A STUDY of UNDERGROUND MINE AUTOMATION

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DEDICATION

This thesis is dedicated to my wife Sharon and son Scott for their support and understanding through the many days and nights of work.

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ABSTRACT

A review of automation, robotics and communications technology has established the need for the development of a communications infrastructure capable of supporting future underground hard rock mine automation systems. A series of underground experiments were undertaken at Copper Cliff North Mine to evaluate the design criteria and performance of several communications infrastructures. The work successfully demonstrated the capability of real-time operation of voice, data and stationary video communication, as well as surface-to-underground tele-operation of a load-haul-dump machine. This was achieved with a communications system consisting of a broadband bus linked to leaky feeder coaxial cables by means of distributed antenna translators. The success of the trials permitted a strategy for mine automation to be devised. The economic benefits of mine automation were estimated by means of economic models developed for the mine. Projected benefits, evaluated in terms of mining cost reduction, throughput time and quality improvement, were concluded to be significant. As a result of the analysis, future research and development is concluded to be best targeted at improving ore grade, optimizing process productivity and maximizing machine utilization.

RÉSUMÉ

Après avoir passé en revue la technologie actuelle en systèmes de communication, de robotique et d'automatisation dans les mines souterraines à roche dure, il est apparu évident que le développement d'une infrastucture de communications est nécessaire pour advenir aux besoins de demain.

Dans le but d'évaluer leur performance et leurs critères de planification, des infrastructures de communications à charactère technique distinct, ont été testées a la Copper Cliff North Mine. Les résultats des tests ont démontré la compétence de transmettre en temps réel, les signaux de voix, de videos stationnaires et des bandes de données, ainsi que la commande à distance, à partir de la surface, d'un chariot chargeur-déchargeur. Le système en question est composé d'une ligne de communication à large bande, connectée à des lignes de transmissions coaxiales à fuite, par l'entremise d'un système de décodage de distribution d'antennes.

Le succès des tests entrepris a ouvert la voie à de nouvelles stratégies d'automatisation minières, aux avantages économiques évalués par le biais de développement de modèles économiques particuliers à la mine. Les bénéfices projetés, estimés en réduction de coûts d'opérations minières et de production, ainsi qu'une amélioration de la qualité, ont été concluants. Finalement, l'analyse indique que l'objectif prioritaire de la recherche et le développement de demain, devrait se concentrer sur l'amélioration de la teneur en minerai, l'optimalisation du procédé de production et la maximalisation de l'utilisation des machines.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Analog to Digital	A/D
Automatic Haulage Truck	AHT
Artificial Intelligence	AI
Amplitude Modulation	AM
Automated Mining Systems Limited	AMS
Business Area Analysis	BAA
the number of discrete signals per unit time	BAUD
Computer Aided Design	CAD
Computer Aided Software Engineering	CASE
Cable Television Industry	CATV
Citizens Band	CB
Canadian Centre for Automation and Robotics in Mining	CCARM
Canadian Centre for Mineral and Energy Technology	CANMET
Computer Integrated Manufacturing	CIM
Continuous Mining Systems Limited	CMS
Canadian Standards Association	CSA
Critical Success Factors	CSF
centimetres	cm
Compact Underground Borer	CUB
Distributed Antenna Translator	DAT
Digital to Analog	D/A
decibel	dB
Department of Communication	DOC
Electromagnetic Interference	EMI
U.S Federal Communications Commission	FCC
Frequency Division Multiplexing	FDM

Frequency Modulation . . . . FM
Flexible Manufacturing System . . . . FMS
Gigahertz . . . . GHz
High Frequency . . . . HF
Hardrock Mining Inc. . . . . HDRK
hertz . . . . Hz
International Business Machines . . . . IBM
Integrated-Computer Aided Software Engineering . . . . I-CASE
Integrated Computer Integrated Manufacturing . . . . ICAM
Institute of Electrical and Electronic Engineers . . . . IEEE
Intelligent Manufacturing Systems . . . . IMS
Information System . . . . IS
In-The-Hole . . . . ITH
kilobit . . . . kb
kilohertz . . . . kHz
Local Area Network . . . . LAN
Low Frequency . . . . LF
Load-Haul-Dump Machine . . . . LHD
Load-Haul-Dump Machine Maintenance Assistant . . . . LHDMA
milliamp . . . . ma
Metropolitan Area Network . . . . MAN
Manufacturing Automation Protocol . . . . MAP
McGill Research Centre for Intelligent Machines . . . . McRCIM
decibel using a one milliwatt divisor . . . . dBm
Media Access Unit . . . . MAU
megabit . . . . mb
Medium Frequency . . . . MF
Megahertz . . . . MHz
Mine Operating System Project . . . . MINOS
Management Information System . . . . MIS

Modulator/Demodulator	MODEM
millisecond	ms
Occupational Health and Safety Act	OHSA
Process Allowance Time	PAT
Private Branch Exchange	PBX
Personal Computer	PC
Pulse Code Modulation	PCM
Programmable Logic Controller	PLC
pounds per square inch	psi
Radio Frequency	RF
Random Access Memory	RAM
receive	rx
Revolutions per Minute	RPM
Supervisory Control and Data Acquisition	SCADA
second	s
Super High Frequency	SHF
Sensor Interface Unit	SIU
Time Division Multiplexing	TDM
transmit	tx
Total Quality Improvement	TQI
Ultra High Frequency	UHF
United States Bureau of Mines	USBM
Ultraviolet	UV
Vertical Crater Retreat	VCR
Video Cassette Recorder	VCR
Very High Frequency	VHF
Very Low Frequency	VLF
voltage	volt
wattage	watt
Wide Area Network	WAN

1 INTRODUCTION

In recent years, some hardrock mining companies have begun to recognize the need for automation of their facilities to compete internationally. Research has addressed the development of remote and automated systems for mining through either incremental or radical change. The research thrusts initially have been in the development of new underground mining equipment: particularly by Inco Limited, Noranda Inc. and the Potash Corporation of Saskatchewan (Canada); Mount Isa Mines Limited and Pasminco (Australia); LKAB (Sweden) and Outokumpu Oy (Finland). The equipment has invariably included a local computer system that was not integrated within the mining operation. The manufacturing industry would term these "islands of automation". In order to bridge these islands, in mining as in manufacturing, an infrastructure had to be established that would communicate, manipulate and utilize information throughout the mining operation. Moreover, the infrastructure was required to be independent of the primary mining process so as to be capable of supporting both existing systems and longer term technology developments.

Traditional hardrock mine communication systems comprise telephone links from surface to relatively few strategic locations underground. Personal communication links between members of the workforce, underground and on surface within the mine environment of a complex array of excavations, have been virtually non-existent. Management of the workforce has subsequently evolved into a system whereby supervisors brief and debrief workers at the start and end of shift, while routinely visiting workplaces on a fixed schedule during the shift. This limited method of communications has resulted in incomplete knowledge of underground activity, and has constrained management by impairing efficiency in manpower deployment, materials distribution, production control and environmental monitoring. Moreover, it has promoted the traditional viewpoint that mining is "an art more than a science"[1]. Miners working in remote and isolated underground locations have been required to be self-sufficient and resourceful, in order to contend with the dynamic and challenging underground environment.

In the last five years, there have been several attempts to develop underground voice radio communication systems for the workforce[2,3,4] that have met with some limited success. Principal problems are related to bandwidth capacity and speed of communication, and to limited economic justification. Therefore, as of 1990, only a few of Canada's 200 mines had successfully implemented personal radio communication systems. Some of the main technical challenges to underground radio communication include the following:

* restricted capability of radio to penetrate rock
* atmospheric dust
* excessive moisture
* the possibility of premature initiation of electric blasting caps by the radio signal
* rigorously confined space
* the proximity of electrical equipment.

In the 1970s, the advent of the mainframe computer transformed some aspects of the management of the Canadian underground mine, principally through the implementation of conventional business applications such as payroll, accounting, inventory, mine planning and reserves estimation. These applications were fed by the traditional document flow from underground activity; shift-end reports, requisitions, time cards and work orders still constituted the principal vehicles for information flow in the complex mine administration system. This still remains standard practice across the industry today. As a consequence, mine management and control continue to be limited in depth of detail and in responsiveness, due to inadequacies within information systems. Acceptance of this state of affairs within the industry has contributed to a remarkable lack of research into real-time monitoring and control, information engineering and the decision-making base for mine management and control over the last twenty years. No prior formal research exists on the classification and nature of information fundamental to the management and control of underground hardrock mining activity in an automated facility. As well, very little work has been performed on the development of automation and information engineering for mining.

In the early 1980s, the Canadian mining industry responded to the industrial recession and rising offshore competition by reducing the workforce and improving productivity, consequently reducing unit production costs. For example, at Inco Limited, one of the largest Canadian mining companies, the workforce was downsized and new mining methods evolved to exploit a developing trend in mechanization. Through the last decade, the development of new mining machinery related to drilling, blasting and rock transport has been significant. In the latter half of the 1980s, an awareness of the potential for the automation of such machines grew within the Canadian industry[5]. This focused attention on individual machine development and automation, but with no recognition of the overall underground automated and integrated mining system. Similarly, the means by which automated unit operations could be linked, eliminating the potential mining islands of automation, was not addressed. Of equal significance was the lack of recognition given to improved infrastructure and the prospects for radical change in information flow, and what this could potentially bring to mine management and control.

Personal research experience over the last six years had indicated the need for this communication and information infrastructure to integrate mining systems. This experience included:

* development of a machine health and monitoring system for underground Load-Haul-Dump (LHD) vehicles and an integrated

expert system for machine diagnostics[6,7].

* development of an automated electric truck, operating as a robotized underground haulage unit[8].
* research and development related to blasthole drilling[9].

It became apparent in 1987 that it would be critical to integrate these potentially automated machines, basic to each unit operation, through an effective mine-wide communication infrastructure overlaid by a complete information system. The system was envisaged to require two-way communication with multiple channels for voice, data and video transmission throughout the mine. In 1987, a proposal was presented to Inco management and Industry Science and Technology Canada to research and develop such a communication system on a prototype basis. Moreover, the experimentation was to be established under experimental conditions in an actual underground mine[10]. In 1988, the concept of the automated underground hardrock mine viewed as being equivalent to an ore manufacturing system was established and added to the research plan. The project commenced in 1989, as part of this present work. Copper Cliff North Mine of Inco was identified as the site for experimentation with a prototype mine-wide communication system.

1.1 Study Problem

By 1988, it had become apparent that fundamental research on an overall management strategy for underground mine automation was required, in parallel with communication and information system research and economic modelling. This would be essential to apply automation rationally and effectively in the fully automated hardrock mine of the future, and to realize the full potential of the economic benefits of mine automation. The main issues that required resolution were:

* a survey of international research underway in automation and

communication systems for underground mining, to develop the overall criteria for infrastructure development in a automated facility;

* the specific means by which a comprehensive, mine-wide communications system could be developed to support the fully automated mine;

* the strategy through which the mining sub-systems should be integrated to facilitate full mine-wide automation in the future;

* the establishment of an economic model that would allow the assessment of the impact of the mine automation strategy.

These issues, as the basis for Ph.D studies, were considered to offer significant support for sustaining the international competitiveness of the Canadian mining industry, and for advancing Canadian mining automation technology.

1.2 Study Hypothesis

The hypothesis of this work can be stated as:

> a high speed, high bandwidth communication infrastructure that supports mine-wide information systems and enables automation in underground hardrock mining is needed to enhance the economic viability and the safe performance of the Canadian mining industry.

1.3 Contributions of this Study

The original contributions of this study are: innovative developments in underground communications infrastructure; a mine automation strategy; and the modelling and analysis of the resulting economic benefits. The infrastructure developed is capable of supporting voice, data and video information to and from stationary and mobile locations. It was tested and proven in a series of experiments culminating in the teleoperation of an LHD from surface to underground. A unique mine automation strategy is presented which is designed to maximize the benefits that can be realized from this communication infrastructure. An original fundamental economic model was developed and fitted with real operation data to assess the potential benefits of the strategy.

The communication infrastructure experimentation reported here is unique in its approach. This research has resulted in the first successful full-scale experimental system of its kind implemented in Canada[11]. The strategy that is proposed has evolved with experiences gained from the communication infrastructure experimentation and other projects described earlier (page 3 and 4). The potential economic benefits of automation are evaluated for the first time in the modelling and analysis performed as part of this work.

The research reported in this thesis has already contributed to two major developments that stem from its successes: the formation of Automated Mining Systems Inc. (AMS)[a] [12]; and a PRECARN Associates Inc.[b] feasibility study for automated mining. On July 5th, 1991, Inco, Falconbridge, CCARM, McRCIM and the Centre for Resource Studies were awarded a contract by PRECARN Associates Inc. to undertake a feasibility study to develop "Robotic Systems for Mining Applications" now called "Mining Automation Plan" or MAP[13]. The

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[a] On March 31st, 1991, a new joint venture company was formed between Continuous Mining Systems Limited (CMS), an Inco Limited subsidiary, and Ainsworth Automation inc., a subsidiary of Ainsworth Electric Limited.

[b] PRECARN Associates Inc. is a consortium of 36 prominent Canadian industrial companies with the goal of initiating research and development programs in Artificial Intelligence and Robotics led by industry.

original proposal was based on the research work presented in this thesis[14], and is considered to be a natural extension of it. The MAP study has outlined three interrelated automation projects: delineation data-collection and interpretation; infrastructure development; and modelling and economic and policy studies.

1.4 Thesis Outline

This thesis concerns the development of a mine communication and information infrastructure to support automation and the consequent strategy for underground hardrock mine automation. It also assesses the potential economic contribution of mine automation. Chapter 2 reviews the prior research on mine automation and on communications infrastructure. Chapter 3 then addresses the information engineering requirements for an underground hardrock mine. Chapter 4 focuses on communication infrastructure and on the application of information engineering to underground mining.

Chapters 5 and 6 report on a series of underground experiments with radio communication at the Copper Cliff North Mine. A communication infrastructure was designed and implemented in the mine. Controlled experiments were conducted to determine the suitability of such a system to support underground mine automation.

Chapter 7 develops a strategy for underground hardrock mine automation and examines the implications of this new communications infrastructure, in terms of its current characteristics, capabilities, and future research and development directions. Chapter 8 develops the economic model used to evaluate the strategy proposed in Chapter 7. Evaluation criteria used for economic analysis were mining cost, throughput time and quality improvement. In chapter 9, conclusions based on the thesis experiments and the analysis recommend a strategy through which the mining sub-systems should be integrated in order to achieve an automated underground hardrock mine.

2 PRIOR RESEARCH IN MINE INFORMATION AND AUTOMATION

This chapter examines the state of knowledge of automation research within Inco Limited and external to the organization to provide background for the need for the development of telecommunications infrastructure. It then probes the specific research underway in integrated mine automation facilities and ends with an investigation of stationary and mobile communication systems in existence for mining.

2.1 Mine Automation Information Dependency

Mine automation has reached various stages of sophistication, depending on deposit type. For example, coal and potash mines are highly mechanized and automated underground processes in a longwall environment. These types of softrock mines tend to be highly advanced in terms of mechanization, and some are already on the verge of automation. Hardrock mining by contrast is relatively undeveloped, in terms of the application of automation and information systems. In the last decade, however, hardrock mining companies around the world have slowly come to focus on the development of machine automation and robotics. Research in this field has evolved in Canada, USA, Sweden, Australia and Finland.

2.1.1 Inco Limited Research

Within Inco, the following projects have evolved since 1984:

LHD monitoring system[6]
LHD maintenance assistant development[7]
Computerized In-The-Hole drill[9]

Automatic haulage truck[8,15]

Experiences with these projects have been important in understanding and defining the infrastructure criteria for mine automation.

In 1987, the LHD monitoring project was started on 3400 level at Copper Cliff North Mine to provide maintenance information through an onboard computer system that monitored 72 sensor points on the machine. The information was collected by a device called a "Sensor Interface Unit" or SIU that could then display the information on the Operator Display Unit or transfer it to a base station computer via a radio communication network as illustrated in figure 1. Communication was established using a dome antenna, running at 450 Mhz, connected to a coaxial (coax) cable that linked a Citizen's Band (CB) radio to a computer card for toggling the microphone port. This enabled the collection of data from the machine at varying rates ranging from milliseconds to minutes. Difficulties arose with respect to the ability to transfer the information, as the machine had to be in the proximity of a single antenna. To solve this problem, a four-hour buffer was designed in the electronics, so information would not be lost. The first prototype of the monitoring system led to several conclusions:

* such computer systems, on the machines and in the operating areas, could survive in the mining environment;
* sensors and electrical connections on the LHD needed to be hardened;
* valuable information about LHD performance and health-related parameters could be gathered in real time;
* the potential hazard of premature initiation of electric blasting caps required a review of RF communication underground;
* completion of the first LHD monitoring system allowed the projection of similar systems and led to the determination that the primitive communication system then in use would

need significant improvement;

* flexible information systems using common database formats would be in the future, to collect and utilize the data generated by the proposed monitoring systems.

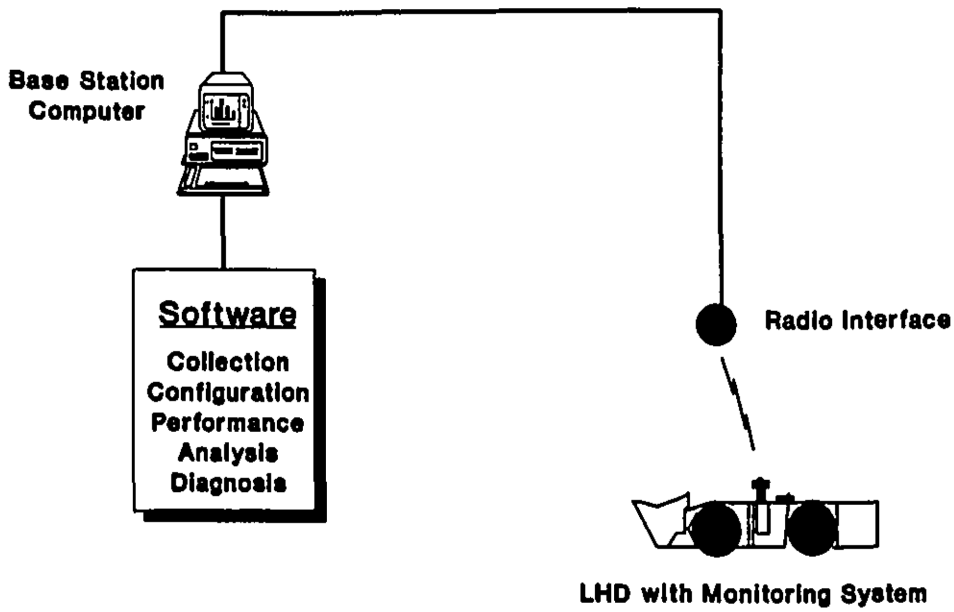

Figure 1 : LHD Monitoring System Components, after Baiden(7).

A second phase of the LHD Monitoring System was the development of an "expert system", the "LHD Maintenance Assistant" (LHDMA). The objective of the project was the utilization of the data collected from the LHD, for online diagnostics of maintenance problems on the machine, or for use as a diagnostic system for operations without machines with online monitoring. An important side benefit of the project was the opportunity to educate maintenance and operating personnel. The concept can be applied in the future, by all maintenance personnel in the mining operation, for troubleshooting and repair of mining equipment.

A concept diagram of the LHDMA is shown in figure 2, consisting of a front end, inference engine[c] and diagnostic and repair portion. The front end incorporated data files for components on the machine and reported symptoms of problems and machine history built up by the monitoring system. The inference engine used the information from the front-end and rules-of-thumb stored in a knowledge base to reach conclusions about particular problems. If the problem was not within the domain of the LHDMA, then more information would be sought to reach a conclusion, otherwise, the system would refer the problem to a specialized maintenance expert. The diagnostic and repair section used the conclusions reached in the inference section to determine the action required to perform maintenance. The results of this work were:

- expert system technology was available for a system of this type;
- expert knowledge proved difficult to obtain;
- distribution and updating of the expert system around a mining operation was difficult without a significant communication infrastructure.

In 1987 computerized ITH drilling was tested at Inco as part of a CANMET project. In this project, Inco, CANMET and Vadeko International Inc. collaborated to develop the sensing, hardware and software systems for ITH drilling. This work is reported by Pathak and Dias[9], 1986, and Baiden[9] 1990. After 1988, CANMET and Vadeko involvement ceased and Inco continued to work on the project.

The ITH rig was mounted with sensors for setup, mast alignment, operation and hole deviation as depicted in figure 3 showing the rig and computer system. The

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[c] An "inference engine" is the software tool at the heart of an "expert system" to infer premises or conclusions depending on the chaining methodology.

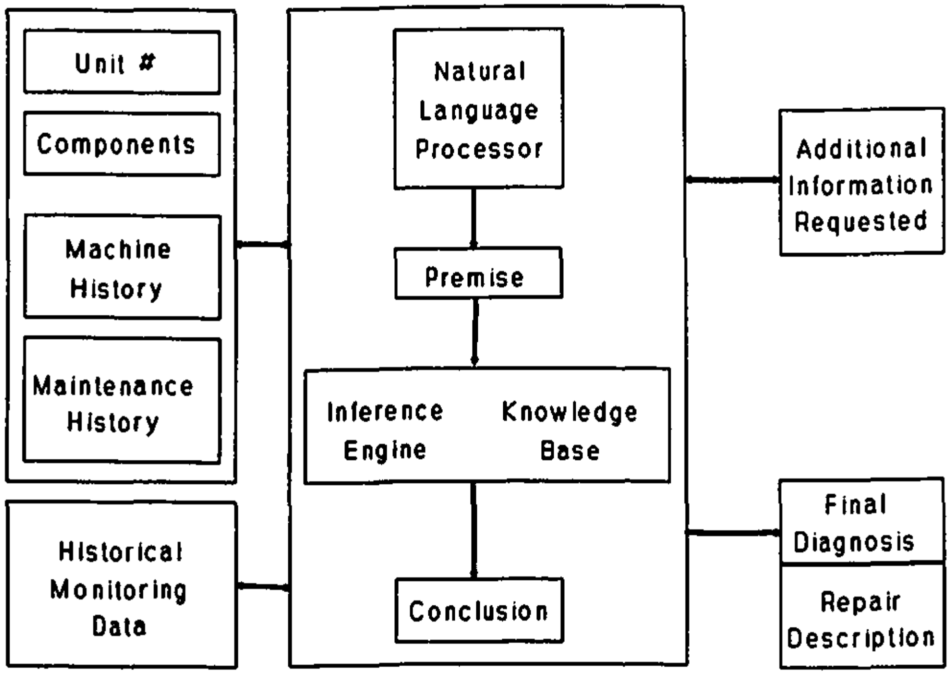

Figure 2 : LHD Maintenance Assistant Concept, after Baiden(8).

procedure for operating the rig was:

* a bubble-memory cartridge was loaded with hole data from a CAD system in the engineering office;
* the driller then inserted the cartridge into the ITH rig;
* using a laser and surveying marks in conjunction with the hole data, the machine was set up on the collar of the hole;
* once on the collar, the mast was aligned for the appropriate dip and swing of the hole;
* with the hole ready for drilling, a sensing rod was positioned directly behind the hammer;
* the drilling process was started and monitored for deviation and process optimization.

The sensing rod consisted of two inclinometers, a computer and microwave transmitting unit. On the rig end of the hole, a "hall effect" sensor was used to

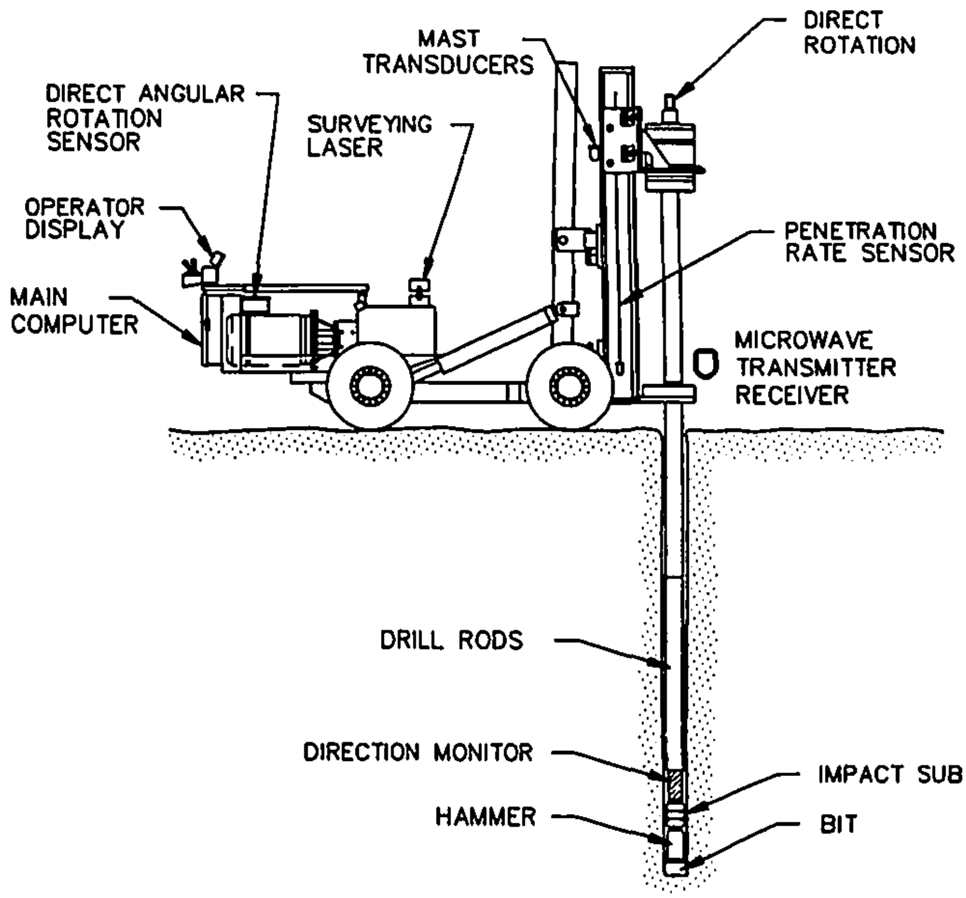

Figure 3 : Computerized ITH Drill Rig

determine rotation speed, and a penetration rate sensor was used to measure penetration rate and to count rods for hole length. As the drilling process began, the information generated by the sensing system was reported to the bubble-memory cartridge for comparison with the planned hole in the engineering office. The results obtained by this testing were:

- a computer system capable of supporting ITH drilling was proven;
- it was learned that deviation measurement was possible using a sensing system mounted behind the hammer and possible modifications and improvements were identified;
- it was learned that information movement was necessary to

the operation of a computerized drill rig, if the benefits of improved hole accuracy and reduced dilution were to be achieved.

The Automatic Haulage Truck (AHT) project was started in 1985, with the objective of developing an automatic guided vehicle capable of transporting 70 tons of ore from a drawpoint to a dump point. Papers have been presented on the AHT, shown in figure 4, by Baiden[8] 1990 and Kitchener[15] 1986. The truck concept uses electric power to drive two pumps that drive hydrostatic wheel motors for efficiency. The truck was controlled by using angular transducers to determine the location of the truck relative to the track; a computer system then calculates a steering angle which is communicated to linear actuators for physical steering. Locomotion was controlled via the same computer system by providing a swash plate angle from the computer system to the physical swash plate to achieve the desired speed. The truck is powered by a 600-volt trolley line that serves the dual purpose of power and communication. The CYPLEX™ modem links the truck to a wayside controller housing a Programmable Logic Controller (PLC) at 1200 baud.

As surface testing began, it became apparent that there was a need for a more comprehensive communication system for the truck: video cameras were required for viewing the truck in operation; voice communication was required to aid in troubleshooting; and more data bandwidth was needed to transfer information between the truck and wayside control station. In 1990 when the project moved to field testing at Little Stobie mine, the need for better communication became even more apparent, as now an LKAB chute was used for loading the truck and no personnel were to be allowed in the area. This all required communications bandwidth that could handle computer data, video and voice systems underground. The conclusions reached in the course of this project were:

* a automatic guided mining vehicle is practical in the near

future;

- there is a need for a communication system capable of supporting automation on the scale of such a vehicle.

Figure 4 : Automatic Haulage Truck

2.1.2 Other Research

Research in automation and robotics is underway in other organizations, including Noranda, Falconbridge and HDRK in Canada. In other countries work is underway by the United States Bureau of Mines (USBM), Lulea University, Atlas Copco, Tamrock, Cherchar and Mount Isa Mines.

Noranda and CCARM have reported on projects related to mine automation, including an Optical Guidance System for Mine Vehicle Automation[16], and Ventilation Control[17]. The optical guidance system development consists of a tape guidance system for LHDs and a distributed antenna communication system. Field test work reported, to date, appears quite promising although it is a single system and is not integrated into an overall mine communication system to allow productivity improvements. Similarly, the ventilation control system uses another separate communication system to monitor and control ventilation around the operation. These two independent systems are inexpensive to install and are very useful to the operations for automation of the particular process. However, if automation is to proceed by an accumulation of single-system approaches, significant potential savings arising from integration will be overlooked.

HDRK Limited[d] has three main projects underway: the Wirth Continuous Miner, the EIMCO TM60 Roadheader, and the Loose Rock Detector[18]. The Wirth Continuous mining machine and the TM60 Roadheader are two of the most significant developments underway in the hardrock mining industry today for the investigation of primary mechanical rock breaking, even though public results have not yet been reported. The loose rock detector reportly allows the detection of unstable ground up to 15 tons in size, but the research gives little consideration to the automation of equipment.

Falconbridge automation research has focused around the development of HDRK projects, the Compact Underground Borer (CUB)[19] and an automated mine planning system called "CAMPS" (Computer Aided Mine Planning System). The HDRK projects were discussed in the previous paragraph. The CUB project is mechanical rock cutting project similar to the Wirth Continuous Mining machine, that has had some limited success but is currently on hold. The CAMPS planning system is one of the few R&D projects in information engineering that is targeted at underground hardrock mining. It is based on a solid modelling approach and when complete will be a significant improvement over the Autocad™ mining

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[d] HDRK Limited is a consortium of mining companies (Inco Limited, Noranda Limited, Falconbridge Limited and Kidd Creek Mines) which collaborate on joint research and development projects.

systems currently being used throughout the mining industry. It also represents the first software steps towards combining a CAD system with a computer-controlled mining machine which can be compared to an engineering design software system linked to a NC lathe or milling machine that is used in automated manufacturing or CIM[20].

