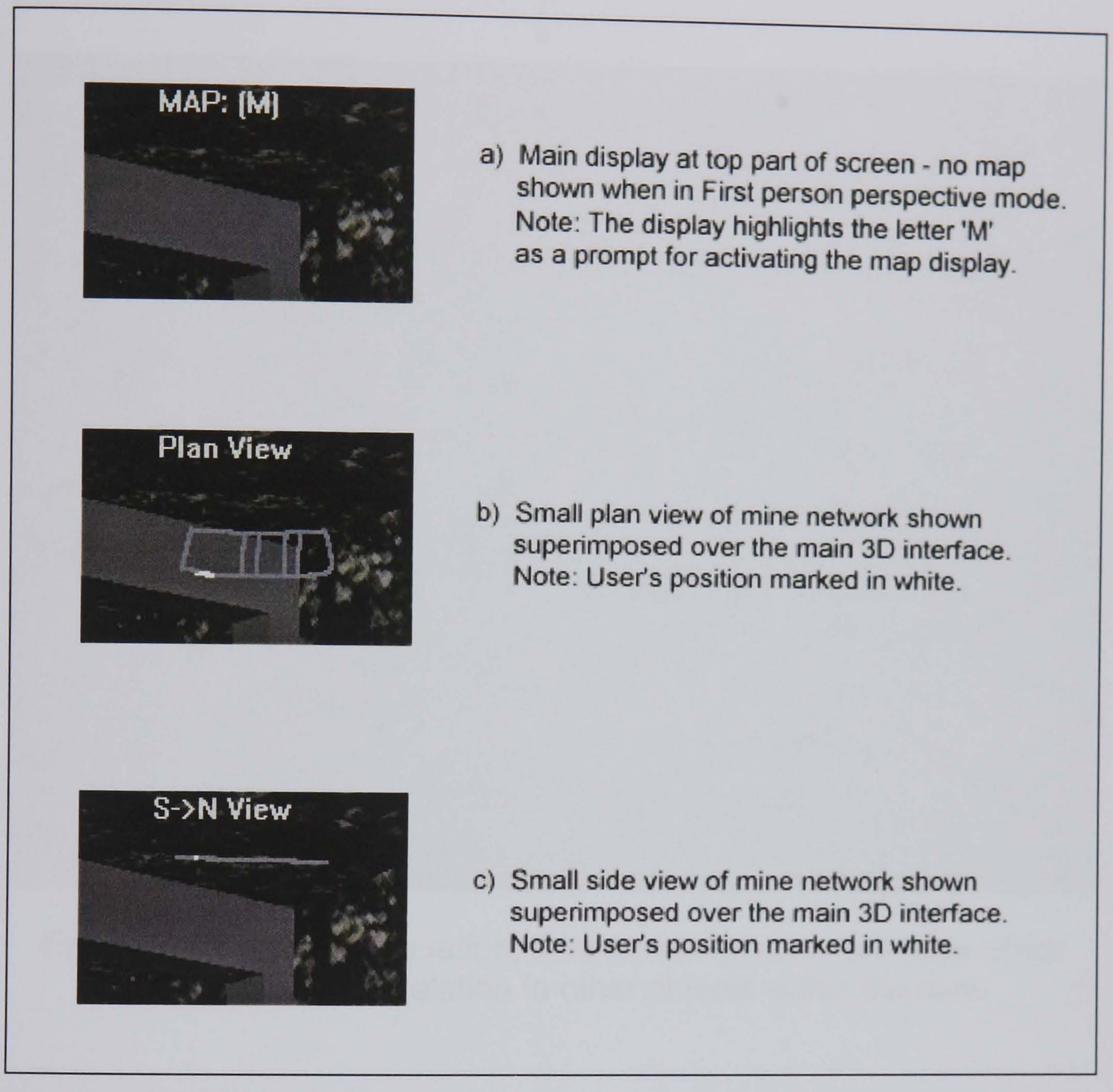


Figure 7. 16 Additional map views showing the mine network

Figure 7. 16, above shows these map views. They have been superimposed over the main 3D interface display when the user is in first person perspective mode so as to avoid cluttering of the main display. The users position, in terms of the cell which the user is in, is marked on the network in white. The side view shows the network from a cross-sectional point of view and is useful in ascertaining inclines. Pressing the 'M' key on the keyboard (see section 7.3.8 for further explanation) cycles through the map views.

User observation, third person perspective view

Finally a view mode was included to enable the user to view himself from outside of the mine infrastructure. This view tracks the user by keeping the user at the centre of the screen at all times (see **Figure 7. 17** below).

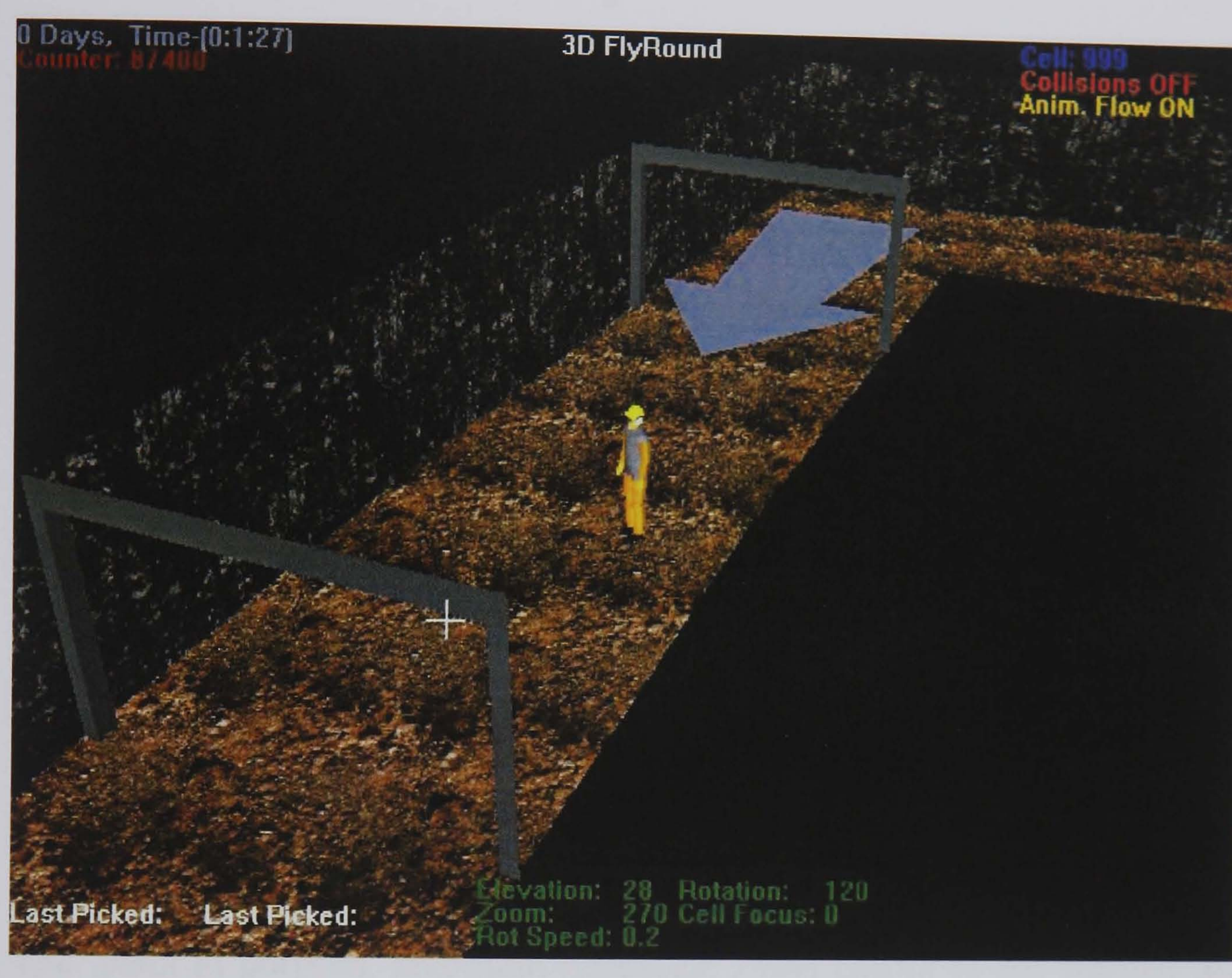


Figure 7. 17 User observation, third person perspective view which shows the user in relation to other objects within the mine

A miner object is loaded into memory and is displayed at the exact position in 3D space as to where the user was last when in first person perspective mode. The orientation is also set to equal the direction that the user last faced. Controls have been provided to zoom in and out and rotate around the figure so as to obtain the best view of the environment directly surrounding the user.

7.3.7 User tracking throughout the mine

The movement of the user through the mine had to have certain conditions attached to it in order to represent realistic movement and to avoid unrealistic scenarios such as breaching the walls by inadvertently moving through them into the rock. Various aspects to control the user and keep movement in check were therefore programmed into the simulation.

a) Collision detection

Collision detection is used in Fire-VR to restrict the movement of the user, when in first person perspective mode, from leaving the roadway. This is needed because it is easy to over compensate with movement commands when using VR applications at first and a user who leaves the main designated paths could soon become disorientated. A collision detection sub-routine was developed based on principles implemented by (Shimrat 1962) and (Hacker 1962). It was the requirement that the user, when collision detection was switched on, would be forced to stay within the walls of the roadway section. Cell boundary information was already available from the MakeMine program (see section 7.2). This information is refined in order to reduce the width of each cell (so that the user is unable to approach the walls too closely) and then stored in a data structure to be accessed by the 3D interface code.

The 'point in polygon' algorithm (Heckbert 1994) checks to see whether the user's position is within the boundaries of the polygon which is defined by the outline of the refined cell data structure discussed above. By sequentially checking each refined cell structure against the position of the user, the code produces an exact account of which cell number the user is currently in, if it is indeed within a cell at all. This process occurs each frame and if the user suddenly steps outside of the roadway section into a no-go area the procedure flags this as being a collision fault (i.e. the user has collided with a wall). When this happens the interface can revert the users position to the last position that was detected as being valid (i.e. where no collision fault had occurred).

In first person perspective mode, it is desirable that the user is not allowed to leave the roadway and pass into the rock strata. This collision detection facility can be switched on and off as desired.

The algorithms and the code written for the collision detection routines are fast and reliable due to the nature of the cell structure outlined in section 7.2. Because each cell fits exactly with each other in a tessellating structure, it can be assumed that if the user's position does not appear within any of the polygons outlined by the cells within the network then the user has stepped out of the tunnel. Because the walls of the individual cells are always vertical, the collision detection algorithm only needs to check against the floor plan of a cell thus relieving the computational strain usually associated with collision detection routines.

Finally, because the routines programmed for collision detection work by calculating whether or not the user is present within each cell, the code also provides a method of reporting which cell the user is currently in. This information is used to form the display for the map views shown in **Figure 7. 16** as well as being used to report information for the hand-held display unit, see **Figure 7. 12.**

b) Height adjustment algorithm

The Fire-VR prototype application is able to model networks which are based on more than one plane and therefore the roadways can climb and descend. Because of this fact, a routine was programmed which would keep the user a pre-set height above the floor of the mine roadway at all times while the user moves through the mine. Information extrapolated from the refined cell structures (discussed above) was again used in this process. The height of the user is adjusted every frame to be the equivalent of approximately 6 feet above the roadway floor at all times. This is achieved by calculating a plane in memory based around 3 vectors from the cell data (two vectors from one node of the cell and one vector from the other node [3]). The user's position on this plane is then calculated by firstly determining the normal vector of this plane (using the cross product of the two vectors derived from the planes defining points) and then calculating where this normalised line intersects with the plane. This point directly locates the position on the surface of the plane (and the appropriate cell) where the user's position is in 3D space. The y co-ordinate of the user's position is then adjusted to incorporate the 6 feet height adjustment needed to maintain correct eye viewpoint in the first person perspective view.

Because this adjustment is made every frame before redrawing the screen the user, when travelling through a series of uneven and inclining/declining roadway sections, follows the roadway terrain exactly. User orientation (i.e. facing forward) is kept the same giving a more realistic effect when travelling up or down an incline.

7.3.8 User Interface to Fire-VR

User interactivity is one of the major benefits from incorporating the EnvSim-VR and VentSim-VR components into Fire-VR. The ability for the user to be able to walk round a 3D world and interact with objects within the world gives the simulation a more immersive feel. This immersion into a virtual mine environment gives the EnvSim-VR and VentSim-VR sub-systems the potential to be utilised as an aid to training. By creating interactivity, there are a number of possibilities open for training personnel in key areas of fire / explosion prevention and management; one of the key aims of this research.

Simple mouse based control was programmed to allow the following interaction with the 3D world: -

- Movement in all 6 planes; +/-X, +/-Y and +/-Z

[3] Only 3 points in 3D space are needed to define a plane

- The ability to react with objects within the mine such as opening and closing of ventilation doors.
- Observing changing gas levels within the mine.
- The ability to create events at locations to test reactions from key personnel e.g. a fire may be set to occur at a specific section of roadway and the event can then be tracked as its environmental effects traverse through the mine aided by the management of the ventilation system. Other user interactivity events could be the creation of firedamp, carbon monoxide or dust at the face. By configuring the system with many alternative events and then observing how the user interacts with these events risk assessments can be made and progress in the users training of different management scenarios can be monitored.

Additionally, facilities to include further interaction possibilities could be implemented such as: -

- Slowing down / reversing booster fans
- Adjusting regulators in a real time scenario.

a) Moving around the world in Fire-VR

In FIRE-VR, the mouse pointer can be moved across the screen; the user is given a visual cue as to where the mouse pointer is located by a cross hair, which is drawn at the mouse screen co-ordinates. Movement in the world is actuated by the mouse. By clicking the left mouse button to go into movement mode, the user can then proceed with the following control methods.

When Fire-VR is in movement mode the mouse can be moved up, down, left and right as before except that the cursor splits into two and a line is drawn between the two cursors as shown in **Figure 7. 18** below. The arrow can be moved around and depending on which direction it is pointing, affects the way the user moves through the mine (i.e. forward, backwards, turn left and turn right). This gives a very fluid way of moving, yet is uncomplicated.

To return out of mouse movement mode, the user clicks the left mouse button again.

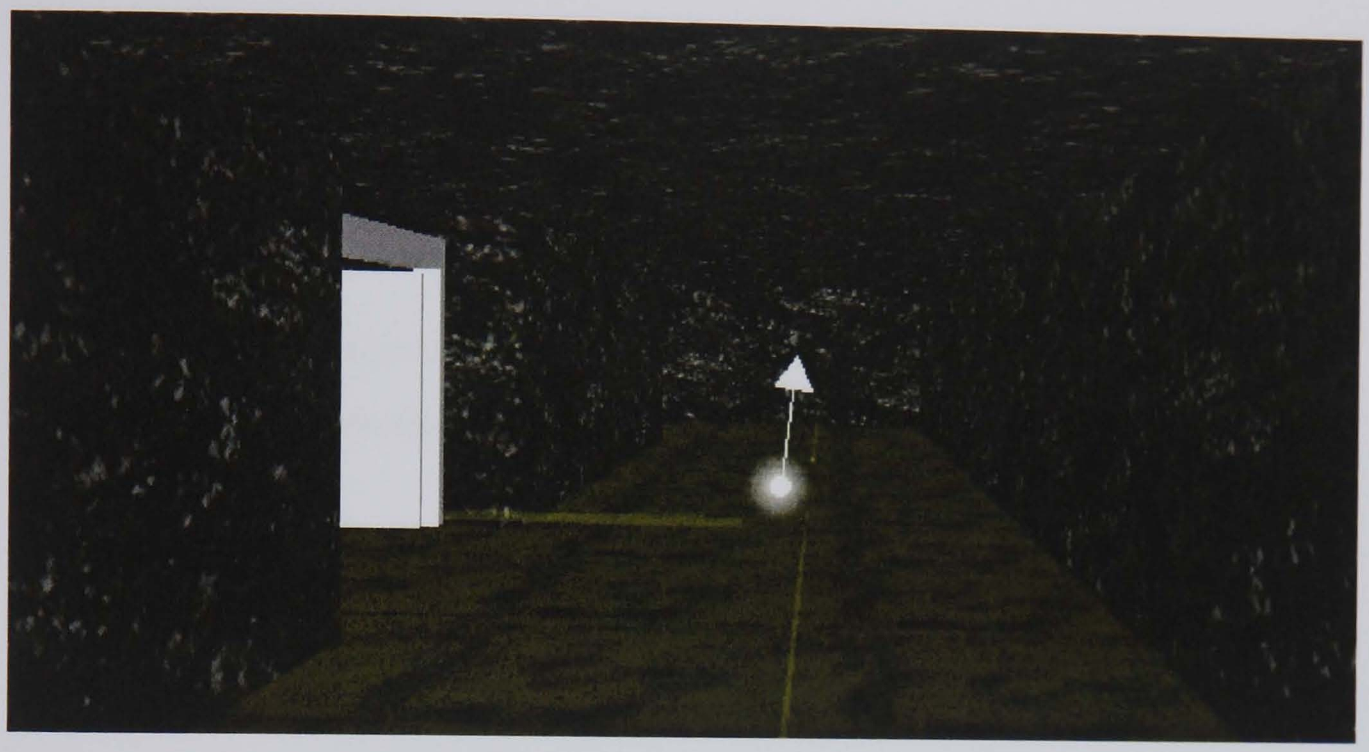


Figure 7. 18 User moving through the mine using mouse control

By using the direction arrow, the user can move in most directions. If, however, the user wants to move up (assuming collision detection is not switched on), down or to side step to the left or right then the control key can be pressed before the user clicks the left button to go into mouse movement mode. By holding down the control key the user is priming the control system to change the effect of the direction line. In this mode, the direction arrow allows for upward and downward movement when directing the line forwards and backwards. Moving the arrow to the right or left, side steps rather than the usual left and right rotation.

b) User control commands

As well as controlling the movement of the user in VR, additional keyboard controls have been programmed to control other aspects of the simulation. These are listed in Appendix 6 but a summary of what some of the more common ones are given below: -

Scrolling of the main map view up, down left and right.

Provides an easy, fast way of viewing the entire mine.

Collision detection (on/off switch)

Used in controlling detecting whether the user has left the roadway.

Flow rate monitor (on/off switch)

Switches on and off the moving arrow display showing airflow through mine.

Map view mode (4 settings)

Used to change map view from : not present, small plan view, small side view and finally complete plan view.

Gas display mode (6 settings)

This mode, when the user is in any third person perspective mode, activates the display mode for reporting gas levels within each cell. Oxygen, nitrogen, methane, carbon dioxide, carbon monoxide and smoke levels can all be displayed. Colours used in this display are defined in section 6.2.2.

Display intensity adjustment (100 settings)

Allows the intensity of the cells gas and smoke information display to be increased and decreased so as to allow for greater readability of small fluctuations in the display.

c) User interaction in Fire-VR

Interaction with objects within the world

If the user aligns the cross hair with an object on the screen, such as a ventilation door, they can then click the right mouse button to change various functions for that object. In the case of the ventilation door, a facility for clicking on the door with the right mouse button closes or opens that door depending on its current state.

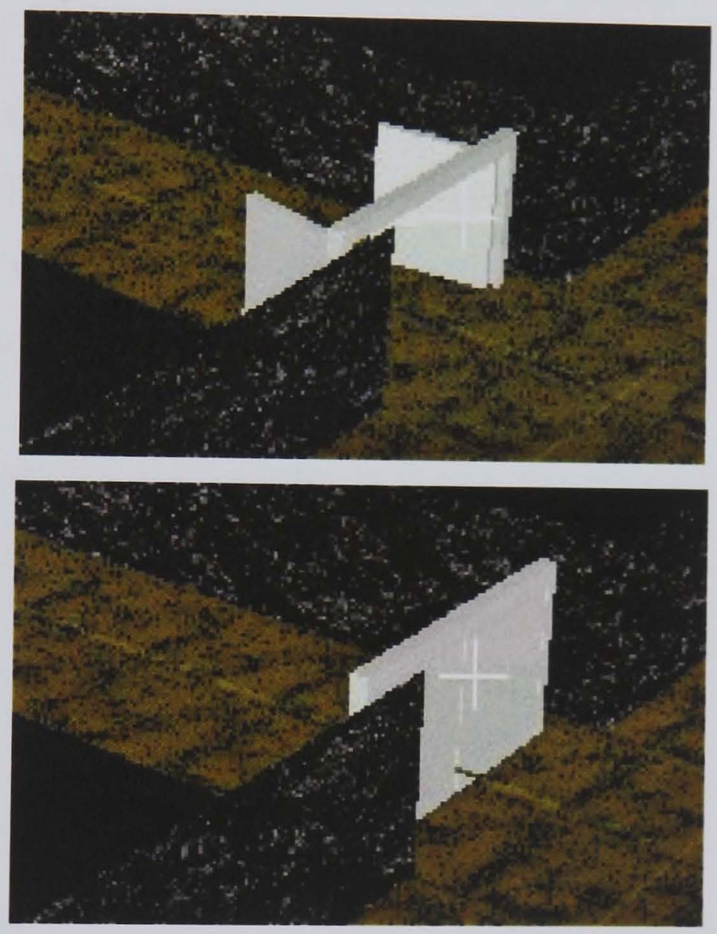


Figure 7. 19 Right clicking on a ventilation door to open / close it

Output of user actions to file

Objects within the world can be selected by right clicking with the mouse button. This facility was programmed so as to allow a simple interface for the user to interact with the world. Objects were designed and programmed into the main Fire-VR application which can be interacted with via the mouse and user action. The example items which were included into this research are described in section 7.3.9 below. When an item is selected, the users actions are outputted to a text file. This text file effectively describes the users actions throughout the running of the simulation and potentially could be used in monitoring a users training via pre planned example scenarios set up for the user to react with.

An example use of this facility would be the potential to monitor which objects within the world the user reacts with when a disaster situation such as a fire has broken out i.e. did the user interact with the fire extinguisher or make contact with the supervisor first?

7.3.9 Representation of objects within the world

The following example world objects were designed and created using 3D studio Max 2 ®. They have been included as example objects which typically would be present within a mine environment and which would be useful in creating example scenarios (see **Figure 7. 20**).

Figure 7. 20 Example objects; Fire extinguisher, telephone, roof support and miner.

Each object is converted to the Direct X® file format required by the main Fire-VR application using the Direct 3D® converter program, Conv3DS.exe, supplied as part of the Direct X® developer SDK.

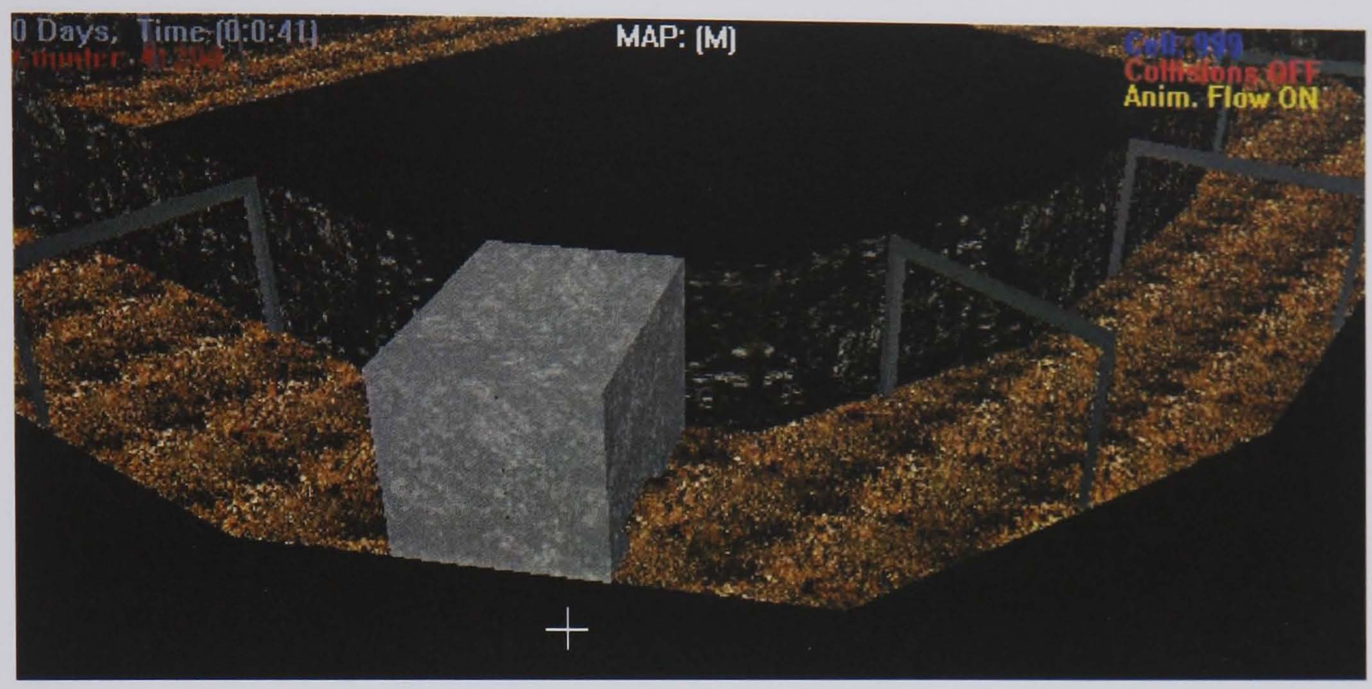


Figure 7. 21 Stopping implemented to impede the airflow in a section of roadway

Textures are applied to these objects where appropriate (see **Figure 7. 21**).

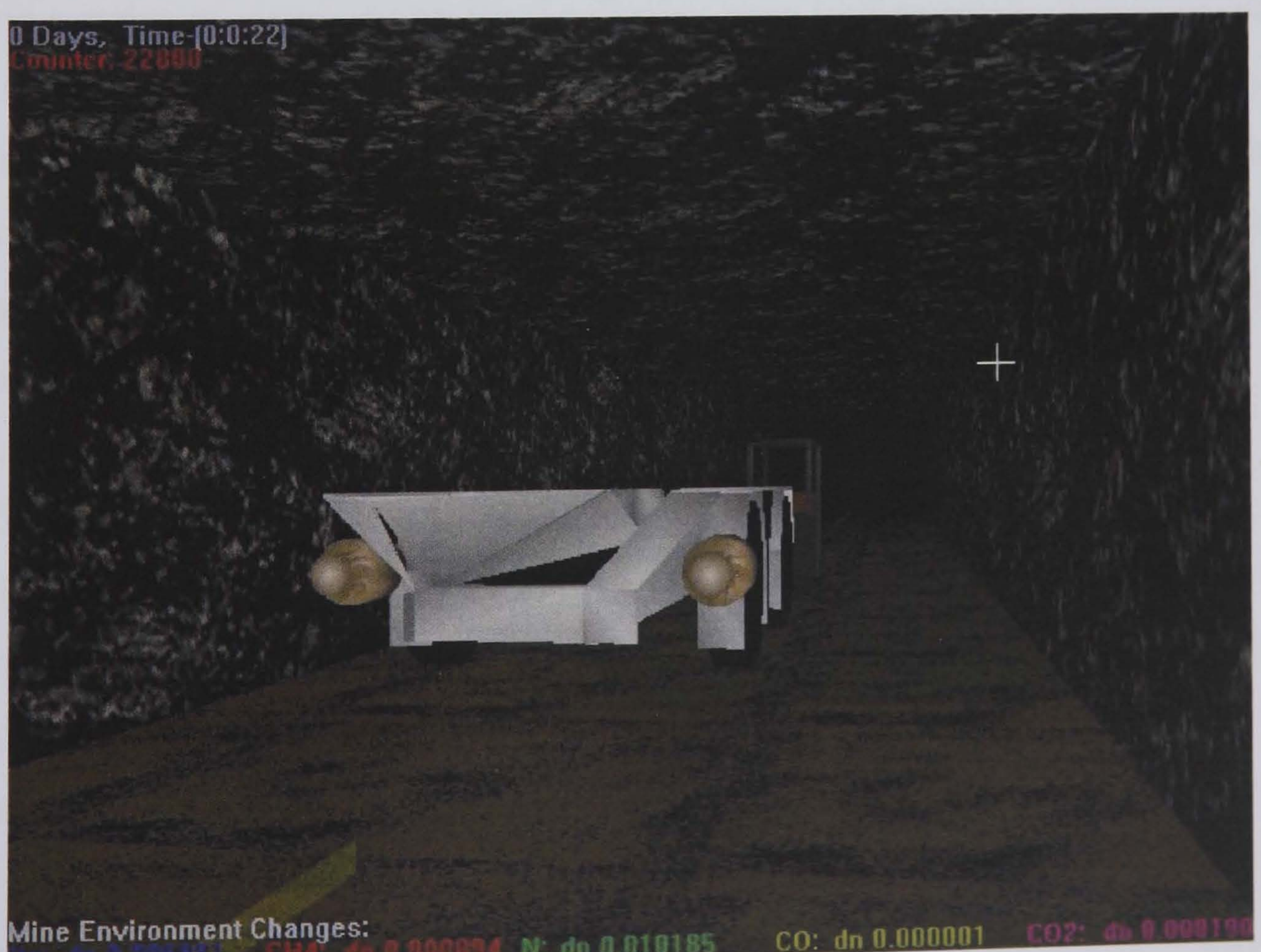


Figure 7. 22 Shuttle car object loaded into mine as object for interaction purposes

7.4 Conclusions

This chapter has described the 3D interface to VentSim-VR and EnvSim-VR and forms the major part of the Fire-VR application used to realise the research interests of this work. The supplementary programs required in order to produce working mine networks and to implement them into a 3D simulation in VR have been described. MakeMine is a program created for converting a mine description file into a full 3D implementation of the same network which can then be used in the main Fire-VR application for the user to interact with or observe in world space. The way MakeMine creates the mine infrastructure has been described and the benefits of producing the mine 3D infrastructure in this way have been examined.

The programming tools used to produce the interface have been discussed and consideration was given to include the standard colour coding defined in previous chapters for consistency.

The display of graphical and numerical information was given consideration and a series of visual modes for the display were implemented. The main VR first person perspective view was designed with minimal, non real-world objects in view so as to maintain realism to the user. A secondary visual mode, with various additional features was also implemented so that further information could be utilised by the user. Additionally, a plan view was also implemented into the simulation.

Consideration was given to finding the most effective way of implementing a visual representation of smoke and colourless gases within the 3D interface. Moving arrows which travel at speeds relative to the flow of air in each cell and who's opacity level also visually represents the rate of flow, were programmed to give the user a visual display of general air flow movement within the mine. Gas levels were modelled by implementing translucent cell wraps which give a representation of the relative concentrations in each cell.

Collision detection and height adjustment algorithms were programmed to create a movement model that could cope with user errors and also provide a realistic movement model for the user to traverse through the mine roadway sections.

Movement routines were programmed to allow the user many different options for exploring the example mine networks and these have been described.

Example interactive scenarios have been specified which allow the user to interact with the mine VE. Models were created which were loaded into the VE as examples as to what Fire-VR could be used for. Interaction was implemented in the form of shutting and opening ventilation doors. The possibilities of examining user actions via the use of an action recording output file were also examined.

The following chapter describes evaluative example networks created using the tools and programs described in chapters 5-7. Also, a comparative study to check data from a well known network ventilation simulation against a similar implementation from Fire-VR is presented.

Chapter Eight

Evaluation of the Fire-VR simulator

8.1 Introduction

In the following chapter, some of the potential applications of Fire-VR are examined in a number of test situations.

As a method of validation of the VentSim-VR component of Fire-VR, a series of evaluation networks were inputted into the Mine Description file format, using the editor software developed for this research, and then tested against an established ventilation package; VnetPC™. The results obtained for one example network are presented in section 8.2 below.

The EnvSim-VR component of Fire-VR has been applied to a variety of typical mining situations, described in this chapter, in order to demonstrate the potential of the Fire-VR prototype system in terms of developing methods of training for personnel faced with managing hazardous scenarios within the mine environment. Example scenarios have been selected to explore the possibility of using Fire-VR in mining situations such as ventilation control, the monitoring of fires and explosions and the control of the environment using an inert gas such as nitrogen.

8.2 Evaluation of Fire-VR using a test network

Caizaya and McPherson (1987) and McPherson (1993) use a simple network consisting of 3 retreat longwall faces with a main fan providing the ventilation to compute the optimum positioning and combination of main and booster fans. This example mine was also used in later work by Yang et al (1998) in optimizing the ventilation using generic algorithms. The same example mine is presented in this section in order to validate the Fire-VR ventilation simulation by comparison of the results with those from VnetPC™. The topologically correct map for this network is shown below in **Figure 8. 1**.

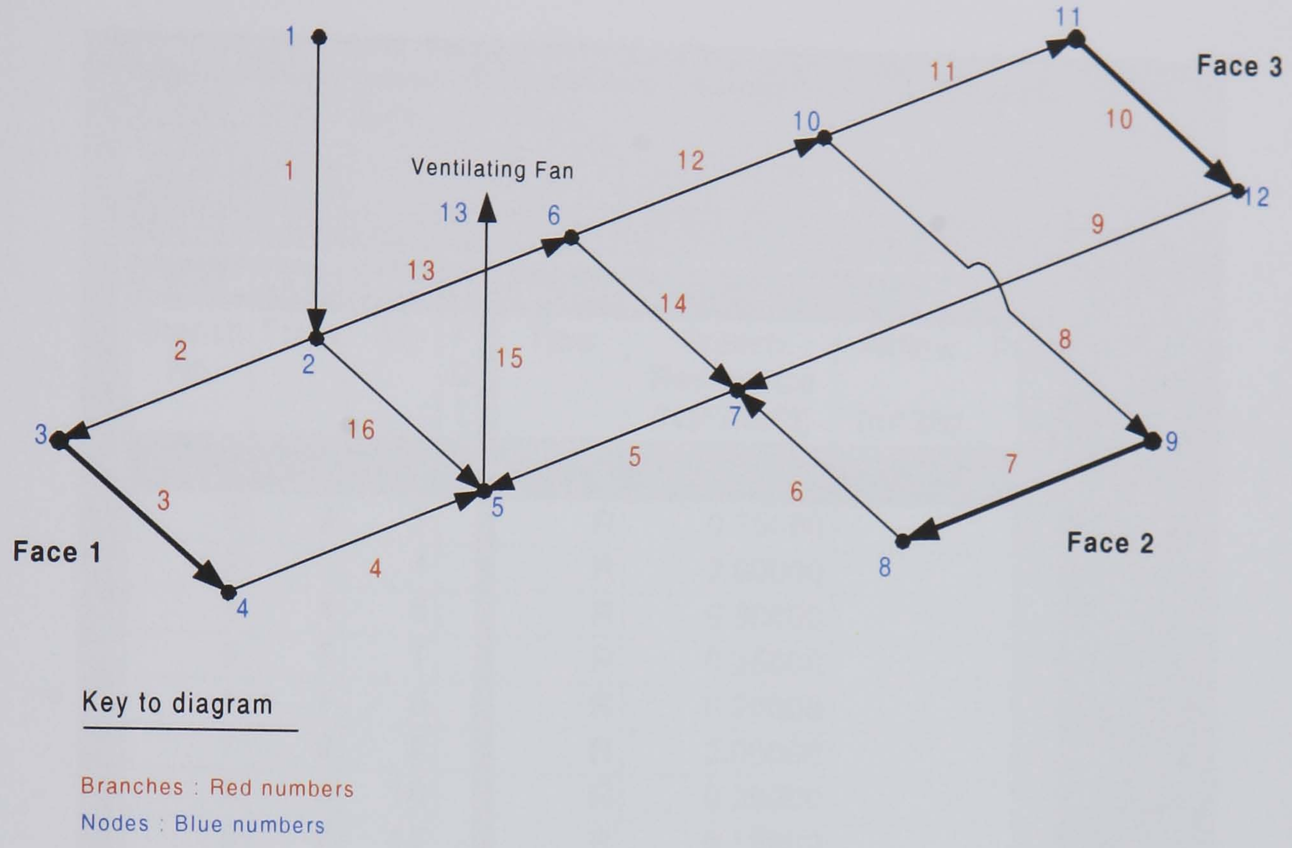


Figure 8. 1 Example test mine ventilation network (after Calizaya et al, 1987)

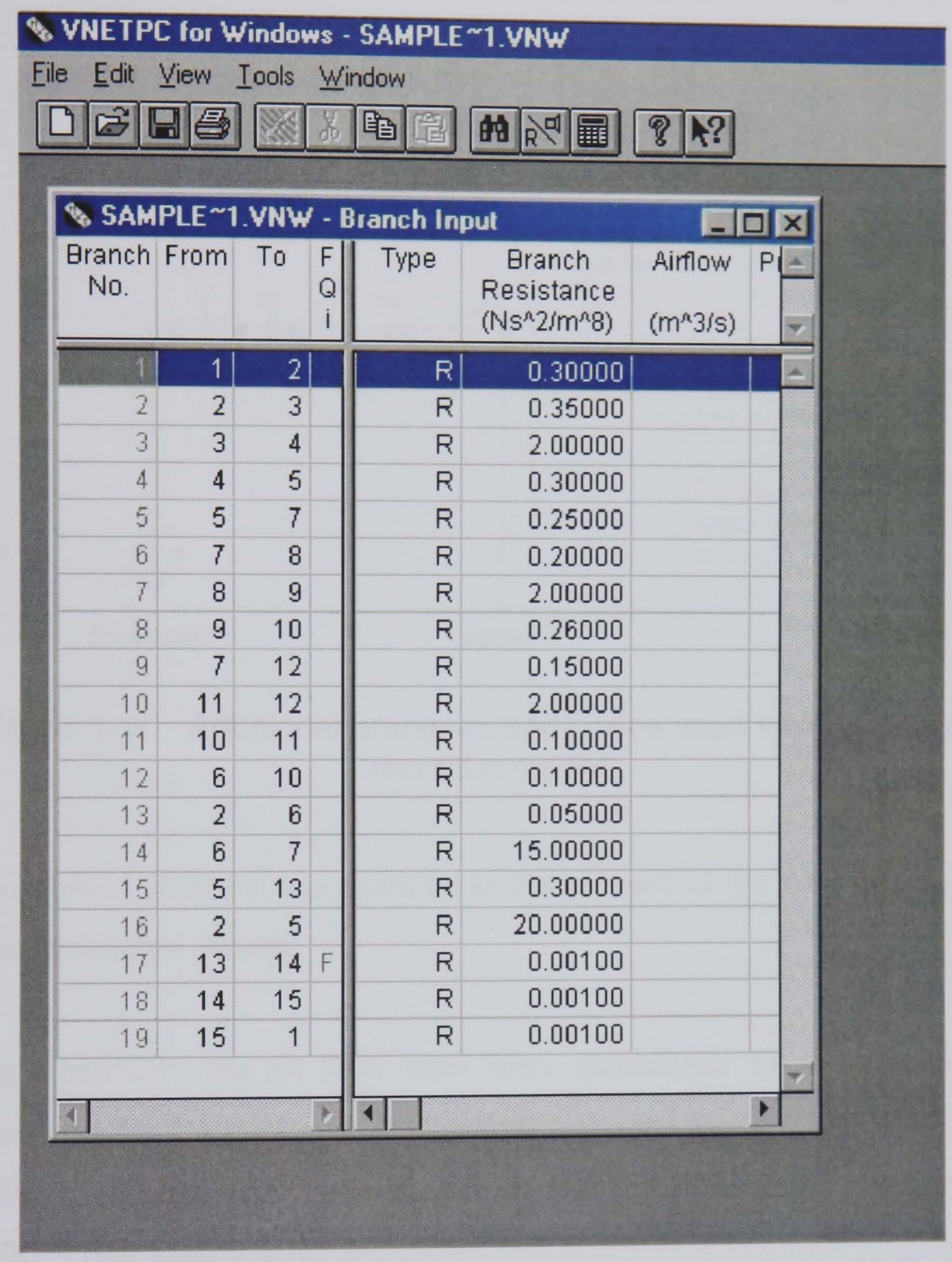
VnetPC's™ ventilation model uses a similar system to that used by VentSim-VR except for the following minor adjustments to the network information structure, shown in **Table 8. 1**, below: -