Mintronics Limited of North Bay has reported work on the development of a laser based guidance system for the operation of underground trucks[21]. It is similar to the work undertaken at Noranda with CCARM. The system has been fully tested in an underground mine at Falconbridge, on a 13-ton haulage truck. This type of system is another component of technology that will be required to achieve mine automation, but without integration into a communication infrastructure the productivity gains will be limited.

The USBM is working on automation projects at their branches in Pittsburg and Spokane with the main project of interest is the "Continuous Coal Miner"[22], is a teleoperated machine with a control room located close to the mining face. This unit is the most automated coal mining machine in the world today, as it provides a variety of sensing systems for mining control and for maintenance of the machine.

Lulea University has a variety of equipment research underway in the areas of machine monitoring, machine teleoperation and drilling; much of it is similar to research underway in Canada. Work has been done at the Zingruvan mine, with a teleoperated LHD in close proximity to a control station. The LHD uses a video based system and a painted line technique for guidance[23,24]. Atlas Copco, using research begun at Lulea, has reported the development of a "Computerized Drill Jumbo"[25] and the Simba Automated ITH and Uphole Drills[25]. This work is comprehensive, but again it concentrates on the automation of single pieces of equipment without any consideration of the issues of complete integration.

The LKAB Kiruna mine has been working in conjunction with ARA Inc. Finland on the SALT (System of Automated Loading and Transport) project[26] that is similar to the work undertaken at Zingruvan. This same work to teleoperate a LHD using a control room and a buried wire technique for the guidance[27] has also been reported by Tamrock. A control room with video monitors combines with a line-of-sight communication system to demonstrate the potential of this technology, but, once again there is a lack of integration into the entire mining operation. Tamrock has also reported the development of other automated equipment such as the "Data Solo Uphole Drill" and the Datamaxi Computerized Drilling Jumbo[28].

Bourbonnais[29] has reported the development of a microwave communication system for the monitoring and control of coal mining equipment in hazardous conditions. This work has been very successful but once again this is only a local communication system, working line-of-sight, and not an integrated approach.

Mount Isa Mines in their Australian operations has work underway in the teleoperation of an LHD although it is not yet publicly reported. The work appears to have been quite successful, with the mining of a complete stope using a local video-based teleoperation system. Like ARA Inc. in Finland, they combines a local control room and a communication utility to complete the task. King has been working with Mount Isa, and has reported initial developments in an Autonomous Vehicle using ultrasonics[30] based on experience gained in the field.

Hardrock underground mining research efforts have focused on the development of automated equipment that will need real-time communication capability. However, real-time communication has virtually been ignored, and this will prove to be a problem as the real-time communication needs of this type of equipment becomes apparent.

2.1.3 Integration of Intelligent Machine Systems

Many mining operations around the world have stationary systems that allow the automation of systems for conveying, pumping and hoisting. Since this technology is relatively stable, a major focus in mining presently is the development of teleoperated and automatic mobile equipment to improve productivity and safety performance while reducing costs.

To exploit the potential benefits of teleoperation and automation technologies, it is imperative that the development of such mining systems be integrated with a versatile real-time communications architecture. King[31] recently reviewed the machine developments underway for various mining methods, including continuous miners for high wall and longwall mining in coal and Load-Haul-Dump (LHD) machines, drills and tunnel borers for hardrock mining. He reported that the following areas of research were common to all:

1) machine intelligence
2) robust components
3) supervised autonomy
4) navigation and guidance
5) geological perception
6) environmental perception
7) location perception
8) machine health perception
9) machine vision
10) obstacle detection and avoidance
11) path planning
12) closed-loop control
13) real-time multiple tasking computer architecture
14) intelligent user interfaces
15) teleoperation

Until recently, almost all robotics research has focused on individual machines with no common system for cohesion. Relatively few researchers have recognized the need to develop real-time information systems to integrate intelligent mining equipment and technologies.

In 1988, Wolfenden and Shaw[32] discussed the need for an integrated approach to tunnelling automation. Specifically, they discussed the need for adoption of the Integrated Computer Aided Manufacturing (ICAM) model that consists of four levels: factory, cell, station and process. To fully utilize a model like ICAM, a global real-time communication standard must be adopted such as the General Motors' Manufacturing Automation Protocol. For tunnelling automation applications, the authors further discussed the need to work with broadband telecommunications to support the transmission of supervisory control and video information in a multichannel environment. In 1989, Edwards[33] discussed the same ICAM distributed computer control system and also reviewed the work on MINOS, an operating system for the automation of particular coal mining functions such as material handling and pumping. The system was developed at the National Coal Board which also supported the need for an integrated approach.

Owen[34] discusses the application of mine-wide maintenance systems for the management of resources for coal production, using the MINOS operating system. He reports that pilot tests that prove significant savings are attainable for mining operations, although there is a need to develop a data communications strategy for the effective movement and management of information. A specific recommendation is the need for "improved standards of external support services and communications".

In 1990, Vinograd[35] discusses the need for a distributed approach to the application of remote control and automation. He aimed to prove mathematically that distributed control systems with a real-time communication system are a necessity for development of an automated mine; it is apparent that the Soviets used the approach recommended by King, Wolfenden and Shaw.

Based on the experiences of other researchers as discussed in this section, and experience gained at Inco, it became apparent that a real-time communication infrastructure capable of supporting mine-wide information systems must be developed, to support automated mining and to facilitate the integration of the majority of mining processes. The next sections will focus on alternatives for real-time underground communication infrastructure, based on existing systems on the market.

2.2 Underground Communications

The state of the art in underground communication systems must be discussed in two distinct groups: stationary and mobile. The reason for the distinction is the relative advancement of stationary versus mobile communications. Stationary communication systems are relatively advanced in comparison to radio frequency based systems; wherever the stationary infrastructure (cable) goes, telephones, data transfer and video information can be utilized, regardless of the environment. Mobile communication on the other hand is advanced on surface, as evidenced for example by cellular telephones, but faces unique challenges in the underground environment because radio waves do not propagate well in rock. Sophisticated communication can be carried on in outerspace, on surface, and even underwater. However, underground mines cannot communicate at the bandwidths necessary to automate the operations, due to lack of infrastructure for both stationary and mobile capabilities.

2.2.1 Stationary Communications

Several methods exist for communication to stationary locations ranging from PBXs to WANs. Some of the systems include the LAN, CATV system, MODEM and MAN making up a part of a wide vocabulary of acronyms associated with contemporary communication systems. Basically the categories of stationary communication systems can be categorized as:

* telephone exchanges
* data networks
* video networks

The typical telephone communication system consists of telephones connected via copper conductors to digital switching stations and then out over vast networks. Underground, these systems are point-to-point via the copper conductors. The process of mining, which involves continuous development of new working areas, leads to isolation of new areas until the infrastructure catches up at greater depth or further out from the shaft.

Data networks can consist of a number of systems that could include:

* point-to-point connection
* baseband networks
* broadband networks

The state of the art at most mine sites is the use of point-to-point connection for programmable logic controllers (PLC) and baseband networks for engineering office computer networking. Broadband networks and fibre optics have been used in some mines, e.g., Inco's Creighton mine[36], but these have been used almost exclusively for video cameras around the operation.

Video networks can consist of point-to-point and the multiplexed type when used in stationary systems. Video information point-to-point is straightforward and used in many mines to monitor the process. Similarly, multiplexed types are used at some mines for the movement of video information from underground.

All of the above systems, although not found in all mining operations, are used on a daily basis to aid operations staff in achieving their targets for production. Typically, the infrastructure consists of several separate cable systems, as shown in figure 5, that are costly and extremely difficult to maintain. The cables shown in this figure cost approximately $250/ft; this does not include installation or maintenance.

2.2.2 Mobile Communications

Several types of mobile communication systems have been developed for underground mining that are similar to surface radio systems. The wavelengths used for radio communication systems are shown in figure 6[37] and range from Very Low Frequency (VLF), 10^3Hz to Ultraviolet (UV), 10^{15}Hz. In the mining industry a number of frequency ranges have been attempted, each requiring various electronic support. A brief outline of the types is useful for an understanding of the state of the art of the current technology levels.

Three main wavelengths have been used for underground mobile communication systems: Very Low Frequency (VLF), Medium Frequency (MF) and Very High Frequency (VHF). Medium Frequency and Very High Frequency systems have been in competition for the last number of years with mining operators and recently Very Low Frequency systems have been gaining popularity in Australia

In the early 1980s several types of Medium Frequency (MF) radio systems were installed to perform voice and data functions at the following operations:

- Ruttan Mine, Hudson Bay Mining and Smelting[38]
- Hoyle Pond Gold Mine, Kidd Creek Mines Limited[39]
- Quirke Mine, Rio Algom Limited[40]

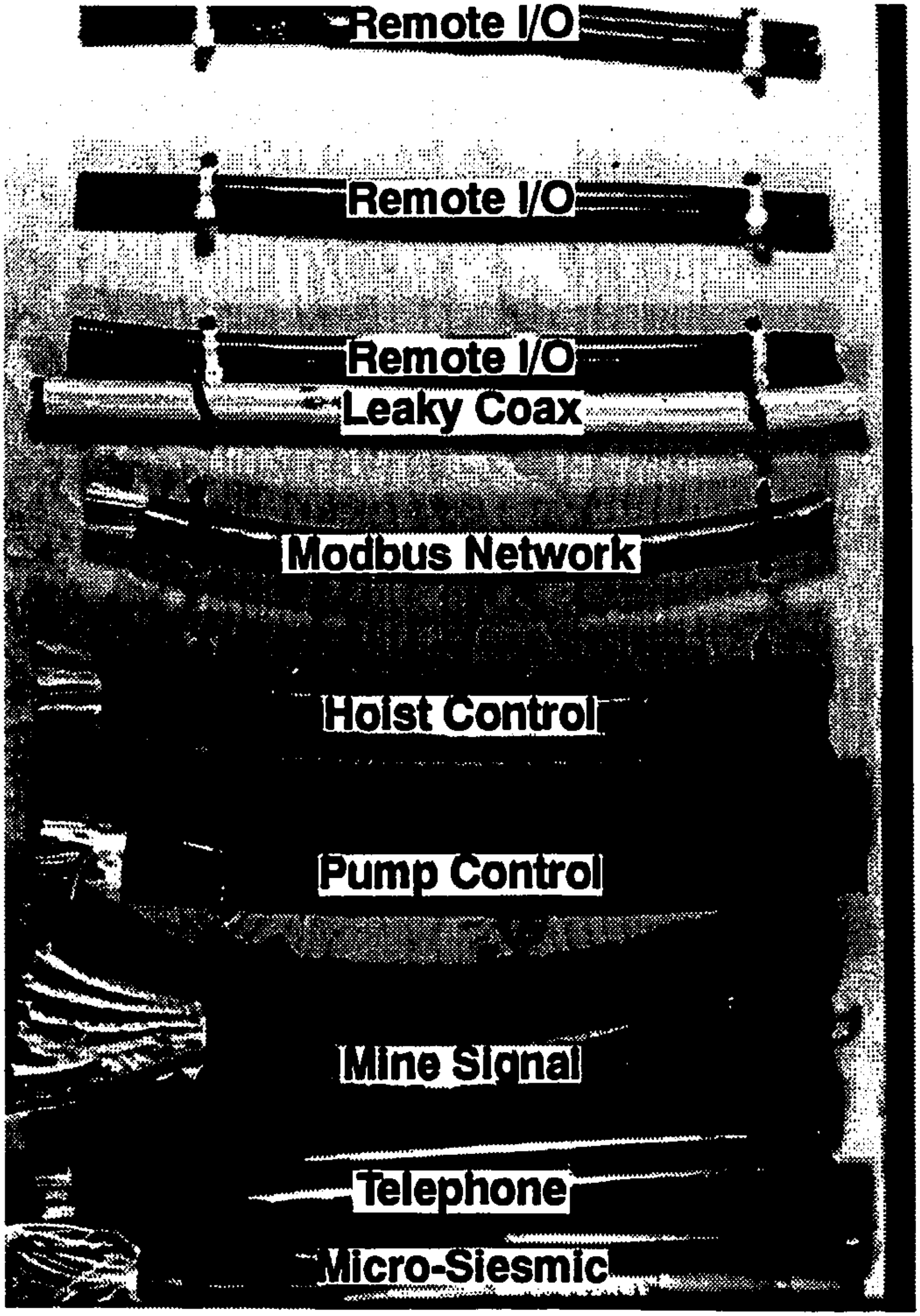

Figure 5 : Cross-section of Information Cables in North Mine Shaft

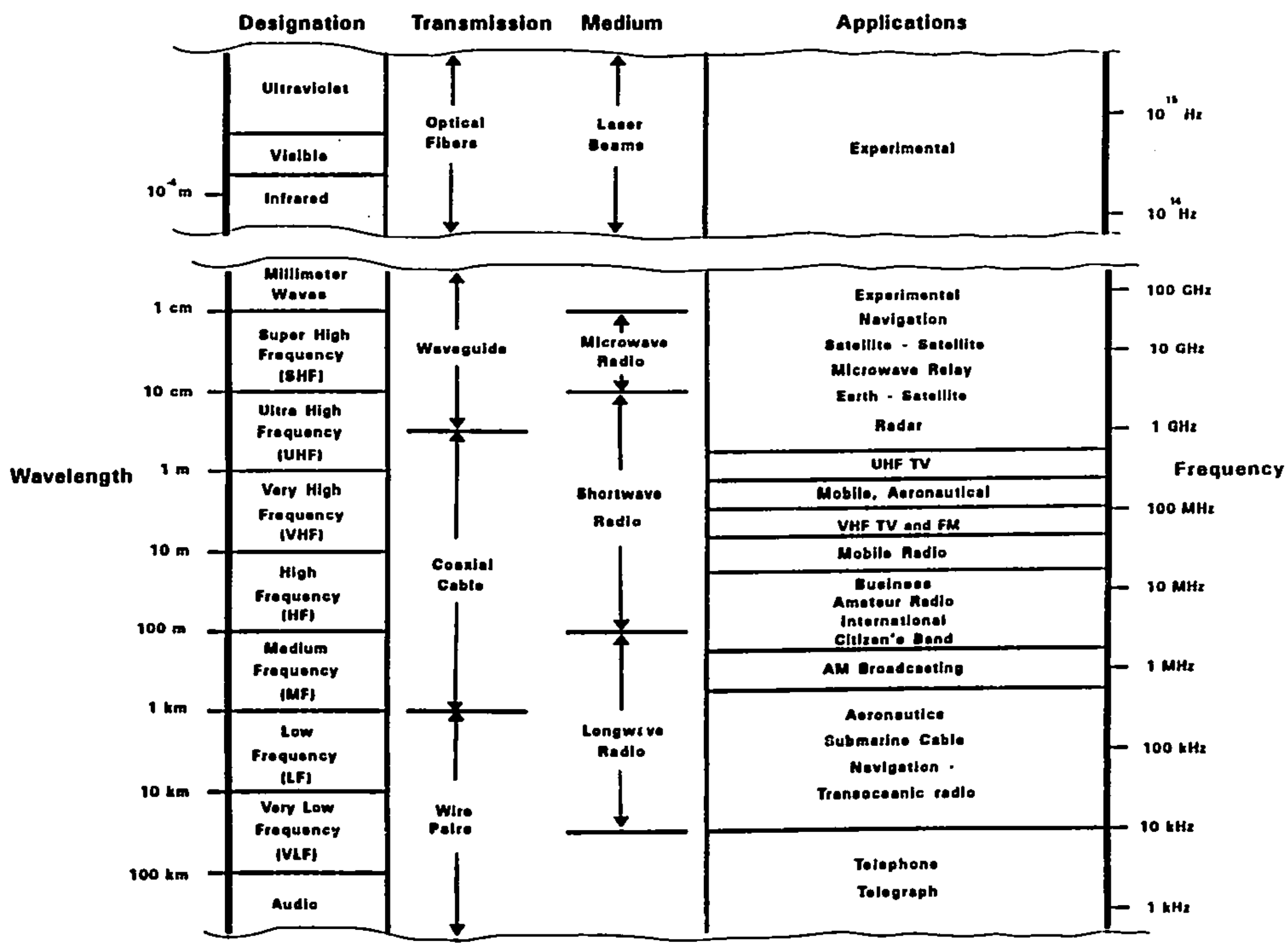

Figure 6 : Radio Frequency Spectrum, after Carlson(37).

* Lockerby Mine, Falconbridge[41]
* Creighton Mine, Inco Limited[42]

The principle employed was inductive coupling of the radio signal, at 430 Khz and 290 Khz, to existing pipes and/or a small copper antenna. The Ruttan operation reported the use of a second channel for data transmission to mobile equipment at 190 Khz and 593.5 Khz. The data were sent from the key-pad of the mobile machine to the base station of the system and then transferred to an interface computer and finally to an IBM™ Personal Computer. The information input was used to report operating parameters such as tons hauled in ore and waste.

One creative application of MF radio equipment was for cage communications at Inco's Creighton Mine. An MF radio set, permanently attached in the hoist room to the hoist cable, allowed the cage operator to communicate directly with the hoistman over the hoist rope at 88 kHz.

Although these systems worked at several mines, they suffered from some severe disadvantages, including maintenance difficulties, ergonomic problems, antenna health problems and bandwidth capacity limitations. Virtually all MF system testing and purchase terminated in the late 1980s.

In the late 1980s, following the demise of the MF systems, the next trend in underground radio was toward VHF systems. These systems can be classified into two types: "Leaky Coax" and "Distributed Antenna"; almost all VHF radio systems installed are based on Leaky Coax Antenna. The Distributed Antenna system also merits review, since it is similar to the system developed in this thesis.

Several operations have installed Leaky Coax systems, including:

* Lanigan Mine, Potash Corporation of Saskatchewan[3]

* Polaris and Sullivan Mines, Cominco Limited[43]
* Marblaegis Mine, British Gypsum Limited[44]
* Crean Hill Mine, Inco Limited[45]

The VHF Leaky Coax systems are based on the leakage of radio waves out of a loosely-shielded coax. This turns the coax into an "antenna" and allows off-the-shelf radios to couple with the antenna, typically in the VHF and UHF ranges. The Leaky Coax system works well and standard radio equipment can be used. A drawback of these systems is their limited multichannel capability and the lack of high bandwidth transmission capacity.

A system that used broadband (CATV) technology combined with discrete antennae was reported by Babik and Jones, 1983[46]. This technology distributed antennae on a broadband cable system around the operation for the movement of voice, data and video. Babik and Jones not only discussed the testing of voice transmission, but also the potential for data and video transmission over the system, although it was not tested at the time. At the time, the project was considered too costly, difficult to maintain; it also suffered from multipath problems (where two radio signals are received at slightly different times creating an echoing effect in the voice). An extension of the pilot project never took place.

Saindon, Triventi and Chevrette[4] report loss of video signal and multipath problems in more recent tests at the Gaspé Mine. The multipath problems are reported to have caused extreme distortion when the transmitting video antenna was at a point equidistant to the two antennae mounted on the broadband. Distributed Antenna communications systems have not been adopted because of their drawbacks, foremost of which are the multipath problems, which will probably make such systems unsuitable for general mine use in the future. As well, these types of systems put electronics directly in the work environment, which will make them difficult to maintain.

VLF radio systems have been under development in Australia for a few years[47] and have been proven to allow successful transmission underground through rock. The VLF systems may in the future replace stench gas as a warning system, since it can act like a paging system. However, the limited bandwidth and one-way transmission capabilities will not be sufficient for mine automation requirements.

Microwave transmission of video has been tested underground in French mines[29]. This transmission medium has been reported only in softrock (coal) applications to date, where it has provided a good quality video picture. However, it relies on line-of-sight applications, and is therefore unsuitable for underground hardrock mining.

A recently reported system has been developed by Modular Mining Systems for underground mining and has been installed at the Finsch mine[48], for the dispatch of equipment. The information movement capabilities are good but the function is limited to data communication for dispatching the equipment.

2.3 Summary

No communications system capable of supporting automated equipment in a fully integrated mine is in existence today. The new communications needs must be defined and met in order to facilitate advances in automation technology for underground hardrock mining. The capabilities of existing underground communications systems fall significantly short of the requirements of a new generation of mining equipment under development. This equipment needs voice, data and video transmission for both stationary and mobile locations. Without a system capable of supporting these functions, the automation of such equipment will be neither technically nor economically feasible.

3 REVIEW OF INFRASTRUCTURE DESIGN REQUIREMENTS FOR MINE AUTOMATION

In order to develop effective design criteria for future mine information infrastructure, a long-range view of mining from the point of view of automation must be established to allow subsequent economic analysis later in this work. Within the mine of the future, equipment and systems must interact with computer hardware and software at levels achieved to date only in automated factories. When considering the context of automated mining, as in manufacturing, three primary considerations are required for system development: first, the management requirements; second, an understanding of the information system support; finally, the establishment of communications bandwidth to support the most demanding need. This section outlines the mining needs economically and functionally for the development and modelling of mine automation based on an information infrastructure.

3.1 Management Information Requirements

To establish the needs of management in an automated mine, the decision making process must be considered. Management is defined as a process by which predetermined goals are achieved through the use of resources (people, money, energy, materials, space and time). Resources are considered inputs to the process and the attainment of goals the output. The degree of success is measured as a ratio of outputs to inputs, i.e. the organization's productivity.

Today, when considering the whole environment (figure 7) in which these decisions must be made, the pressures on management are enormous. For example, hardrock mining companies in Canada face unique challenges: ore grades are dropping relative to foreign deposits; mining is taking place at much

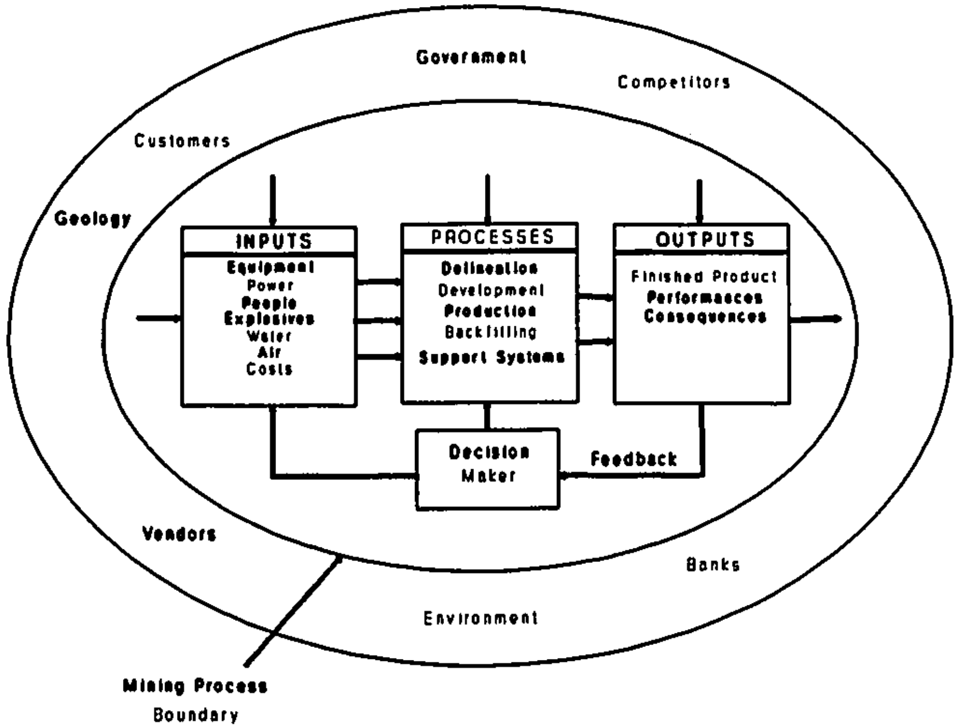

Figure 7 : The Mining Process and its Environment

greater depths, raising costs and creating rock bursting and ground movement problems; some deposits, such as Cigar Lake uranium deposit, can be hazardous to the health of employees. Regulatory pressures add costs, while competitive pressures necessitate improved productivity and reductions in cost. And improved worker safety is a high social priority.

A review of productivity trends for Inco, figure 8, shows a massive improvement in productivity from 1975 to 1985[49]. This resulted from two interrelated changes: a massive cut in the workforce in combination with the introduction of bulk mining methods, specifically Vertical Crater Retreat (VCR) mining. As a result, costs (figure 9) improved dramatically. In addition safety showed similar improvements (figure 10), with fewer lost-time accidents and a lower rate (lost-time/hrs) as fewer personnel were exposed to the environment through reduced labour and concentration of the mining areas.

If the same graphs are viewed from 1985 to the present, it is clear that productivity has slipped and costs have been rising. Safety performance has remained constant. No major innovations, similar to those that improved performance in the late 1970s, are on the horizon, except for the adoption of a technological approach to mining using automation and information technology which forms the basis of this thesis. The changes proposed will require fundamental improvements in mining technology that can only be enabled with communication infrastructure overlaid by a complete information system for mining.

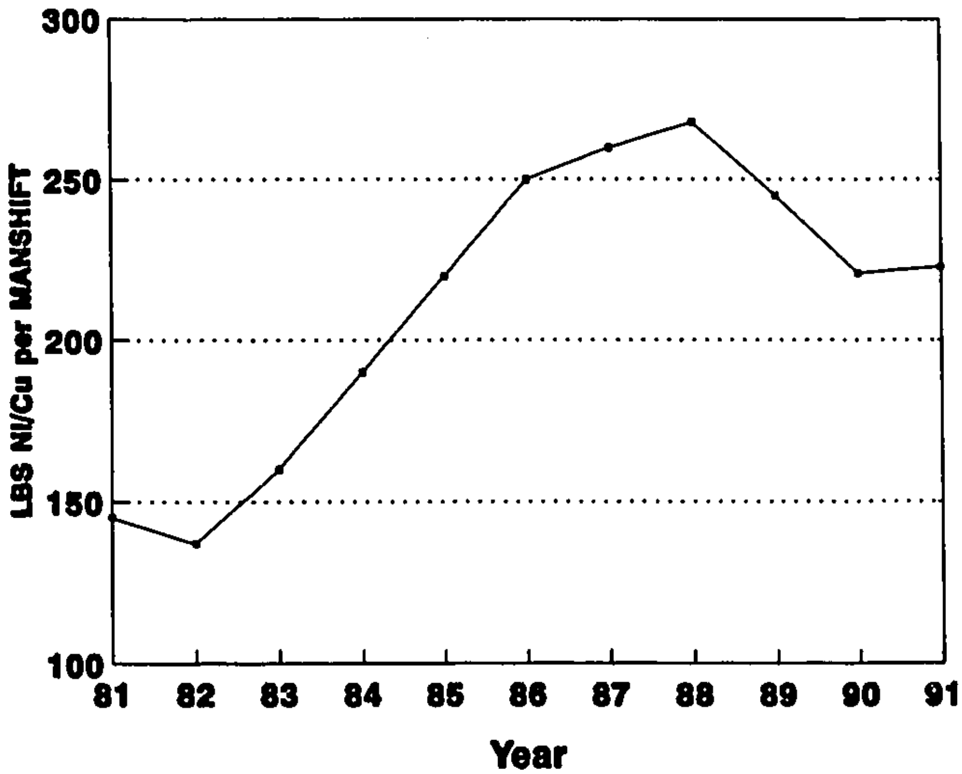

Figure 8 : Productivity vs Time at Inco Limited(49).

The utilization of information technology should provide decision aids for management to run the business more efficiently and effectively. The basic decisions made by management consist of three types :

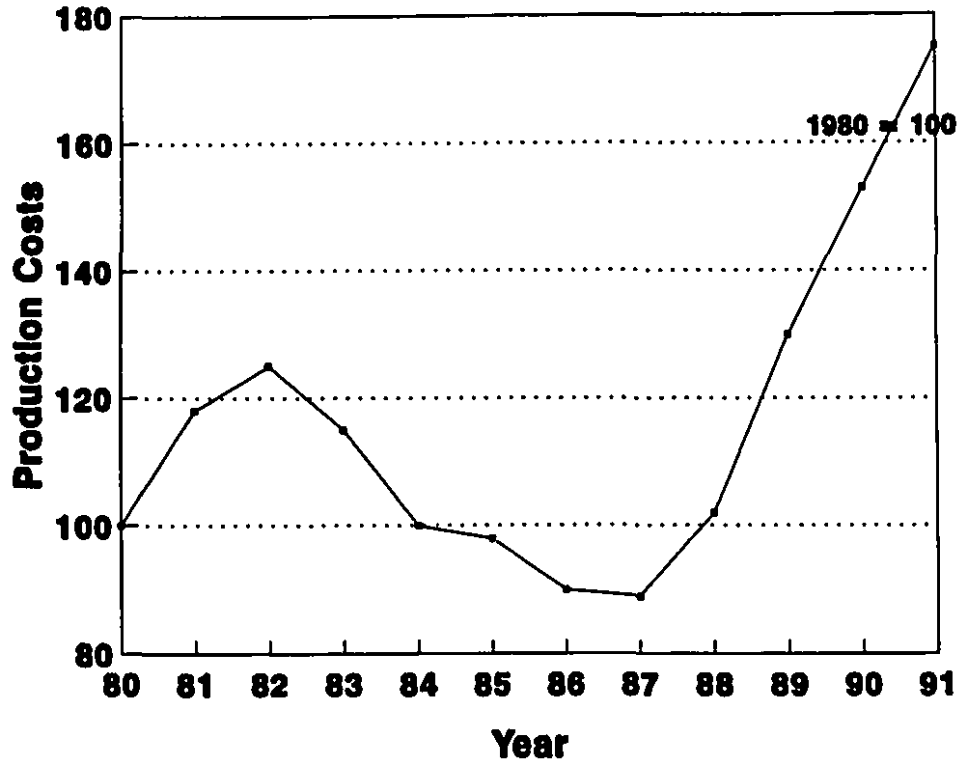

Figure 9 : Cost vs Time at Inco Limited(49).

* structured
* semistructured
* unstructured

The type of control issued takes place at three levels :

* operational
* managerial
* strategic

The type of information system required is related to the type of decision and level of control, as shown in table I[50]. For example, an unstructured decision in a strategic scenario would require an expert system, because judgement and experience would be required to make that type of decision. The collection of online data from a piece of mining equipment, on the other hand, would require a transaction-processing system.