Vnet PC for windows	**Fire-VR (prototype)**
Inter-node connections labelled as branches.	Inter-node connections labelled as cells.
Branches numbered from 1 upwards	Cells numbered from 0 upwards.
Nodes numbered from 1 upwards	Nodes numbered from 0 upwards

Table 8. 1 Data file differences between Fire-VR and VnetPC™ for Windows®

The test network shown in **Figure 8. 1** was constructed in the VnetPC™ software in the form shown below in the network branch input screen (see

Figure 8. 2). Each branch consists of two nodes labelled 'To' and 'From' in a similar form to that used by Fire-VR. The associated resistance value inputted for each length of roadway is also shown. [3]



Branch No.	From	To	F Q i	Type	Branch Resistance (Ns^2/m^8)	Airflow (m^3/s)	P
1	1	2		R	0.30000		
2	2	3		R	0.35000		
3	3	4		R	2.00000		
4	4	5		R	0.30000		
5	5	7		R	0.25000		
6	7	8		R	0.20000		
7	8	9		R	2.00000		
8	9	10		R	0.26000		
9	7	12		R	0.15000		
10	11	12		R	2.00000		
11	10	11		R	0.10000		
12	6	10		R	0.10000		
13	2	6		R	0.05000		
14	6	7		R	15.00000		
15	5	13		R	0.30000		
16	2	5		R	20.00000		
17	13	14	F	R	0.00100		
18	14	15		R	0.00100		
19	15	1		R	0.00100		

Figure 8. 2 Entering node and branch data into VnetPC™ for windows

Branch 17 was included in order to supply a driving force, in the form of a main fan. Because of the way in which Fire-VR handles fans and the world cell (see section 5.4.1) further branches, 18 and 19, were required to provide for this functionality. Similar cells, in terms of data values, were therefore

[3] It can be seen from the table that faces have a relatively high resistance to that of a normal section of roadway and branches 14 and 16 are very high resistance implying only leakage air flow will occur (synonymous with ventilation doors, shut).

included in the VnetPC™ example in order to make both examples from VnetPC™ and Fire-VR as equivalent as possible. Very low resistance values (compared to those used in the rest of the mine network) for the world cell, spacer cell (essential in Fire-VR) and the main fan were used so as not to particularly affect the resistance paths through the mine. These additional branches are shown in **Figure 8. 3**.

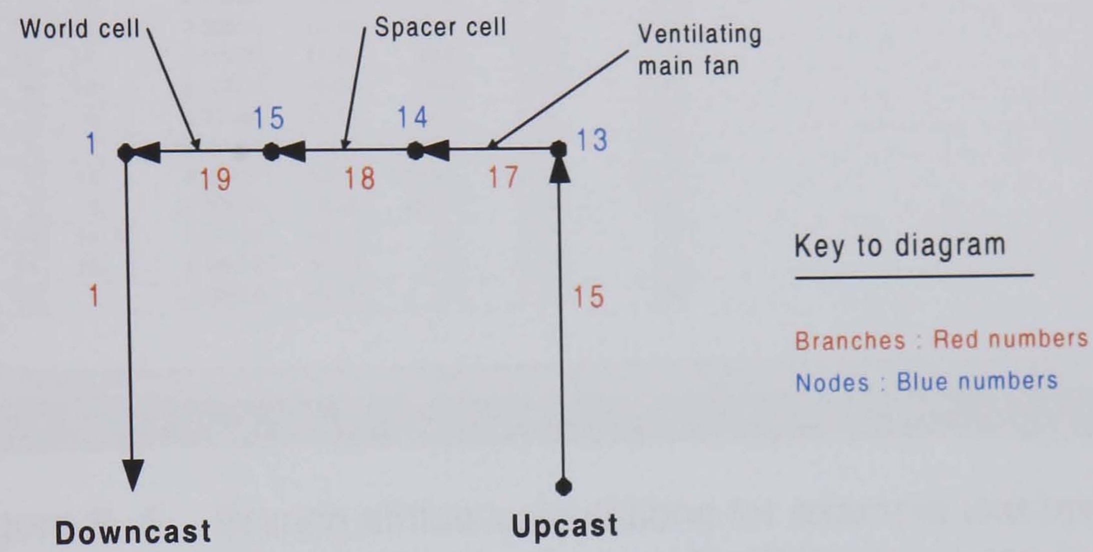
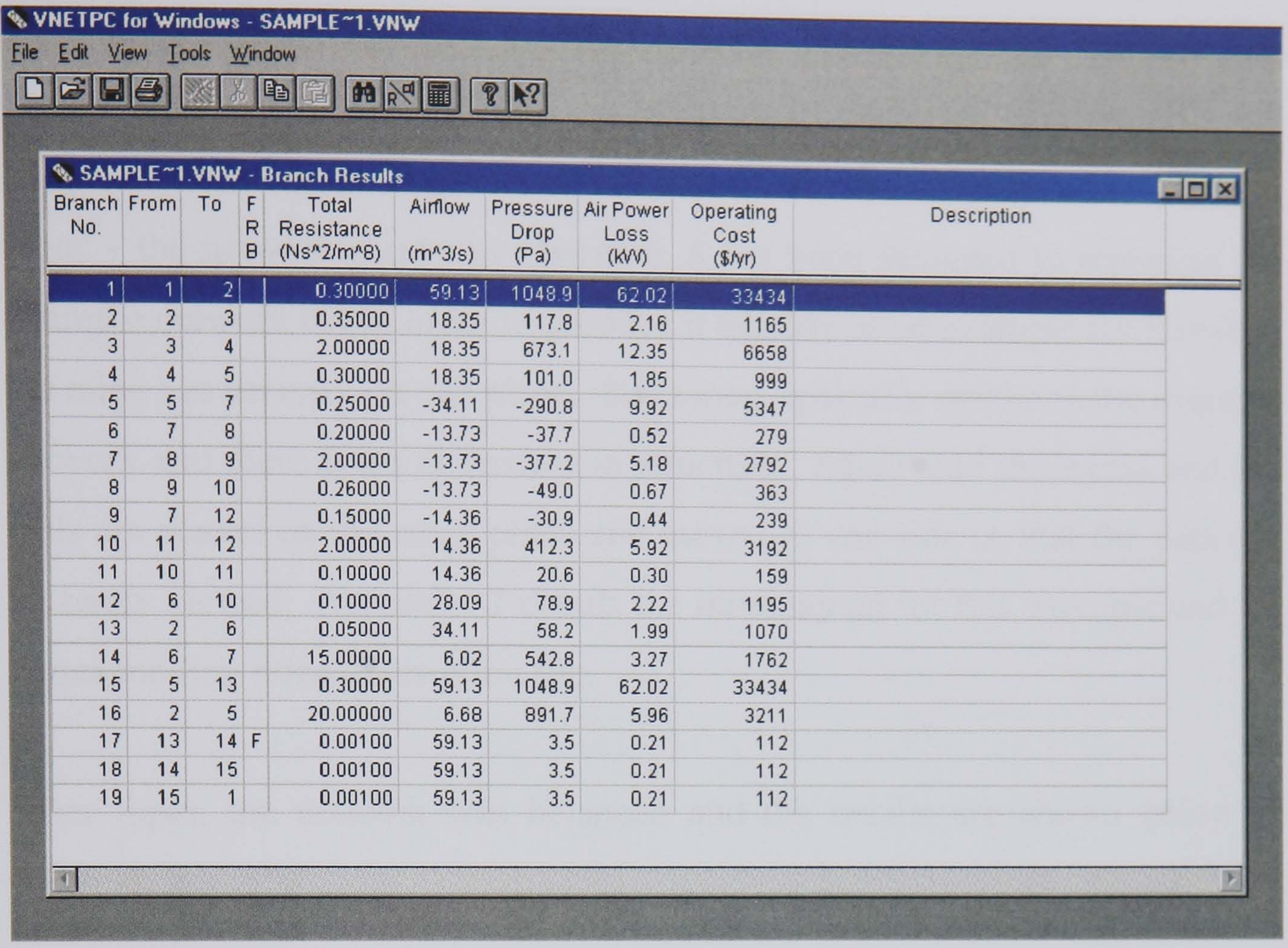


Figure 8. 3 Additional branches and nodes used to construct the example model

A main fan of 3000 Pa was specified in the network as the main driving force for the ventilation system.

Using VnetPC™, the air flow rates were determined for each section of roadway for the Calizaya example network discussed above above (Calizaya et al, 1987). These results are shown in the following table displayed by VnetPC™ (see **Figure 8. 4**).



VNETPC for Windows - SAMPLE~1.VNW

SAMPLE~1.VNW - Branch Results

Branch No.	From	To	FRB	Total Resistance (Ns^2/m^8)	Airflow (m^3/s)	Pressure Drop (Pa)	Air Power Loss (kW)	Operating Cost ($/yr)	Description
1	1	2		0.30000	59.13	1048.9	62.02	33434	
2	2	3		0.35000	18.35	117.8	2.16	1165	
3	3	4		2.00000	18.35	673.1	12.35	6658	
4	4	5		0.30000	18.35	101.0	1.85	999	
5	5	7		0.25000	-34.11	-290.8	9.92	5347	
6	7	8		0.20000	-13.73	-37.7	0.52	279	
7	8	9		2.00000	-13.73	-377.2	5.18	2792	
8	9	10		0.26000	-13.73	-49.0	0.67	363	
9	7	12		0.15000	-14.36	-30.9	0.44	239	
10	11	12		2.00000	14.36	412.3	5.92	3192	
11	10	11		0.10000	14.36	20.6	0.30	159	
12	6	10		0.10000	28.09	78.9	2.22	1195	
13	2	6		0.05000	34.11	58.2	1.99	1070	
14	6	7		15.00000	6.02	542.8	3.27	1762	
15	5	13		0.30000	59.13	1048.9	62.02	33434	
16	2	5		20.00000	6.68	891.7	5.96	3211	
17	13	14	F	0.00100	59.13	3.5	0.21	112	
18	14	15		0.00100	59.13	3.5	0.21	112	
19	15	1		0.00100	59.13	3.5	0.21	112	

Figure 8. 4 Branch airflow calculations for example test mine ventilation network simulated using VnetPC™ for windows

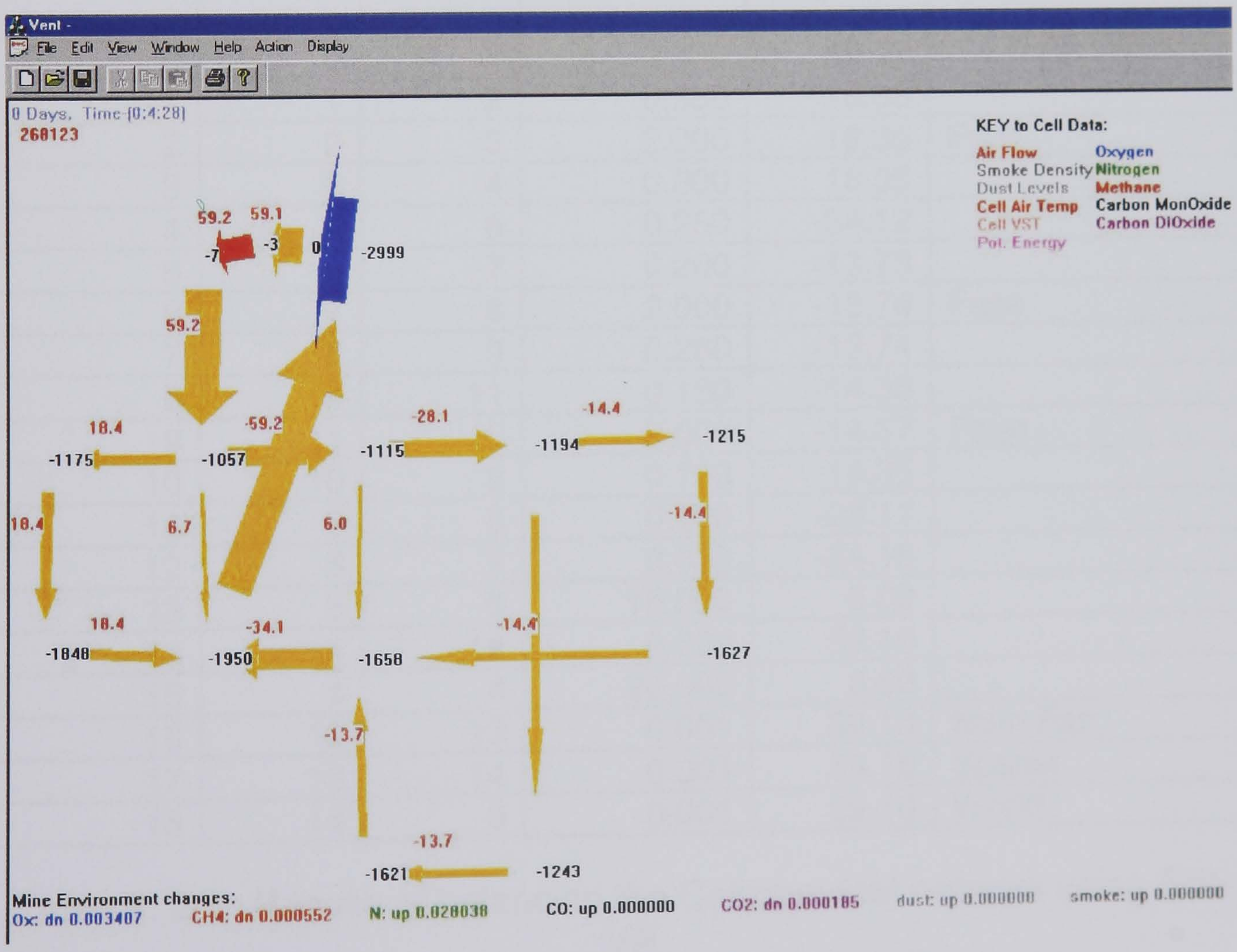


Figure 8. 5 Example test mine ventilation network simulated using Fire-VR (2D interface)

The same network was then inputted into the 2D interface of Fire-VR (see **Figure 8. 5**) using the editor program and methods discussed in chapter 6.

Note: - the network shown in **Figure 8. 5** has been designed to represent the example network but in order to produce it quickly as an example for Fire-VR, the mine has been set on one plane. It is topographically similar to the example network and there is no difference in structure. Shafts and the world and fan cells are placed on the same plane and moved to one side so that the data can be easily viewed. Appendix 7 details the mine layout for this example and the corresponding mine description file.

After input, the network was balanced and the results are shown below in **Table 8. 2**: -

Cell Number	**Node (from)**	**Node (to)**	**Resistance of cell**	**Airflow rate in m^3 / s**	**Type of cell**
0	0	1	0.300	59.17	
1	1	2	0.350	18.36	
2	2	3	2.000	18.35	Face
3	3	4	0.300	18.35	
4	4	6	0.250	-34.12	
5	6	7	0.200	-13.73	
6	7	8	2.000	-13.74	Face
7	8	9	0.260	-13.74	
8	6	11	0.150	-14.35	
9	11	10	2.000	-14.37	Face
10	10	9	0.100	-14.35	
11	9	5	0.100	-28.11	
12	5	1	0.050	-34.15	
13	5	6	15.000	6.02	
14	4	12	0.300	59.16	
15	1	4	20.000	6.68	
16	12	13	0.001	59.16	Main Fan
17	13	14	0.001	59.16	Spacer
18	14	0	0.001	59.16	World

Table 8. 2 Results of balancing the Calizaya test network using Fire-VR

The results obtained from running the test network on Fire-VR compare favourably with data from VnetPC™. Any negative figures shown in the flow rates for both **Figure 8. 4** (results from VnetPC™) and **Table 8. 2** (results from Fire-VR) are due to results which have been calculated to flow in the opposite direction to the order in which the first and second nodes in a branch or cell are specified when defining each cell / branch (this opposing flow is shown by the negative flow rate and can be ignored using absolute functions because the actual direction of flow is defined by the relative pressure drop between the two nodes). The difference between the airflow results for each system are minimal; not more than 0.04 m^3 / s difference in the worst case (which equates to a percentage error of 0.12 %) and only 0.0153 m^3 / s on average. These differences are attributed to the slightly different way in which Fire-VR and VnetPC™ handle fans within the balancing routines and because, in any balancing algorithm, oscillations can occur which means that the final results shown above could be discretely changing.

In the next section this network has been expanded to incorporate more resolution and a slightly expanded network structure for more realism. This example is used to show some example mine scenarios which have been programmed to explore the potential of Fire-VR.