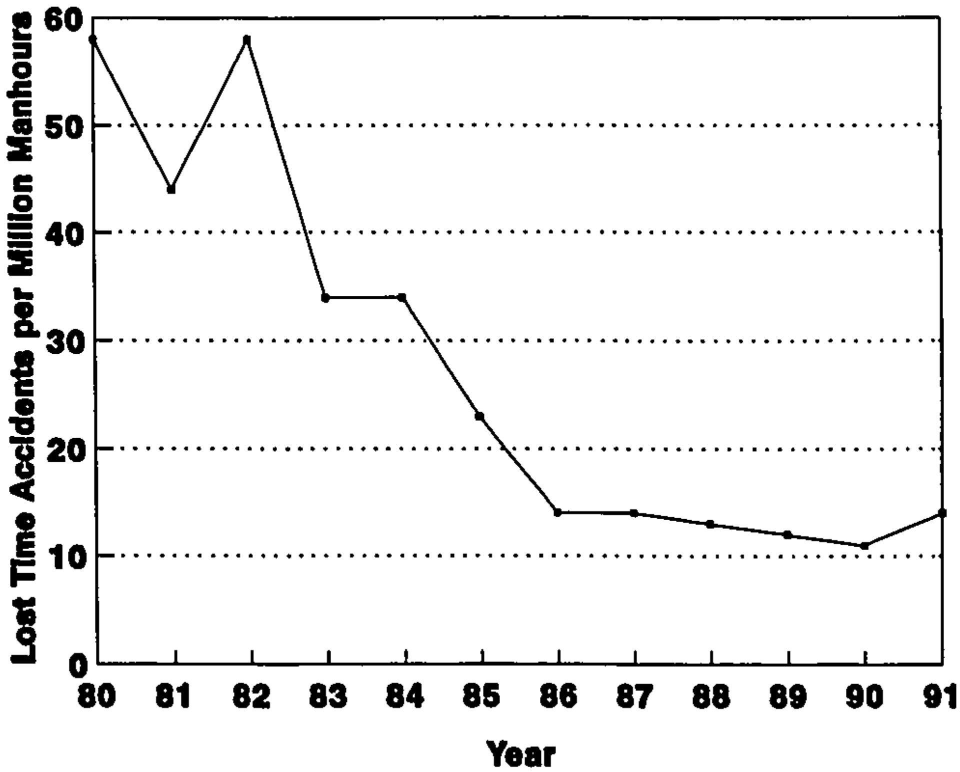

Figure 10 : Safety vs Time at Inco Limited(49).

The management of mines today consists mainly of verbal and written communication, with pictures and drawings to demonstrate location of work and the action to be performed. If a problem occurs in the operation due to insufficient information, the geographical distance encountered in a mining operation can cause a significant lag in information movement that subsequently slows the entire process and consumes resources in a waiting state. The development of communication infrastructure overlaid with an information system that supports voice, data and video communication and permits rapid response to problems and changes, offers the potential to radically change the mining organizations of today, making the businesses more efficient and effective.

Table I : Type of Decision and Control with Information System(50).

Type of Control / Type of Decision	Operations Control	Management Control	Strategic Planning	Support Needed
Structured	Accounts Receivable Order Entry	Budget Analysis Short Term Forecasting Personnel Reports, Make or Buy Analysis	Financial Management, Investment, Warehouse Location, Distribution Systems	Management Information Systems, Operations Research Models, Transaction Processing
Semi-structured	Production Scheduling, Inventory Control	Credit Evaluation, Budget Preparation, Plant Layout, Project Scheduling, Reward Systems Design	Building New Plant, Mergers and Acquisitions, New Product Planning, Compensation Planning, Quality Assurance Planning	Decision Support Systems
Un-structured	Selecting a Cover for a Magazine, Buying Software, Approving Loans	Negotiating, Recruiting an Executive, Buying Hardware, Lobbying	R&D Planning, New Technology Development, Social Responsibility Planning	Decision Support Systems, Expert Systems

3.2 Information System Design

As mining companies are forced to become more productive through global markets and competition, information systems must be employed to assist in the achievement of this goal. Information system tools have evolved historically, as shown in table II[51], and can be classified into five categories:

* transaction processing systems
* management information systems
* office automation systems
* decision support systems
* expert systems

These categories make up a complete set of tools that, when combined and applied by electronic means, will result in an overall facility strategy called "Computer Integrated Manufacturing" (CIM). CIM has been defined as follows:

> In its broadest sense, CIM is a technological base, a way of doing business -- not just a specific system or even a set of applications. The focus of CIM is on the automated flow of information, among engineering, production, and various support groups.[52]

A further definition was supplied by Goldhar :

> A combination of computer aided design (CAD) and computer aided manufacturing (CAM) and flexible manufacturing systems (FMS) including robotics. The use of digital electronics in the form of computers and communications links to create the efficiency of high degrees of integration without the rigidities created by mechanical integration. In effect - the Factory of the Future is essentially a computer system with flexible machines and robots as the output devices in place of printers, disc packs and plotters.[53]

Mining today uses three subsets of information systems related to the enterprise, to mining and processing operations, and to marketing. The enterprise

Table II : Historical Computer Tools(51).

PHASE	DESCRIPTION	EXAMPLES OF TOOLS
Early	Compute, "crunch numbers", summarize, organize	Calculators; early computer programs; statistical models; simple operations research models
Intermediate	Find, organize, and display decision-relevant information	Data base management system, MIS, filing systems
Current	Perform decision-relevant computations on decision-relevant information, organize, and display the results. Query-based and user-friendly approach. "What if" analysis	Financial models, spreadsheets, trend exploration, operations research models, CAD systems, decision support systems
Just beginning and in the Future	Interact with decision makers to facilitate formulation and execution of the intellectual steps in the process of decision making	Expert systems

information systems in use consist of the traditional software applications for accounting, payroll, timekeeping, purchasing and inventory control as shown in figure 11[54]. Mining and processing operations use a group of tools, starting in the engineering offices where geological modelling, automated drafting, spreadsheets and some database applications are applied; recently, some mines have started to develop process control systems that range from exploration to process control of pumping, material handling and ventilation. Finally, the mine

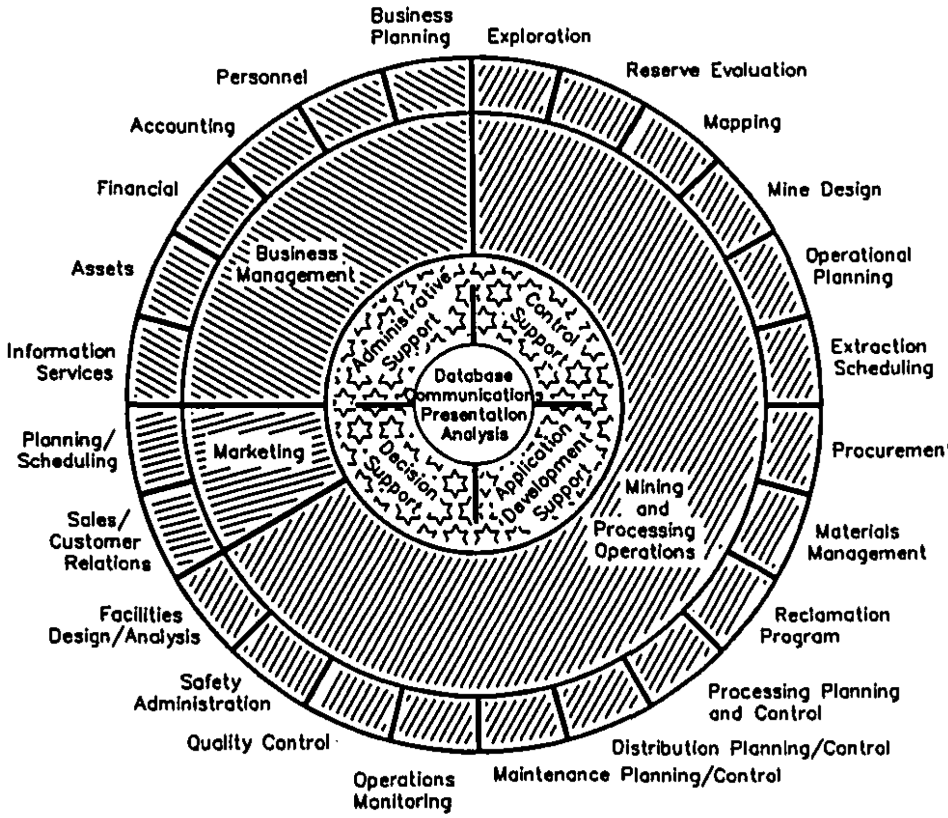

Figure 11 : Mining Related Information Systems(54).

operations have had limited exposure to marketing systems of the company, rarely going beyond such factors as maximum permissible cost and an awareness of product value. These three areas of information system applications are not integrated; there is only limited capacity for sharing information between applications. These systems work well in the current environment, but to facilitate automation and the application of CIM, this must be integrated.

CIM requires an integrated information system radically different from the systems currently in use. CIM, applied to mines, offers the same benefits foreseen for manufacturing facilities:

* reduction in work in progress inventories
* reduction in final goods inventories

* indirect and direct labour will be substantially reduced.

The IBM™ Don Mills plant is an excellent example of the impact of application of these techniques, it achieved massive improvements in output from 1970 to 1990, with essentially the same amount of resource inputs[55]. A more global perspective is illustrated by Goldhar:

> Computer-integrated manufacturing (CIM) embraces fully integrated, close coupled, high variety but continuous-flow systems in which lead times for new product introduction or improvements will be drastically reduced. Work in progress inventories will disappear; costly final goods inventories, used to buffer the factory from uncertainties of the marketplace, will not be as necessary; and both direct and indirect labour will be substantially reduced.[56]

3.3 Communication Infrastructure

Computers in mining operations have been used sparingly to date. However, if a communication infrastructure could be developed that supports voice, information systems, process control, engineering systems, and automation (specifically mobile equipment teleoperation), then computer utilization would make more sense. This infrastructure would also facilitate the movement toward CIM for underground mining, achieving the benefits that factories committed to CIM have achieved. This section discusses the basic communication infrastructure needs of the mining operation to support a CIM environment.

3.3.1 Capabilities

The development of an underground communication infrastructure requires investigation of the capabilities available to surface applications. The surface systems available consist of telemetry, voiceband data, voice, high-speed data, teleconferencing video, video and broadband information retrieval. As shown in figure 12[57], each has different bandwidth capabilities. In order to establish automated mining requirements, manufacturing communications capabilities must be compared.

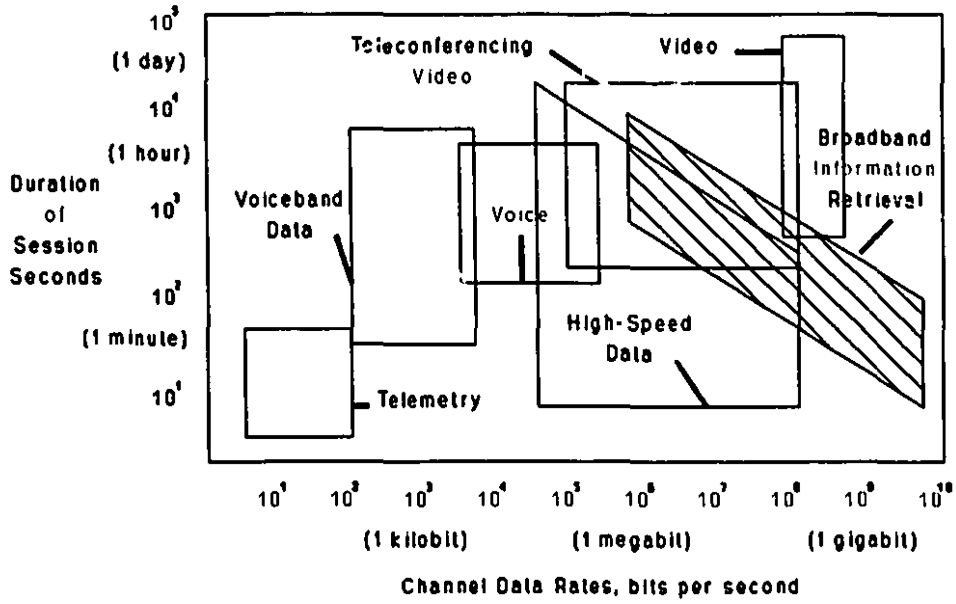

Figure 12 : Speed versus Capacity and Information System Type(57).

Some basic assumptions are needed to provide voice, data and video to underground mining. Figure 12 indicates that video transmission is the most stringent requirement of the system; therefore, video bandwidth must be the upper-limit design criterion for the system if equipment is to be teleoperated underground. The only area in figure 12 capable of supporting this criterion is broadband information retrieval, as shaded in the graph.

Since mining requires flexibility and teleoperation where equipment cannot be physically connected to the system, these guidelines can be translated into information infrastructure requirements of multichannel high speed cable and radio networking. Radio transmission requires allocation of the radio frequency spectrum underground. In surface applications, the Department of

Communications (DOC) allocates the frequency spectrum to ensure radio signals are not mixed together, causing cross-talk. For underground mining, the DOC has stated that mining can allocate the spectrum as required, as long as there is no interference with surface frequency allocations. Therefore, as long as the radio transmission equipment is kept below surface, isolating the electromagnetic energy, mining companies have access to the complete radio spectrum. With the complete radio spectrum available, the potential to teleoperate numerous pieces of mining equipment is available if the appropriate system can be developed to use the spectrum.

3.3.2 Capacity Requirements

In order to define the communication infrastructure capacity requirements, a speed of communication must be determined for the equipment that is being controlled. All process instruments, sensors and actuators on the machine must be sampled in some total time T for real-time operation of equipment as illustrated by Edwards[33]. This total time is made up of three components:

$$T > n(T1 + T2 + T3)$$

where

- n = control loops of equal priority
- T1 = total computational time (dependent on complexity of program)
- T2 = total time for Analog-to-Digital (A/D) and Digital-to-Analog (D/A) conversion of process output and input data per control loop
- T3 = total time for data communication per loop to and from the computer

For the purposes of this work, Total Time for Data Communication per loop to and from a computer, (T3), is the main concern for the development of a suitable communication system for automating a mine. The formula for T3 is given as:

$$T3=(n(m+r)+p)b^{-1}$$

where n = number of messages to be transmitted per scan of monitored process

m = number of bits into which each message is coded for serial Pulse Code Modulation (PCM) transmission

r = extra bits/message for error checking

p = bits required per scan to maintain communication protocol and synchronism

b = available baud rate (bits/second)

Typical bandwidth requirements for voice, data and video are shown in table III. As can be seen in this table, the most extensive use of bandwidth, 6 MHz, comes in broadcast video systems. This is equivalent to approximately 6,000,000 baud. Using this equation, and considering data communications parameters of

m = 8 bits standard communications length

r = 8 bits for error checking

p = 1 single bit parity checking

b = 6,000,000 baud

T3 = 15 milliseconds,

The potential total number of messages that can be transmitted per second of the monitored process is 562 with 6 MHz of bandwidth available. Using the automatic truck system as an example, real-time steering requires a 15ms scan time at 14.4 KPH (9 MPH). Therefore, with this bandwidth capability 562 similar steering algorithms could be run simultaneously over a data communication system with a dedicated 6 MHz channel. This example points out that, if video bandwidth can be achieved, control problems will not be a factor. A steering system such as this is far more demanding then any control problem in a mine which at most would require a high-speed 64,000 baud data link.

Therefore, if an information system can be developed with the capability of video bandwidth, there will be enough capacity to run any control problem in the mining operation.

Table III : Bandwidth Requirements

SYSTEM	BANDWIDTH Hz
Telegraphy - 100 words/minute	170 - 400
Telephony	3,000
High-Speed Data Transmission - 1000 bits/second	2,000 - 3,000
AM Radiotelephony - Commercial - Broadcast	 6,000 8,000 - 20,000
FM Radiotelephony - Commercial - Broadcast	 36,000 180,000
Radiotelegraphy - frequency shift	600
AM Facsimile	5,000
FM Facsimile	25,000
Broadcast Television	6,000,000

Edwards[33] reported a case study for measurement of pick forces at Cotgrave Colliery (U.K.) that supports this conclusion. Even with 128 samples required per 0.5 seconds, the total baud rate required was only 4136. The current radio remote controls on the market require 2400 baud for real-time control of the machine line-of-sight. If a system can be developed that will support broadcast video, the control communications can be handled easily. Therefore, if support for multiple 6 MHz channels could be developed, all control can be handled and the design criterion becomes the movement of broadcast video information.

3.3.3 Component Information Systems

The main information flow components in mining are: primary process, secondary support systems, and management information systems. The communication infrastructure must support these three information system components. This section discusses the requirements of each type.

3.3.3.1 Primary Process

The primary processes of delineation, development, production and backfilling require many equipment types to accomplish these functions. The most demanding systems, in terms of information requirements, are those that require full broadcast video. Mobile equipment is the main consumer of bandwidth, so, for the purposes of information flow requirements, consider the phases of the machine development (manual, teleoperation and autonomy) that could lead to total automation as outlined in figure 13. Teleoperation, because of the lack of information movement capabilities, is divided into two categories, local teleoperation and remote teleoperation.

In manual operation, the information flow requirements are almost nonexistent, as the operator processes all the information locally at the machine. The only information to be moved is done manually, in the form of log books for production and maintenance at the end of shift. Local teleoperation requires approximately 2400 baud; this is line-of-sight work, mainly to maintain safe working conditions. Information requirements with remote teleoperation increase significantly, as now the requirements become two channels of video for transmit and receive, monitoring data, control data and voice for maintenance purposes.

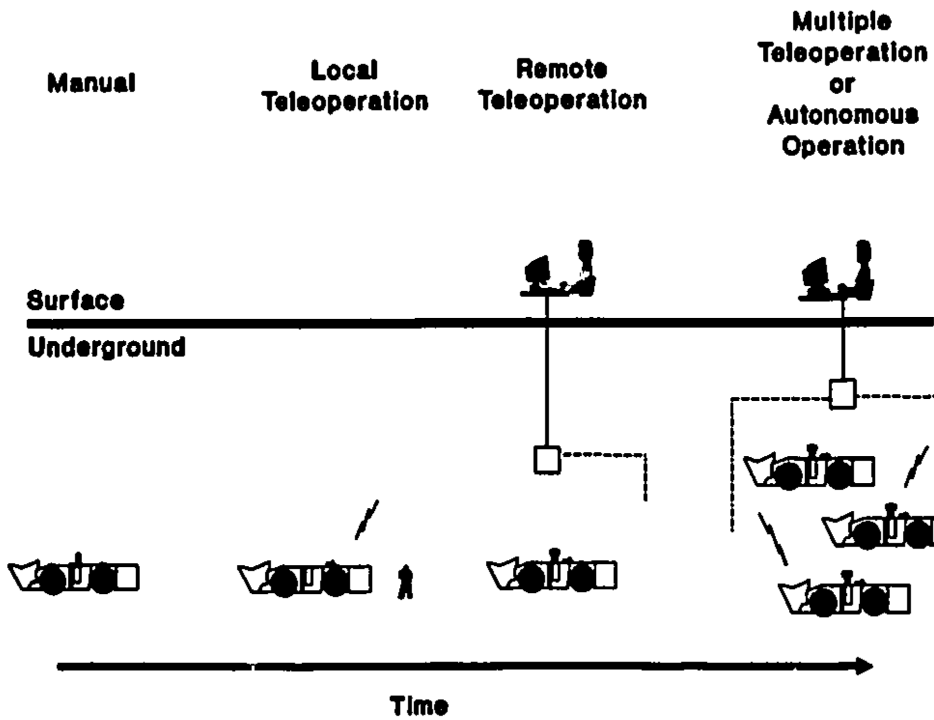

Figure 13 : Machine Development

This takes the bandwidth requirements to 12.498 Mhz, as illustrated in figure 14. Autonomous operation of equipment will have a reduced information load compared to teleoperation, as it will involve local processing on the machine and supervisory control of the system. From a bandwidth point of view this means that only a "transmit" video channel will be required, thus saving 6 Mhz of bandwidth, with other potential savings in the monitoring and control channels of the communication as the machine becomes more intelligent. Figure 15 shows the bandwidth requirements for one machine as it moves from manual to autonomous. The most severe load on the system will be in the remote teleoperation of equipment. Therefore, it must be recognized that the overall level of communication moves up significantly once remote teleoperation is generally employed.

The amount of information to be moved throughout the operation will increase

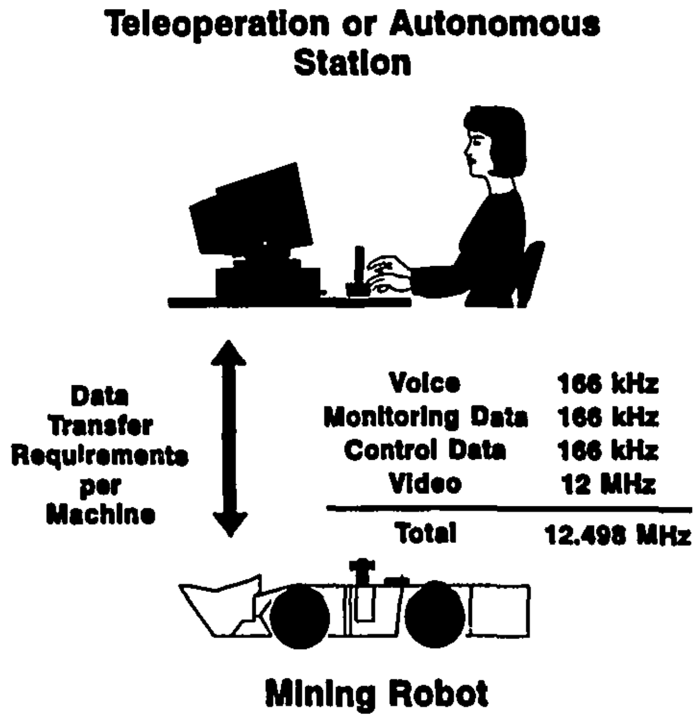

Figure 14 : Single Machine Data Requirements

dramatically as the industry moves toward full automation. Communication infrastructure capable of supporting automation and the large volumes of information flow required for mining does not exist presently. For example, supervised autonomy will require two-way transmission of voice for machine maintenance, control data, monitoring data and video. When reviewing this from a data transfer point of view, 12 MHz will be required for video per camera if real-time is needed and varying bandwidths for each of the voice, monitoring and control channels probably each in the order of 166 kHz, for a digital signal, depending on the number of sensors, actuators and local processing capabilities. As well, these parameters are only for a single machine and do not include multiple machines or varying types of machines.

A more rigorous example is based on one operator running multiple machines. To accomplish this task, from an information point of view (assume three

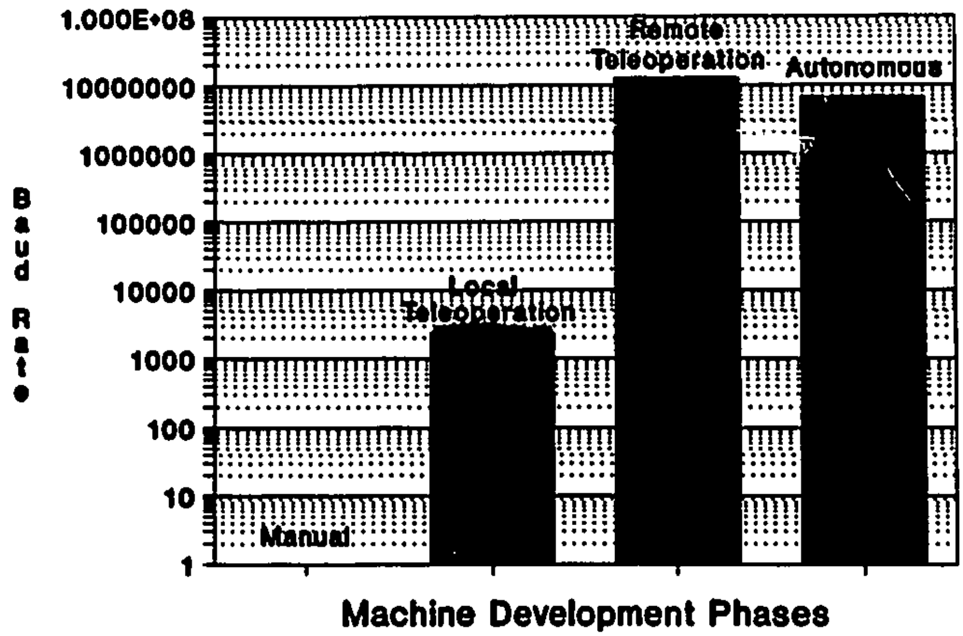

Figure 15 : Information Flow Requirements - Single Machine

machines per operator), there must be the capability for three independent video channels (36 Mhz), three machine health monitoring systems and three control systems. As well, the software systems for supplying machine information on the process and maintenance of the machines must also exist on the system. This would require a total of 36.996 Mhz of bandwidth.

Based on these parameters, the type of information system required for remote controlled and automated mining must support large bandwidth and speed capacities. Broadband communication over coax is acceptable for the direct connection of mining machines, but the missing element is the need for flexibility in mining necessitating RF communication capability. This translates into a requirement for a broadband radio link to all mobile equipment.

3.3.3.2 Secondary Support

Secondary support systems consist of the process control and engineering systems that must be supported by the mine network, as they are the interfaces with the mine. The software systems currently run on personal computers and include process control software for the operation of PLC and industrial computers. As well, they also must support the spreadsheet, CAD and database applications.

The software and process control systems used throughout the network require bandwidth and speed. In the short term, most of these devices will probably use RS232 connection. In the future, Manufacturing Automation Protocol (MAP) will be required, as these devices will be networked together. The bandwidth requirements for MAP are the equivalent of three video channels or 18 MHz. As well, the engineering office network will require 4 MHz in the short term but in the future should be integrated with the MAP portion of the network.

3.3.3.3 Management Information

The Management Information Systems (MIS) provide corporate information such as accounting, payroll and purchasing. At present, the networking function is minimal as only a gateway link is needed. In the future, however, as the manipulation of large amounts of data become feasible the communication infrastructure will become more critical.

Databases in the operation will reside on a mine local computer, and any remote database manipulation will be done by a central data generation system which shares the database information from the mines and plants. This will result in an increase in the bandwidth required to give the appropriate response time, both to the operation and onward to the corporate information systems.

3.4 Automated Mining

For purposes of this thesis an Automated Mine is defined as :

A mining operation which exploits the capabilities of sensors, actuators, computers and software to maximize work, productivity, safety and profit, by getting the right information to the right place at the right time.

To obtain this objective three key components are required: a full understanding of the process to be controlled: a solid reliable communication infrastructure capable of moving large amounts of information; and finally, dynamic information systems to process the information quickly and reliably. Once these components are in place, management of the automated process can be performed using information generated by engineering and planning systems. This information can then be directly fed to robots and/or process control systems for task planning and implementation, followed by information reporting on the performance and health of the device and the progress in the mining cycle.

The first step to accomplishing the automated mine is a thorough understanding of the mining process, which is illustrated in figure 16. The primary process can be broken into four major components: delineation, development, production and backfilling. Along with these fundamental components there are support and management systems.

Delineation of the orebody is the first step of the mining process. This thesis only concerns itself with delineation after the mining operation is started and assumes a sufficient database of information has been established by the exploration geologist to start the development of the orebody. The delineation process from this point consists of assessing the deposit, locating the ore, sampling the ore and modelling the orebody to determine suitability for mining. The endpoint of the process is the gathering of sufficient information to detail the orebody in terms of quantity and quality of the formation. This information is used to determine a method of attack for ore removal and for blending of ore within the mine and the entire operation if necessary. Typically, delineation is

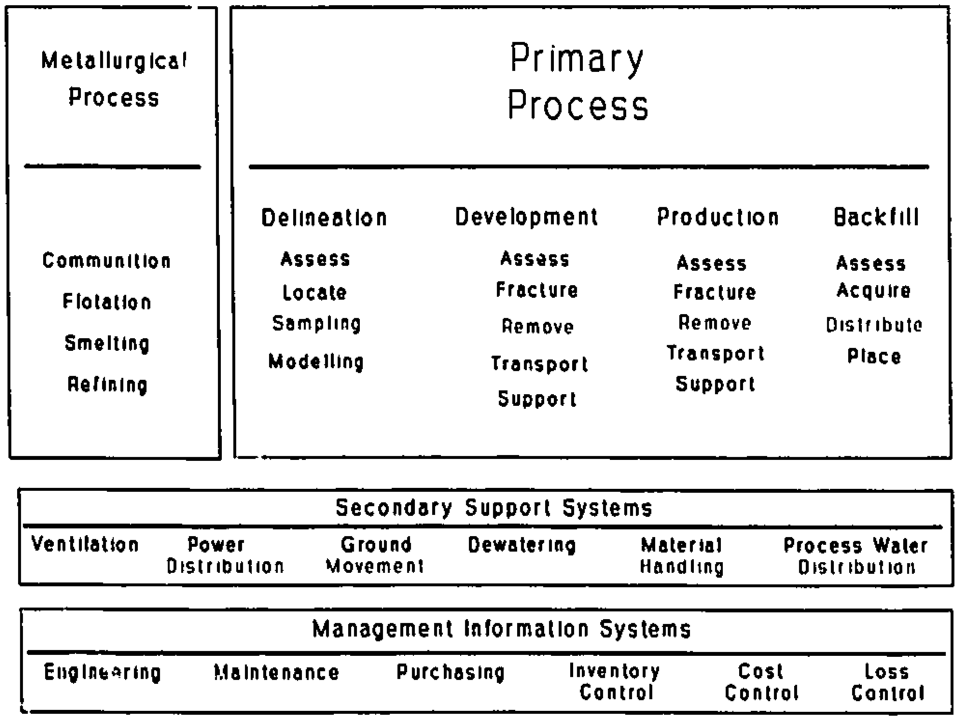

Figure 16 : Mining Process Representation

performed by geologists and diamond drills. The diamond drill creates holes in the rock, retaining core for the geologists to evaluate, by eye and in the laboratory, for rock mass quality, quality of ore and quantity of ore. This information is used to determine production schedules for the mine, along with constant observations during operations to prove a hypothesis. In the automated mine, a machine similar to a diamond drill will supply information online to a geological database, for immediate use by the rest of the mining, process for planning and ground control.

The development process consists of making horizontal and vertical holes in the ground, sufficiently large to permit movement of personnel, equipment and supplies to the mining area, and of ore and waste rock to surface for further processing. The basic steps are assess, fracture, remove, transport and support. Necessary equipment includes:

* survey equipment
* shaft jumbos
* raise borers
* jacklegs and stopers
* raise climbers
* drift jumbos
* explosive loaders
* clamshell
* tunnel and raise boring machines
* shovels
* load-haul-dump vehicles
* trucks
* bolting and screening equipment
* shaft and drift lining equipment

The present development process is labour intensive, and many organizations are working on ways of automating this task.

In an automated mine, this process will be divided into two subprocesses: one or two for vertical holes, and one for horizontal openings. There may be a number of these subprocesses working at the same time. The information used by these processes is identical:

* planning
* surveying
* process monitoring
* process control

The production process consists of fragmenting ore for transport to surface for metallurgical processing. This is typically done in the same fashion as the development process (of assess, fracture, remove, transport and support), with information about the process being supplied from the delineation and development processes. Drilling will be done using production drills ranging from drift jumbos to longhole and ITH machines. Blasting machines will load the holes and prepare the site for initiation, using information about geology and hole location to optimize the blast. Finally, the fragmented material will be transported using machines ranging from LHDs to loaders, trucks and conveyors.

The automated mine will have one operator running multiple machines, and will eventually have only maintenance personnel underground. Figure 17 is an example of the information flow required for automated production drilling. This information should also be available to the milling, smelting and refining processes, to plan their production levels.

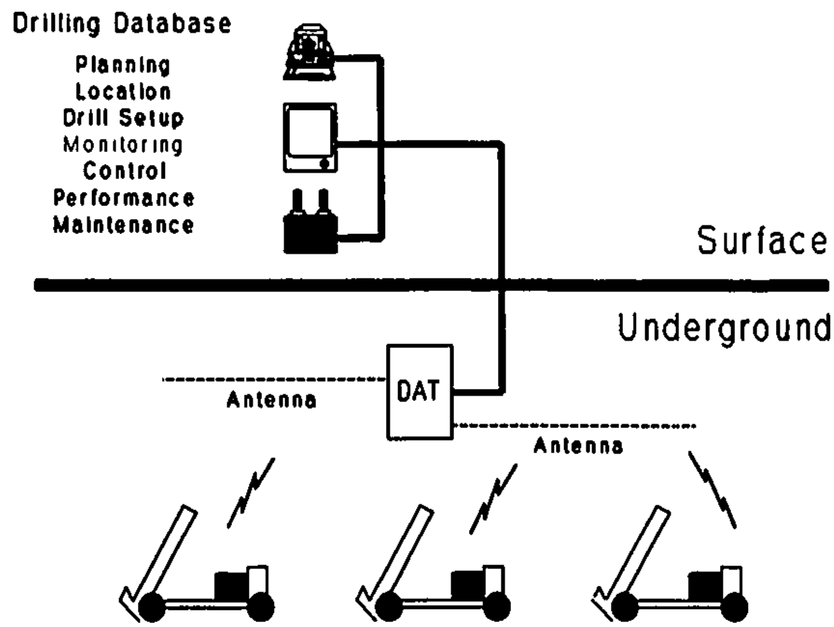

Figure 17 : Automated Drilling Process

Backfilling uses a variety of granular materials which are mixed together and transported to the top of the stope to be filled, by means of pumps, valves and piping. The basic process is: assess, acquire material, distribute and place. In the automated mine this process will require only one or possibly no operator at the pour-site. The system operator will require information for process monitoring and control.

The secondary systems for supporting the primary processes include ventilation, power distribution, ground monitoring, material handling, dewatering and process water distribution. Each one of these systems will need data movement similar to that required by process control systems in surface plants. Because they are underground, video cameras in specific locations will also be required. These systems are the easiest to automate, and in some mines they have already been automated. The important point is, these systems must not be ignored in considering the information infrastructure requirement of any operation.

Mine management systems are used for engineering, planning and control of the operation, maintenance, purchasing, warehousing, cost control, personnel and safety. These systems are software related, and require constant feedback from the production process.

3.5 Summary

Current information systems for underground mining are inadequate for automated mining. Significant work is required for the development of communication infrastructure to support automation. One of the main considerations is the ability of the systems to lead to the application of CIM techniques. To date, no work has been performed in the development of communication infrastructure and information systems for automated mining.

Such development will require support for voice, data and video communication, to and from stationary and mobile locations. It will require the establishment of information systems to integrate electronic systems with machines and robots. Mobile video transmission for equipment teleoperation represents the most demanding requirement on the communication system. The communication system must be broadband in order to handle voice, data and video. No such capability presently exists for mining. Therefore, research into the development of a broadband radio system with underground capabilities is required.

4 UNDERGROUND COMMUNICATIONS TECHNOLOGY

This section discusses underground communications technology theory and environmental considerations leading to the development of concepts for system experimentation and economic analysis. The results of this section also assist in the definition of the underground experimentation work.

4.1 Theory

Multiplexing, local area and radio network concepts were studied as a basis for definition of the underground experiments at North Mine reported in Chapters 5 and 6. This section reviews the technology to build the communication infrastructure and support the information systems and mining systems.

4.1.1 Multiplexing

Critical to the understanding of the concepts developed in this section is multiplexing. Multiplexing is:

> designation of a system for transmitting and receiving simultaneously two or more messages or signals over a common circuit using carrier wave.[58]

There are two basic types of multiplexing: frequency division multiplexing (FDM), and time division multiplexing (TDM).

4.1.1.1 Carrier Signal

Carrier signals are the continuous audible tones exchanged by modulator/demodulators (modems) over telephone lines. Without a carrier, no transmission or reception can occur. Modem carriers are sine waves with fixed frequency (tone), fixed amplitude (strength) and constant variation.

The changing of the carrier in predetermined ways can represent information. Digital information requires only two states and thus two alterations to the carrier signal. Modulation accomplishes the change and demodulation detects the change.

There are three different ways that the carrier can be modulated to carry the analog or digital information: altering the amplitude, changing the frequency, and changing the phase angle. The two most common methods are called "Frequency Modulation" (FM) and "Amplitude Modulation" (AM).

4.1.1.2 Frequency Division Multiplexing

FDM is basically a carrier system where the electromagnetic spectrum is split into a number of frequencies or channels, allowing multiple transfer of signals[e]. Since the modems are radio-frequency based and the signal can be moved via a cable system or a radio antenna system, this technique has application in underground mining. Although it requires a modem, it allows numerous individual high speed channels which can be used for real-time communication.

4.1.1.3 Time Division Multiplexing

TDM is a technique to divide the communication into parts or messages on a transmission medium[f]. TDM makes a basic assumption that the entire medium is available at all times. TDM is utilized in computer networking because it is

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[e] Broadcast radio is an example of FDM, with numerous stations coexisting on the air waves. In this form of communication, each channel is assigned a transmitter-receiver pair or modem to transfer the signal.

[f] This technique involves putting the signal directly on the transmission medium, while sharing of the medium is done by time slice allocations to particular channels or users.

relatively low cost.

4.1.1.4 Combination Systems

FDM and TDM can be combined to achieve a hybrid system that can be used for a large number of applications. On a particular frequency, a TDM system can be run for computer networking or video cameras. The hybrid systems function like individual systems the previously discussed, and offer the combined advantages of their particular schemes. As well, by combining FDM and TDM together, the costs of the system would be reduced even further.

4.1.2 Local Area Networks

A Local Area Network (LAN) is used in an organization to move information. The LAN is made up of physical components that, when connected together, allow the movement of voice, data and video information, depending on the modulation methods.

The major considerations in a network system are topology, access method, modulation method and transmission media. Each will now be discussed, along with the standards being developed in the computer industry, since these are significant to the communication and information infrastructure engineering for future mine automation.

4.1.2.1 Topology

The topology is the pattern of connection of the computing devices to the cable system. The topologies used in LANs, figure 18[59], are : ring, star, bus, tree and mesh.

The most common network topology type is the bus. The computing equipment is connected to a single circuit (figure 18a) that allows messages or packets of information to be broadcast, simultaneously, to all computers on the bus. They are then allocated access either by a control node or the nodes contend for access.

Star networks (figure 18b) consist of a central controlling point, with each station connected to the centre via point-to-point lines. These are used with switched local networks such as PBXs and data switches, but not usually for LANs. They have the disadvantage of a single point of failure in the central controlling unit, although if this central unit is suitable the network will be fairly reliable for an office environment.

Branching tree LANs (figure 18c) are typically used in CATV type networks. This type of network is electrically identical to a bus, except that the branches must be connected through properly-designed impedance-matching devices. If the network is not correctly assembled, data signal reflections will cause it to malfunction.

The bus, star and branching tree function basically in the same manner. A computer with a message acquires access to the network and broadcasts a signal to all computers. All computers receive the message and all discard it except for the computer the message is addressed to.

In ring topology (figure 18d) all computers are connected in series and the signal is transmitted along the chain in packets. The next computer on the ring receives the packet, regenerates it and transmits it to the next computer. The packets flow in one direction with all machines retaining the message until the sending machine removes it from the network.

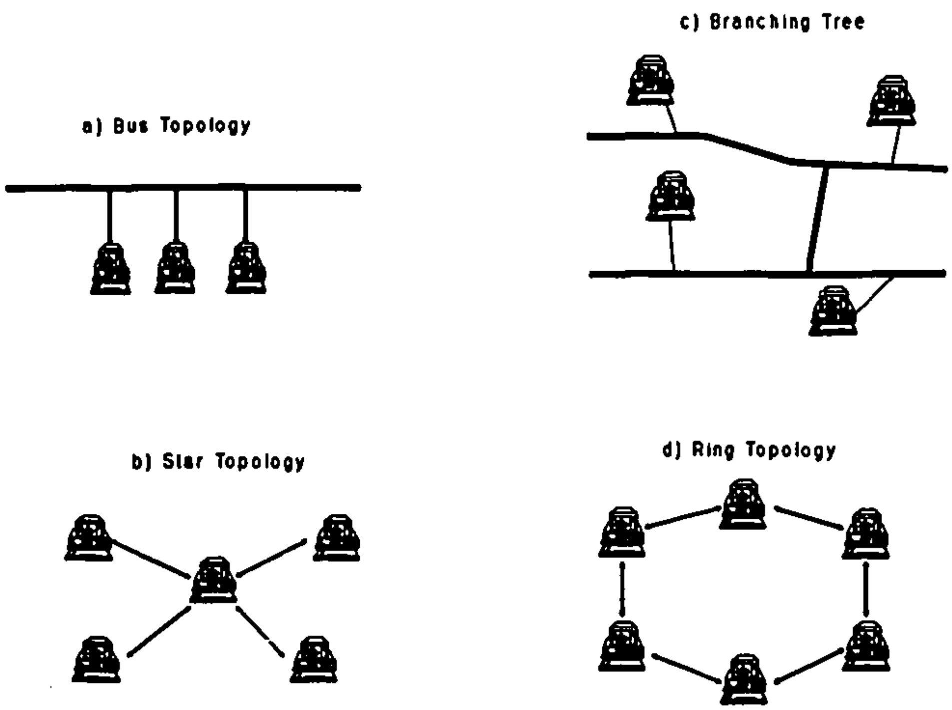


Figure 18 : Network Topologies(59).

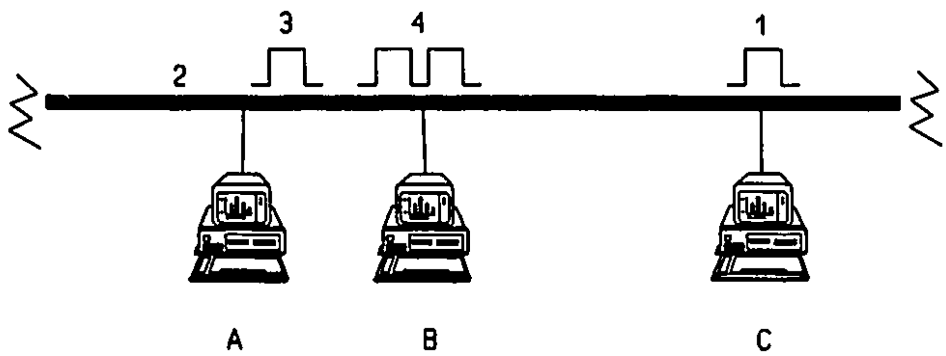
4.1.2.2 Access Method

There are two access methods for computers on a LAN: contention and noncontention. This section will discuss both methods.

Contention Access

A contention access can be considered as a single line with a number of machines vying for access at the same time. Control of the network is distributed among all machines. When a computer has a message to send, it listens to the network. If it is idle, the computer then transmits the data.

This works effectively as long as two computers do not transmit simultaneously. Figure 19[60] shows the case were two machines transmit at the same time. Since there is a delay between the time when a data pulse is transmitted and it is received, neither station is aware that the other is sending. Therefore, these two transmissions will **collide.**



1. Station C transmits acquisition pulse
2. Station A listens to network but pulse from C has not arrived.
3. Station A transmits pulse, which collides with pulse from C.
4. Station B detects collision and transmits jamming signal.
5. Both A and C stop transmitting and wait random time before retransmitting.

Figure 19 : Collisions on a Contention Network, after Green(60).

During the time i.e. the **collision window,** in which the pulse is sent from the sending machine to the most distant computer on the network the other computers are blinded to potential collisions. In one kilometre of coaxial cable, the collision window is approximately five milliseconds wide. Potential collisions on a contention network restrict the length of the cable system; otherwise the collision window will be too long. The practical limitation of a contention LANs operating at 10 mb/s is in the order of 1.6 kilometres.

An entire packet of data transmitted before a collision was detected would mutilate both signals, and valuable network time would be wasted in retransmissions. The most common protocol for managing access and collisions in a contention network is called "Carrier Sense Multiple Access with Collision

Detect" (CSMA/CD or Ethernet). A CSMA/CD computer node acquires the network by transmitting a single pulse. It monitors the pulse for mutilation by another computer acquisition pulse. If there is no mutilation, the computer has access to the network and transmits the data. If there is mutilation of the pulse, any computer detecting the collision transmits a jamming signal and both machines stop transmitting.

The procedure followed during a collision is called a backoff algorithm. If a computer attempted to acquire the network immediately following a collision, repeated collisions would occur. To prevent this, computers must wait a random time before the next attempt.

Noncontention Access

CSMA/CD is a statistical access method based on the probability that all computers will get enough of a share of the network to send their data. Although it is unlikely, it is possible that a machine could be excluded from the network by this method during periods of heavy load.

A noncontention system, called token passing, overcomes these drawbacks. A token is a unique code of bits that circulate around the network following a predetermined route. When a computer has data to send, it captures the token, transmits its message and replaces the token on the network. This is a deterministic system which offers greater control of the network. If a computer has data that are equal to or higher in priority than data from another computer, a portion of the bandwidth is allocated to this data message.

One station must be equipped to recover any token that is lost or mutilated. This can occur if a station fails or loses power at the time it has a token. The functions required by a control computer must include:

* removal of persistently circulating packets
* removal of duplicate tokens
* control of priority
* addition and removal of computers.

All computer nodes must be equipped to assume control if a machine fails.

Ring and bus topologies dominate in token networks and have no limitations in terms of distance, other than distortion. The distortion occurs due to pulse spreading along the cable. This can occur in copper conductors due to capacitance and in optics due to the internal reflections of light, and requires regeneration of the signal.

4.1.2.3 Modulation Methods

LANs use one of two methods of pulsing a data signal on the transmission medium: baseband and broadband. Both baseband and broadband accept identical data streams from the computer node, but they differ in how they access the network. A baseband system uses a transceiver that matches the impedance of the cable and transmits pulses at the data transfer rate. A broadband system interfaces with the network via a radio frequency modem to modulate data to the assigned channel.

Baseband

A baseband network is composed of computers, transceivers and the transmission medium. Computers send a data stream to the transceiver where it is formed into packets that are pulsed directly on the transmission medium. The transmission medium can be ribbon or paired copper wire, coaxial cable or fibre optic cable.

In fibre optic cable, data pulses drive a light transmitter, which turns a laser on and off corresponding to the binary code of the data signal. Baseband is a purely TDM system.

Broadband

Broadband networks can use a coaxial cable and amplifier system capable of passing frequencies from 5 Mhz to 400 Mhz as shown in figure 20[61]. Video channels each occupy 6 Mhz, providing the capacity for over 60 one-way channels, each of which can be used for voice, LAN and video communication. The primary advantage of broadband LANs is their greater capacity when compared to the baseband. A broadband can use multiple sub-carriers and frequency division multiplexing, to allow multiple baseband networks to function on the same cable system.

There are two types of broadband coaxial systems: single and dual cable. In a single cable broadband, the transmitting and receiving signals are sent along the same cable on different frequencies. The dual cable system sends the transmitting channels on one cable and the receiving on the other. Head-end equipment is used to shift the transmit and receive frequencies in a single cable system, and couple to the transmit and receive cables in a dual system.

Computer nodes in a broadband network interface with the transmission medium through radio frequency modems consisting of a transceiver tuned to the network transmit and receive frequencies. There are two types of radio frequency MODEMs - fixed frequency modems and frequency agile MODEMs - that can change frequencies within the MODEM.

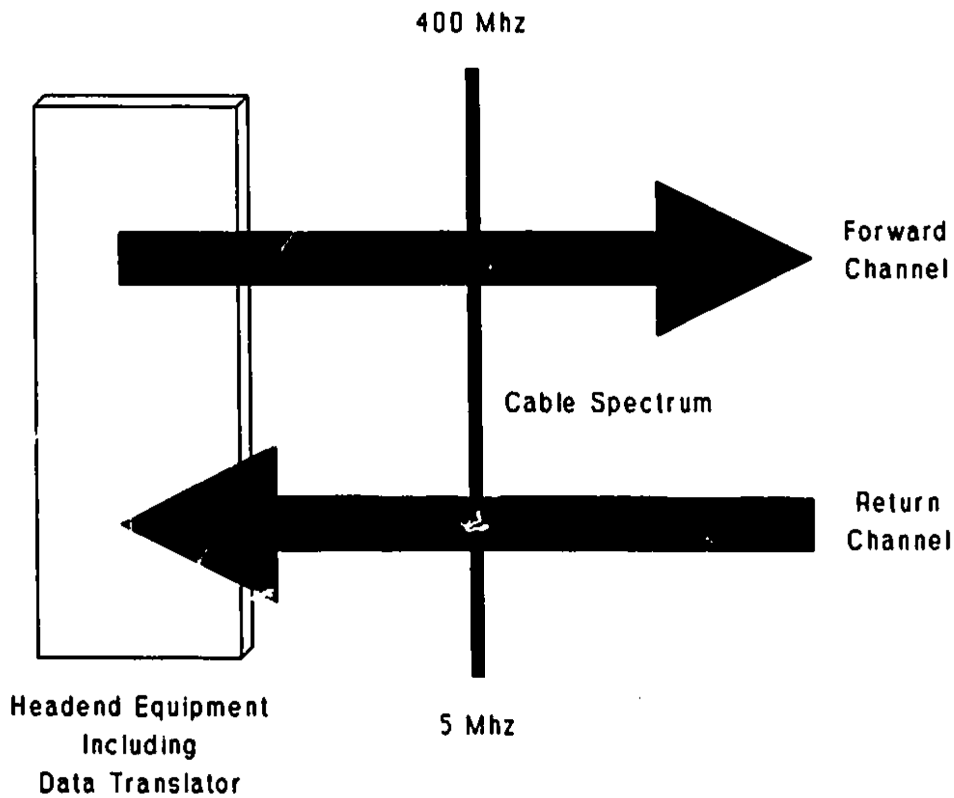


Figure 20 : Broadband Cable Spectrum, after Wilson(61).

4.1.2.4 Transmission Media

The transmission media that can be used in LANs are twisted pair, coaxial cable and fibre optic cable. Radio and light signals can also be used, in special cases.

Twisted Pair

Twisted pair consists of a pair of copper conductors twisted together. The primary advantages are low cost and ease of installation and maintenance. The disadvantages of the twisted pair are that the bandwidth is too narrow and the coverage lengths too short. Moreover, the cable is susceptible to electromagnetic interference (EMI) without shielding.

Coaxial Cable

A coaxial cable consists of one or more centre conductors surrounded by a dielectric and shield of flexible braid or semirigid copper or aluminum tube, with an outer PVC jacket. The advantages of coaxial cable are it is inexpensive, has high bandwidth, is widely available, can be easily extended, and can be installed by moderately skilled workers. Coaxial cable is very resistant to EMI and weather, if installed properly. Its only real disadvantage is its speed, which is slightly less than in fibre optics, depending on the dielectric as illustrated in table IV[62].

Table IV : Velocity of Signal Propagation in Coaxial Cable

DIELECTRIC MATERIAL	PERCENT OF SPEED OF LIGHT
Vacuum	100%
Foam	81%
Polyethylene	38%
Gas Injected	88%
Solid	66%

Fibre Optic Cable

Fibre optic cable is a glass or plastic tube that transmits a light signal using a series of mirrored surfaces. A lightwave system which employs fibre optic cable uses a combination of electronic and light technology to transmit information. The major advantages of fibre optic systems are its high immunity to EMI and high potential capacity. The disadvantages include expense due to costly electric-to-light conversion at tap points. As well, special tools and techniques are required for installation.

4.1.2.5 Standards

This section discusses a working group within the Institute of Electrical and Electronic Engineers (IEEE): the 802 Committee. This group is charged with setting standards for computer networking. These standards are reviewed below, as they form the base for mining communication and information infrastructure. Development of these standards has taken place over many person-years of work, and they can be applied to the mining industry with relatively little modification.

IEEE 802 Committee

In 1980, the IEEE established a committee to develop LAN standards (project 802) with the framework shown in figure 21[63]. The committee's objective was to establish standards for the physical and data link connections between devices. The established requirements were:

* existing data communications standards were to be incorporated into the IEEE standard as much as possible;
* network was intended for light industrial and commercial use;
* maximum network size was two kilometres;
* data speed on the network was between 1 mb/s and 20 mb/s;
* network standard was to be independent of the transmission medium;
* failure of any device on the network was not to disrupt the entire network;

* there was to be no more than one undetected error per year on the network.

Ethernet was not considered suitable, due to the blockage that can result under heavy load conditions. Three standards were selected: a bus contention network, similar to but not identical to Ethernet; a noncontention network for token passing bus; and a noncontention network for token passing ring.

The 802 standards are published in six parts:

802.1 Overview Document
802.2 Link Layer Protocol
802.3 Contention Bus
802.4 Token Bus
802.5 Token Ring
802.7 Physical Layer

CSMA/CD LAN IEEE 802.3

The 802.3 standard is a network based on CSMA/CD for commercial or light industrial use. The specification supports Media Access Units (MAUs) for baseband and broadband coaxial cable and baseband fibre cable.

The network can consist of cable segments a maximum of 500 metres long at a maximum signalling rate of 20 mb/s. Five segments can be connected together using four repeaters for a total coverage of 2500 metres.

Token Bus LAN IEEE 802.4

A token bus LAN, figure 22[64], uses the same topology as a CSMA/CD but control flows in a logical ring. The messages are broadcast on the bus, with

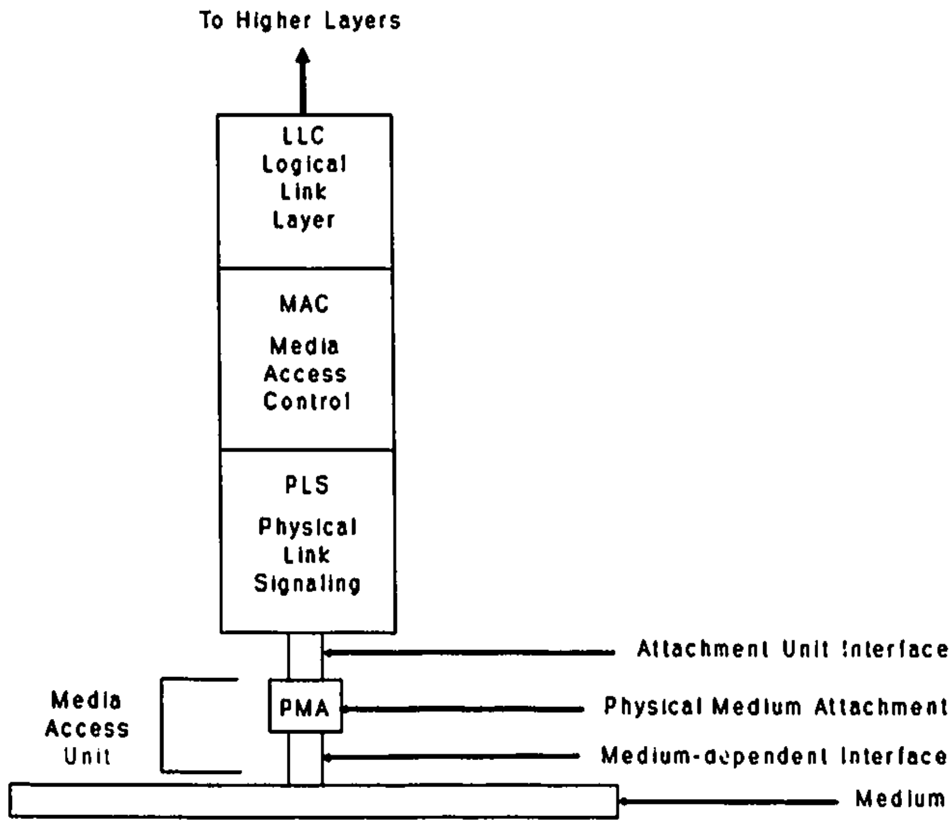


Figure 21 : IEEE 802 Standard, after Green(63).

control passing in sequence from node to node. Each node has the address of the preceding and succeeding nodes. The token bus standard is the basis for Manufacturing Automation Protocol (MAP) developed by General Motors Limited and computer manufacturers.

Token bus allows a larger network than CSMA/CD with a range from 1,280 to 7,600 metres depending on cable grade. This type of network can also be extended by repeaters to make its size, in terms of distance, virtually unlimited.

Token Ring LAN IEEE 802.5

The token ring is both logical and topological. Each node is a repeater, allowing

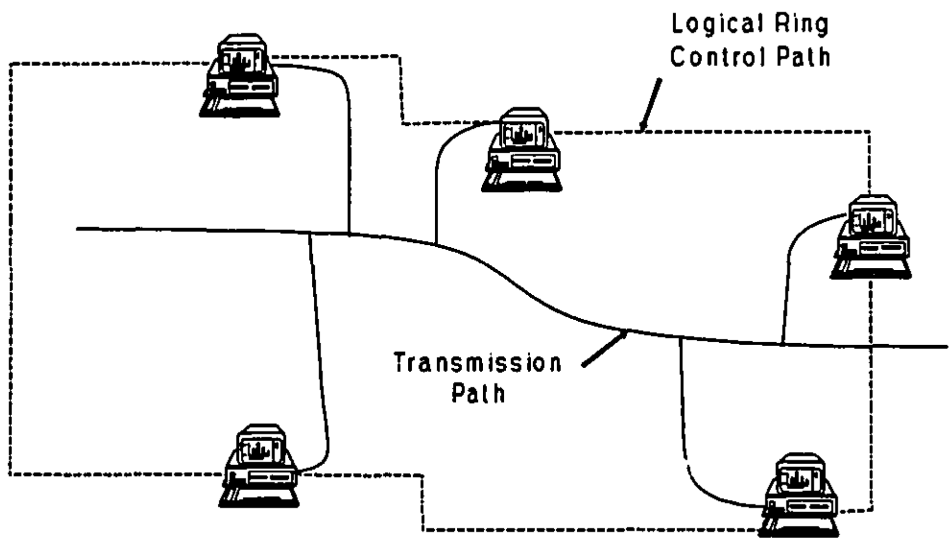


Figure 22 : Token Bus LAN, after Green(64).

the communication signal to bypass the node or pass the token. Figure 23[65] is a representation of a token ring network. Higher speeds can be achieved with this protocol as it is a noncontention system requiring no retransmission on errors. This standard is used for baseband networks only.

4.1.3 Radio Frequency Networks

This section reviews radio networks and their application to underground mining and their similarity to computer networking. Therefore, it discusses topology, access method, modulation methods and transmission media as in the stationary systems review.

4.1.3.1 Topology

In the underground environment there are three potential topologies: free space line-of-sight, bus type antenna systems and distributed antenna as shown in figure 24. Free space line-of-sight is direct communication as on surface. Bus-type

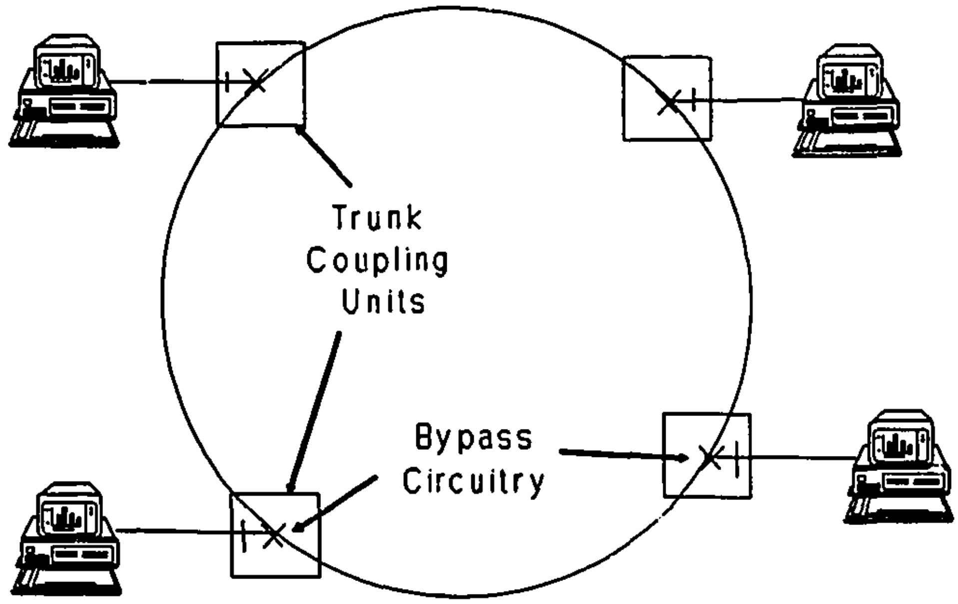


Figure 23 : Token Ring LAN, after Green(65).

antenna systems are based on continuous antenna systems that allow communication via the antenna. Distributed antenna systems use discrete antennae along a cable system for communication. Each of these methods can be applied along with a combination.

Free space and continuous bus antenna provide absolute coverage around the antenna and within a few hundred metres with no RF problems. Discrete antenna systems have the potential to divide coverage along boundary areas, resulting in multipath problems.

4.1.3.2 Access Method

As in computer networks there are two access methods to the radio network: contention and noncontention.