8.3 Evaluation of Fire-VR – Ventilation control

A test network was created using the Fire-VR suite of programs in order to evaluate the suitability of Fire-VR as a tool for controlling the ventilation within a mine. The test network is topographically similar to the example network used by Calizaya et al (1987) except that additional resolution has been included in the form of approximately 3 cells per roadway span (primarily because the original network consisted of a single branch/cell per length of roadway only). Other changes include the replacement of crossroads with the introduction of staggered T-junctions to assist with the design of the network using Fire-VR. In order to keep the resistance through all paths within the mine similar to those in the original example, some cells have been assigned to have negligible resistance e.g. the world cell or a cell between two very close T-junctions. The schematic for this mine network is shown in **Figure 8. 6.**

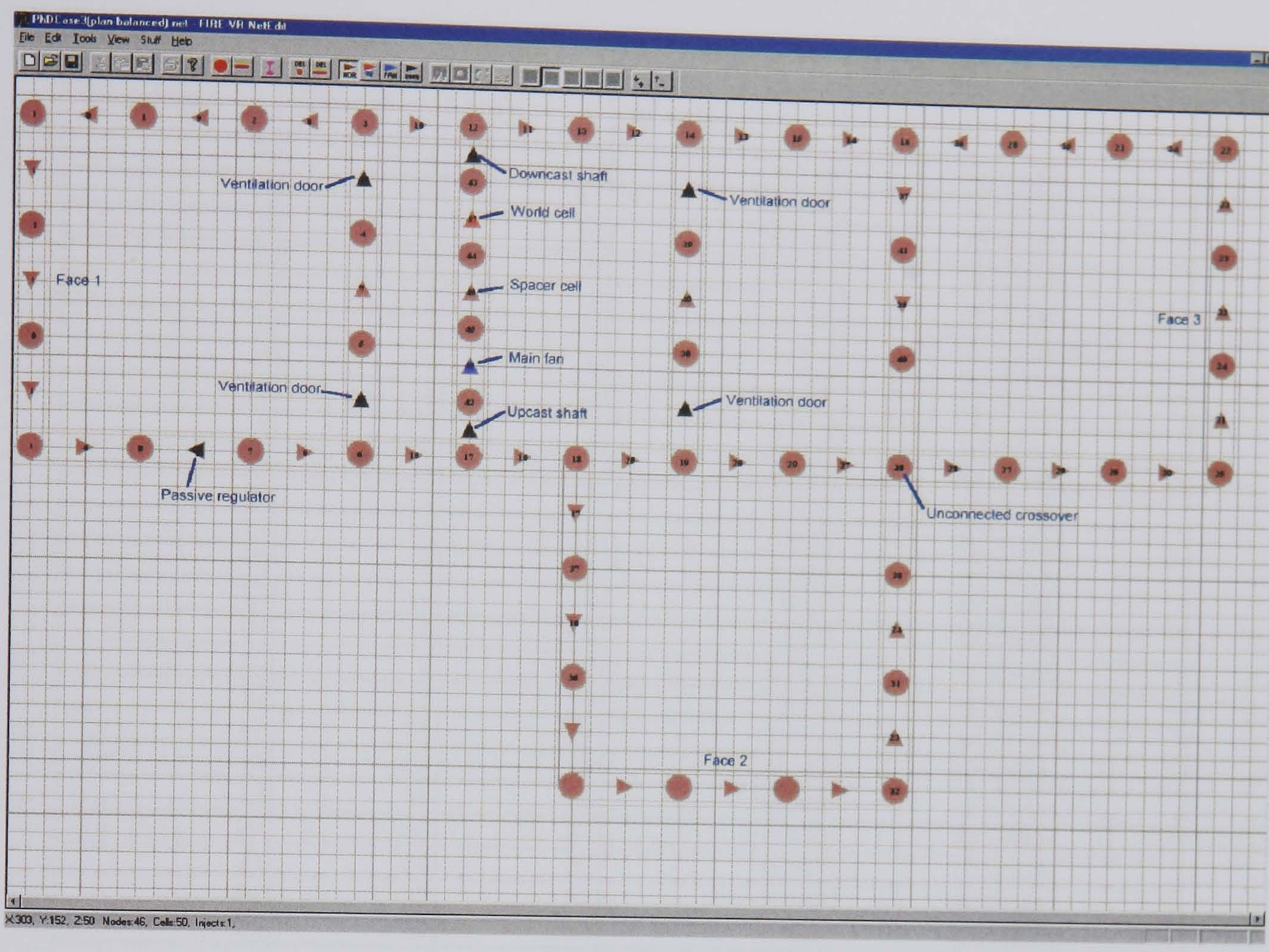


Figure 8. 6 Higher resolution network created with the Fire-VR editor software (labels have been annotated).

The resistances for each of the roadway sections and faces have been calculated to equal that of the first model. This was achieved by assigning a proportional resistance based on the number of cells within the section and the original total resistance.

As before, the network consists of a single main fan and downcast and upcast shafts for the intake and return airways. Additionally, ventilation doors have been included as access points to enable personnel to travel between the intake and return airways. The doors are doubled up so as to provide an airlock which prevents / minimises pressure losses when personnel and equipment traverse the access routes. A passive regulator, in the form of a door fitted with an adjustable orifice, has been included to control the airflow to face 1. This example has been chosen to show the ability of Fire-VR to be used in ventilation control scenarios. The network, shown in **Figure 8. 6** and described in **Table 8. 3** below, was created and the 2D interface was used to balance the network with the regulator sliding door initially being fully open.

Cell Number	**Node (from)**	**Node (to)**	**Resistance of cell**	**Type of cell**
0	1	0	0.116	NORMAL
1	0	11	0.667	NORMAL
2	11	10	0.667	NORMAL
3	10	9	0.667	NORMAL
4	9	8	0.1	NORMAL
5	8	7	0.1	DOOR(regulator)
6	7	6	0.1	NORMAL
7	5	4	0.05	NORMAL
8	3	2	0.116	NORMAL
9	2	1	0.116	NORMAL
10	3	12	0.001	NORMAL
11	12	13	0.025	NORMAL
12	13	14	0.025	NORMAL
13	14	15	0.05	NORMAL
14	15	16	0.05	NORMAL
15	6	17	0.001	NORMAL
16	17	18	0.25	NORMAL
17	18	37	0.067	NORMAL
18	37	36	0.067	NORMAL
19	36	35	0.067	NORMAL
20	35	34	0.667	NORMAL
21	34	33	0.667	NORMAL
22	33	32	0.667	NORMAL
23	32	31	0.052	NORMAL
24	31	30	0.052	NORMAL
25	18	19	0.001	NORMAL
26	19	29	0.03	NORMAL
27	29	28	0.03	NORMAL
28	28	27	0.03	NORMAL
29	27	26	0.03	NORMAL
30	26	25	0.03	NORMAL
31	25	24	0.667	NORMAL
32	24	23	0.667	NORMAL
33	23	22	0.667	NORMAL
34	22	21	0.033	NORMAL
35	21	20	0.033	NORMAL
36	20	16	0.033	NORMAL
37	16	41	0.052	NORMAL
38	41	40	0.052	NORMAL
39	40	30	0.052	NORMAL
40	38	39	0.05	NORMAL
41	17	42	0.3	SHAFT
42	43	12	0.3	SHAFT
43	4	3	10	DOOR
44	39	14	10	DOOR
45	6	5	10	DOOR
46	19	38	10	DOOR
47	44	43	0.001	WORLD
48	42	45	0.001	FANMAIN
49	45	44	0.001	SHAFT

Table 8. 3 Data for the mine description file for the amended test network using Fire-VR

The regulator, described by cell number 5 in the above table, was initially allocated a resistance of 0.1 Ns^2/m^8. This is based around the assumption that the cell where the regulator is situated has a resistance of 1/3 the total roadway section resistance value (due to the fact that 3 cells describe the section and they are, in this case, equally split). The resistance value of 0.1 Ns^2/m^8 is the same as the resistance of the two surrounding cells and because of its low resistance implies that the door is in fact open. This was used as a starting point because potentially the door can range from low resistances such as 0.1 Ns^2/m^8 (door open) through to mid range resistances such as 5.0 Ns^2/m^8 (door shut and regulator panel fully open) and to high resistances such as 10.0 Ns^2/m^8 where both the door and the regulator panel are shut.

In the following example application, the initial airflow to face 1 was found to be approximately 18.46 m^3 / s using the default resistances utilised in the first example (this is shown in **Table 8. 4).** The aim of this study is to reduce the flow rate of air to face 1 to a steady 10 m^3 / s.

Fire-VR was used to progressively change the resistance of the return airway of face 1, so as to regulate the airflow to that face. The decreasing resistance value associated with the ventilation door and the regulator is analogous to the sliding shut action associated with progressively closing the regulator panel.

8.3.1 Regulator, ventilation door open

After balancing the network with the 2D interface to Fire-VR, the following results (**Table 8. 4**, below) were obtained when running the example mine: -

(Results are shown for faces only and are the mean for all cells within each section described).

Regulator resistance: 0.1 Ns^2/m^8	
Area of the mine network	**Airflow rate in m^3 / s**
Face 1	18.4613
Face 2	13.9335
Face 3	14.5677

Table 8. 4 Airflow rates through each face when regulator has a resistance of 0.1 Ns^2/m^8

8.3.2 Ventilation door shut and regulator progressively shut

The regulator was partially closed (by progressively raising the resistance of the door) in order to increase the resistance within the section of roadway until the flow of air through face 1 was reduced to 10 Ns^2/m^8. This equated to a resistance of 8.85 Ns^2/m^8 as shown in **Table 8. 5** below.

Regulator resistance: 8.85 Ns^2/m^8	
Area of the mine network	**Airflow rate in m^3 / s**
Face 1	10.0010
Face 2	15.6694
Face 3	16.3837

Table 8. 5 Airflow rates through each face when regulator has a resistance of 8.85 Ns^2/m^8

Fire-VR has therefore been successfully applied to model the action of regulators in controlling the airflow to a face. In the above example, by reducing the airflow to face 1, the subsequent effect is that more airflow is diverted to the other two faces.

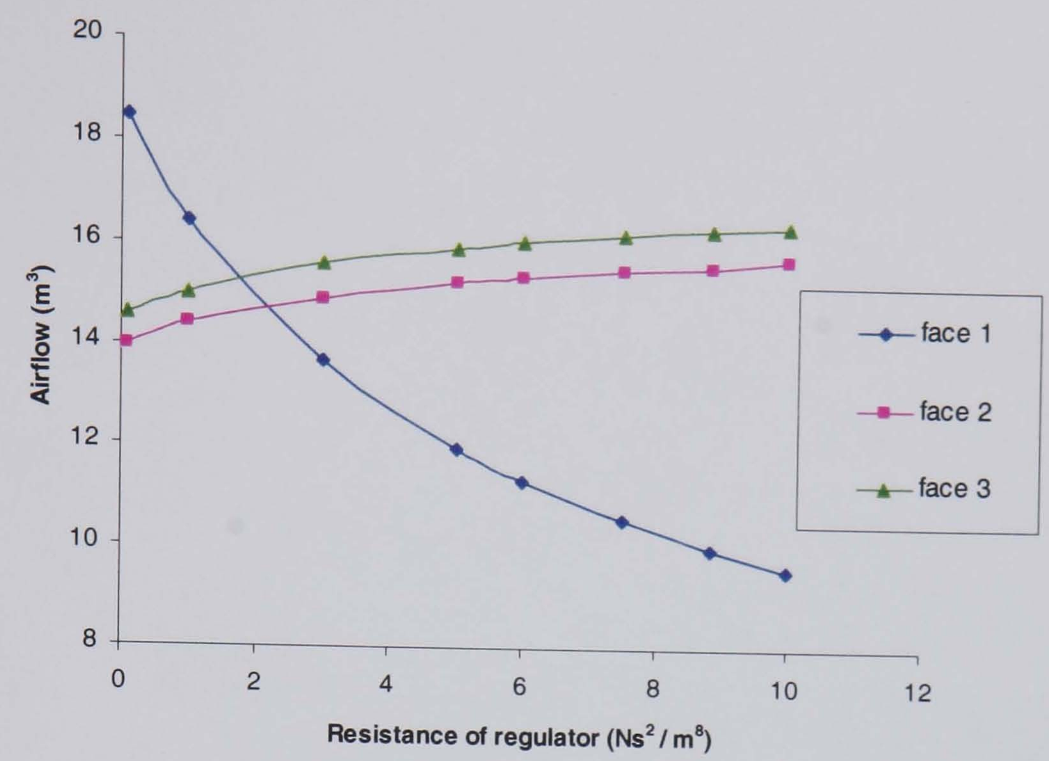


Figure 8. 7 Relationship between airflow and regulator resistance (regulator at return from face 1)

This relationship between the regulator resistance and the effect on the airflows to each face is shown in **Figure 8. 7**. Due to the installation of the regulator in the path of face 1, the airflow to this face is affected most by any changes in resistance made by the regulator.

Finally, the test network was converted into 3D by the MakeMine program and the relationship between airflow and regulator resistance was examined using the facilities provided by the Fire-VR 3D interface. **Figure 8. 8** below shows the modelling of this scenario in 3D.

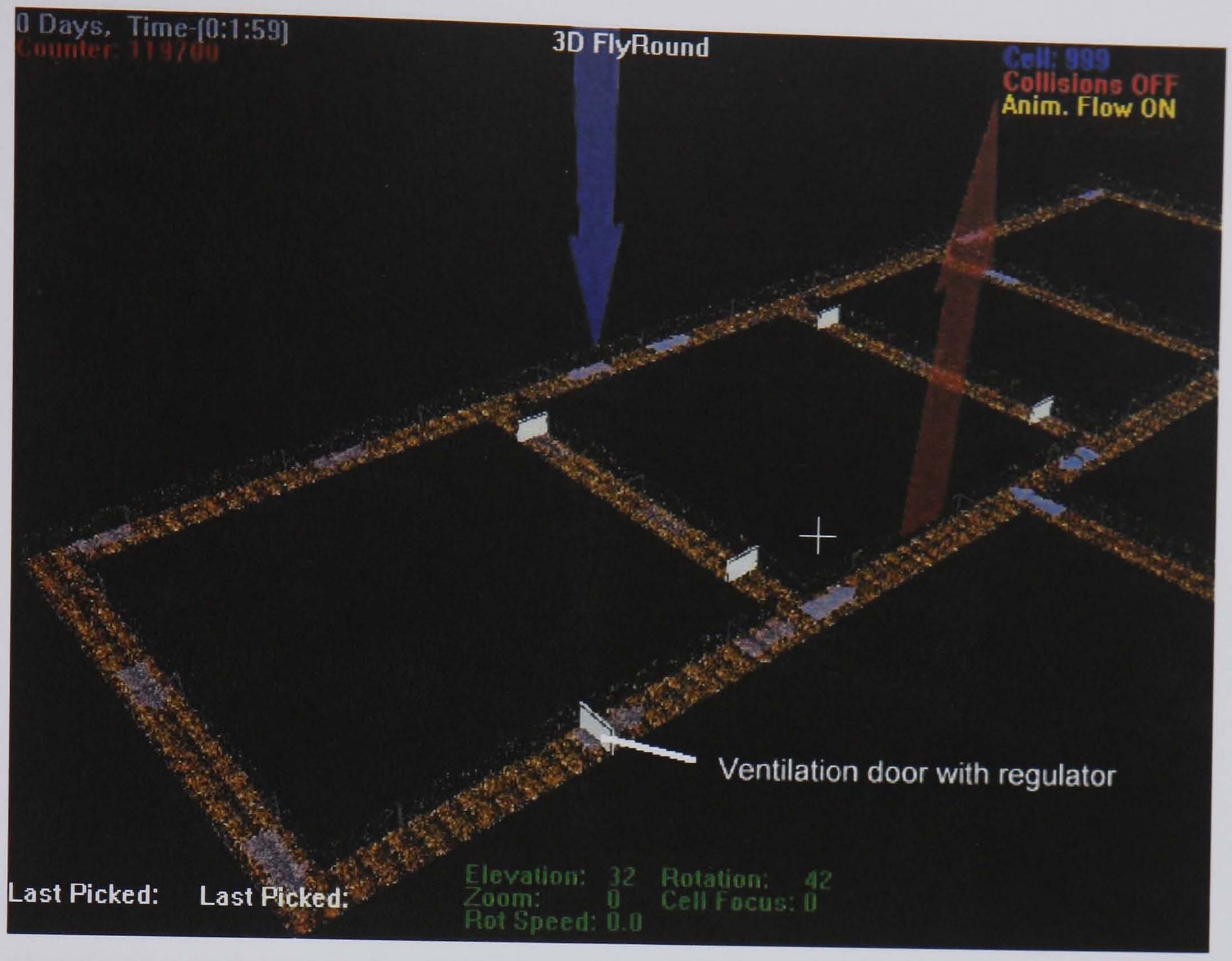


Figure 8. 8 Monitoring flow rates to face 1 using the Fire-VR 3D interface

In the above diagram, the view is of the mine from 3rd person perspective view with face 1 clearly shown in the bottom left portion of the screen. The regulator, set in a ventilation door, is shown in the centre lower half of the screen. The downcast shaft is represented as a large blue arrow (blue is used to signify clean air) whilst the upcast shaft is represented as a large red arrow (red being used to signify used return air).

The 3D system is ideal for application in this study to show the relative airflow rates created at face 1 when changes to the regulator are made. The 3D arrows which move from the downcast shaft, through the mine and then out through the upcast shaft clearly show the airflow rates at each roadway section within the mine. As well as the 3D arrow structures providing a visual cue as to the airflow through each roadway section by means of the arrows speed, additionally the arrows can be seen to increase in transparency as they slow down. This is an alternative way in which airflow is shown in the 3D interface and is useful when presenting static images such as that shown in **Figure 8. 8** when it is obviously impossible to demonstrate movement.

8.4 Evaluation of Fire-VR – External monitoring

8.4.1 Introduction

To show one of the potential applications of Fire-VR in the early detection of fires the following example scenario is presented based on the same network described in the previous section.

In this study, Fire-VR has been used to show its application in typical monitoring situations which are employed in British coal mines. The monitoring techniques discussed in section 2.3.2 are implemented to provide an example scenario where the early warning of potentially hazardous gases have been known to help in the early detection of mine fires. For this study, it was decided to use Graham's ratio (see section 2.3.2) as a method of reporting incipient heating in the mine primarily because it is one of the most widely used indicators for the early detection of fires. Fire-VR is able to output environmental data associated with each cell within the mine network. This data can be used to produce charts which clearly show changes in gaseous levels within a mine in a typical way analogous to surface monitoring stations.

A simulated tube-bundle monitoring system was initially programmed into Fire-VR at a key point around the mine and then a small fire was programmed as an event to occur at face 1. The simulated tube-bundle system was created at the end of the return roadway from face 1; between the ventilation door with passive regulator and the T-junction joining the return airway, the roadway from face 1 and the ventilation door access area (see **Figure 8. 8**).

8.4.2 Fire profile

A smouldering fire was programmed to occur at the face, based on a profile created from producing carbon monoxide via the injection method.

The profile for this example fire and the conditions set for this study are given as follows: -

- CO is produced in the region of the cell in order to represent an oxygen deficient, fuel rich slow burning fire typically found in occurences of spontaneous combustion of goaf behind a working face.
- The CO profile, introduced into the designated cell, was chosen to produce a profile of between 0 and 0.014 % (typical CO levels in return mine air are in the region of 0.005 % (Rabia 1988)) - see **Figure 8. 9**.
- No other combustion products such as carbon dioxide are released in this profile, for this example.
- Time is measured in computer cycles (based on 1 cycle of iterative calculation of the VentSim-VR subsystem).
- Oxygen deficiency, used in calculating Graham's ratio, is set at a constant value of approximately 1.9 %. Oxygen is held at this value for the sake of simplifying the model (to monitor one variable only) whereas, in a real mine system, oxygen levels are constantly fluctuating due to human respiration, internal combustion engines and consumption by fire. This is considered appropriate because we are focussing on the principle of data retrieval and the modelling of how the results are affected by the change of environmental conditions. In a real mine system this data would be retrieved by real-time monitoring equipment giving an accurate analysis of gaseous components.

8.4.3 Execution of the test network and results

The test network was adjusted to include the CO inject profile described in the previous section. Sample data were taken from a simulated tube bundle system from the return airway of face 1 and the following chart was then generated in order to show the gas sample profile of CO (see **Figure 8. 9** below). A simulated oxygen deficiency ratio was also created using a negative inject profile applied to the network and the network was then balanced.