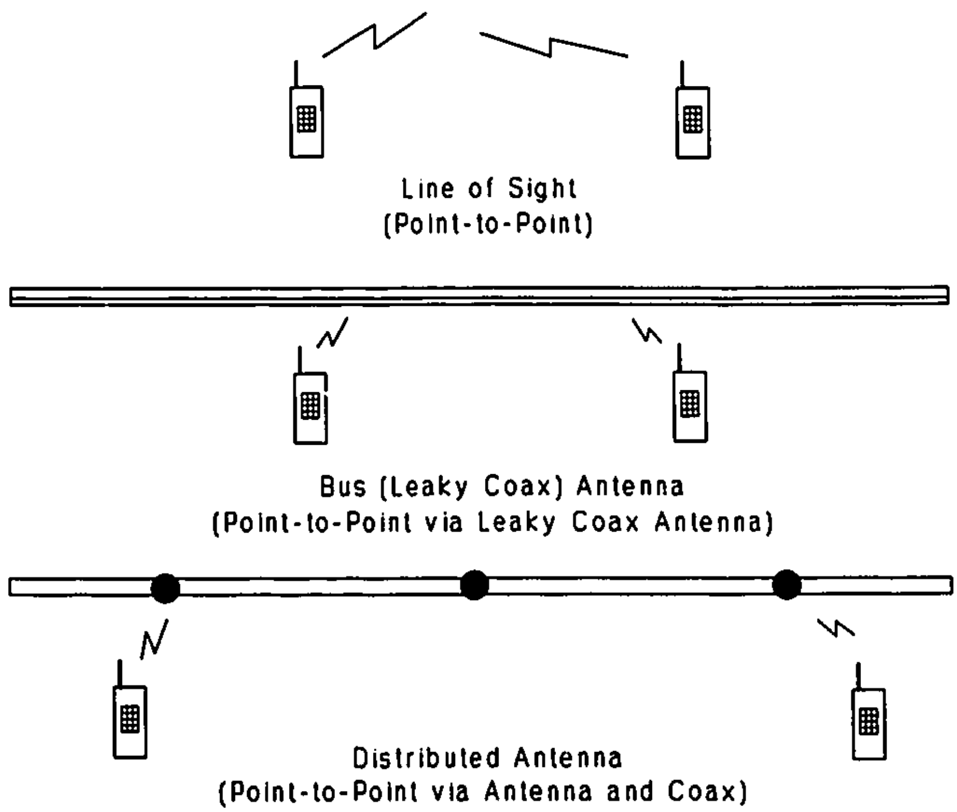


Figure 24 : Underground Radio Communication Topologies

Contention Access

Contention access occurs in walkie-talkie systems. All radios are on the same frequency and contending for the frequency for transmission. When a radio receives access to the system it locks out the other radios on that frequency. This type of system is an open system: every radio has access, but, it suffers from the drawback that it cannot allow private communication. However, private communication is an absolute necessity for voice, data and video communication if the RF network is to be used for control of computer networks and mining equipment. On the other hand, the open-channel approach is required by mining personnel working in the operation. For example, more than two people may need to be in contact simultaneously for shaft inspection or other purposes.

Noncontention Access

Noncontention access is used in radio systems when a frequency scanning radio is used to hook into multiple frequencies. As the radio locks in on a frequency, this radio is the sole owner of the frequency. This type of access would typically be used for telephone-type communications underground in private point-to-point systems.

4.1.3.3 Modulation Methods

Four main types of modulation methods are used for radio communication: Amplitude Modulation, Single Sideband, Frequency Modulation and Spread Spectrum.

Amplitude modulation involves impressing a signal, for example voice, on a carrier signal. The change in amplitude of the carrier results in a signal for transmission. Amplitude modulation results in four frequencies being produced: the signal (for example voice); the carrier; the sum of the two frequencies; and the difference of the two frequencies. The sum and difference frequencies are called sidebands. In an AM signal, all the information is contained in the two sidebands. The carrier and one sideband contribute nothing to the communication while 75% of the power is consumed in transmitting them. The efficiency of the transmitted signal is significantly improved by the use of Single Sideband. Frequency Modulation involves reducing and increasing the frequency, based on the signal for transmission. Spread Spectrum radio systems basically transmit digital addresses and code signals from radio to radio for a very secure transmission system. These systems were used in the military because of their ability to supply secure communication and have recently been declassified. Spread spectrum offers some advantages for mining applications, including: reduced power on a particular frequency (reducing the potential for premature blasting cap ignition) and secure communication (because it is based on a coded digital signal).

4.1.3.4 Transmission Media

Radio frequency transmission media are slightly different from computer network transmission media, due to the fact that RF typically travels in free space. Two types of antennas can be used underground: leaky coax and discrete, as discussed previously.

4.2 Environmental Considerations

This section discusses some of the major environmental considerations for the development of an underground communication system: radio wave propagation, RF emissions and blasting caps, coverage, maintenance and durability.

4.2.1 Radio Wave Propagation

Radio wave propagation underground has been studied by many people in the mining industry over a number of years, as discussed in the literature review. Some frequencies of electromagnetic waves can penetrate rock and others cannot. The lower frequencies can travel through rock while the upper frequencies tend to be more localized. Table V lists frequencies and their rock penetration characteristics, bandwidth capabilities and direction sensitivities.

VLF and LF radio are in the 5 to 500 Khz range. This form of radio wave penetrates rock and thus would not require a full line-of-sight antenna system. Since there is potential for only a few Khz of bandwidth, the use of video signals and high speed data would not be feasible in this frequency range.

Table V : Underground Electromagnetic Properties

Frequency	Penetration of Rock	Bandwidth Capabilities	Direction Sensitivity
VLF	Yes	Low	No
LF	Yes	Low	No
MF	Limited	Low	No
HF	No	Medium	Yes to a limited extent
VHF	No	High	Yes will go around corners
UHF	No	Very High	Yes although can go around some corners
SHF	No	Excellent	Yes only line of sight
Light	No	Excellent	Yes only line of sight

MF radio is in the order of 0.5 to 5 Mhz. This type of radio wave is a magnetic induction type. The signal can be induced onto metallic objects like screen, piping and even the orebody. While some radio systems have been developed and proved moderately successful, the bandwidth capabilities are still limited to a single video channel.

HF, VHF, UHF and SHF ranging from 5 Mhz to 100 GHz, cannot penetrate rock and gradually become more direction-sensitive as the frequency increases. These frequencies have excellent bandwidth characteristics and can transmit video, high speed data and voice signals.

Light includes infrared and visible between 10^{11} and 10^{14} Hz. These frequencies have excellent bandwidth capabilities but are totally direction-sensitive. For example, the light beam would have to be pointed directly at the receiver to transmit, thus making it unsuitable for transmission in the mining environment, where some non-line-of-sight work is required.

The frequencies most suitable for use in automated mining will be the HF, VHF, UHF and some SHF ranges. These are capable of transmitting a high bandwidth signal and have some ability to travel into the workings without being totally direction-sensitive. All frequency ranges may have some use underground. For example, VLF may replace stench gas since these radio waves will penetrate the rock. The higher frequencies will be more suitable for video information, high speed data and voice transmissions to be moved to and from the mine workings. The disadvantage of these frequency ranges is the inability of the radio waves to penetrate rock. This necessitates an antenna system of some sort to propagate the signal within the operation.

4.2.2 RF Emissions and Blasting Caps

RF emissions are a major consideration in the development of an underground mining communication system, as the electromagnetic power emitted by the system can ignite electric blasting caps. This section discusses the ignition process and the implications for communication system development.

An electric blasting cap is shown in figure 25[66]. The leg wires are typically shunted to protect them from premature initiation from radio frequency and power sources. When the leg wires are unshunted they will act as radio antenna when tuned to the correct frequency. Two cases for tuning the leg wires (antenna) exist, as shown in figure 26[67], the dipole and long wire circuits. The tuning length (L) for the dipole circuit is calculated by:

$$L = n\frac{\lambda}{2}$$

where

$\lambda = Wavelength$

$n = 1,2,3,4,5, etc.$

while

$$\lambda = \frac{c}{f}$$

where

$c = speed\ of\ light$

$f = frequency$

and the long wire circuit by:

$$L = n\frac{\lambda}{4}$$

where

$\lambda = Wavelength$

$n = 1,2,3,4,5, etc.$

The worst-case condition occurs when the legs wires of the cap act as antenna. As seen in the equations, as the frequency increases into the higher ranges (100 to 2000 Mhz), the potential for leg wires to be tuned (table VI) increases, and the potential for premature initiation arises. If a current to the bridge wire of the cap exceeds a threshold current value, the cap will ignite. To determine the hazard, the ranges of the firing currents of blasting caps must be ascertained. The statistics supplied by the manufacturer indicate that electric blasting caps have an ignition range from all-fire at 240 ma to no-fire at values less than 220 ma.

The Occupational Health and Safety Act[68] (OHSA) regulations have addressed this issue. Section 167 states that:

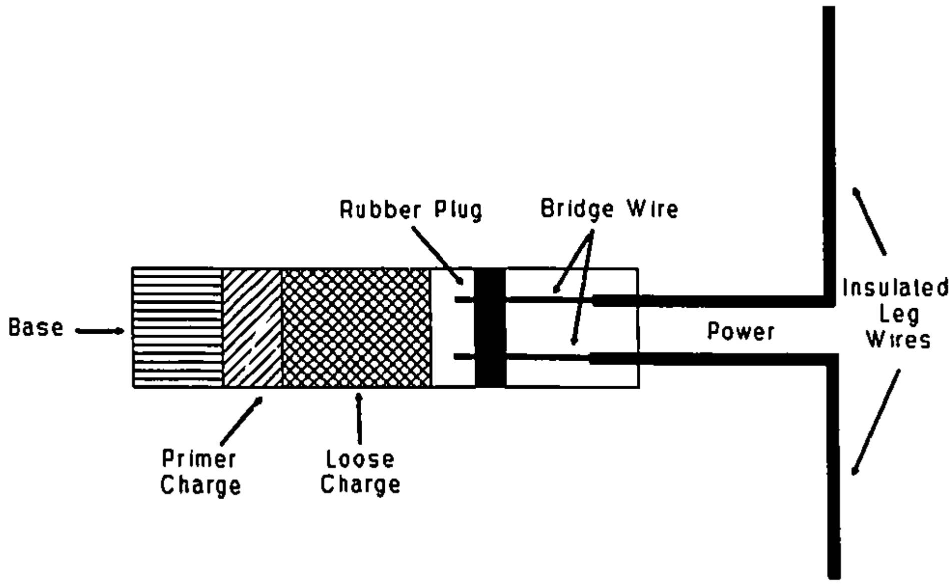


Figure 25 : Blasting Cap Components, after Bauer(66).

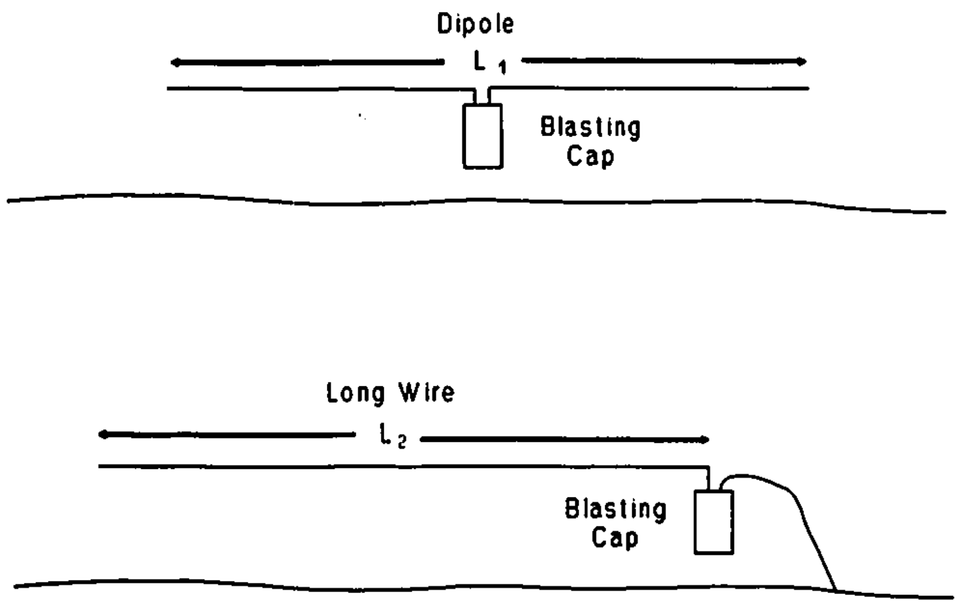


Figure 26 : Blasting Circuits Affected by Radio Waves(67).

"167. Any device or system that is capable of producing radio frequencies

Table VI : Leg Wire Length Tuned at Varying Frequencies

Frequency (Mhz)	L_1 (mm)	L_2 (mm)
100	148.8	74.4
500	29.8	14.9
1000	14.9	7.4
5000	6.0	3.0

or of radiating electromagnetic energy shall,

a) be tested for hazards to electric blasting caps as specified in CSA Standard Z-65-1966, "Radiation Hazards from Electronic Equipment"; and

b) be used only when precautions are taken against,

  i) setting off any electric caps and

  ii) the inadvertent operation of any blasting or any other device which may respond to the radio frequencies or the radiated energy. R.R.O. 1980 Reg. 694, s. 167."

Z65-1966[69] states that, for mobile transmitters, the power and distances in Table VII must be met or testing of the radio transmitter must be completed to ensure that no more than 60 ma of power (less than one watt of transmission power) is emitted, this is a factor of safety of three or four.

The implications for communications system development are that mobile radios must not exceed one watt of radiated power or 60 ma of current output from the transmitter. If this is not possible, a protective shield must be used around the antenna to ensure that blasting caps cannot be moved in the RF field around the antenna. In the longer term, an alternate ignition system for blasting must be

Table VII : RF Power vs Minimum Distance Requirements(70).

Transmitter Power (Watts)	Minimum Distance (metres)
1 - 10	3
10 - 30	7
30 - 60	10
60 - 100	20

developed to allow the use of higher power for communication.

4.2.3 Coverage

A typical hardrock underground mine consists of vertical and horizontal openings many miles in length. When considering the automation of a mining operation the coverage requirements must be established. From the perspective of coverage, there are four key considerations over the area to be covered. The system:

* must supply multiple full video bandwidth channels;
* must supply real-time capability everywhere in the operation;
* must support multichannels for voice, data and video;
* must support stationary and mobile information systems underground.

Research and development related to underground communication systems must include all requirements.

4.2.4 Durability

The final requirement of the communication system is durability. The mining environment is in some ways much easier to deal with than other environments, in that the temperature is constant. In other ways the environment is very difficult, as it is dynamic in nature: mining is carried out in a particular area only for a finite time period, and then the area is abandoned. This puts unusual demands on a communication system, by requiring minimization of:

* system components;
* components in the working environment;
* effects from blasting;
* effects from ground movement;
* effects from ground water;
* effects of mining machinery;
* effects from power distribution systems.

In other words, the system must be capable of working continuously in a mine environment with blasting, large machinery, ground water and RF noise.

4.2.5 Maintenance

Another key consideration is the ease of maintenance of the system. Typically, mines at the present time find technical skills in short supply. Therefore, the system must be easy to maintain and the following criteria must be met:

* simple to connect;
* easy-to-get components;
* simple to splice;
* simple to troubleshoot;
* simple to expand and install.

If these criteria can be met, the system will be readily accepted by the operations personnel for immediate use in the mine.

4.3 Underground Communication System Concepts

This section establishes the main concepts that define the information infrastructure requirements for automated mining. With the concepts generated in this section, the communication and information infrastructure will be defined sufficiently for experimentation to proceed.

4.3.1 Underground Communication Criteria

To support the development of a automated mine, communication infrastructure is an absolute requirement as a foundation. Using the information discussed early in this section, the concepts for an underground communication system will be outlined. These concepts form the basis for the experimentation portion of this thesis work.

A foundation communication system for automated underground hardrock mining must provide:

* support for voice, data and video;
* support for stationary and mobile locations;
* capability to move all forms of information at high speed (near real-time);
* support for multichannel communications;
* ease of installation and maintenance;
* support over large linear distances;
* failsafe operation;
* flexibility;
* compatibility with electronic devices already on the market;
* compliance with standards set out by the computer and communication industry;
* cost effective performance.

Figure 27 illustrates the concept of the communication infrastructure requirements for underground mining. The concept uses a backbone network connected to a "smart antenna" for the transmission and reception of voice, data and video, to and from stationary and mobile locations.

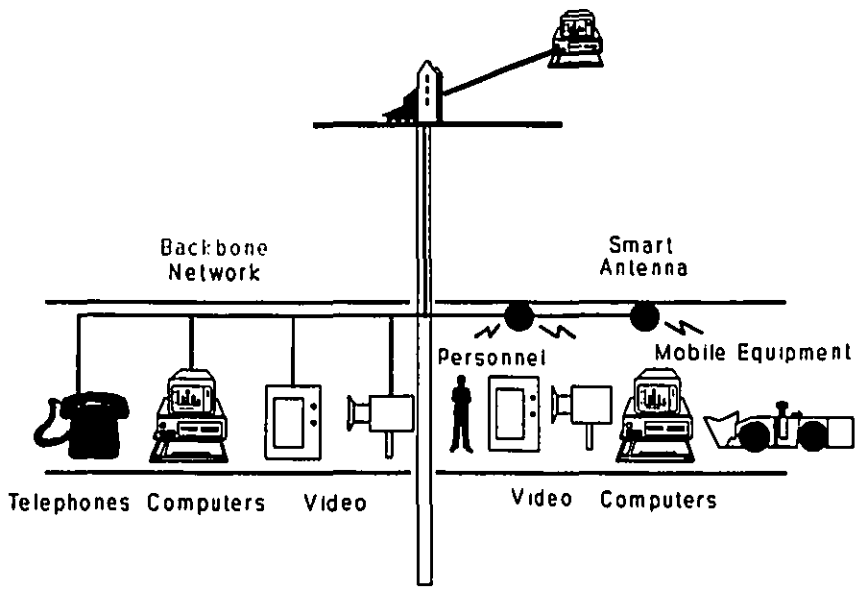


Figure 27 : Underground Communication System Concept.

4.3.2 Underground Information Network

This section outlines the alternatives for the backbone and radio communication in an underground network. Each section is divided into medium, topologies, transmission techniques and protocols.

4.3.2.1 Network

This sections discusses the alternatives for network communication of voice, data, and video to be included in the backbone portion of the underground information system.

Topology

Of the network topologies available, the most suitable for an underground mine is a branched tree. This most closely resembles the layout of a mining operation and the methods used in the operation. This topology offers the advantage that minimum infrastructure (low cost) can be installed in the initial development of the operation and system expansion can take place as the operation grows.

Medium Access

The alternatives for medium access are CSMA\CD, Token Bus and Token Ring. CSMA/CD, while a useable protocol, suffers from a major drawback: the potential for data collision due to the length of the network required underground. Typically a CSMA\CD network does not exceed 1.6 kilometres in total length, while the mine coverage required significantly exceeds this limit. For this reason, a token passing system is an absolute requirement for a mining operation. Token Ring and Token Bus type access protocols are dependent on the network topology. Since token ring protocol requires a ring cable system and the topology selected for the mine is a tree or bus structure, the most suitable protocol is the Token Bus. This protocol allows the best coverage and speed for network operation, as data collisions will not occur because the protocol is based on a noncontention system.

Modulation Method

Since the mine network must carry multichannel, voice, data and video, and linear distances are large, the most suitable method of modulation is broadband. Broadband allows all forms of information required in the operation to be moved over long distances at high speed.

Medium

Three potential alternatives for cabling the mine backbone are: twisted pair, coaxial cable and fibre optics. Twisted pair, while cheap, does not support the types of bandwidth capacities needed for voice, data and video transmission. As well, this type of cable system is not suitable for protection against EMI. Fibre optic cable supplies the bandwidth needed for an information system for underground. However, there are several cost disadvantages. First is the cost associated with converting from electricity to light for signalling purposes. Second, the cost per tap is quite high and, due to the number of taps that would be required in a mine, this system would be unsuitable. Finally, the costs of installation and maintenance are high. Coax cable, while not having the same potential bandwidth capabilities as fibre optics, has many advantages which make it suitable for use in an underground mine. These are:

* adequate bandwidth capabilities;
* ease of installation and maintenance;
* inexpensive;
* easy expansion and interfacing;
* good resistance to EMI and weather;
* commercial availability.

4.3.2.2 Radio

This section reviews the radio communication alternatives for the underground communication infrastructure. Due to the volume of information and the associated bandwidth requirement, the lower frequencies of the radio spectrum were not considered viable for the infrastructure.

Medium

There are three main RF antenna systems possible for underground radio communication in a mine. These are discrete antennae, leaky coax antenna and distributed antenna. Both the discrete antennae and the distributed antenna systems will work effectively, but both suffer from multipathing problems that require careful installation of the antenna. A leaky coax is more suitable for a mining operation, in that it leaks the radio signal over the entire length of the cable system, wherever it is installed. This allows excellent coverage, combined with minimized multipathing problems due to other antenna, and minimum dead zones.

Topologies

The topology used for radio transmission systems is quite different from the broadband network bus, in that it requires minimizing the amount of electronics actually in the mine workings to minimize the chances of the system being damaged by mining. To accomplish this goal, a combination system is considered the most viable: the broadband bus is used as a backbone and radio is distributed through the operation using star topology. This topology allows the centralization of the electronics, reducing the potential for damage while providing the service required. As well, the topology should allow for expansion, as future automation techniques to continue to develop.

Transmission Techniques

The system developed must be capable of supporting all radio transmission techniques used today, so as many "off-the-shelf" products as possible can be used. To support the establishment of a radio computer network integrated with a broadband computer network, there must be support for secure reliable transmission. Therefore, since spread spectrum radio transmission offers the best noise immunity and security, it will be the desired transmission technique for the radio computer network.

4.3.3 Underground Network System Development

This section outlines the configuration adopted for the underground information system developed during this research. It presents the most suitable alternative, given the environmental, backbone and radio system requirements.

In testing, the medium that most successfully met the requirements was coaxial cable. Coax cable can be used for both backbone and radio communications as they both transmit radio waves. The only difference between the two was that the backbone coax was shielded, while the "Leaky Coax" allowed RF signal to leak out of the cable and couple with other RF devices. This cable had the added advantages of high bandwidth facilities, high speed communication, relatively inexpensive cable and tap cost, very simple maintenance and the ability of multiplexing signals. To effectively integrate the radio network with the broadband network, a single electronic mapping device ("Distributed Antenna Translator" or DAT) was required that would allow the free flow of signals for voice, data and video through both communication networks. A DAT system as shown in figure 28 was required, in order to satisfy the present and future needs of the mining industry for a communication system to manage mine automation.

4.4 Conclusion

The concept developed for an underground computer network for automated hardrock mining is based on combining a broadband CATV network with leaky coax antennae via a "Distributed Antenna Translator" or DAT. The experimental work described in chapters 5 and 6 was designed to establish that voice, data and

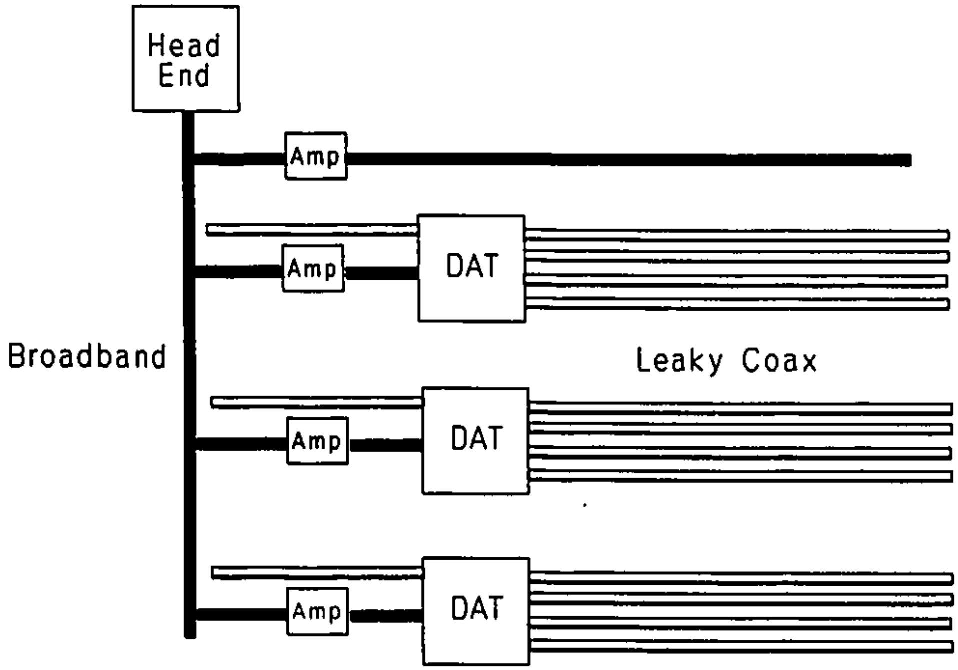


Figure 28 : Underground Information System Schematic.

video communication can be achieved to and from stationary and mobile locations anywhere in the operation.

5 COPPER CLIFF NORTH MINE : PRELIMINARY RADIO FREQUENCY EXPERIMENT

This chapter discusses the preliminary radio frequency experimentation at Inco's North Mine. The results presented here were used to determine the feasibility of an underground radio frequency network for mining which would support automation.

5.1 Objective

The objective of the preliminary North Mine experimentation was to evaluate the most suitable radio transmission frequency, problems associated with radio transmission underground and any background noise. This experimental work was undertaken to provide preliminary information for the development of the communication infrastructure unique to the actual mining environment. It is basic to the final experiment (see Chapter 6).

5.2 Site Description

The testing took place on the 3400 foot level at the Copper Cliff North Mine. The drifts on 3400 level are 5 X 3 metres. There are three main drifts 300, 200 and 175 metres long (see figure 29).

The drifts on the level had a rough surface and the back was covered with rockbolts and screen. Dust was observed on the back and the walls of the drift. Electrical transformers (6900/600 Volt and 600/110 Volt) were located on the level in the main shaft drift and the garage respectively. Cable distribution of 6900 volt power occurred from the disconnects in the electrical switch room to the transformer in the main shaft drift. The entire level uses 600 and 110 volt

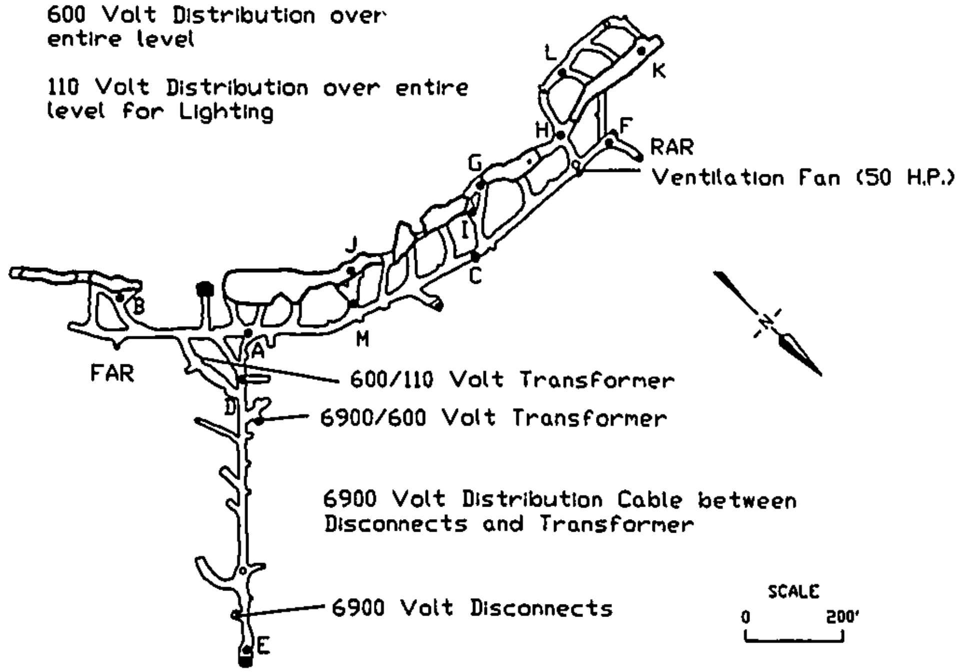


Figure 29 : 3400 Level Plan

distribution. One portable ventilation fan (50 HP) was installed in the west end of the drift.

Some factors that were considered to affect radio wave propagation underground were:

* no line-of-sight conditions existed except in the main drifts;
* overhead cabling and ventilation ducting consisted of horizontal runs, with regular supports and drops, which could cause scattering, diffraction or signal generation;
* there were high voltage lines (6900 volts, 3 phases) and 600 volt distribution transformers on the level;

* LHDs covered a minimum of 50% of the drift cross-sectional area;
* The alternators in the LHDs had the potential to generate RF noise;
* The rock was considered a low absorption material from a RF perspective.

During the experimentation, normal mining activities took place, including tramming and drilling on the level.

5.3 Equipment

The equipment used for the radio frequency experimentation comprised:

* 4 - VHF and UHF portable radios (4 watts)
* 4 - VHF and UHF mobile radios (10 watts)
* 1 - Analog voltmeter (Simpsons)
* 1 - Wattmeter including terminators, loads and feed through elements
* Communication monitoring equipment with Spectrum Analyzer (Ce-50)
* 1 - RF attenuator
* Coaxial cables
* Leaky Coax cable
* 1 - 3M Modulator (Channel 3)
* 1 - VCR
* 1 - RCA Portable Television

5.4 Frequency Band Measurement

VHF and UHF radios were used to determine the most useable frequency band for underground. Walks with the VHF and UHF radios determined that the UHF band demonstrated a **longer** coverage distance and a **higher** signal-to-noise ratio than VHF. Although, this determination was subjective, as it measured by ear the quality of the voice signal, all subsequent tests were conducted in the UHF band (462.5 Mhz).

5.5 Fixed Transmitter - Moving Receiver

The next test was to determine the applicability of surface radio equipment to the underground environment in a tunnel with moving equipment.

5.5.1 Method

A mobile radio (transmitter number one) was installed at point A (see figure 29) on the wall of the drift. A portable radio (transmitter number two) was hand held at the same intersection by a man standing in the middle of the tunnel. The signal was received by a mobile radio (receiver number one) placed on top of a LHD. The LHD was then moved from point A to point B then from point A to point C stopping every 20 metres for measurements.

5.5.2 Results

The signal received from transmitter number one had a mean value of -89 dBm with a standard deviation of 3 Dbm over a distance of 120 metres on either side of point A. The signal measured had maximum and minimum values as a normal consequence of multipathing.

The signal received from with transmitter number two had a mean value of -86 Dbm, twice as much as the measurements with transmitter number one. This was contrary to expected results, as transmitter number one generated 8 watts in power and transmitter number two generated 5 watts. The reasons for the discrepancy were the differences in antenna directional gain and the changes in obstructions in the drift. Table VIII shows the analysis of the system losses. Based on the system loss analysis, losses on the 3400 level were relatively constant in the two scenarios. Therefore, the radio environment was concluded to be stable for the application of surface radio equipment to a moving machine.