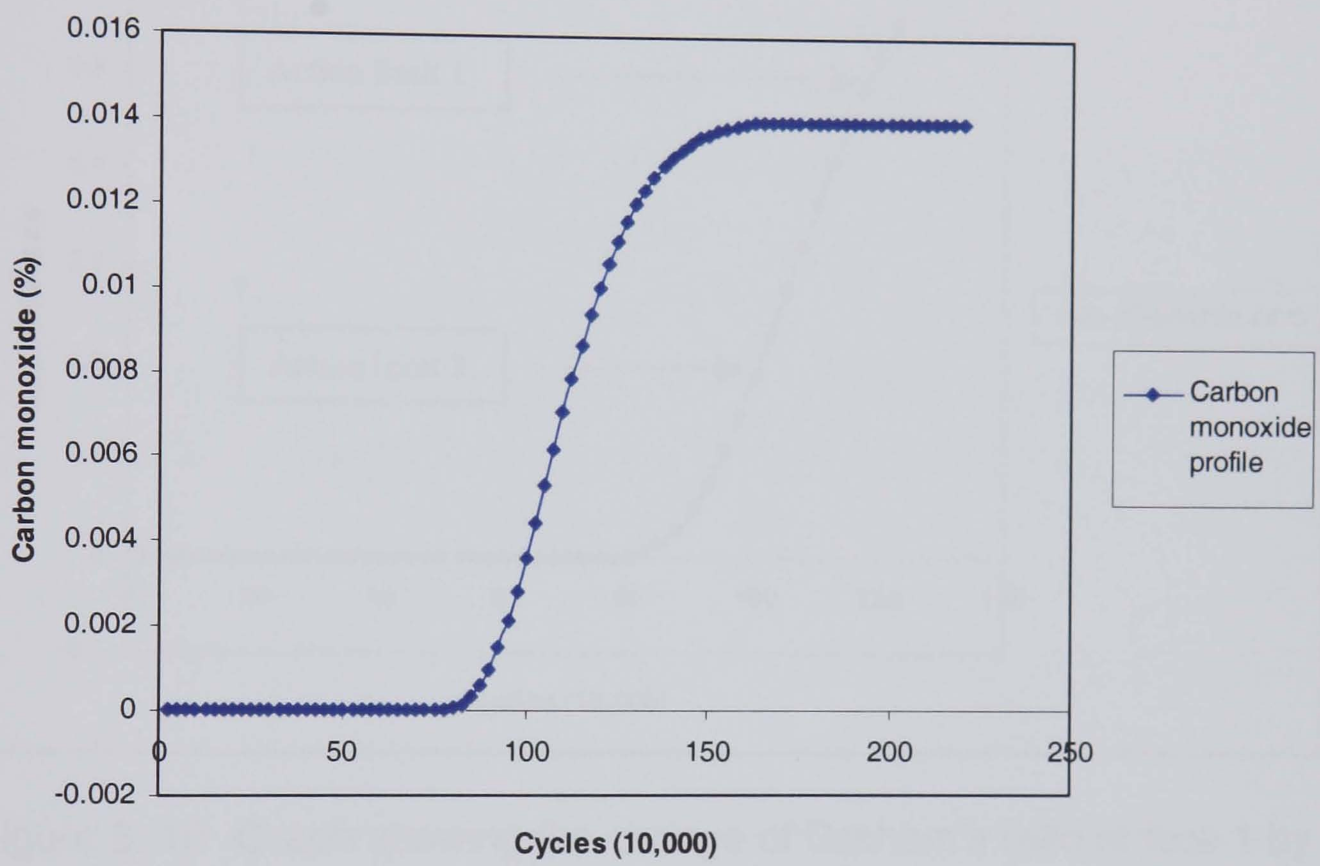


Figure 8. 9 Graph showing the build-up of CO levels at face 1 by monitoring the return airflow.

The inject for CO is steady and it can be seen from the graph that the CO content at the sample point reaches a maximum of approximately 0.014 %. This is the point when intake air, providing continual ventilation, limits the further build up of CO in the return airflow.

Graham's ratio is calculated using the current data of carbon monoxide and oxygen at the simulated sampling point using equation 8.1 given below.

$$I = (CO_{(at\ tube\ bundle)} / |(O_{2\ (at\ tube\ bundle)} - O_{2\ (at\ intake)})|)*100\% \qquad .....8.1$$

The results gained from calculating the Graham's ratio for the test network are shown in **Figure 8. 10**.

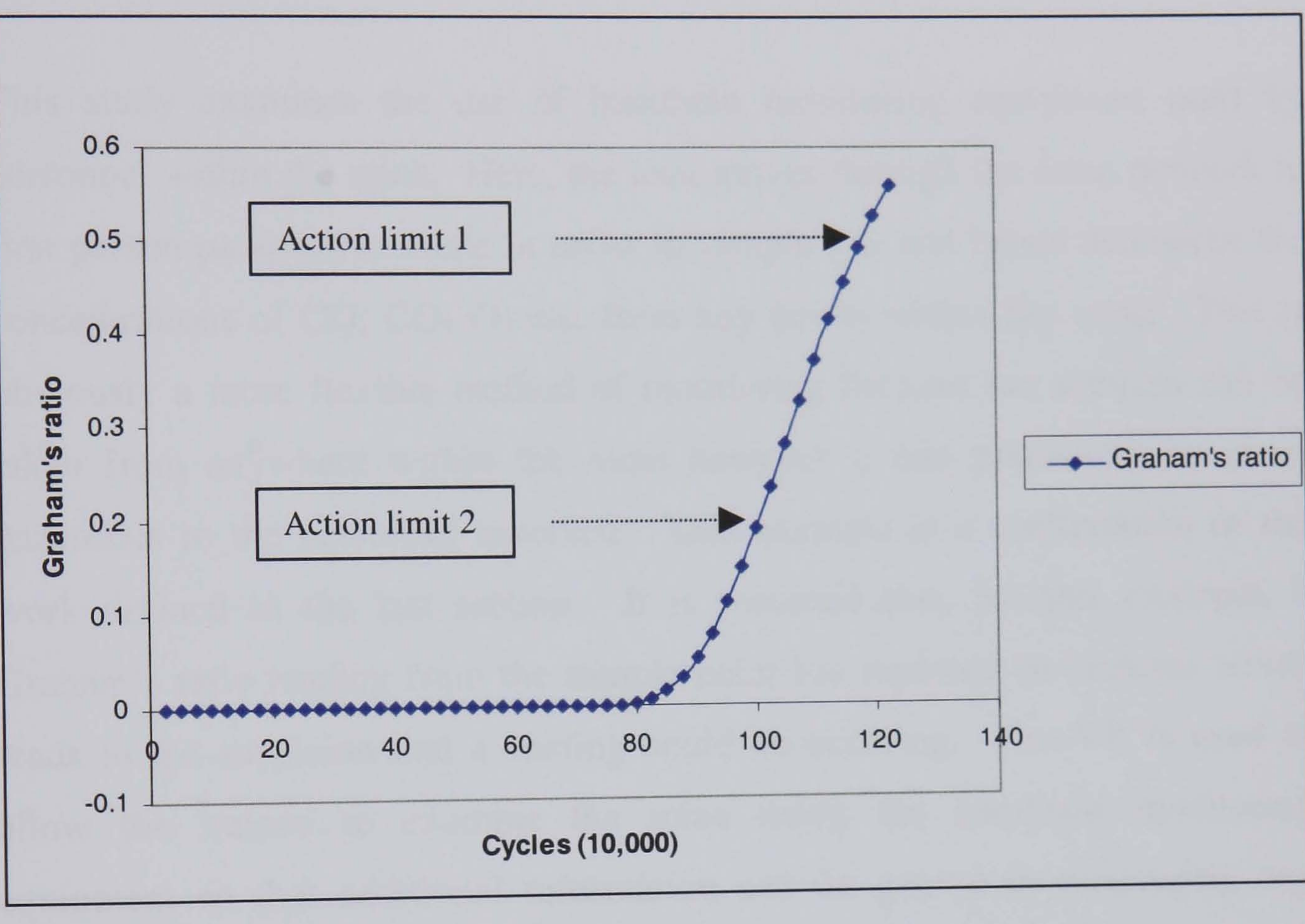


Figure 8. 10 Graph showing the change of Graham's ratio at face 1 by monitoring the return airflow

The Graham's ratio is used as a method of monitoring for potential fires within the mine. Rabia (1988) suggests that a Graham's ratio (I) of > 0.5 (**Figure 8. 10**, Action Limit 1) implies that a fire is continuing to burn. When this is reduced to I = 0.2 (**Figure 8. 10**, Action Limit 2) then the fire is said to be under control. A typical scenario would be the constant monitoring of Graham's ratio and CO levels (probably also other oxygen deficiency based ratio's e.g. Young's) with the aim of being able to quickly identify a possible fire. When an alarm is sounded as to a potential heating, as defined by an increase in the Graham's ratio then further investigative work would follow. The following example, based around the information and data gained in this section, has been applied to show this further investigation in action. The potential for use in training exercises / demonstrations is also explored in the next section.

8.5 Evaluation of Fire-VR – Internal monitoring

8.5.1 Introduction

This study examines the use of handheld monitoring equipment used by personnel within the mine. Here, the user moves through the mine network in first person perspective mode in order to sample gas and hence determine the concentrations of CO, CO_2 O_2 etc. from key points within the mine. This is obviously a more flexible method of monitoring because the samples can be taken from anywhere within the mine however it can potentially be more hazardous to the personnel involved. This example is a continuation of the work defined in the last section. It is assumed that, for this example, a Graham's ratio reading from the sample point has reported an increase which leads to the suspicion that a heating could be occuring. Fire-VR is used to allow the trainee to examine the mine using the handheld monitoring equipment so that additional information can be gained in diagnosing any potential impending threat to the safety of the mine and its personnel.

8.5.2 Locating a fire using the handheld gas monitoring unit

The handheld gas monitor, described in section 7.3.5, is used to enable the user to examine the constituent gas profile within a particular section of roadway. As the user moves through the mine network, the display on the handheld unit is constantly updated to give the user information about the environment. **Figure 8. 11** below shows the user turning the corner from the intake roadway into the roadway section which represents face 1 used in the previous examples. The users position can be seen from the miniature plan view at the top centre of the screen with the location being highlighted in white. The time, in computer cycles, is at the same point as the time frame in **Figure 8. 9** where the fire has just started and CO levels are beginning to rise. The handheld display unit (shown in the bottom right hand corner) clearly shows both the CO level at zero (to 3 decimal places) and also a calculated Graham's ratio of zero at this stage in the simulation. The view of the user in **Figure 8. 11** is orientated along the face, with fresh air being supplied from the left of the screen by the intake roadway. As the user walks down the face, the data on the handheld unit is observed to considerably change.

Figure 8. 11 Travelling towards the face from the intake roadway

A small distance along the face, the data changes, showing an increased level of CO and also an increase in the Graham's ratio (see **Figure 8. 12**). At this stage of the example simulation, the CO level is 0.012 %, with a Graham's ratio of 0.053.

Figure 8. 12 Increased Graham's ratio and carbon monoxide possibly indicative of a slow burning fire in the vicinity

This example application of Fire-VR, shows the potential that VR has with regard to training. The last example, demonstating the tube-bundle type analysis of gas levels within a mine, has been extended to provide a method for data measurement on a more localised basis. The user is able to experiment with methods of locating / identifying potentially hazardous environmental conditions using the Fire-VR software as a training tool. In the next example study, Fire-VR is used to show the benefits of visualising the mine environment by using VR and the graphical methods of representing data within the simulation.

8.6 Evaluation of Fire-VR – Fire control using inertization

8.6.1 Introduction

In this study, the Fire-VR simulation has been used to expand further on the example scenario discussed so far by incorporating a method of controlling a mine fire. The visual features of Fire-VR greatly enhance the representation of environmental scenes of potential disaster situations for the user to consider. The training implications of this are an obvious advantage of the research. Although mine fires are infrequent in the UK, other mining communities around the world (see Appendix 1a,b,c) do not have such a good track record. The reduction of the frequency of mine fires is generally influenced by the fact that the training of personnel has improved dramatically. By using the visual aids provided by Fire-VR and its virtual reality interface, it is expected that the training of personnel in exercising fire fighting / prevention procedures can only decrease the probability of these situations occurring. With further development, it is suggested that some of the techniques employed by Fire-VR could play a key role in personnel training programs.

Following on from the previous example of when a heating has been found, via external monitoring and then confirmed and located via the handheld monitoring equipment, this example is concerned with demonstrating the potential of Fire-VR to represent, graphically, a technique of fire fighting for training purposes.

8.6.2 Method of control

The techniques of inertization have commonly been employed since the mid 1970's in coal mines where spontaneous combustion occurs relatively frequently (McPherson 1993). Both carbon dioxide and nitrogen can be used for this technique, however nitrogen is the most commonly used gas because it is very easy to produce cheaply in large quantities due to it being a by-product of the commercial production of oxygen. The aim of the technique is to reduce the oxygen content to lower than 10% to inhibit flaming combustion and in the case of controlling smouldering fires, reduce further to less than 2%.

A section of face 1 from the original mine has been remodelled for this example using the NetEdit program. This mine network is a section which focuses entirely on the area where the fire has been found to occur. The following assumptions for this example have been implemented: -

1. The level of CO% in the affected area is sufficient to warrant the ceasing of mining activity and the evacuation of non-essential personnel. The area has then been sealed off with temporary stoppings (as close as possible to the fire without endangering the lives of personnel). The stoppings are kept partially open on the return side so as to allow displacement of the air within the section by the injected nitrogen.
2. When the stoppings are in place, normal ventilation of the affected area ceases and the concentration of the gases, within the sealed off section, are defined as follows (based on figures suggested by Rabia 1988) : -
    - O_2 = 6.0%
    - N_2 = 74.0%
    - CO_2 = 5.0%
    - CH_4 = 12.0%
    - CO = 3.0%
3. The heating will be controlled by smothering via inertization (the reduction of the percentage oxygen by replacement with an inert gas such as nitrogen) so as to reduce oxygen levels to less than 2% to suppress smouldering.
4. Ventilation flow is assumed to be negligible to the area due to the erection of the sealing stoppings.
5. Nitrogen is introduced into the sealed area at a rate of approximately 5 m^3/s (based on typical flow rates for this method described in McPherson (1993)).

6. Sensing points are installed through apertures within the stoppings in order to provide analytical data of gas concentrations within both ends of the sealed off area.

8.6.3 Environmental modelling of inertization process

Data from the simulated sensory equipment at each end of the sealed off area was collected from Fire-VR. **Figure 8. 13**, below, shows the decrease in oxygen levels and the additional effect of the removal of other gases, including the products of combustion such as CO, following displacement by the injected nitrogen. This demonstrates the usefulness of inertization in reducing the oxygen content to the required < 2 % in order to inhibit smouldering and the ability of Fire-VR to model such procedures.

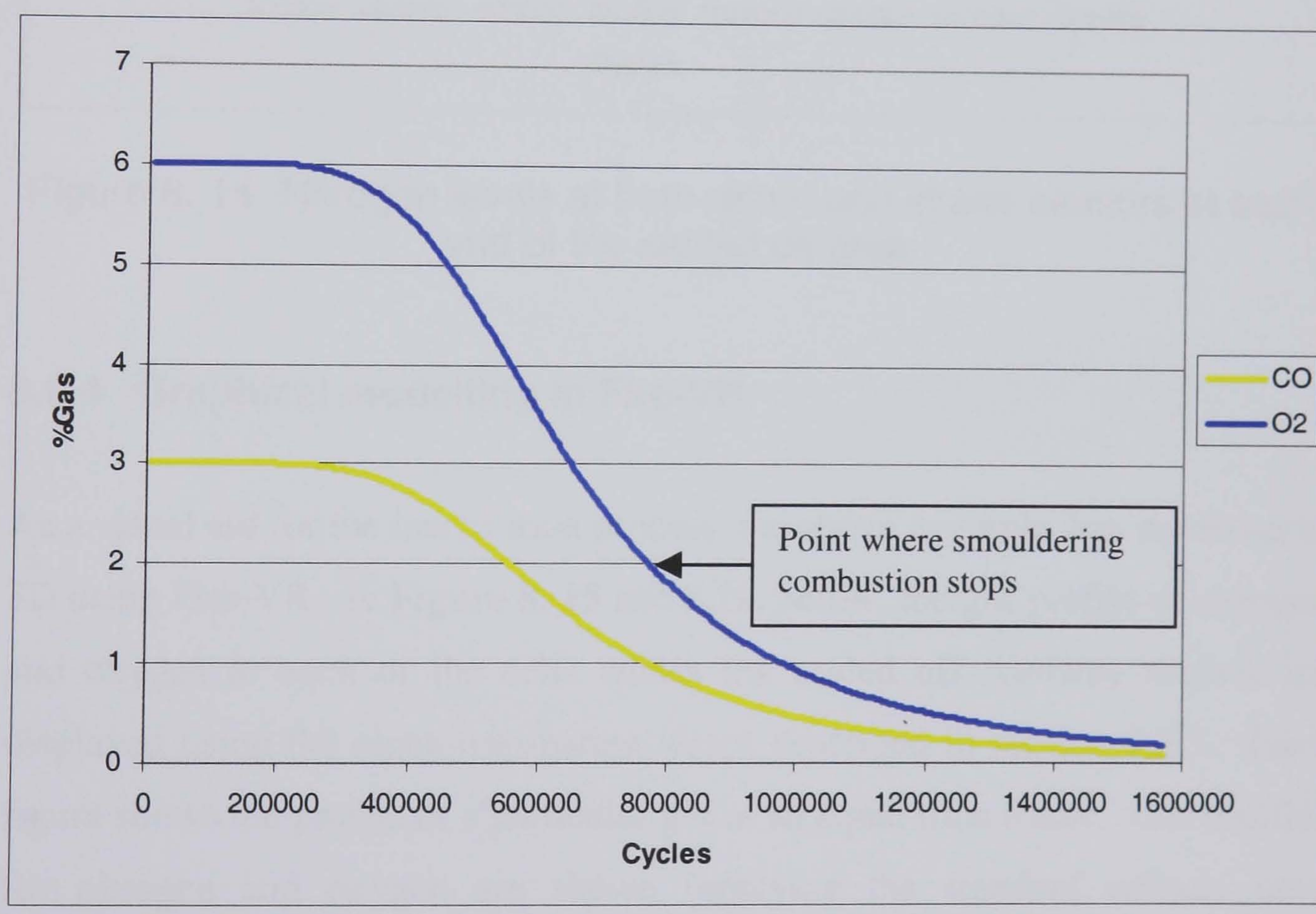


Figure 8. 13 Concentration of O_2 and CO gases from the sensing point at the return end of the sealed off area

In **Figure 8. 14**, the build up of injected nitrogen used for inertization is shown to steadily increase until 100% concentration is reached (assuming no leakage).

Data from both the intake and return sensors are shown (the lag between the two readings represents the time taken for the volume of air within the sealed area to be displaced).

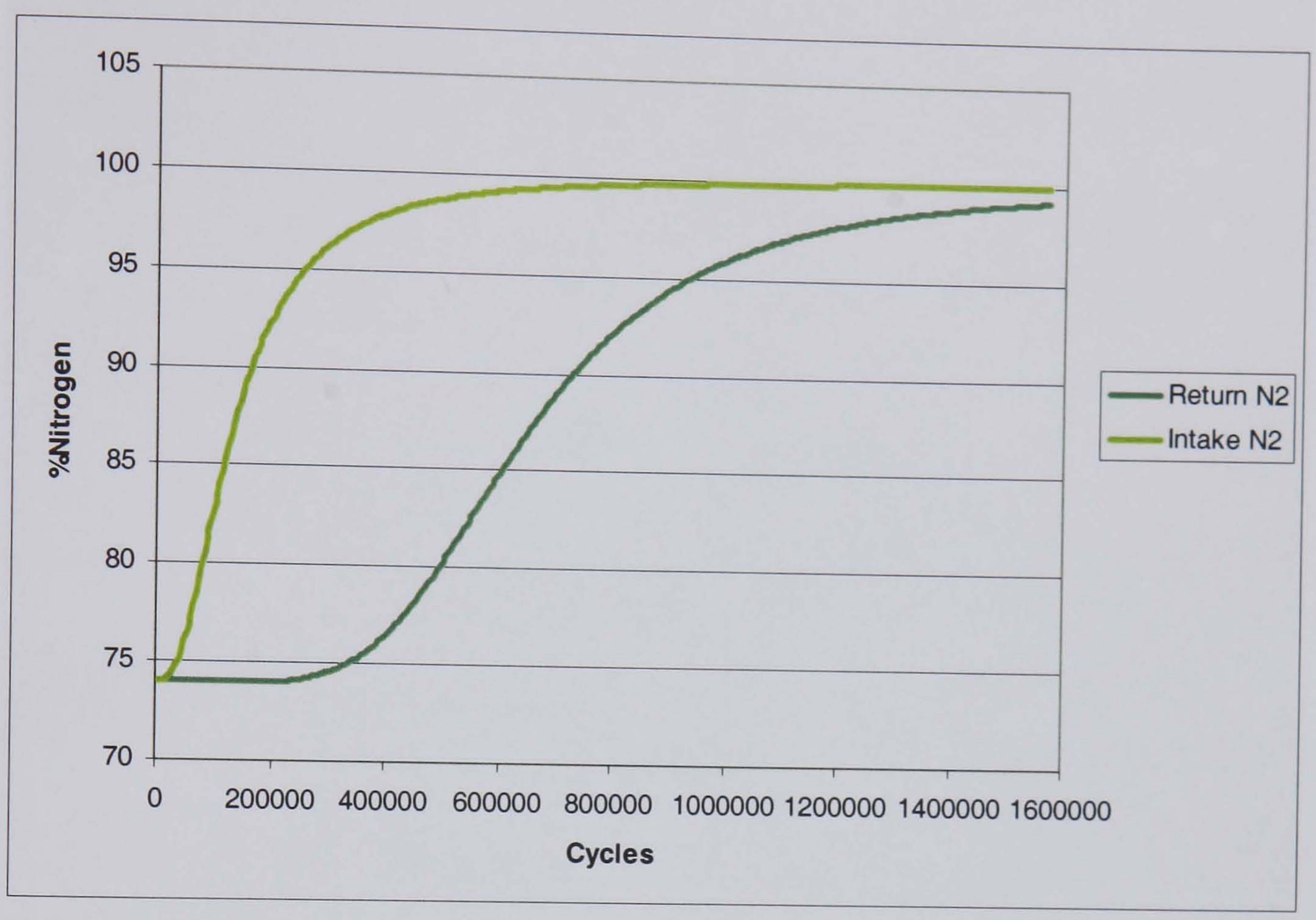


Figure 8. 14 Nitrogen levels at both return and intake sensors at each end of the sealed off area

8.6.4 Graphical modelling in Fire-VR

As a visual aid for the inertization process, the above example was modelled in 3D using Fire-VR. In **Figure 8. 15** and **8.16**, below, the gas profile of nitrogen and oxygen in each of the cells within the sealed off roadway section are displayed using the alpha-transparent wraps described in section 7.3.5. Each figure shows the profile of a particular gas at an equal time frame. Gas profiles for nitrogen and oxygen are shown (applying the standard colours used throughout this research; see section 6.2.2). The intensity level for displaying the extent of transparency has been adjusted to give a gradual change in the level of opacity between adjoining cells. In the case of nitrogen, where the percentage level of gas ranges from 74 to 100%, the intensity level was defined so as to scale the opacity level to this range. This means that nitrogen levels of approximately 74% are completely transparent. This method was found to represent any increase in the percentage nitrogen more appropriately than when defining the transparency range from 0 – 100 %.

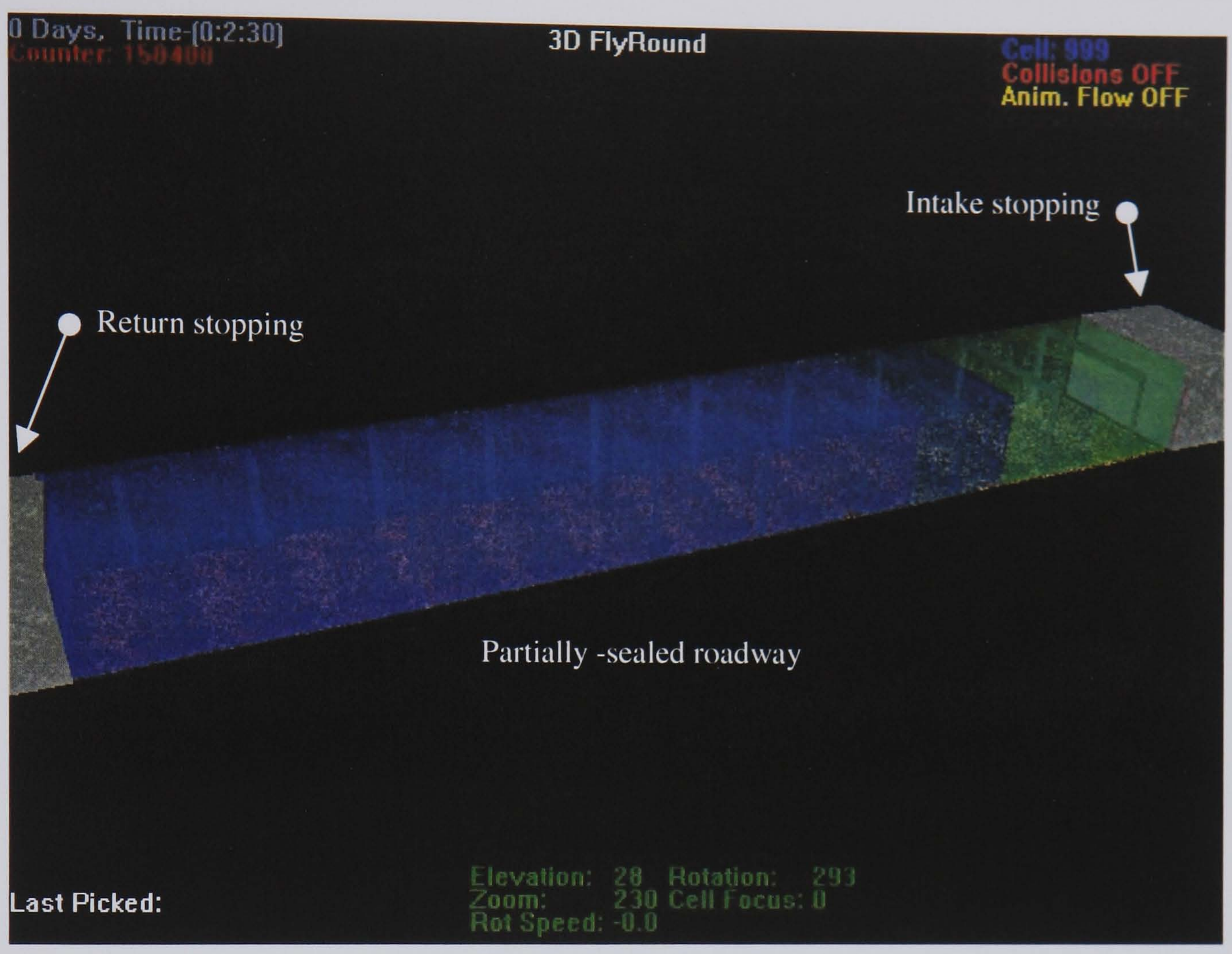


Figure 8. 15 Visual representation of inertization process using nitrogen

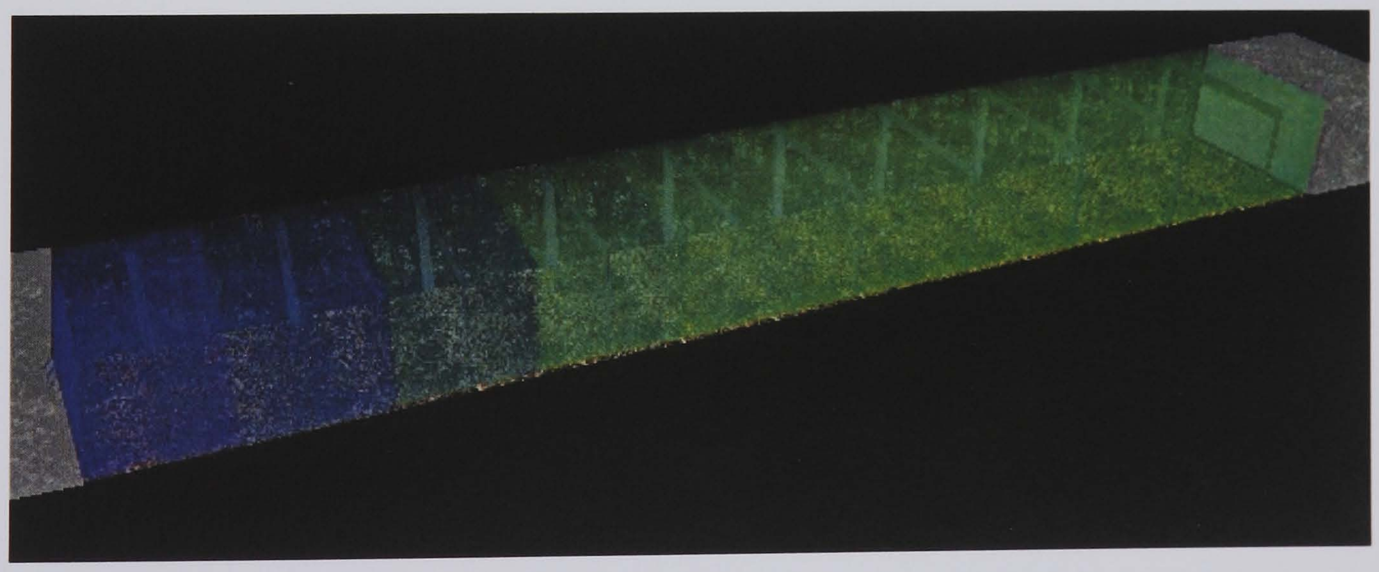


Figure 8. 16 Progression of nitrogen through the partially - sealed section of roadway showing the displacement of oxygen

8.7 Summary

A number of representative case studies have been described to show some of the potential applications of Fire-VR. The data determined using the VentSim-VR component of Fire-VR was found to compare favourably with results from VnetPC™ using an example mine network. Example scenarios for utilising Fire-VR have then been created (using regulators, handheld monitoring and external monitoring procedures utilising Graham's ratio) in order to demonstrate its application in mine fire detection and control procedures.

Finally, the graphical representation of inertization, a well practiced method of fire control, has also been demonstrated.

Chapter Nine

Conclusions and recommendations for future work

9.1 Conclusions

9.1.1 Introduction

The research carried out for this thesis involved the development of a virtual reality simulation for the modelling of ventilation networks within an underground mining environment. The control of ventilation is of critical importance in the management of safety of mine personnel and also plays a key role in the management of the environment within the mine (without adequate ventilation, potentially explosive gases can quickly build up to hazardous levels). The study has examined current research in both the fields of mining engineering and computer graphics associated with virtual reality. These technologies have been inter-linked in order to produce the Fire-VR software, a unique simulation capable of modelling a variety of underground mining scenarios for the user to interact with. It is postulated that the facilities offered by this research and development could be applied in certain areas of training of personnel both in terms of the visual display of current mining techniques and also, fully interactive computer based learning in the form of virtual reality. By combining the virtual reality visualisation with a model for the mine network a unique tool for simulating mine ventilation has been produced.

9.1.2 Research Aims

The research aims of this thesis were to: -

1. Conduct objective research related to the mining and minerals sector in the areas of explosion / fire prevention and management.

2. Investigate extending traditional methods of analysis of mine networks using innovative VR technology.

3. Explore ways of representing mine environmental data using novel 3D graphics.

4. Create a prototype system on a standard desktop PC which could be applied to real world situations in the mining sector and used to produce example scenarios for training purposes / demonstrations.

9.1.3 How the Research aims were achieved

These research aims were met by the design and development of a prototype virtual reality system, Fire-VR, which is able to model a variety of ventilation configurations within a mine. During method development, the research objectives were considered as discrete components with the aim of creating a modular solution. It was felt necessary to adopt this approach as work in the field of computer imaging and graphics is evolving at a significant rate. By modularising the Fire-VR system into its associated sub-systems for modelling ventilation flow, environment modelling and the graphical display; the system has been designed to be more readily adaptable to improvements as and when the technology allows modifications to be made. Specific attention has been made in chapters four and five in relation to the consideration of this modularisation.

In order to successfully model the environmental data required for this study, a suite of C++ based programs were created. It was concluded that in order to provide the processing power and flexibility needed, it would be necessary to create the software components for both the simulation and visualisation aspects of the Fire-VR system in order that a complete unified system could be established.

Fire-VR encompasses VentSim-VR, EnvSim-VR and the display interfaces. For this research, the VentSim-VR component of Fire-VR utilises a ventilation model based around the Hardy Cross iterative algorithms whilst the EnvSim-VR component, which models environmental information within the mine, has been created around a bespoke set of algorithms based on conservation of energy principles. The 2D and 3D interfaces to the simulation have been constructed from MFC™ and Direct X™ API's.

The modelling of complex environmental conditions such as those required to define a model which can simulate fires and explosions are notoriously computationally intensive. This study sought to examine the complex issues associated with modelling the environment within an underground mine with the aim of producing a model that would be representative of the world, yet which would not be so complex that the system would be impossible to run in real-time on a standard PC. The study initially examined the possibility of using CFD based models for providing the ventilation system used by Fire-VR Because of the constant speed and processing limitations of such a PC, inevitably the simulation model for both VentSim-VR and EnvSim-VR had to be simplified. However, the potential use of a CFD based model was examined in view of future possibilities to increasing the detail of the model. Some of the possibilities for such improvements are discussed in the section on future recommendations later in this chapter.

In order to meet the research aims of this thesis and to maximise the flexibility and potential application of Fire-VR, a number of features were implemented into the prototype system including : -

- Supporting mine editing software (NetEdit) to allow the rapid creation of mine network files for use by the Fire-VR software.
- Novel methods of data visualisation for environmental information (gas flows modelled by moving arrows, of variable rate and opacity)
- A highly configurable, environment processing system capable of creating a variety of spontaneous and pre-defined events (allowing a multitude of possible training scenarios).

- A number of facilities for enhancing user interactivity with the mine environment e.g. handheld gas monitoring equipment for reading gas levels at certain points and the facility to activate equipment (e.g. fire extinguishers, telephones etc) and also the opening / closing of ventilation doors.

The virtual reality subsystems in terms of the Fire-VR front-end, namely the 2D and 3D interfaces, also had to be carefully defined in terms of a trade-off between detail and speed. Models created in the 3D interface were kept to a minimum number of polygons with simple texture maps being used to give additional detail in order to minimise slow down within the real-time system.

9.1.4 Research results

Fire-VR has been researched and developed into a fully functioning virtual reality application. Many possible example applications of its potential in training and demonstration can be created with the tools developed for the prototype system.

The virtual reality subsystems in terms of the Fire-VR front end, namely the 2D and 3D interfaces had to be carefully defined in terms of a trade-off between detail and speed.

The use of virtual reality has been found to be an ideal medium for visualising the spatial distribution of invisible gases and for modelling ventilation and environmental data.

In chapter 8, some example Fire-VR scenarios have been presented including the application of regulators, tube bundle monitoring systems, hand-held monitoring equipment and the inertisation of the atmosphere using nitrogen. The Fire-VR system has been used in order to model established mine networks with the aim of testing its ability to model ventilation flows. The results were found to compare favourably with data obtained from VnetPC™.

Fire-VR's ability to graphically display movement of airflow can be used to great effect during demonstration exercises. Examples can also be created where Fire-VR is used to model a fire and the associated user interactive events. Fire-VR's ability to model these processes in 3D graphics provide visually innovative methods of user training.

9.1.5 Potential application

The need to continuously improve training in the areas of hazard identification, ventilation management and risk assessment is a recognised priority in most mining organisations. New technologies such as virtual reality offer a method of assisting with this improvement. The research carried out for this thesis offers potential for the training of workforces in a relatively short time span. It would also be relatively inexpensive whilst being less dangerous than traditional 'in the field' training. The cost of the platform for a PC based virtual reality system is readily affordable. This situation can only get more cost effective as the technologies mature. The Fire-VR prototype therefore offers an additional contribution to more traditional forms of training techniques and facilities currently available.

9.2 Recommendations for future work

This study was intended as a preliminary attempt at constructing virtual environments and associated computer virtual reality based systems for the mining community. The models produced provide basic ventilation and environment modelling capability for the purpose of conceptual training. Fire-VR would benefit from constant renewal and evaluation as the many technologies and concepts that define the system are improved upon. As computer hardware prices continue to fall yet processing power continues to improve, this may allow for the utilisation of additional resources in the simulation. One area which would inevitably benefit from these improvements, is the graphical modelling of the environment. A greater number of mine objects could be added giving the model an improved visual appearance and further visual cues to aid the realism of the virtual reality experience. Additionally, a move from the desktop VR system discussed in this thesis to a more immersive system could become a possibility. More sensory feedback devices such as heaters and fans, situated around the user's seat, and controlled by the environmental model, could provide realistic cues as to the orientation and position of the user within the mine (to provide temperature controlled air across the face of the user to simulate the airflow encountered in the mine).

The VentSim-VR component of the simulation requires a finite period of time to balance out and reach a steady state thus making the simulation difficult to calibrate to time when the user interacts with the environment in a way which has a direct effect on the ventilation model. This could typically occur when the user adjusts a ventilation door. This is an inevitable short coming of the system and its genre. It is recommended that this is addressed when increases in computer power allows this stabilising of the ventilation model to occur in such a small time frame that the error becomes discounted as negligible.

Another potential area of improvement could be the increase in the number of nodes and cells which define the mine network description files leading to higher resolution models, again leading to an improved visual appearance of the simulated world. Alternatively, when the technology becomes available the node and cell based model could be removed and a more complex cellular automata or CFD based model would be recommended instead. This would also allow for the potential of modelling thermodynamics within the simulation, a welcome improvement.

Although a prototype system, Fire-VR can be used to model a number of possible mining scenarios. In particular, the user selecting facility which was included could be utilised further to examine trainees ability to carry out complex tasks under the pressure of a simulated emergency situation. Fire-VR includes the facility to load up a variety of objects which the user can interact with, but due to time constraints available for the research in this area and the time consuming nature of building individual computer objects, this application has not been incorporated to its full potential. It is recommended that future work should include more objects which can be interacted with.

In summary, these suggested future developments could extend upon the concepts already presented to further enhance the potential of the Fire-VR software in training applications.

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APPENDIX 1a

China Coal Mine Blast Kills 77, Injures Eight

BEIJING (Reuters) - A gas explosion at a coal mine in northeastern China last week killed 77 people and injured eight, the Xinhua news agency said Friday.

Officials were still investigating the cause of the accident at the state-owned Wangjiaying coal mine in Liaoning province on January 24, Xinhua said, quoting the Ministry of Coal Industry.

Chai Zhaoxi, director of the safety department under the Ministry of Coal Industry, said the fire in the mine shaft has been extinguished.

The explosion killed 77, he said, adding that only one of the eight injured miners remained in critical condition.

Officials could not be reached for comment during the Lunar New Year holidays.

Three other major accidents at coal mines claiming more than 10 lives each have already marred 1998.

Last week's blast ripped through a new shaft that was not yet operational when a large team of workers was installing equipment, he said.

"Therefore, it caused many more casualties than a usual accident," Chai said. Normally only 30 miners work in a shaft at a time.

A team, consisting of officials from the ministries of coal industry and labour and the provincial government, went into the shaft on Friday to investigate the accident, Xinhua said.

"But they won't get a sure answer on the cause of the accident until the water in the 300-meter (984-foot) long shaft is completely drained away, which will take three to four days," Chai said.

Shafts at Wangjiaying mine have an average depth of 1,312 to 1,640 feet, Chai said, adding that the coal bed has a high gas content.

"Over 10 cubic meters of gas are released with every ton of coal produced," he said.

The medium-sized Wangjiaying mine began operation in 1987 with a designed production of 1.2 million tons per year, Xinhua said. It gave no further details.

Major accidents in Chinese coal mines killed 2,028 miners last year, up nearly 30 percent from the previous year, local media have said.

The number of serious accidents, or those claiming 10 or more lives, rose more than 21 percent last year to 102.

The sharp rise in the death toll from serious mishaps prompted the Ministry of Labor to issue an urgent circular calling on coal mines to review and improve their safety measures.