Table VIII : System Loss Analysis

Condition	Transmitter #1 Dbm	Transmitter #2 Dbm
Transmitter #1 : (mobile radio)		
Power = 8 watts	39	
3 m of coaxial RG-58 + conn.	-4	
Antenna directional gain	-6	
Radiated Power	29	
Transmitter #2 : (portable radio)		
Power = 4 watts		36
Antenna omnidirectional		-14
Radiated Power		22
Receiver #1 : (mobile radio)		
3 m coaxial RG-58 + conn.	-3	-3
Antenna Gain	0	0
Free Wave Path Loss (130 m)	-67	-67
Obstruction and Sector Loss	-48	-48
Received Signal	-89	-86

5.6 Fixed Receiver - Moving Transmitter

The purpose of this experiment was to identify the RF propagation characteristics and the margin available for design with moving radio equipment.

5.6.1 Method

An antenna (receiver number one) was fixed to a water pipe at two locations for testing. The first was at point A and the second at point D just outside the refuge station on the level. Portable radio units (transmitter number two) were carried down the drift toward the shaft station point E and towards points B, F, G, H and I from A. Static readings were taken at points F,H,G,K,M,J and B (see figure 29). Then to determine the RF margin available, an RF attenuator was inserted in the receiver-antenna coaxial link.

5.6.2 Results

Point D - Point E

The received signal had a mean of -86 Dbm with a standard deviation of 5 Dbm over the 180 metre distance. The signal exhibited multipath characteristics by fluctuating between maximum and minimum values.

Point A - Point B

The received signal amplitude was the same as the Fixed Transmitter - Moving Receiver results of the previous section.

Point A - Point F

The received signal showed a mean of -86 Dbm with a standard deviation of 12 Dbm over the 300 metre distance. The signal exhibited multipath characteristics as evident from the signal fluctuations.

Static Readings

Table IX shows the results obtained for these measurements. Analysis of the table shows that fairly strong signals were received even though no line-of-sight conditions existed. The U.S. Federal Communications Commission (FCC) considers -102 Dbm a commercially acceptable signal.

Table IX : RF Static Measurements

Source Location	Signal Level, Dbm
B	-87
F	-101
H	-111
G	-118
J	-92
K	no signal
M	-83

RF Attenuator Addition

The addition of an RF attenuator showed that a margin of 20 Dbm was available at point J. This means that 1/120 of the power would yield an acceptable signal.

5.7 0 Dbm Transmitter

The purpose of this experiment was to measure the RF margin available for radio system design.

5.7.1 Method

In order to further test the quality of signal available, an experiment was performed that consisted of mounting a communication monitor (transmitter 3) at point D. Portable radio units (receiver 2) were carried by men toward point E. The RF output power was then set to 0 Dbm, -10 Dbm and -20 Dbm to measure to signal quality.

5.7.2 Results

As the radios were walked to point E, their performance was measured using a Receptivity Scale (Table X) in terms of voice quality. At 100 metres from point D with a power level of -20 Dbm the reception was considered 5-5.

Table X : Receptivity Scale

5 - 5 Scale	Signal Level (Dbm)
1 - 5	(below -126)
2 - 5	-120
3 - 5	-114
4 - 5	-108
5 - 5	(above -102)

At point E with power levels of 0 Dbm, -10 Dbm and -20 Dbm the reception was considered 5-5, 3-5 and 1-5 respectively. A system analysis for point D to E is shown in table XI.

The RF transmission levels were higher than expected. The most probable

Table XI : System Analysis

Transmitter 3 : (signal generator) radiated power (1 mWatt)	0 Dbm
Receiver 2 : (portable radio antenna gain	-14 Dbm
Free Wave Path Loss (180 m)	-70 Dbm
Sector Loss Obstacle Loss (none because considered straight line)	-18 Dbm nil
Received Signal	-102 Dbm

explanation for this is the presence of bolting and screening. The metal attached to the drift walls seems to provide an electromagnetic reflector.

5.8 Background Noise Measurements

The purpose of this sub-experiment was to determine the background electromagnetic noise in a typical underground operating environment.

5.8.1 Method

The communication monitor was switched to Spectrum mode. The frequency spectrum was then swept between 100 and 800 Mhz at 10 Mhz intervals. The antenna was oriented to achieve maximum components of the vertically polarized electric field.

5.8.2 Results

Table XII shows the monitored signal levels greater than -120 Dbm and the frequency of those signals. This corresponds to the minimum level that a commercial portable radio can handle with a normal antenna. As can be seen by the table, there is sufficient signal power to cause interference to communication channels of the same frequency. The most crowded band of interference is between 400 and 500 Mhz.

During the sweep, it was observed that every 100 Mhz, starting at 100 Mhz, there was an interfering signal. Although there was no proof, it was speculated that the harmonics might have been induced by power line interference. There were several other suspected sources of noise besides power lines, including:

* ITH Drills
* Drill Jumbos
* Mine Telephones
* Conveyor Belt Motors
* Hoist Motors
* Fluorescence of sodium vapour lamps
* LHDs

5.9 Video Transmission Quality

The purpose of this sub-experiment was to test the suitability of the leaky coax radio frequency transmission in the mine workings at the power levels available in the operation.

5.9.1 Method

The investigation of video transmission quality required the installation of 300

Table XII : Recorded Noise Levels

Frequency (Mhz)	Strength of the Monitored Signal (Dbm)	Comments
100	-95	
200	-100	Harmonic of 100 Mhz
300	-110	Harmonic of 100 Mhz
400	-95	Harmonic of 100 Mhz
425	-110	
439	-110	
441	-120	
455	-115	
486.5	-115	
499.9	-110	
500	-95	Harmonic of 100 Mhz
535	-115	
550	-105	
552	-105	
600	-95	Harmonic of 100 Mhz
700	-95	Harmonic of 100 Mhz
750	-105	
800	-90	Harmonic of 100 Mhz

metres of Leaky Cable on 3000 level. The cable was connected to a modulator and the RF port of the VCR. A movie was run on the VCR, and the signal was transmitted over the Leaky Coax. The testing procedure consisted of walking on the level with a portable television set, while viewing the screen and listening to the audio quality to determine suitability. Figure 30 shows the equipment and connections used in the experiment.

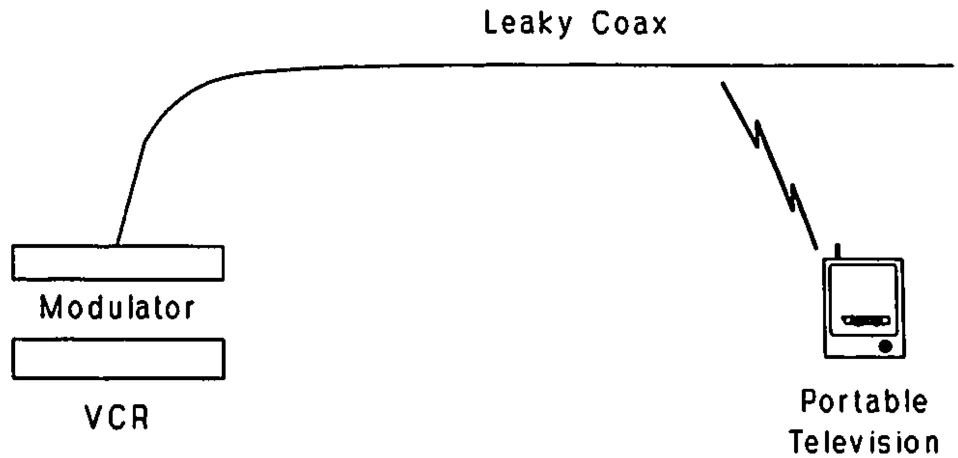


Figure 30 : Video Quality Experiment

5.9.2 Results

The performance during the test resulted in a perfect video and audio reception directly under the leaky coax cable antenna. As the television was moved into the cross cut (approximately three metres from the leaky coax antenna) a momentary fading of the video picture was experienced. The television was moved into the back of the drill sill in line of sight of the leaky coax antenna and at approximately 30 metres away the colour of the picture was lost. The television was then moved so that it was no longer line of sight by positioning the television so that a rock pillar was between the leaky coax and the television. This resulted in a snowy picture, and as it was moved farther around the corner of the drill sill, the picture was lost and then finally the audio was lost as shown in figure 31.

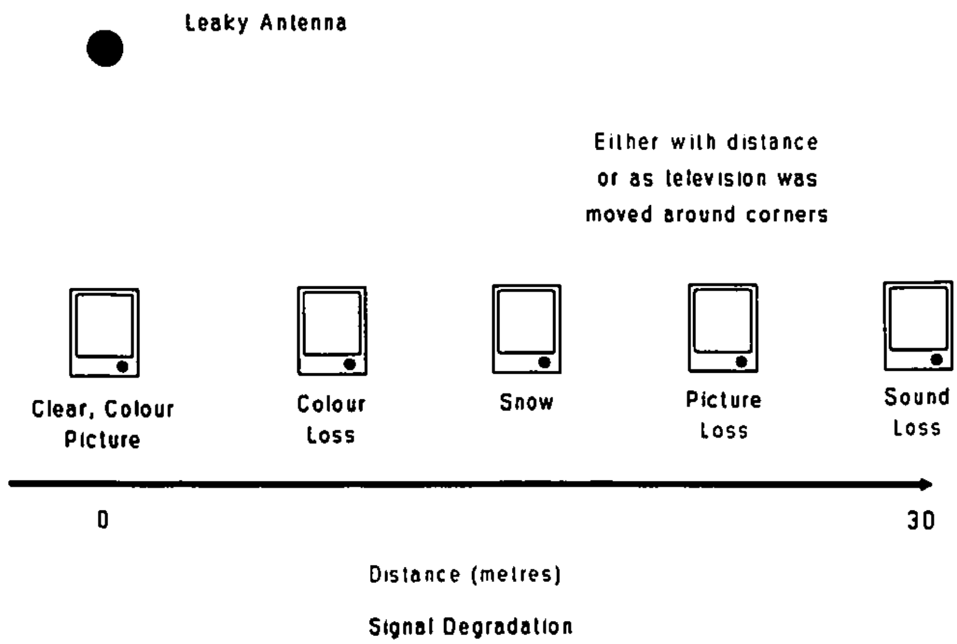


Figure 31 : Television Signal Degradation

5.10 Summary

The most suitable frequency band for RF transmission underground proved to be in the UHF range. RF transmission underground offered no significant problems that would prevent the development and use of a communication system.

The recorded values for signal level were higher than expected. The most likely explanation of this is considered to be the presence of metal screening on the back acting as an electromagnetic reflector, similar to the inductive coupling experienced in MF radio systems. Some experimentation should be performed in the future to determine the reason for the improved performance.

There was sufficient noise generated underground, probably due to the power distribution systems to affect communication frequencies. As a result, the communication infrastructure developed must account for these potential problems in the system design where possible.

6 COPPER CLIFF NORTH MINE : COMMUNICATION INFRASTRUCTURE EXPERIMENT

The telecommunication infrastructure experiment conducted at Inco's North Mine is discussed in this section. The format of this section covers objectives, methodology, results and conclusions. The establishment of this infrastructure will provide the backbone necessary to define a strategy for mine automation and the economic benefits of this, later in this work.

6.1 Objectives

The objective of the experiment was to develop and test a communication and information infrastructure capable of supporting information systems, and remote controlled and automated mining systems. This system would require the ability to transmit and receive information, including voice, data and video, at all stationary and mobile locations in the operation.

6.2 Prototype System Components

The experimental equipment outlined in this section was installed at Inco Limited's Copper Cliff North Mine. The coverage of the installed communication system consisted of various levels in the mine for the broadband cable system and the 3000 level for testing of the radio interfaces to the system.

6.2.1 CATV Broadband Network

The basic backbone of the infrastructure was a broadband cable system. This consisted of a headend and coaxial cable distributed throughout the operation to transfer signals. The headend consists of equipment for signal processing, modulators, demodulators, signal combiners, data translation units and power supplies. System splitters, directional couplers, and taps direct signal flow to desired paths along the cable system. Filters are used to process signals depending on their frequency. Outlets connect devices to the network. And finally, amplifiers are used to increase signal strength back to the desired levels. The cables used in a coaxial network were divided into three layers :

* the first layer, the trunk cable, transported signals between amplifiers located throughout the operation.
* the second layer, the distribution cable, connected the trunk cable to the underground levels.
* the third layer, the drop cable, linked the distribution cable to the device.

The connection of devices to the broadband required a change of signal via a radio frequency modem to baseband and the device. This connection is shown in figure 32 along with the other components of a broadband system. RF modems can be purchased at a number of frequencies for use with the broadband.

The broadband network at North Mine covered the surface, 2200, 2400, 3000, 3800 conveyor gallery, 3935 and 4000 levels. The installation consisted of a main 2.22 cm. trunk coax mounted in the shaft ready to be expanded to all levels. On the horizontal levels, a distribution cable was run from an active amplifier to the level using passive amplifiers, splitters and taps for coverage. Amplifiers were purchased with redundancy built in and the system was designed such that an amplifier failure would cause the backup amplifier to actuate and in the event of a double amplifier failure, the amplifier could be bypassed totally from the control room on surface.

The broadband was monitored in the control room with software diagnostics to check the health of amplifiers, power supplies and cable sections in the operation. This allowed for monitoring the health of the system in the control room and the location of faults without having to travel underground.

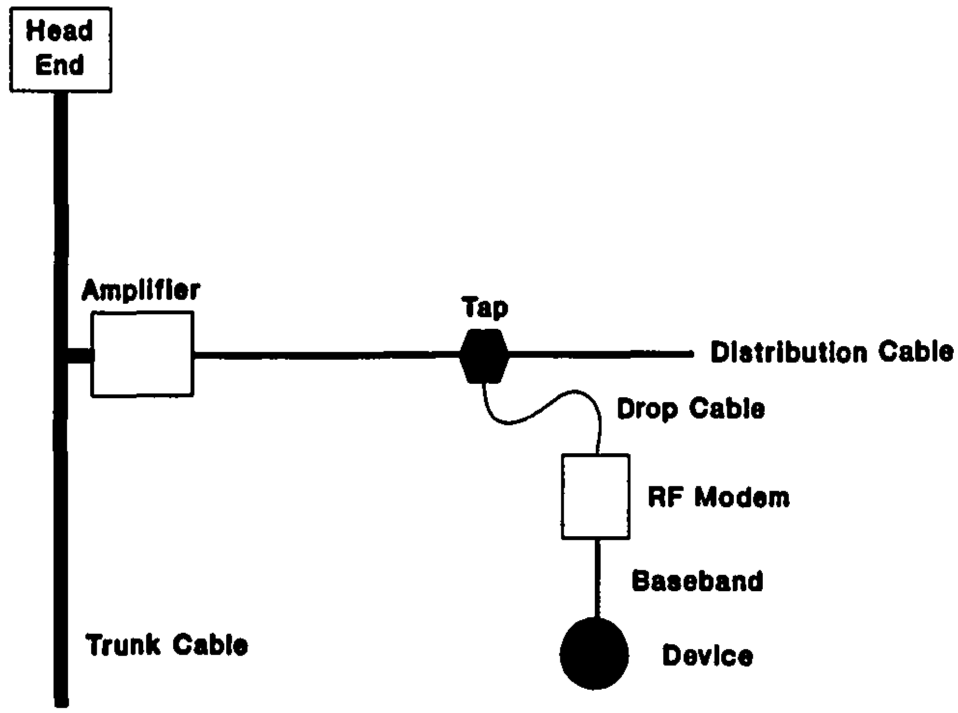


Figure 32 : Components of a Broadband Network

6.2.2 Radio System

The radio system was designed to fit in the broadband architecture previously described. A schematic of the underground information system is shown in figure 33. The devices installed on the test 3000 level included a DAT, trunk and distribution leaky coaxial antenna.

6.2.2.1 Distributed Antenna Translator

The DAT was developed for connection to the broadband cable system so that the RF spectrum of the broadband cable system could be mapped to the leaky antenna and utilized over radio modems to various pieces of equipment. The DAT

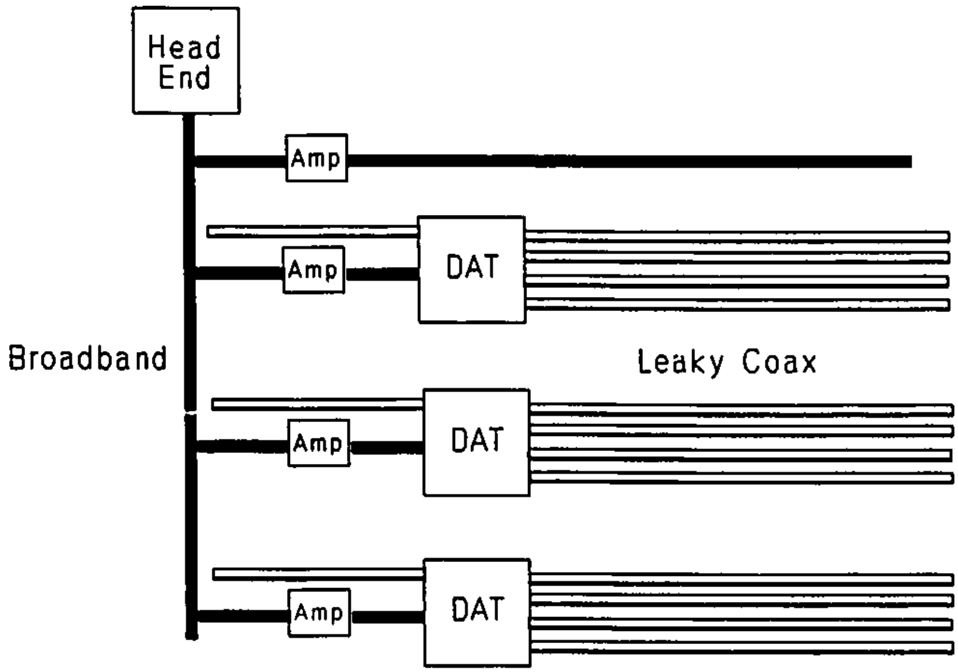


Figure 33 : Information System Combining Broadband and Leaky Coax using a Distributed Antenna Translator

consisted of voice modems, data modems, video translator, power supplies, an IBM™ Industrial Gearbox™ and an antenna combiner.

6.2.2.2 Leaky Coaxial Antenna

The Leaky Coaxial Antenna used for experimentation on the 3000 level consisted of a trunk of Andrews Radiax 2.22 cm., type RXL5-1, and distribution of Radiax 0.95 cm., type RSL2-2, with lengths of 750 metres and 667 metres respectively. The distribution leaky coax was attached to the main trunk by 2-way power splitters, 50 ohm, N-type. The trunk and distribution cable were terminated using Radiax 2.22 cm. N-type plug L42W and Radiax 0.95 cm. N-type plug L45W respectively.

6.2.3 Portable and Stationary Telephone

A portable telephone was developed to attach to the system. This consisted of a standard telephone set with a broadband modem for connection to the broadband cable network. The portable telephone was run with gel-cell batteries or could be plugged directly into 110 VAC. The establishment of communication between the portable telephone and the outside lines consisted of point-to-point modems running at 33 and 225.25 Mhz at 100 Khz channels.

6.2.4 Computer Network System

The computer equipment installed consisted of a server computer (IBM™ Model 95) and seven workstations (IBM™ Model 70). These machines were connected to the broadband via network adapters running on channel 2' [a] at frequencies of tx 53.75 and rx 246 Mhz. The network operating software utilized was IBM™ LAN SERVER™ using OS/2™ as the operating system. In order to operate a system like this, an absolute requirement was a multitasking operating system. Several different pieces of software were then put on the system. These included:

1) Lotus™ 123™
2) Wordperfect™
3) Harvard Graphics™
4) Autocad™
5) LHD Data Acquisition
6) LHD Maintenance Expert System

A gateway was added to the system to allow all computers connected to the network to have access to the Management Information System (MIS) located in the Copper Cliff General Office about three kilometres away.

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[a] 2' is a designation given to a channel on a CATV cable system.

6.2.5 Mine Supervisory Control and Data Acquisition (SCADA) Network

The existing mine SCADA network was originally installed in 1982. The system consisted of 10 Modicon PLCs, ranging from the early 484 model to the current 984. These were integrated together via a SCADA system called "Modvue™". The PLCs are located throughout the mine and on surface. They are used for controlling:

1) Ventilation
2) Pumping
3) Material Handling Circuit
4) Dewatering
5) Hoisting

The control function was not directly part of the experiment as it existed previously. Although, they were connected to the communication system to allow system expansion and growth in the new environment. This entailed the redevelopment of the SCADA to fit in the new environment using FIX DMACs process control software and RS232 connection to the PLCs via broadband MODEMs.

6.2.6 Video Cameras

Four video cameras were installed in the material handling circuit. These allow visual monitoring of the crusher station on 4000 level, loading pocket on 2200 level, skip dump on surface and the conveyor head on 3800 level. The system is software based from the control room allowing for zoom, pan, tilt and focus of each camera individually.

6.2.7 Portable Radios

Four Motorola™ "Sabre™" radios were used in the experiment. These were selected because of their ability to be programmed by an IBM™ PC compatible computer for channel selection and use. The radios were 120 channel synthesized radios with power packs for approximately six hours of power.

6.2.8 Load Haul Dump Machine

The main mobile equipment test-bed for the radio experimentation was a rebuilt ST8A LHD. There were three main subsystems installed on the unit consisting of monitoring, control and video. The unit was fitted with 34 sensors to monitor the health of the machine for the experiment. The machine was also fitted with a remote control unit and two video cameras, mounted looking forward and reverse, for remote control or teleoperation of the machine.

6.2.8.1 Data Acquisition System

The data acquisition system for the LHD consisted of an operator panel, sensor interface unit, radio transmitter/receiver and 34 sensors. The sensors measured a variety of points ranging from pressures, temperatures, RPM and level. A comprehensive table follows later in this chapter.

6.2.8.2 Remote Control System

The remote control unit was purchased from MOOG™. It consists of a series of digital controls transmitted to the receiver on the machine via a 467.750 Mhz radio signal. The unit has controlled all functions of the vehicle including propulsion, braking, steering, digging and miscellaneous functions like lights and ignition. This unit is a standard product used in the mining industry for line-of-sight machine control. The maker of the remote control was not an issue as any similar unit could be used.

6.2.8.3 Mobile Video Cameras

Two black-and-white video cameras were installed for visual control of the machine. The cameras were mounted on the front and the rear of the machine in stationary positions so that the cameras did not move relative to the machine and the operator had a positive reference to the machine. The cameras were connected to the remote control unit interface so that the cameras were switched according to the selected direction of the machine. The video picture was transmitted to the leaky coax via a half dipole antenna on the rear of the machine. Colour cameras were not used as the RF testing proved a signal loss existed, and the first portion of the signal to be lost would be the phase portion of the video signal which would eliminate the colour on the system.

A microphone was added after some initial experimentation as it was determined the operator needed audio feedback to operate the machine.

6.3 Methodology

In order to experiment with the application of voice, data and video services for underground mining, several components had to be designed, installed and commissioned. The goal of the experiment was to run all of the services outlined in this section in real-time simultaneously. Figure 34 shows an overview of the communication system to be tested along with the various sub-experiments. The overall methodology of the experiment was the installation of a broadband communication system, development and installation of the DAT and leaky coax antenna. Followed by experimentation with telephones, PC computer network, Supervisory Control and Data Acquisition system, surveillance fixed video, personal radio, mobile data acquisition, mobile control data transmission and mobile video surveillance. The last three combine to facilitate the experimentation with LHD teleoperation.

6.3.1 Broadband Network

The first step in the experiment was the design, installation and commissioning of a broadband cable system at Copper Cliff North Mine. The system was designed as a backbone to cover the shaft and six levels using "off-the-shelf" components. Following installation, the cable system was commissioned and certified before experimentation would continue.

The configuration of the cable system was a main trunk in the shaft and distribution capability to all levels in the mine. Distribution runs then were fed in from the trunk on surface, 2200, 2400, 3000, 3935 and 4000 levels. On all levels, four and eight port taps were installed to facilitate direct connection to the broadband at 40 metre intervals. The design of the broadband cable utility was made according to IEEE 802.7 specifications. Engineering design was used to determine the location of amplifiers, based on the configuration, so that a frequency balanced system would be designed for underground application.

Installation of the broadband system consisted of installing 2400 metres of 2.22 cm. diameter cable trunk cable in the shaft. At all levels, Directional Couplers were used to split the signal and ready the system for expansion. A total of 2300 metres of distribution cable was installed on the horizontal runs with taps located at 40 metre intervals. Cable status monitors were installed on distribution cable ends to allow display of the diagnostics of the system. Two backup power supplies were installed to insure that the cable system would continue to run in the event of a power failure. Following the cable system installation, the headend unit, located in the control room on surface, was brought online with a Pilot

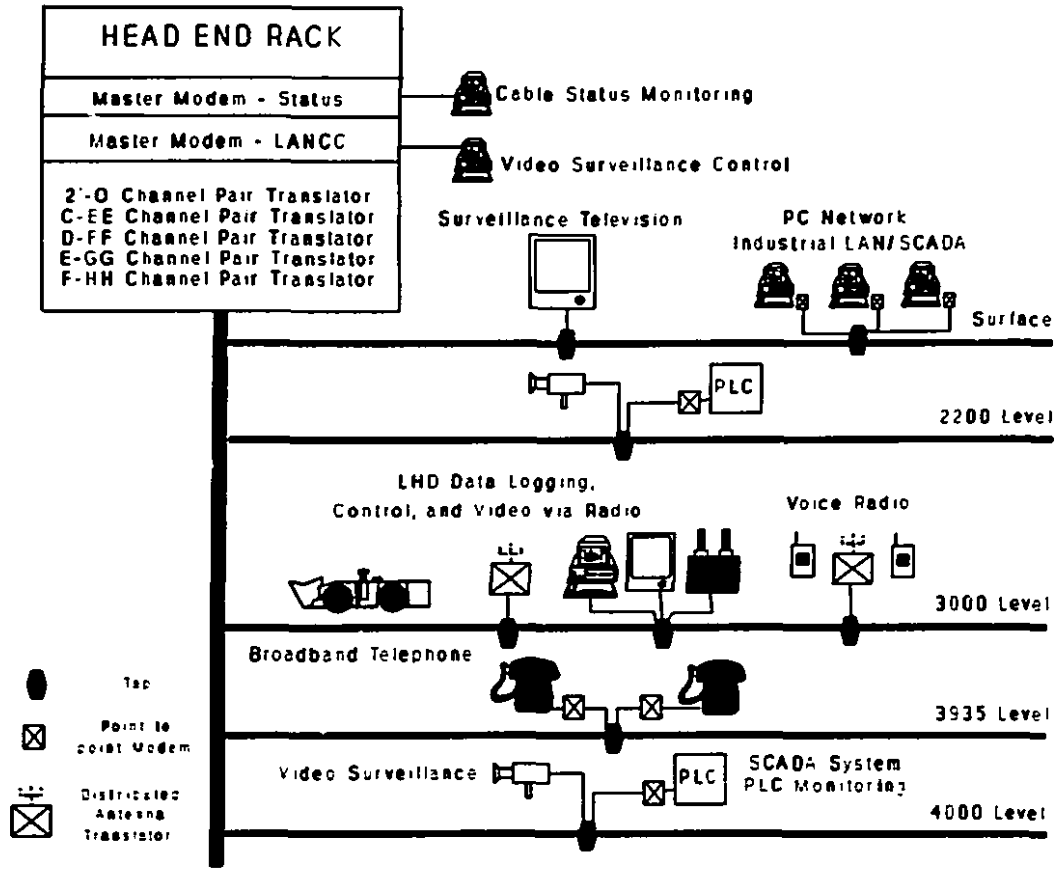

Figure 34 : Broadband System Architectural Overview

Signal Generator, Status Master Modem, LANCC Master Modem and five translators to cover the inbound and outbound channels shown in figure 35.

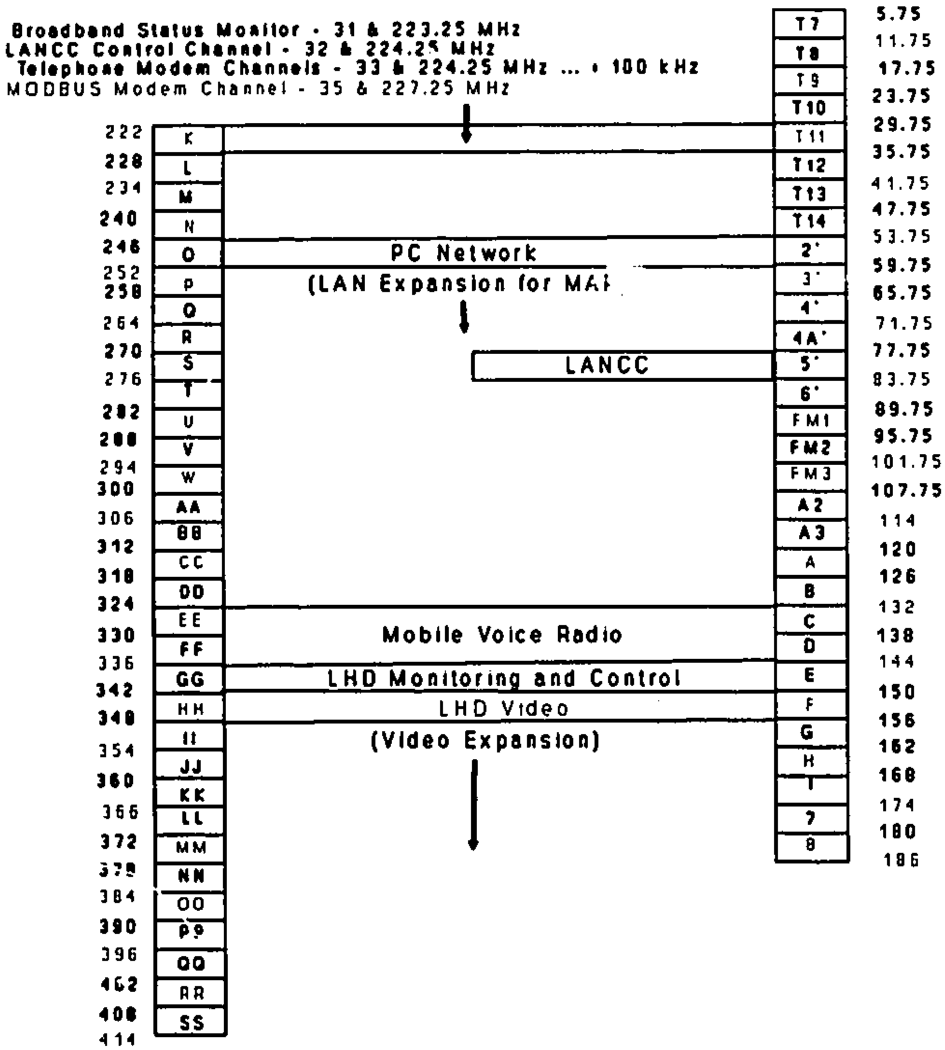

Figure 35 : Broadband Channel Allocation Chart

The Pilot Signal Generator was used to generate a reference signal to check the health of the amplifiers by a comparison of the reference signal with the actual signal. The cable status was monitored using the status master modem, an IBM™ PC and "Quick Alert Software™". The status master modem was used by the IBM™ PC to poll amplifiers, power supplies and status monitors on the health of the network. If any problems occurred the control room would be alarmed via the Quick Alert™ software so that the condition could be rectified. The LANCC™ Master Modem and the five translators will be discussed in subsequent sections.