The circular urged local governments to shut down small and unlicensed mines.

Mining accidents kill an estimated 10,000 people a year in China. The country is dotted with thousands of small, unregulated mines that take few or no safety precautions.

Reut08:49 01-30-98
(30 Jan 1998 08:49 EST)

<http://www.pathfinder.com/news/latest/RB/1998Jan30/270.html>

APPENDIX 1b

Sunday January 18 9:51 AM EST
Raging Fire Traps 25 Russian Miners in Pit
By Natalya Borisova

MOSCOW (Reuters) - A raging fire trapped 25 coal miners 3,000 feet below ground in Russia's Arctic Sunday after an explosion killed two of them.

"The situation is very serious. The fire continues," Yuri Kostin, duty officer at the Fuel and Energy Ministry in Moscow, told Reuters by telephone. "I hope they will survive but the chances are minimal."

Rescue attempts at the Tsentranlaya colliery in the town of Vorkuta would continue through the night, he said.

Prime Minister Viktor Chernomyrdin ordered a special government commission, headed by his deputy Yakov Urinson, to fly to Vorkuta later Sunday to oversee the rescue operation and the investigation into the blast.

The bodies of two miners killed by the explosion early on Sunday were brought to the surface along with 22 survivors, one of them badly injured, a Vorkuta police officer said.

A Moscow-based Emergencies Ministry spokeswoman said the explosion was probably caused by methane.

Fire continued to rage in the pit, raising the temperature inside and hampering rescue workers as they dug through rubble to try to find the 25 miners.

Interfax news agency said the outside temperature in the Arctic region was minus 30 Celsius (minus 22 Fahrenheit).

The Vorkuta basin is the second largest coal field in Russia. Its pits were built by thousands of prisoners in the Gulag camps under Soviet dictator Josef Stalin.

There have been a number of explosions and fires at Russian mines, many of which are old and use outdated equipment.

Last month, 68 miners were killed in an underground explosion in the Kuzbass coal field, the country's biggest, in Siberia. Three other accidents last year killed 13 miners.

The World Bank granted Russia $500 million in credits to restructure its coal industry but much of this has been spent on back pay for miners. Part of an $800 million credit is also due to be spent on the coal industry.

Itar-Tass news agency reported Chernomyrdin considered the frequency of mine accidents "threatening" and said that apart from shortage of funds, the lack of strict safety standards was to blame.

The prime minister vowed to punish the officials responsible, Tass said.

Earlier Related Stories

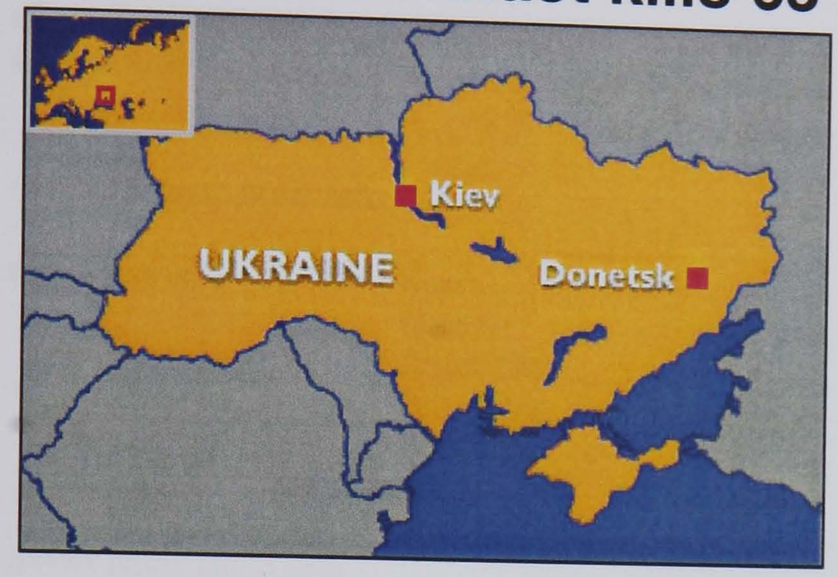
- Russian Mine Blast Kills Two, Traps 25 - Sun Jan 18 7:34 am
- One killed, 26 Missing in Mine Explosion - Sun Jan 18 3:00 am

<http://www.yahoo.com/headlines/980118/news/stories/miners_3.html>

APPENDIX 1c

World: Europe (BBC World News) 8.55 a.m. ET (1255 GMT) April 5, 1998

Ukraine mine blast kills 63



More than 30 Ukrainian coal miners trapped underground after a methane gas explosion were found dead on Sunday, raising the number of people killed in the accident to 63.

The blast, at the Skochinsky pit in the eastern city of Donetsk, was one of Ukraine's worst mining disasters.

Rescue teams continued the laborious and dangerous task of bringing bodies to the surface from a collapsed new seam at the mine, where some 600 men were working when the methane blast ripped through the pit on Saturday morning.

Thirty bodies were found by Saturday evening and rescuers struggled overnight to burrow through rubble 1.2 km (4,000 feet) below ground, to reach survivors. In the end, all had either died in the explosion or had suffocated.

With everyone now accounted for, 43 men were still in hospital, nine of them in critical condition. Rescue workers said some of the injured were poisoned by gas because their personal breathing apparatus failed to work.

"All 63 bodies have been found although only 37 have so far been brought to the surface," Ukraine's deputy coal minister, Viktor Shchepachov, told Reuters news agency.

High temperatures underground and the constant threat of a new collapse or explosion were hampering recovery efforts. "Bringing out the dead is putting the living at risk," Mr Shchepachov said. But he promised that no bodies would be left below.
Deputy Prime Minister Nikolai Beloblotsky, who is heading an investigation into the accident, called it a "national tragedy".

Poor safety record

Emergency officials said they had not determined what triggered the blast. Preliminary findings are expected to be announced later on Sunday. Correspondents say Ukrainian coal trade unions have often warned the government about the safety of the Ukraine's 229 coal mines. More than 160 miners have died in accidents in the first two months of this year.

The Donetsk basin in eastern Ukraine is the former Soviet republic's largest coal mining region, with 225 mines employing 630,000 workers. Coal accounts for roughly 30% of the country's energy production, and nuclear power supplies an additional 25%. Despite these domestic sources, the economy is highly dependent on other former Soviet republics for oil and natural gas, the price of which has risen sharply in the early 1990s.

APPENDIX 2

The following code is a C++ header file used in Fire-VR showing the commonly used data structures required to store variable data from the VentSim-VR simulation while executing.

Comments are preceded with a double forward slash (//)

```
#ifndef NETWORK_H
#define NETWORK_H


//**** General Build info

typedef struct   {     float O;                        // oxygen
                       float N;                        // nitrogen
                       float CH4;                      // methane
                       float CO2;                      // carbon dioxide
                       float CO;                       // carbon monoxide
                 }gas_split;

//**** Node Build info

typedef struct   {     float pressure;                 // pressure var stored at node
                       float temperature;              // temperature at each node
                 }node_condition_info;


typedef struct   {     int xd,yd,zd;                   // display co-ords (2D Interface)
                       float x,y,z;                    // real co-ords
                       int ncells;                     // stores number of
                                                       // cells which surround this node
                       int cells[7];                   // stores actual cell
                                                       // number 'pointer' from this node to
                                                       // surrounding cells


                       char nodetype[14];              // stores what type of node this is. ie
                                                       // NORMAL, INPUTPRESSURE etc


                       node_condition_info cond;
                       node_env_info env;
                       gas_split gas;
                 }node;

//**** Cell Build info

typedef struct   {     float length;
                       float x_sectional_area;
                       float thermal_conductivity;
                       float volume;
                       float resistance;
                       }roadway_struct_info;


typedef struct   {     float pressure;
                       float temperature;
                       float air_velocity;
                       float heat_movement_velocity;

                       float volumetric_flow_rate;
```

```
                        float thermal_volumetric_flow_rate;
            }roadway_condition_info;

typedef struct  {       float cell_air_heat;
                        float cell_strata_heat;
                        float conveyed_mineral_heat;
                        float machine_heat;
                        float explofire_heat;
                        float dust;
                        float smoke;
                        float potential_energy;         // used to hold fuel value of cell
                        bool Event_Fire;                // used to check that an event isn't
                                                        // already happening
            }roadway_env_info;

typedef struct  {       int from,to;                    // node links
                        roadway_struct_info stru;
                        roadway_condition_info cond;
                        roadway_env_info env;
                        gas_split gas;

                        char celltype[14];              // stores what type of
                                                        // cell this is  i.e. NORMAL, FAN etc

            }cell;

typedef struct  {       int seg;
                        float rate;
                        long start,stop;
                        int cell;

                        char injecttype[14];            // stores what type of node this is  i.e.
                                                        // NORMAL, SHUTDOOR etc

            }inject;

typedef struct  {       int from, to;                   // node links
                        int cell;
                        float dooropenresistance;
                        float doorshutresistance;
                        int doortoggle;                 // shut=0;open=1;
                        float x,y,z;                    // store actual position here for door
                                                        // opening/shutting algorithms

            }door;


class CNetwork                                          // main data structure class
{
public:

node Nodes[500];                                        // create array of Nodes
cell Cells[500];                                        // create array of Cells
door Doors[50];                                         // create array of doors
inject Injects[50];                                     // create array of injects
int ninjects,eventinjects;
int nevents;
int nnodes,orig_nnodes;
int ncells;
int ndoors; //number of doors within mine
```

APPENDIX 3

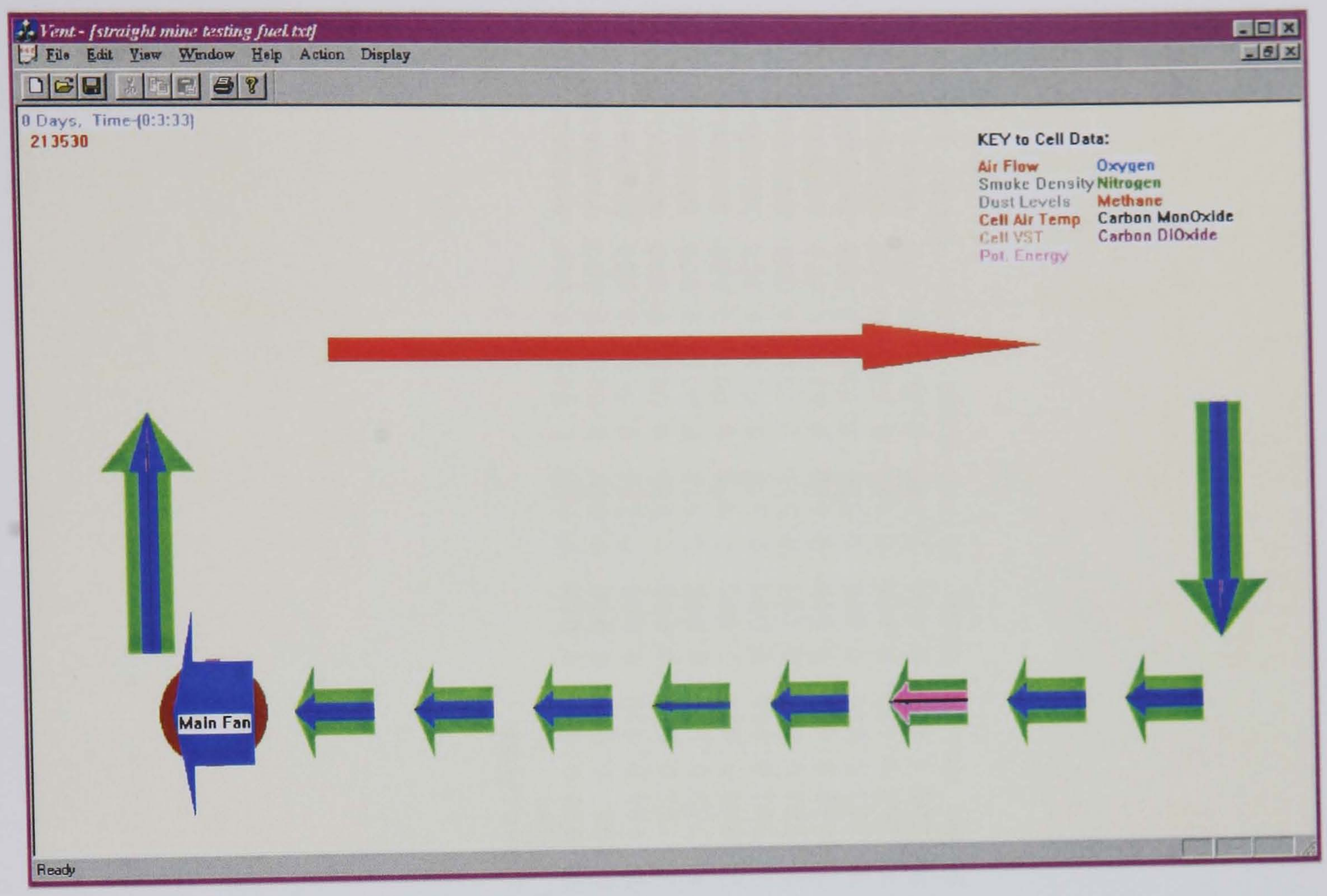


Figure Appendix 3. 1 Example mine structure in VentSim-VR 2D interface (no path splits, 1 main fan)

Example data file for Figure Appendix 3. 1 Example mine structure in VentSim-VR 2D interface (no path splits, 1 main fan)

```
0       //Time in cycles. must be set 0 or greater
12      //node,xd,yd,xf,yf,zf,start_pressure,node type
0       100     200     1000.0 200.0  100.0  -370.0        NORMAL
1       100     500     1000.0 200.0  100.0  -0.0          NORMAL
2       200     500     1000.0 700.0  100.0  -3700.0       NORMAL
3       300     500     1000.0 1200.0 100.0  -3330.4       NORMAL
4       400     500     1700.0 1300.0 100.0  -2960.8       NORMAL
5       500     500     2400.0 1300.0 100.0  -2591.2       NORMAL
6       600     500     2500.0 900.0  100.0  -2221.7       NORMAL
7       700     500     2700.0 600.0  100.0  -1852.1       NORMAL
8       800     500     3300.0 600.0  100.0  -1482.5       NORMAL
9       900     500     3800.0 600.0  100.0  -1112.9       NORMAL
10      1000    500     4100.0 900.0  100.0  -743.3        NORMAL
11      1000    200     4100.0 900.0  100.0  -373.7        NORMAL
12      //Number of cells n, from, to, resistance,x_section,cell_air_heat(J/kg
degC),strata_heat,CellFuel,Ox%,Nitr%,Meth%,CO%,CO2%,Dust,Smoke,cell type
0       0       1       0.100  10.0   613.2  10.0   600.000       19.915 78.674 0.639  0.005  0.579  0.001  0.000  NORMAL
1       1       2       0.001  10.0   0.0    10.0   600.000       0.000  0.000  0.000  0.000  0.000  0.000  0.000  FANMAIN
2       2       3       0.100  10.0   613.2  10.0   600.000       19.916 78.680 0.639  0.005  0.579  0.001  0.000  NORMAL
3       3       4       0.100  10.0   611.6  10.0   600.000       19.925 78.761 0.639  0.005  0.579  0.001  0.000  NORMAL
4       4       5       0.100  10.0   610.0  10.0   600.000       19.942 78.762 0.639  0.005  0.579  0.001  0.000  NORMAL
5       5       6       0.100  10.0   609.2  10.0   600.000       5.941  78.762 0.639  0.005  0.579  0.001  0.000  NORMAL
6       6       7       0.100  10.0   607.6  10.0   600.000       19.941 78.762 0.639  0.005  0.579  0.001  0.000  NORMAL
7       7       8       0.100  10.0   606.0  10.0   600.000       19.941 78.762 0.640  0.005  0.579  0.001  0.000  NORMAL
8       8       9       0.100  10.0   604.4  10.0   600.000       19.941 78.762 0.640  0.005  0.580  0.001  0.000  NORMAL
9       9       10      0.100  10.0   602.8  10.0   600.000       19.941 78.861 0.640  0.005  0.580  0.001  0.000  NORMAL
10      10      11      0.100  10.0   601.2  10.0   600.000       19.941 78.860 0.640  0.005  0.580  0.001  0.000  NORMAL
11      11      0       0.001  10.0   600.0  10.0   600.000       19.950 78.830 0.640  0.005  0.580  0.001  0.000  WORLD
2       //Number of injects/events - format : Inject Nos, Cell Nos, Rate, Start, Stop, inject type: HEAT, DOOR, FAN etc
0       1       -0.050 1000    500000 FAN1ON
1       7       0.025  1000    20000  STRATAFIRE
```

APPENDIX 4 – Test Network Data File

Printout of 'TestNetwork.net'

```
0	//Time in cycles. must be set 0 or greater 1
23	//node,xd,yd,xf,yf,zf,start_pressure,node type
0	200	100	1000.0	200.0	100.0	-353.4	NORMAL
1	200	200	1000.0	700.0	100.0	-703.2	NORMAL
2	200	300	1000.0	1200.0	100.0	-1053.1	NORMAL
3	100	300	1700.0	1300.0	100.0	-1402.9	NORMAL
4	100	400	2400.0	1300.0	100.0	-1752.7	NORMAL
5	100	500	2500.0	900.0	100.0	-2102.6	NORMAL
6	200	500	2700.0	600.0	100.0	-2452.4	NORMAL
7	300	500	3300.0	600.0	100.0	-2802.2	NORMAL
8	400	500	3800.0	600.0	100.0	-3152.0	NORMAL
9	400	400	4100.0	900.0	100.0	-3250.9	NORMAL
10	400	300	4100.0	1300.0	100.0	-3349.8	NORMAL
11	500	300	2900.0	1300.0	100.0	-3272.9	NORMAL
12	500	400	3500.0	1300.0	100.0	-3250.8	NORMAL
13	500	500	4700.0	1400.0	100.0	-3228.7	NORMAL
14	600	300	1800.0	1600.0	100.0	-3256.4	NORMAL
15	600	400	3100.0	1600.0	100.0	-3250.8	NORMAL
16	600	500	4700.0	2000.0	100.0	-3245.1	NORMAL
17	700	300	4300.0	2000.0	100.0	-3253.6	NORMAL
18	700	400	3800.0	2000.0	100.0	-3250.8	NORMAL
19	700	500	3200.0	2000.0	100.0	-3247.9	NORMAL
20	300	300	3800.0	2500.0	100.0	-3700.0	NORMAL
21	300	200	3400.0	2800.0	100.0	-0.0	NORMAL
22	300	100	3400.0	2800.0	100.0	-349.9	NORMAL
26	//Number of cells n, from, to, resistance,x_section,cell_air_heat(J/kg degC),strata_heat,CellFuel,Ox%,Nitr%,Meth%,CO%,CO2%,Dust,Smoke,cell
type
0	0	1	0.100	10.0	1.4	10.0	0.000	19.953	78.882	0.640	0.005	0.580	0.001	0.000	NORMAL
1	1	2	0.100	10.0	2.7	10.0	0.000	19.950	78.858	0.640	0.005	0.580	0.001	0.000	NORMAL
2	2	3	0.100	10.0	4.1	10.0	0.000	19.951	78.862	0.640	0.005	0.580	0.001	0.000	NORMAL
```

3	3	4	0.100	10.0	5.4	10.0	0.000	19.953	78.876	0.640	0.005	0.580	0.001	0.000	NORMAL
4	4	5	0.100	10.0	6.8	10.0	0.000	19.954	78.886	0.640	0.005	0.580	0.001	0.000	NORMAL
5	5	6	0.100	10.0	8.1	10.0	0.000	19.954	78.886	0.640	0.005	0.580	0.001	0.000	NORMAL
6	6	7	0.100	10.0	9.5	10.0	0.000	19.954	78.887	0.640	0.005	0.580	0.001	0.000	NORMAL
7	7	8	0.100	10.0	10.8	10.0	0.000	19.954	78.888	0.641	0.005	0.580	0.001	0.000	NORMAL
8	8	9	0.100	10.0	13.4	10.0	0.000	19.964	78.995	0.641	0.005	0.581	0.001	0.000	NORMAL
9	9	10	0.100	10.0	15.9	10.0	0.000	19.964	79.077	0.641	0.005	0.581	0.001	0.000	NORMAL
10	10	11	0.100	10.0	45.0	10.0	0.000	20.006	78.922	0.639	0.005	0.580	0.001	0.000	NORMAL
11	11	12	0.100	10.0	24.4	10.0	0.000	20.052	78.993	0.643	0.005	0.582	0.001	0.000	NORMAL
12	12	13	0.100	10.0	19.1	10.0	0.000	20.042	78.979	0.643	0.005	0.582	0.001	0.000	NORMAL
13	13	16	0.100	10.0	19.9	10.0	0.000	20.040	79.208	0.641	0.005	0.582	0.001	0.000	NORMAL
14	8	13	0.100	10.0	13.7	10.0	0.000	19.966	78.983	0.641	0.005	0.581	0.001	0.000	NORMAL
15	11	14	0.100	10.0	62.6	10.0	0.000	20.016	79.092	0.637	0.005	0.581	0.001	0.000	NORMAL
16	14	15	0.100	10.0	40.8	10.0	0.000	20.002	79.196	0.638	0.005	0.581	0.001	0.000	NORMAL
17	15	16	0.100	10.0	30.4	10.0	0.000	20.005	79.186	0.638	0.005	0.581	0.001	0.000	NORMAL
18	16	19	0.100	10.0	34.8	10.0	0.000	19.994	78.825	0.634	0.005	0.580	0.001	0.000	NORMAL
19	14	17	0.100	10.0	78.6	10.0	0.000	19.926	78.558	0.632	0.005	0.578	0.001	0.000	NORMAL
20	17	18	0.100	10.0	64.0	10.0	0.000	19.964	78.707	0.633	0.005	0.579	0.001	0.000	NORMAL
21	18	19	0.100	10.0	49.7	10.0	0.000	19.969	78.725	0.633	0.005	0.579	0.001	0.000	NORMAL
22	10	20	0.100	10.0	30.8	10.0	0.000	19.991	78.948	0.639	0.005	0.581	0.001	0.000	NORMAL
23	20	21	0.001	10.0	0.0	10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	FANMAIN
24	21	22	0.100	10.0	30.8	10.0	0.000	19.989	78.942	0.639	0.005	0.580	0.001	0.000	NORMAL
25	0	22	0.001	10.0	0.0	10.0	0.000	19.950	78.830	0.640	0.005	0.580	0.001	0.000	WORLD

2 //Number of injects/events - format : Inject Nos, Cell Nos, Rate, Start, Stop, inject type: HEAT, DOOR, FAN etc

0	23	0.050	1000	500000	FAN1ON
1	14	0.040	5000	90000	STRATAFIRE

APPENDIX 5 – Texture maps used in Fire-VR

Figure Appendix 5. 1 General floor texture

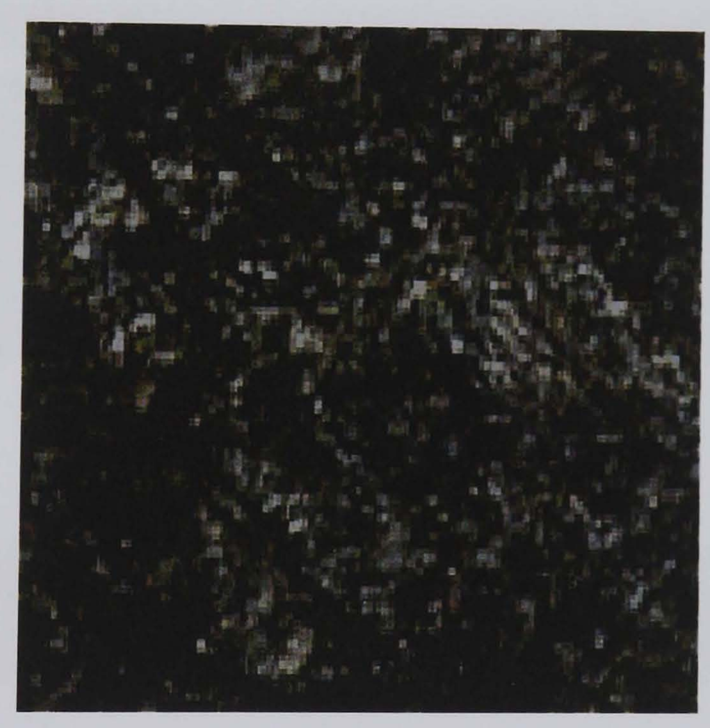


Figure Appendix 5. 2 General coal rock texture

Figure Appendix 5. 3 Fire point sign

Figure Appendix 5. 4 Fire point safety poster showing instructions (text designed to not show detail)

Figure Appendix 5. 5 Label for fire extinguisher to give more detail to fire extinguisher object

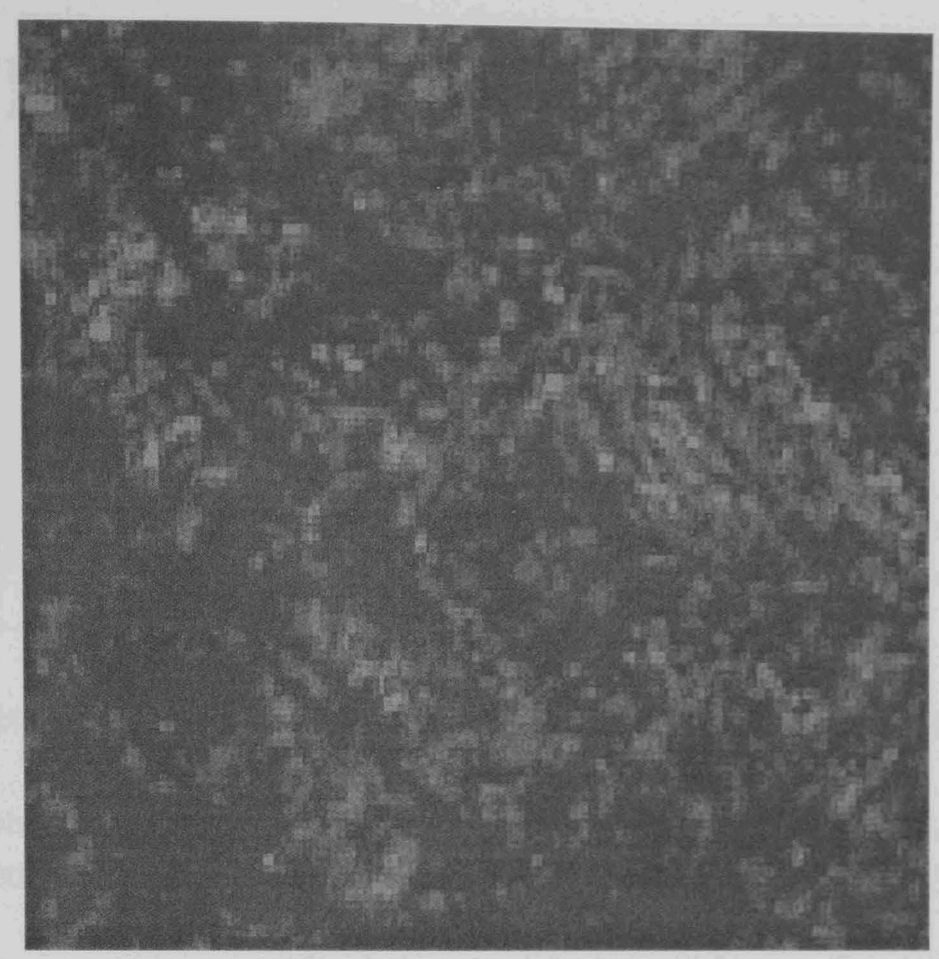


Figure Appendix 5. 6 Texture for stopping

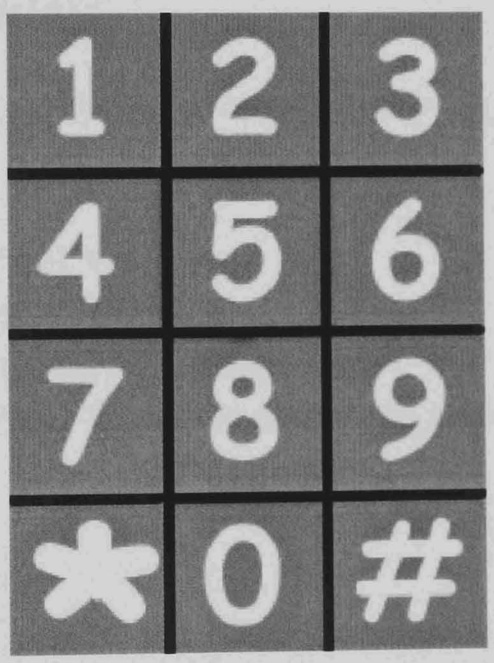


Figure Appendix 5. 7 Texture map for telephone keypad

APPENDIX 6 – Control system for Fire-VR

Movement in the virtual environment:

- **LEFT MOUSE BUTTON** to initiate movement mode, then mouse **FORWARD, BACK, LEFT AND RIGHT** mouse movement to move through the mine environment.

Additional movement controls (applicable when collision detection is off):

- **CTRL** + mouse movement **LEFT** to strafe left (side step to the left)
- **CTRL** + mouse movement **RIGHT** to strafe right (side step to the right)

- **SHIFT** + mouse movement **UP** to make the user look upwards
- **SHIFT** + mouse movement **DOWN** to make the user look DOWNWARDS.

Map views of mine infrastructure:

- **'m'**- Toggle map view display from the following options: -

- Normal view
- Overlaid plan view on normal VR view
- Overlaid side view on normal VR view
- 3D plan view showing mine network from above
- 3D fly around view with camera always orientated to point towards user within the mine network

3D plan view control:

- **'+'** - Zoom into the mine network
- **'-'** - Zoom out away from the mine network
- **'4'** - Move plan view left
- **'6'** - Move plan view right
- **'8'** - Move plan view up
- **'2'** - Move plan view down
- **'7', '9' , '1' and '2'** keys to move diagonally

3D fly around view control method:

- **'+'** - Zoom into the mine network
- **'-'** - Zoom out away from the mine network
- **'4'** - Rotate around user clockwise
- **'6'** - Rotate around user anti-clockwise
- **'8'** - Elevate camera upwards
- **'2'** - Elevate camera downwards

Animations:

- **'f'** - toggle moving arrows display for showing flow rates

Collision detection:

- **'c'** - toggle collision detect routine to stop user wandering from the roadway

Environment display:

- **'1'** - Show oxygen concentration
- **'2'** - Show nitrogen concentration
- **'3'** - Show methane concentration
- **'4'** - Show carbon dioxide concentration
- **'5'** - Show carbon monoxide concentration
- **'0'** - Show smoke cells

Intensity level:

- **'u'** - decrease intensity of gas display (decrease in opacity)
- **'i'** - increase intensity of gas display (increase in opacity)

APPENDIX 7 – example network (Chapter 8)

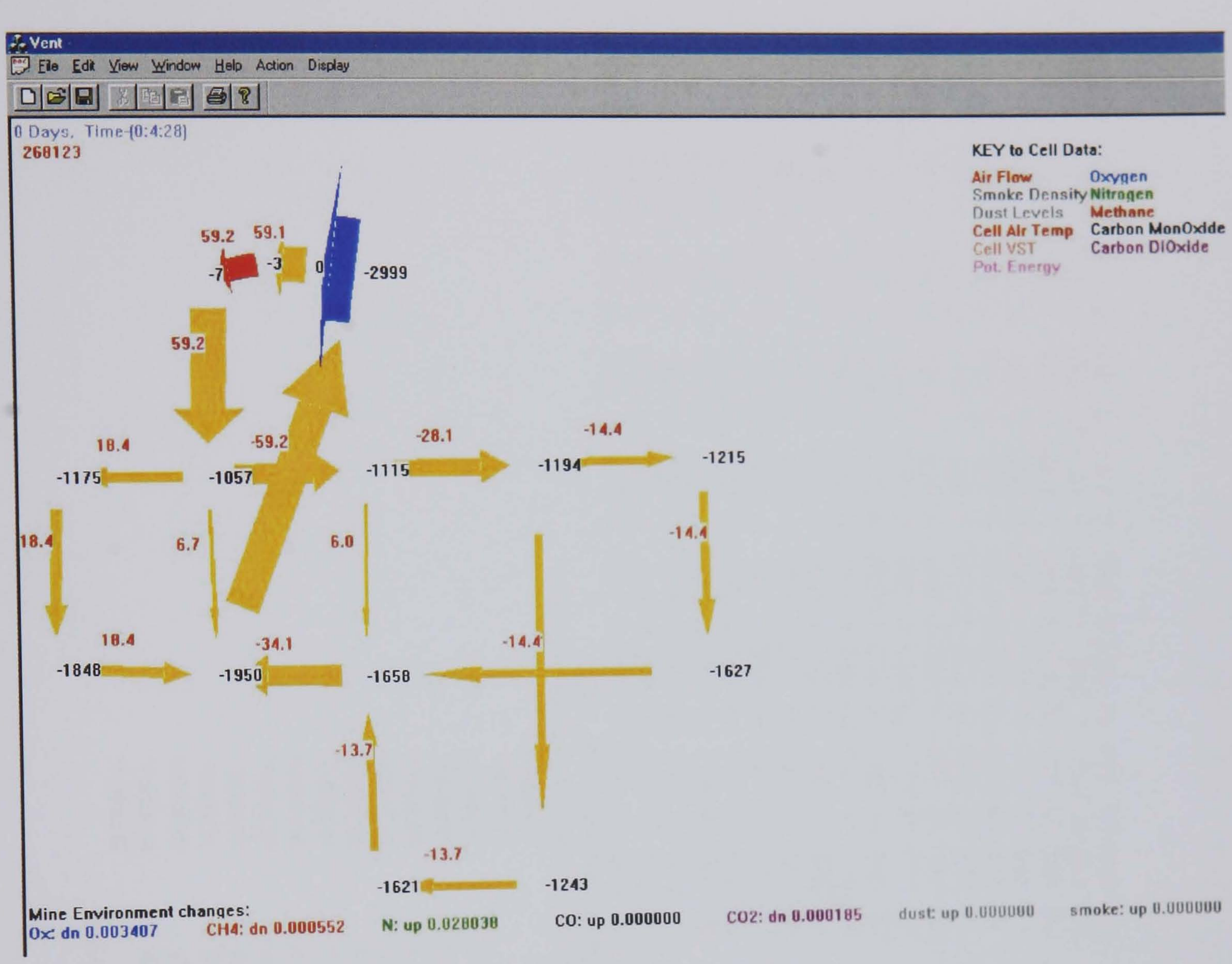


Figure Appendix 7. 1 Example mine structure in VentSim-VR 2D interface (no path splits, 1 main fan)

Mine Description file for Figure Appendix 7. 1 Example mine structure in VentSim-VR 2D interface (no path splits, 1 main fan)

```
227123 //Time in cycles. must be set 0 or greater
15     //node,xd,yd,zd,xf,yf,zf,start_pressure,node type
0      160    0     128    0.0    0.0    0.0    -7.0        NORMAL
1      157    0     295    0.0    0.0    0.0    -1057.2     NORMAL
2      33     0     294    0.0    0.0    0.0    -1175.2     NORMAL
3      30     0     452    0.0    0.0    0.0    -1849.0     NORMAL
4      162    0     458    0.0    0.0    0.0    -1950.0     NORMAL
5      287    0     290    0.0    0.0    0.0    -1115.5     NORMAL
6      285    0     461    0.0    0.0    0.0    -1658.9     NORMAL
7      290    0     636    0.0    0.0    0.0    -1621.2     NORMAL
8      431    0     637    0.0    0.0    0.0    -1243.6     NORMAL
9      431    0     287    0.0    0.0    0.0    -1194.5     NORMAL
10     570    0     282    0.0    0.0    0.0    -1215.1     NORMAL
11     573    0     461    0.0    0.0    0.0    -1628.0     NORMAL
12     288    0     127    0.0    0.0    0.0    -3000.0     NORMAL
13     247    0     122    0.0    0.0    0.0    -0.0        NORMAL
14     208    0     119    0.0    0.0    0.0    -3.5        NORMAL
19     //Number of cells n, from, to, resistance,x_section,cell_air_heat(J/kg
degC),strata_heat,CellFuel,Ox%,Nitr%,Meth%,CO%,CO2%,Dust,Smoke,cell type
0      0      1      0.300     10.0   5.4    40.0   30.000 19.946 78.754 0.639  0.005  0.580  0.001  0.000  NORMAL
1      1      2      0.350     10.0   22.2   40.0   30.000 19.950 78.832 0.640  0.005  0.580  0.001  0.000  NORMAL
2      2      3      2.000     10.0   38.4   40.0   30.000 19.950 78.832 0.640  0.005  0.580  0.001  0.000  NORMAL
3      3      4      0.300     10.0   54.0   40.0   30.000 19.950 78.832 0.640  0.005  0.580  0.001  0.000  NORMAL
4      4      6      0.250     10.0   88.4   40.0   30.000 19.966 78.845 0.640  0.005  0.580  0.001  0.000  NORMAL
5      6      7      0.200     10.0   86.0   40.0   30.000 19.953 78.844 0.640  0.005  0.580  0.001  0.000  NORMAL
6      7      8      2.000     10.0   66.8   40.0   30.000 19.952 78.839 0.640  0.005  0.580  0.001  0.000  NORMAL
7      8      9      0.260     10.0   46.7   40.0   30.000 19.952 78.841 0.640  0.005  0.580  0.001  0.000  NORMAL
8      6      11     0.150     10.0   83.6   40.0   30.000 19.954 78.846 0.640  0.005  0.580  0.001  0.000  NORMAL
9      11     10     2.000     10.0   65.1   40.0   30.000 19.952 78.839 0.640  0.005  0.580  0.001  0.000  NORMAL
10     10     9      0.100     10.0   45.8   40.0   30.000 19.951 78.838 0.640  0.005  0.580  0.001  0.000  NORMAL
11     9      5      0.100     10.0   25.5   40.0   30.000 19.949 78.833 0.640  0.005  0.580  0.001  0.000  NORMAL
12     5      1      0.050     10.0   14.6   40.0   30.000 19.949 78.770 0.640  0.005  0.580  0.001  0.000  NORMAL
13     5      6      15.000    10.0   61.6   40.0   30.000 19.950 78.833 0.640  0.005  0.580  0.001  0.000  NORMAL
14     4      12     0.300     10.0   78.4   40.0   30.000 20.115 79.439 0.645  0.005  0.584  0.001  0.000  NORMAL
15     1      4      20.000    10.0   49.1   40.0   30.000 19.950 78.832 0.640  0.005  0.580  0.001  0.000  NORMAL
16     12     13     0.001     10.0   0.2    40.0   30.000 0.000  0.000  0.000  0.000  0.000  0.000  0.000  FANMAIN
17     13     14     0.001     10.0   78.4   40.0   30.000 20.114 79.433 0.645  0.005  0.584  0.001  0.000  NORMAL
```

```
18      14      0       0.001           10.0    0.0     40.0    30.000 19.950 78.830 0.640  0.005  0.580  0.001  0.000  WORLD
1       //Number of injects/events - format : Inject Nos, Cell Nos, Rate, Start, Stop, inject type: HEAT, DOOR, FAN etc
0       16      0.050  0       300000 FAN1ON
```