Following installation, the system was commissioned by checking all operating parameters at each active location and the ends of the cable. The forward and reverse RF signals were recorded at all test points to ensure system operation and conformance with the IEEE 802.7 specification. Following the commissioning and certification of the broadband cable utility, the remainder of the experiment could continue.

6.3.2 Radio Network

The radio network installed on 3000 level consisted of a Distributed Antenna Translator (DAT), trunk and distribution leaky coax antenna. Broadband drop cables from the distribution branch on 3000 level were connected to the DAT. Radio antenna cable was run on 3000 level in the form of trunk and distribution legs covering the main drifts and the drill sills.

The DAT was located centrally in an electrical room on 3000 level. Four 2.22 cm. trunks were installed from the DAT covering the shaft station, the north and south drifts and a short section in the garage area. Distribution cable was run from the trunk to the workings using 0.95 cm. Radiax cable. The Leaky Coax was attached to the back of the drift using tiewraps with no other special procedures.

The DAT housed electronic equipment for the translation of the experimental radio signals from the leaky coax to the DAT, and to the Broadband. With this system installed the experimentation could begin.

6.3.3 Telephones

The plan for experimentation with stationary voice services was to provide outside Bell services over the broadband. This scenario, shown in figure 36, was designed to allow two telephones underground to be connected via point-to-point modems to the broadband, then out through the head-end translator to a "Centrex™" switching station via two more point-to-point modems and finally, to the outside telephone lines. The telephones underground must have the capability to call underground-telephone-to-underground-telephone and underground-telephone-to-surface-telephone.

The bottom portion of figure 36 shows the allocation of channels on the broadband to map from underground-telephone-to-outside-telephone-line. One

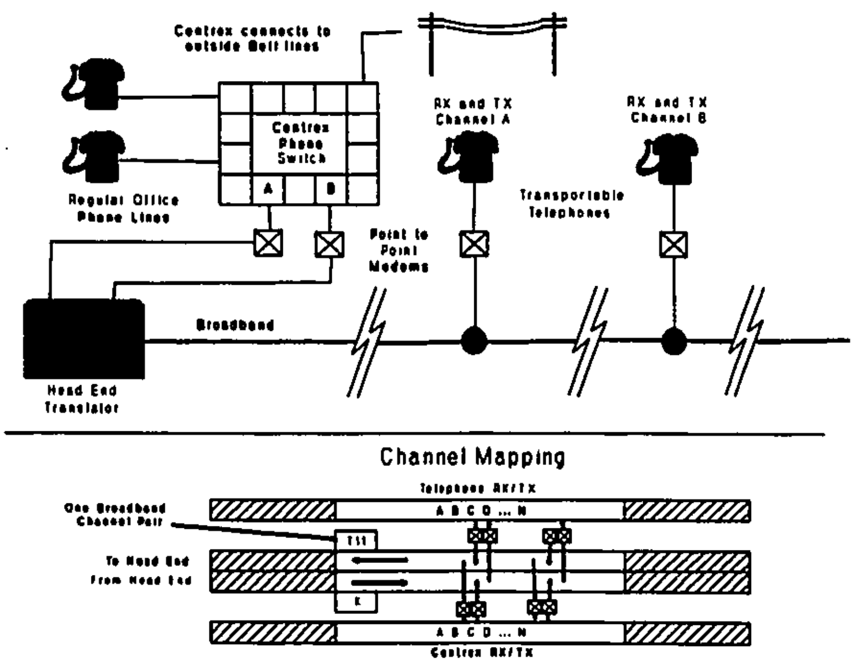

Figure 36 : Broadband Telephone Experiment

broadband channel T11 and K (TX 29.75 Mhz and RX 222 Mhz) had 3 - 100 Khz sub-channels allocated to stationary voice communication. Underground telephones were connected to point-to-point modems which allowed access to the broadband channel. This communication was then mapped via the translator to the Centrex™ switch point-to-point modems.

6.3.4 Radios

The mobile voice system was tested using four Motorola™ "Sabre™" radios in conjunction with the DAT and the leaky coaxial cable. The system was installed so that the RF spectrum used for voice was translated from the wireless distribution onto the allocated channels of the broadband system. A head-end transceiver retransmitted the VHF spectrum back along the broadband and re-radiated it out over the distributed antenna system as shown in figure 37.

A total of three channels were allocated to mobile radio with one being connected to the Centrex™ switch and the telephone lines. The Sabre™ radios were totally programmable using an IBM™ PC. This allowed two scenarios to be tested: radio-to-radio and radio-to-surface telephone. The mobile radio transmitted three channels within the VHF band between 406 and 410 Mhz.

6.3.5 Computer Network

Following the installation of the broadband cable system a translator was installed in the head-end. This was to enable a computer network to be used for CAD systems, SCADA system and the development of an expert system for LHD maintenance shown in figure 38.

The network had two servers installed for disk and peripheral service to the network. The disk server consisted of an IBM™ Model 95 with two-300 mb hard

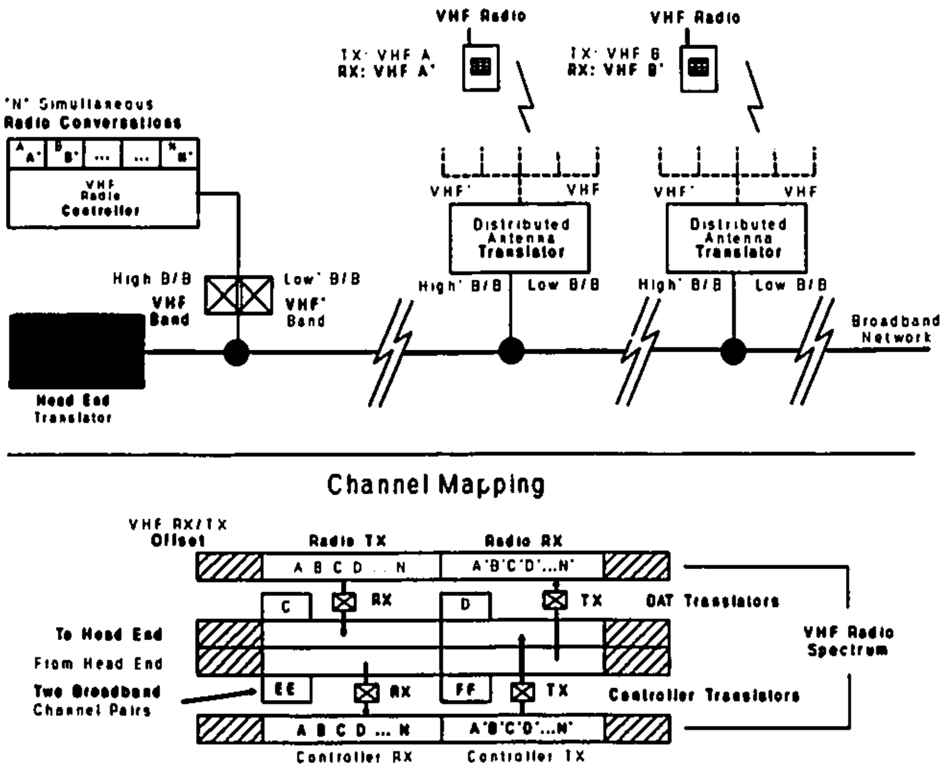

Figure 37 : Voice Radio System

disks, running OS/2™ version 1.3 as the operating system. The software used on the network resided on this computer. Several popular software packages were installed including Lotus™ 123™, Autocad™, Wordperfect™ and The Fix™.

The peripheral server was an IBM™ Model 80. This computer was installed to attach printers, plotters and digitizers to the network. By connecting them in this fashion these devices were available all over the network.

A total of 22 other workstations were installed on the system for the development of the mine planning and operational systems. These machines ranged from IBM™ Model 70 through to clone computers. Each unit had an IBM™ Broadband Network Adapter Card (frequency 2') installed for connection to the

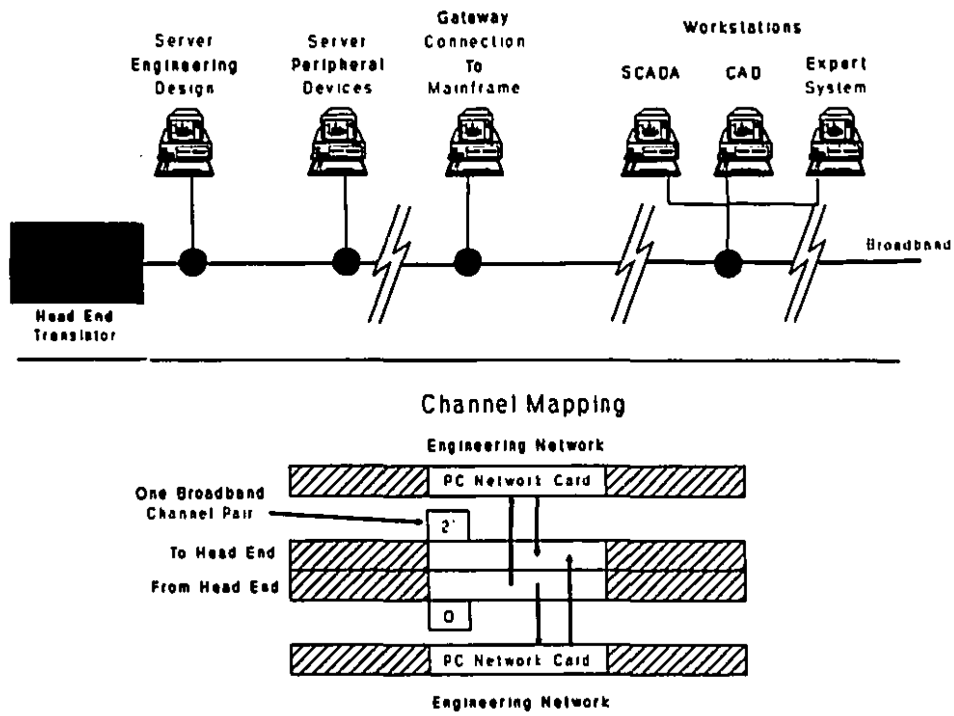

Figure 38 : Broadband Computer Network

network. The card was based on a contention type system using the CSMA/CD defined in IEEE 802.3 as the Token Bus (IEEE 802.4) was not readily available.

6.3.6 Process Control Network

A SCADA system was already in place at North Mine. This system was based on Gould Modicon™ equipment of PLCs and SCADA displays. As part of the development of the communication system, this system was reworked to update it and determine the method of connection in the underground network architecture.

A total of 10 PLCs were located throughout the operation. The units were made up of models ranging from 484s to 984s. The current connection to surface was via twisted-pair lines directly to the SCADA displays. The method of installation on the broadband was by point-to-point modems attached to the RS232 ports of the PLCs. Once the connection was established, SCADA nodes were developed using "FIX DMACS™" software by "Intellution™". Two full SCADA nodes existed on the network along with two view nodes, with "view only" capability. The full and view nodes were also a part of the PC network used in the engineering office discussed in the previous section.

The SCADA nodes are very graphic in nature showing schematics of the mine. A total of 18 process control screens were developed as part of the experiment. The process control system developed to fit on the communication infrastructure is shown in figure 39. In this figure, a number of screens were dubbed for future development. These remained from the original system as the capacity of the system had reached its limit. On the old system, a total of 16 kb was avâilable to the screen developer. On the new system, using a multitasking operating system OS/2™, 16 Megabytes were available eliminating the development bottleneck.

6.3.7 Video Cameras

Stationary video cameras were experimented with in the underground communication system. Experimentation with the stationary video camera system took place on surface at the skip dump, on the 2200 level at the loading pocket and in the main crushing station on the 3935 and 2400 levels at the loading pocket. These points were selected to aid the operation with diagnostics of the material handling circuit and to allow the mine to move further towards automation.

Figure 40 is an overview of the video monitoring system. Two forms of communication had to be established to allow stationary video monitoring together with real-time control data and a video channel. Real-time control needed to be

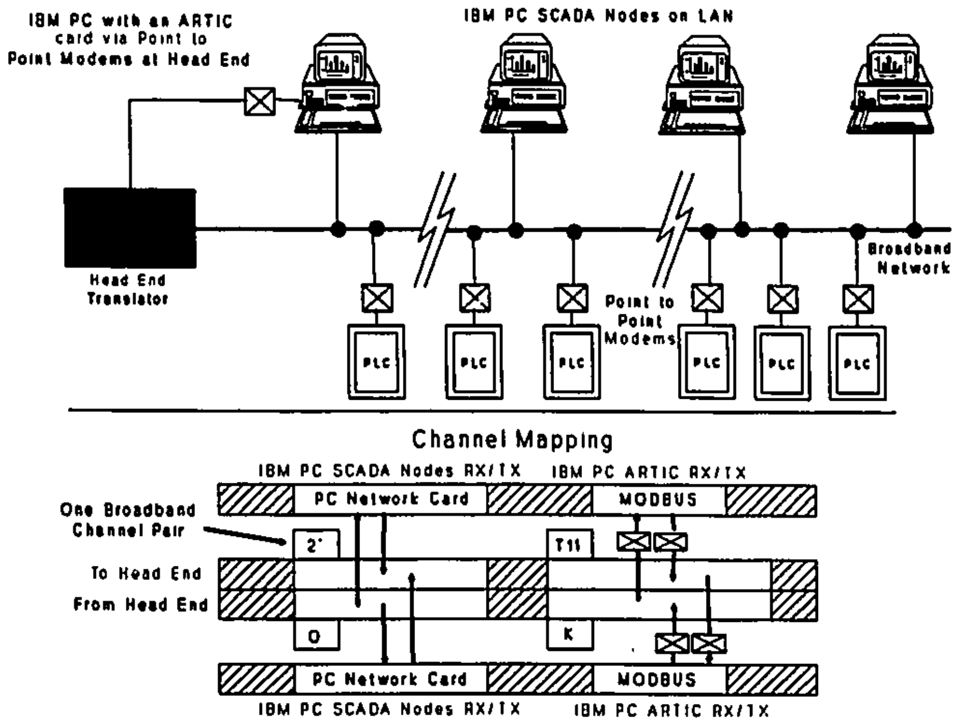

Figure 39 : Process Control System

established between the pod on each camera, the broadband and the LANCC™ master modem, which was to be connected to an IBM™ PC running "Quickview™" software. Channel 5' was established as the video transmission channel. All the cameras were multiplexed so that they could be switched and viewed using one monitor located in the control room. Each video camera was connected to pods for control of the camera functions: pan, zoom and tilt.

The channel mapping was performed on 5' and T11 and K. 5' was used for the video transmission as a one way channel to the head-end. T11 and K were used for two way control of the camera pods. This allowed an RS232 line to exist on the network and control the pods through the IBM™ PC and LANCC™ master modem.

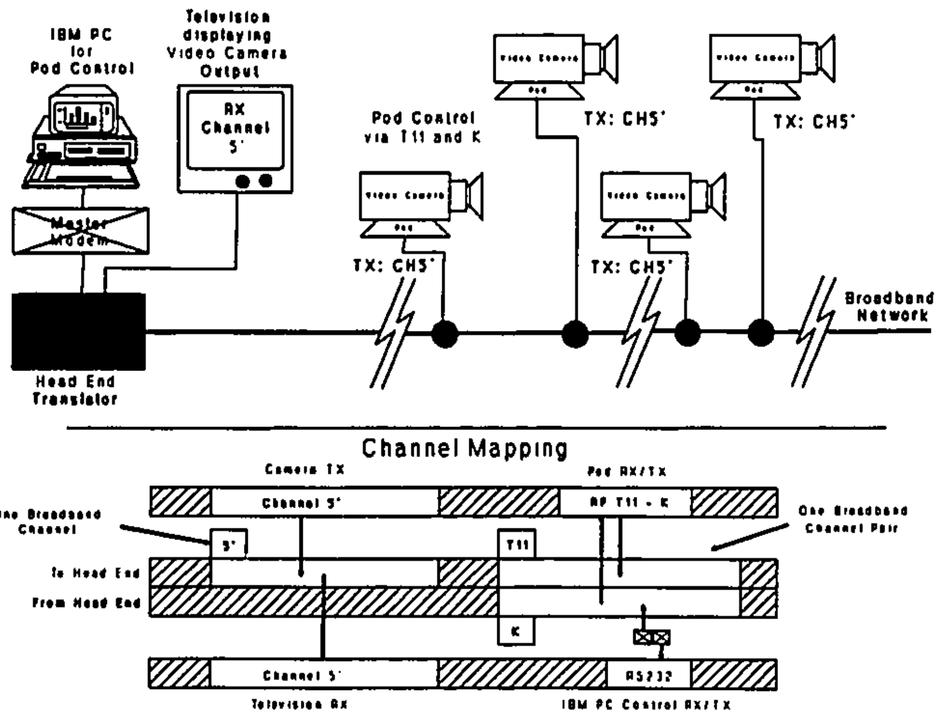

Figure 40 : Stationary Video System

6.3.8 LHD Teleoperation

LHD teleoperation consisted of integrating subsystems on the machine to allow the unit to be run from anywhere on the communication system. In order to achieve teleoperation, mobile control, data acquisition and video monitoring needed to be achieved at real-time speeds. An LHD was selected, since this machine promised to be one of the most severe communication loads on the system, and a machine that was already familiar to mine operations personnel. Figure 41 is a representation of the experiment designed to prove that the communication system was capable of supporting this type of load.

6.3.8.1 Mobile Control System

Currently, LHD units underground are fitted with remote control systems.

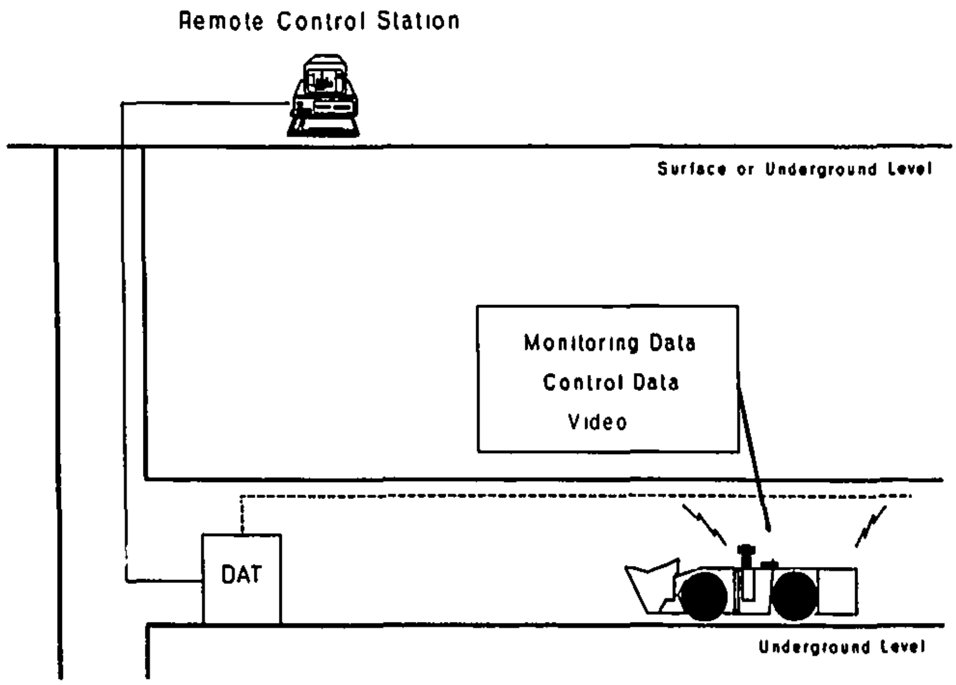

Figure 41 : LHD Teleoperation Experiment

Several brand names exist on the market. However, for the purpose of this test a MOOG™ remote system was used. These systems typically operate under line of sight with a dipole antenna mounted on the transmitting and receiving portions of the system.

In order to test the communication system, the dipole was removed from the transmitting unit and directly connected to a translator and then to the broadband cable system via a drop cable. The transmitting unit was then powered and the signals were moved from the transmitting unit to the translator in the control room on surface and then to the DAT on 3000 level where the signal was mixed and combined for transmission on the leaky coax in the mine workings. The receiving unit on the LHD would then receive signals from the cable system for control of the machine. An overview of the system is shown in figure 42.

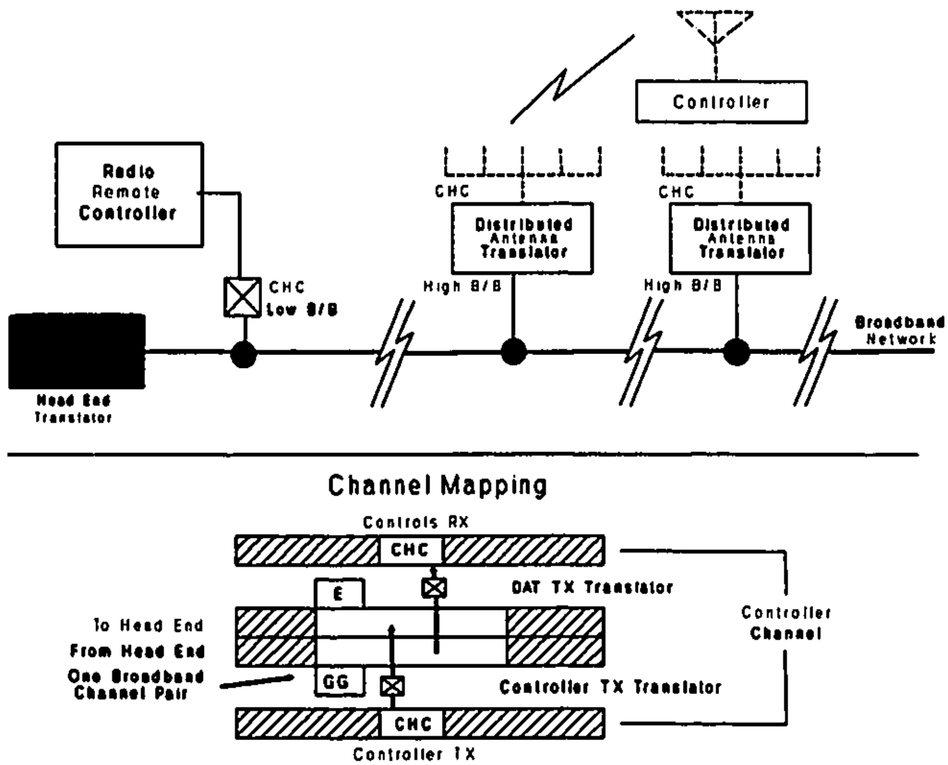

Figure 42 : Mobile Radio Control System

6.3.8.2 Mobile Data Acquisition System

Mobile data acquisition was accomplished by mounting a mobile data acquisition system on a ST8A LHD rebuilt, transmitting the information to the DAT, and then onto the broadband for access on the network as illustrated in figure 43. The mobile data acquisition system consisted of 34 sensors, a sensor interface unit, operator display panel and a CB radio for data acquisition.

The sensors on the machine were mounted to measure the performance of several subsystems on the LHD. These were:

* Engine
* Hydraulics
* Exhaust

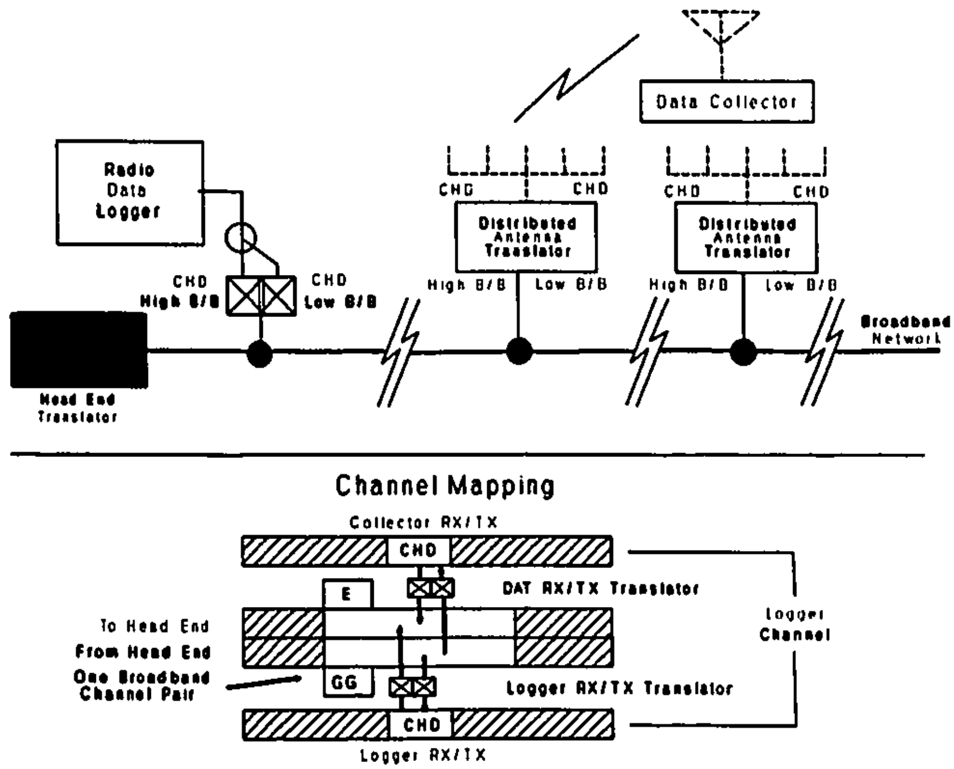

Figure 43 : Mobile Data Acquisition System

* Brakes
* Transmission
* Electrical
* Fuel
* Vehicle Pitch and Roll

All sensors were measured at varying time intervals ranging from a few milliseconds to 15 minutes.

All sensor information reported to the sensor interface unit for processing consisted of digital, analog and timer signals. The signals were processed and then stored for transmission and/or display. The sensor interface unit was mounted under the operator compartment of the LHD with all electrical feeds terminated at this point.

The information generated and processed in the sensor interface unit was transmitted to the operator display for presentation. The display method used a numeric keypad to enter in the sensor number and following to depression of the enter key the information could be viewed by the operator. The operator display panel on the LHD has an 8086 based processor which controlled the display and communication of the information. The basestation controlled the CB radio by toggling the microphone. In the sequence, information is transmitted at 1200 baud over the communication system to a basestation computer. The operator display was mounted above the dash board on the LHD and the radio was mounted under the operator's seat.

The information reported from the LHD was collected via the leaky coax to the DAT and the IBM™ Gearbox™ located inside. This unit had 10 mb of hard disk space, 512 kb of RAM and a broadband network adapter card running on frequency 2'. A second computer, the server IBM™ Model 95 for the system, was then allowed to access the hard disk of the Gearbox™ and information on the health of the machine could then be retrieved.

6.3.8.3 Mobile Video

The mobile video cameras were used to control the LHD providing vision for the operator. A microphone was included in the video equipment using the audio portion of the video channel to act as the operator's ears. Figure 44 is an overview of the system. The two cameras were mounted on the LHD, one on the front and one on the rear, while the microphone was mounted near the rear, by the engine.

The camera switch was integrated with the remote control unit so that the front camera would be viewed when the machine was in forward and rear when in reverse gear. Black-and-white cameras were used as the power limitation related

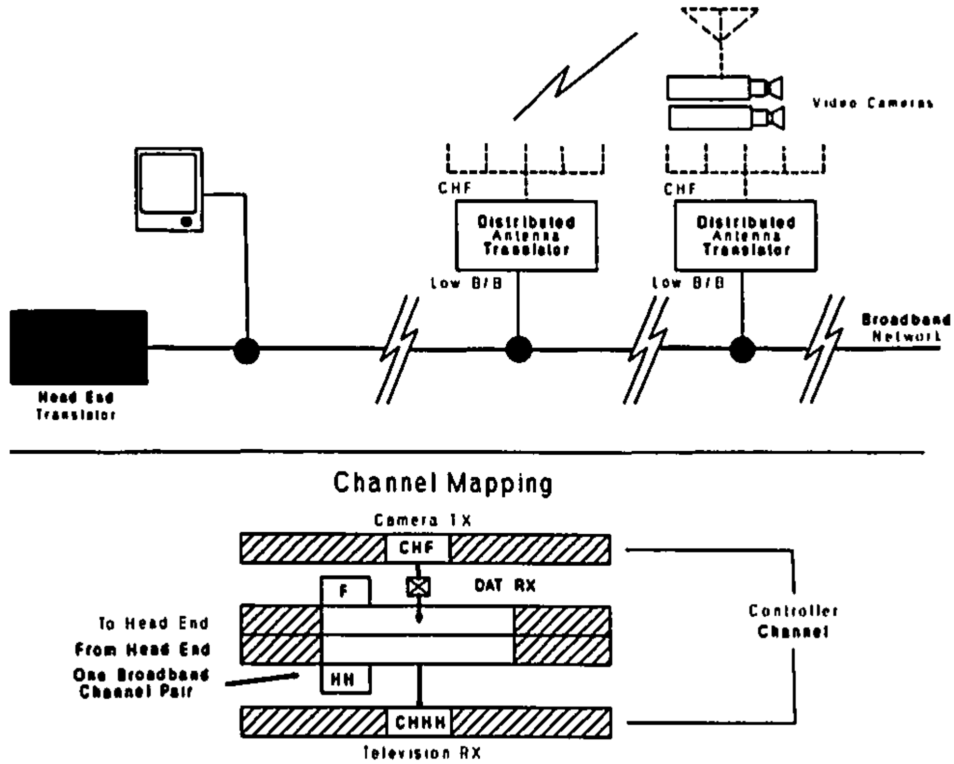

Figure 44 : Mobile Video Transmission

to electric blasting caps would mean that the colour could not be maintained.

The video out from the switch was modulated and transmitted through two half wavelength dipole antennae, tuned for 211 Mhz, to the leaky coax. The signal was then mapped from the leaky coax to the broadband via a translator for viewing on a video monitor anywhere on the system.

6.4 Experimental Results

This section discusses the experimental results achieved as part of this work at North Mine. It is divided into a number of sections which describe the components of the experiment

6.4.1 Cable System

The experimental system was installed at Copper Cliff North Mine in the shaft and on six levels including surface. The 3000 level was used to test the radio communications portion of the experiment.

The head-end for the system was located in the control room on surface. Figure 45 shows the control room and figure 46 is a closer view of the head-end.

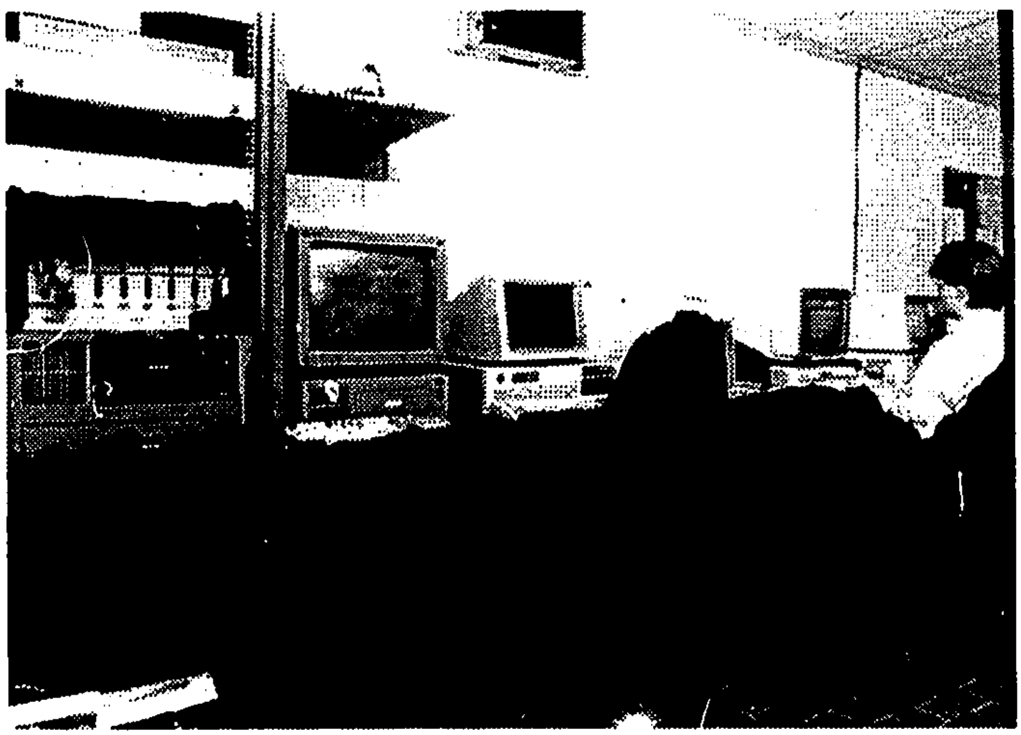

Figure 45 : Control Room

The installation of the broadband trunk in the shaft was developed so the operations could add on to the system readily. Figure 47 shows the cable trunk installed. At each level in the mine a splitter was installed to facilitate expansion while on the levels were the broadband was expanded an amplifier was installed in the electrical switchroom as shown in figure 48. The levels covered by the broadband were surface, 2200, 2400, 3000, 3935 and 4000.

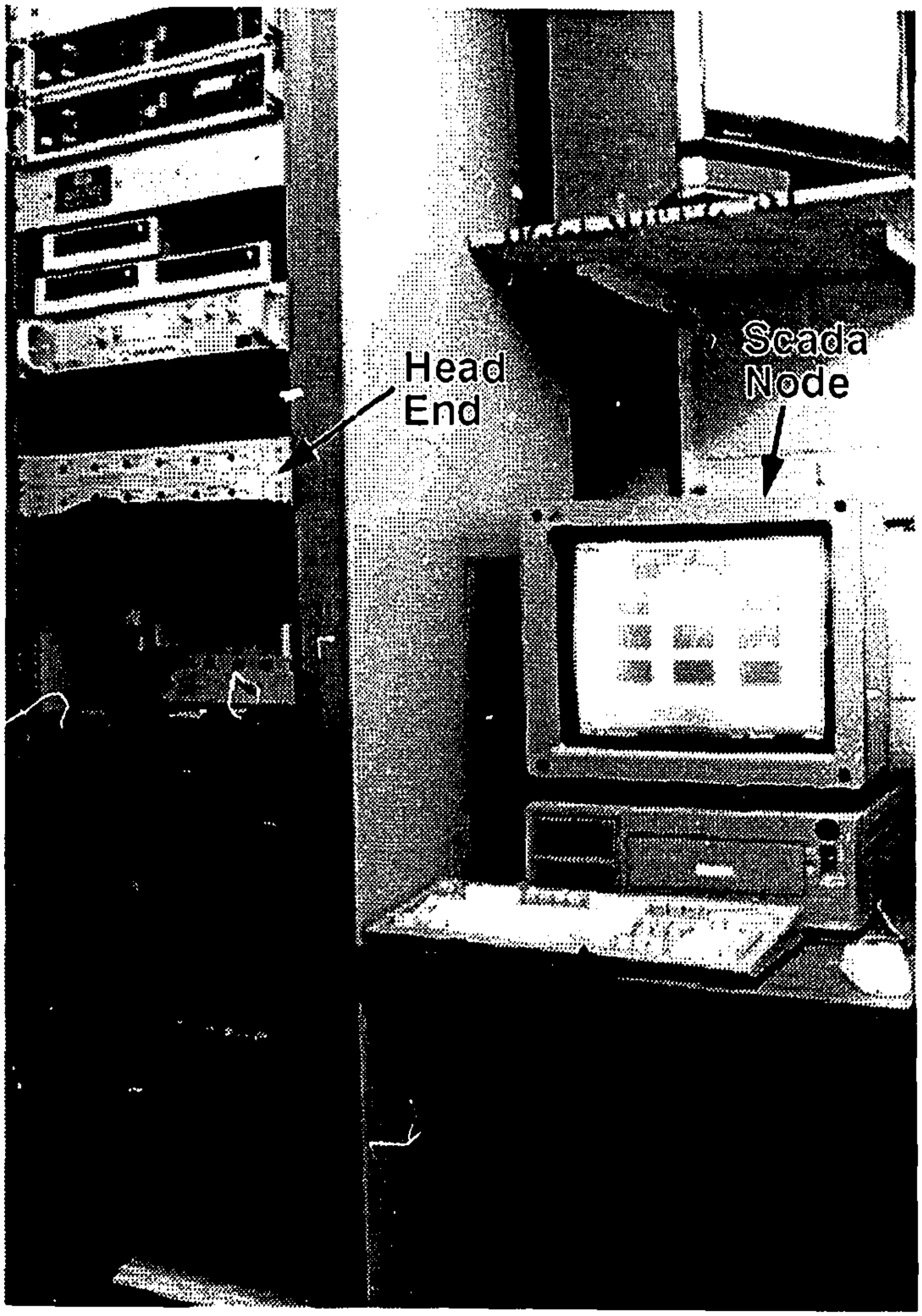

Figure 46 : **Head-End**

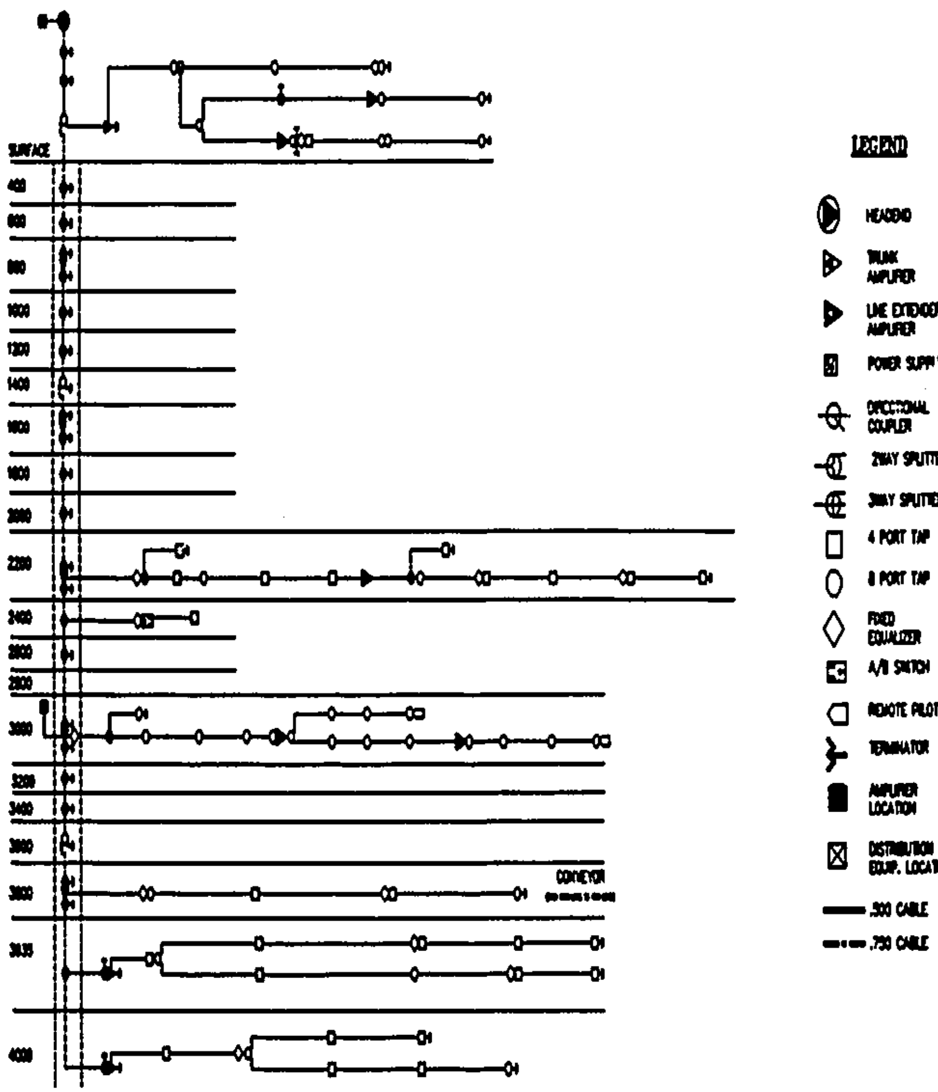

Figure 47 : Broadband Installation in Copper Cliff North Mine

All levels except 3000 had only broadband cable installed. Therefore, since 3000 level had both, it was considered the main test level. The broadband cable installed on the level consisted of trunk distribution from the shaft to the electrical

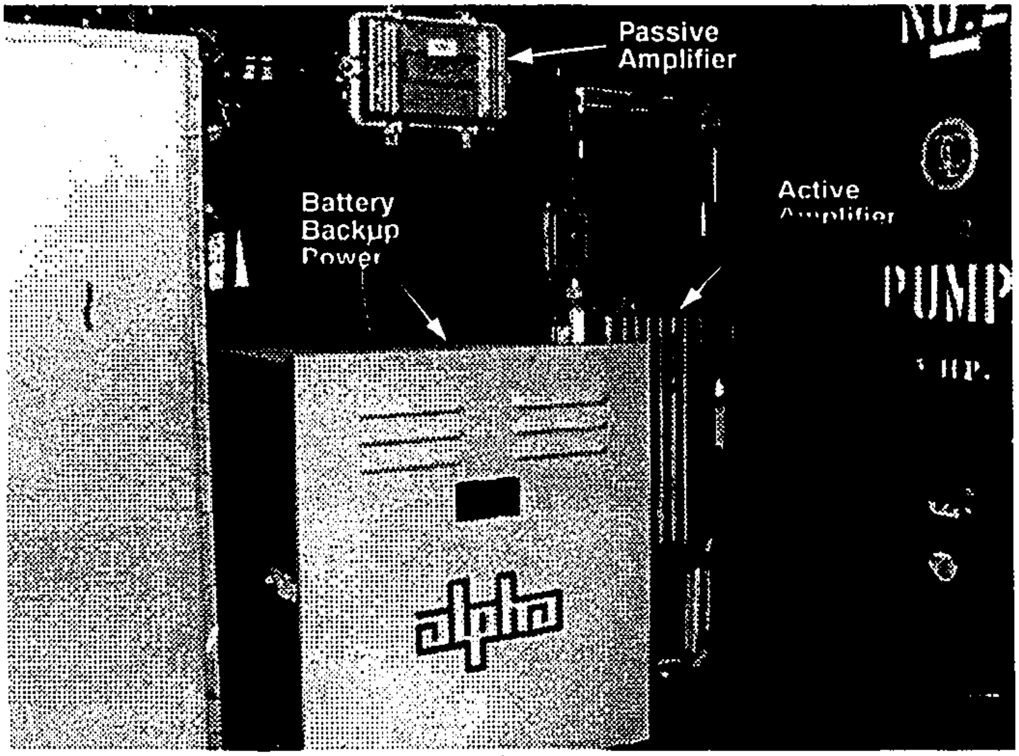

Figure 48 : Broadband Installation in Electrical Switchroom on 3000 Level

room. At this point the signal was amplified and the distribution cable was installed on the level. Figure 49 shows this installation. The distribution cable was installed in the main drifts on the level. Taps were installed at 40 metre intervals so that drops cables 30 metres in length could be used while still maintaining a strong enough signal at the device. At the ends of the broadband installed cable monitors were connected so individual cable segments could be monitored from surface on the "Quickview™" software. This feature proved useful as a cable failure occurred two times during the test period and the software determined the location of the fault. The first time was due to the blasting of a cable section and the second to a rockburst. Both these events were determined immediately and corrective action was taken when appropriate.

The requirement for radio coverage was real-time communication at every point on the level. To achieve this radio coverage a leaky coax antenna system was

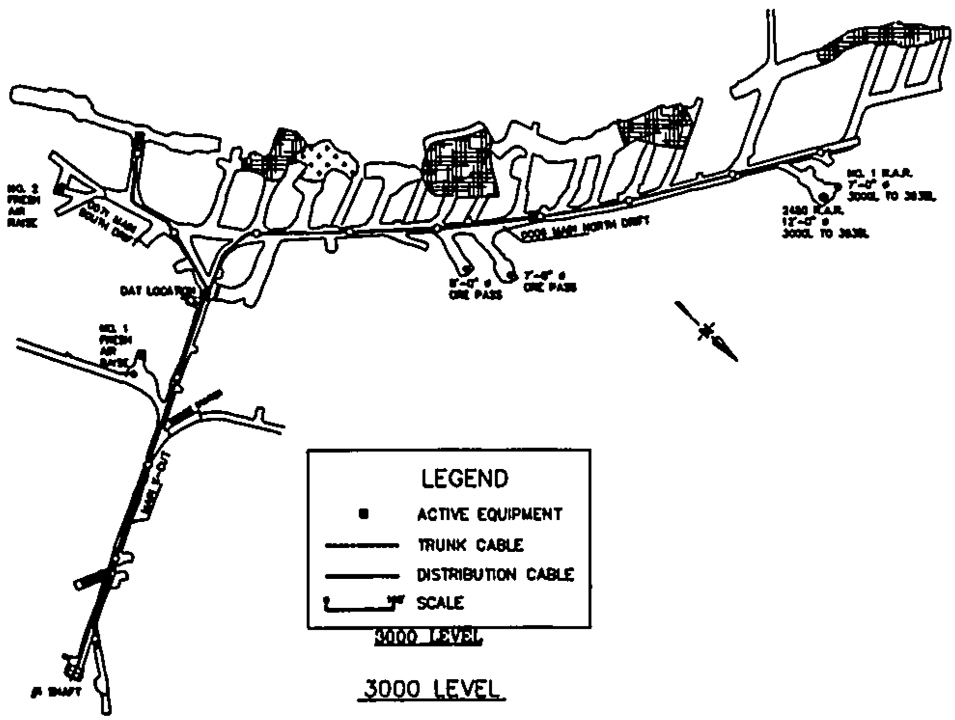

Figure 49 : 3000 Level Broadband Cable Installation

installed on 3000 level as illustrated in figure 50. The DAT developed for the project was installed at a central location near the garage. Figures 51 and 52 show the front and rear of the DAT installed on 3000 level. The front view shows an IBM™ Gearbox™ computer in the bottom and a series of MODEMs and heat sink in the top. The rear portion of the DAT contains the antenna combiner section which mixes the RF signal together for transmission on the Leaky Coax antenna. A central location was selected for two reasons; first, the maximum leaky coax run while maintaining full video spectrum was 700 metres; and second, this would allow the maximization of the broadband cable system which is significantly less expensive than the leaky coax. The leaky coax was installed in trunk and distribution on the level. The trunk consisted of four main segments. At drill sills splitters were installed with 0.95 cm. leaky coax into the area.

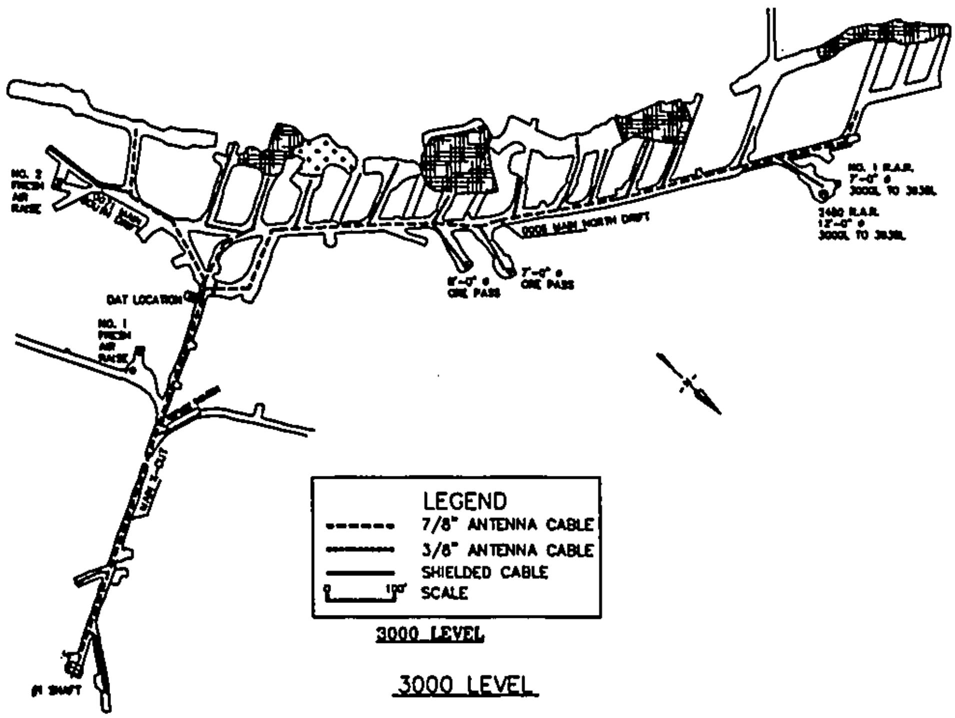

Figure 50 : **3000 Level Radio System Installation**

6.4.2 Voice

The voice experimentation undertaken in this work consisted of the integration of telephone and radio systems. The requirements for success were determined to be:

* telephone-to-telephone
* telephone-to-radio
* radio-to-radio

communications capabilities. The criteria used for measuring success were based on meeting system functionality and quality. Quality was used to measure success however the system functionality was most important as quality could be improved with further electronic development.

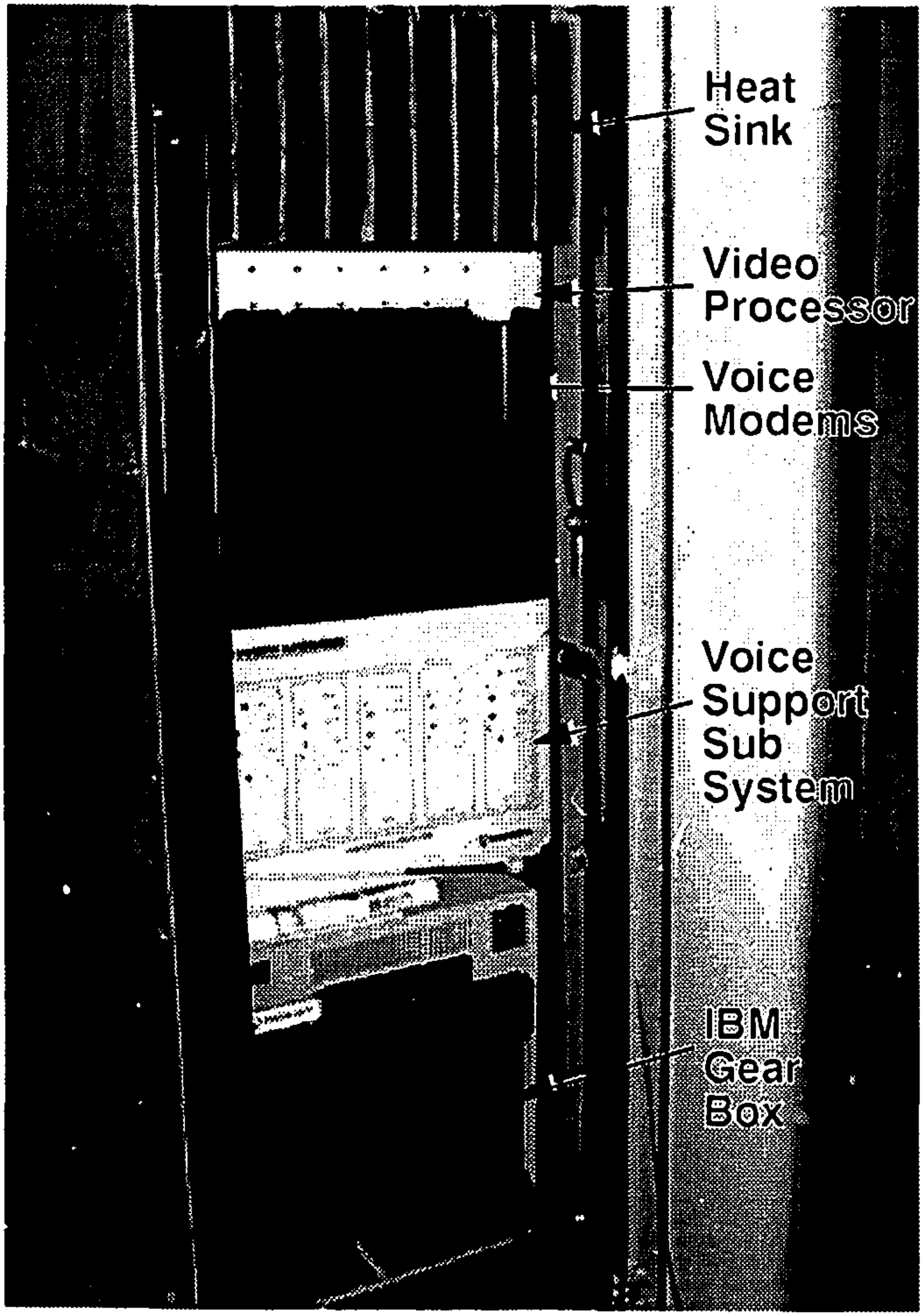

Figure 51 : **Front View of DAT**

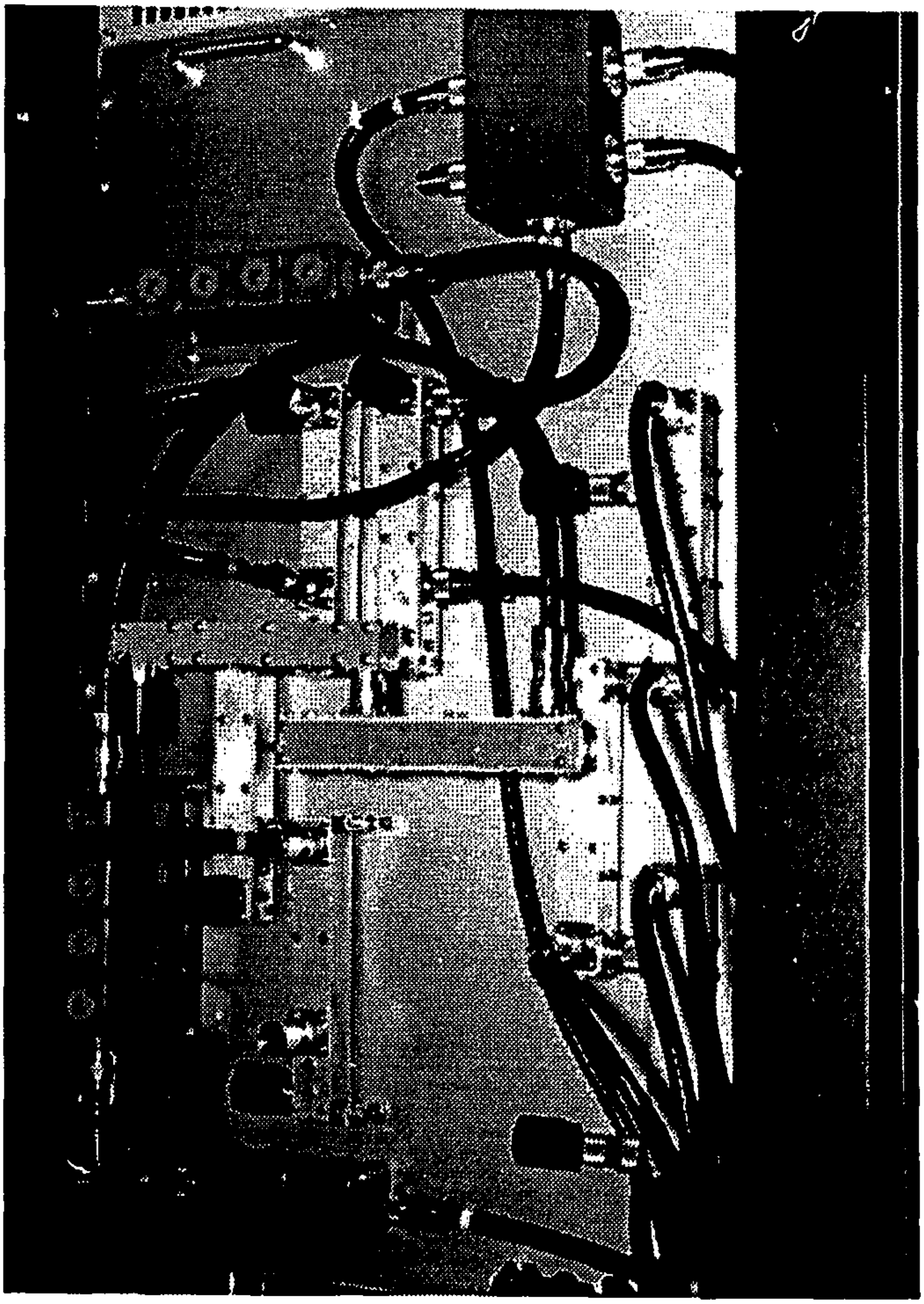

Figure 52 : Rear View of DAT (Antenna Combiner).

6.4.2.1 Telephone

In order to experiment with the telephone system, a portable telephone was created. The telephone consisted of a broadband modem, with telephone and power supplies which could be run from battery or 110 VAC as show in figure 53. A drop line from the broadband was connected to the telephone modem and this allowed telephone communication at any tap on the system.

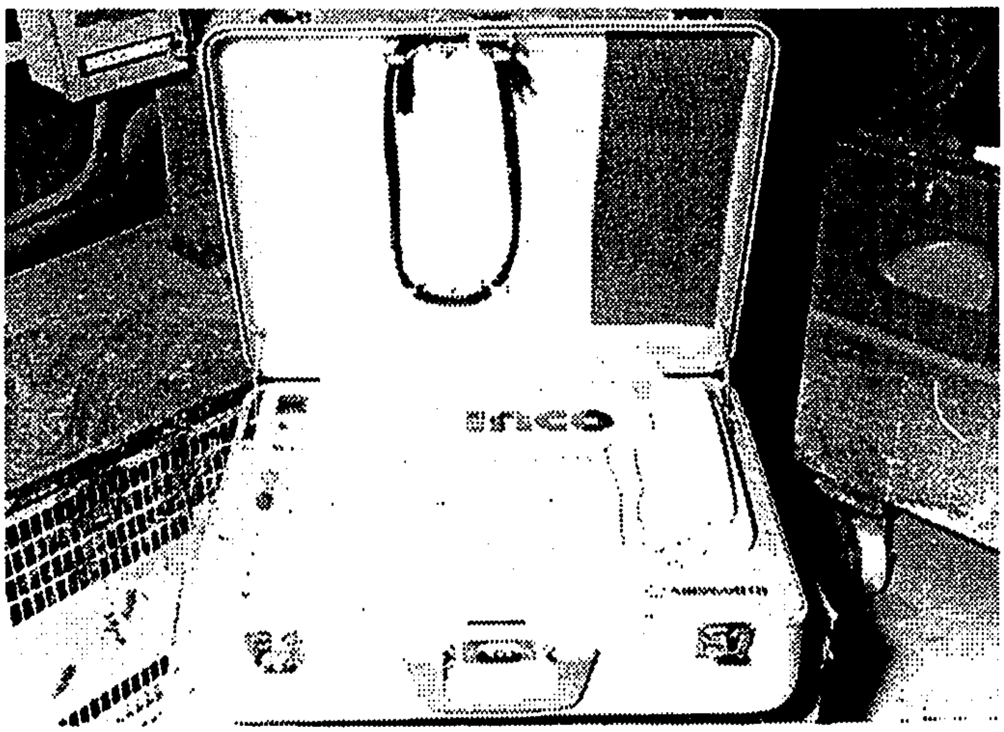

Figure 53 : Portable Telephone

The telephone was installed at several taps in the mine and performed flawlessly as expected since the devices used could be purchased off-the-shelf. To achieve a stationary telephone on the system, the devices used were relatively compact and inexpensive, but, if a portable telephone were to be used in the mine it needed to meet the criterion of an eight-hour power life. With this restriction the telephone became overly bulky and expensive.

6.4.2.2 Radio

Radio experimentation consisted of testing the functionality and quality. The functionality testing consisted of two main areas, the first being system coverage and the second ease of use. The quality was some measure of the voice clarity. All measurements in this section are very subjective.

The experiment used four radios as stated previously. One of the units is shown in figure 54. These units were programmable and allowed the function of a radio and telephone system. To determine system coverage, radios were used at a number of points on the level as illustrated in figure 55. Table XIII shows the point where communication was attempted and the results achieved were rated between 1 and 5 with 5 being perfect reception and clarity. The radios worked successfully at all these points.

Table XIII : Voice Radio Quality Tests.

Position	Perceived Reception Quality
A	5
B	3
C	5
D	5
E	4

The radios used were extremely sophisticated and difficult to use. The functions required in the radio were a combination of telephone and radio characteristics. The requirements of the radio system were not recognized until the radios were tested underground. Several applications in the operation required the use of open channel communication, and not dedicated point-to-point as in a telephone system. Since the radios were programmable, an open channel was added to the system and a suitable communication system resulted.

In terms of the telephone system, the use of the radios as telephones was far too

Figure 54 : Portable Radio

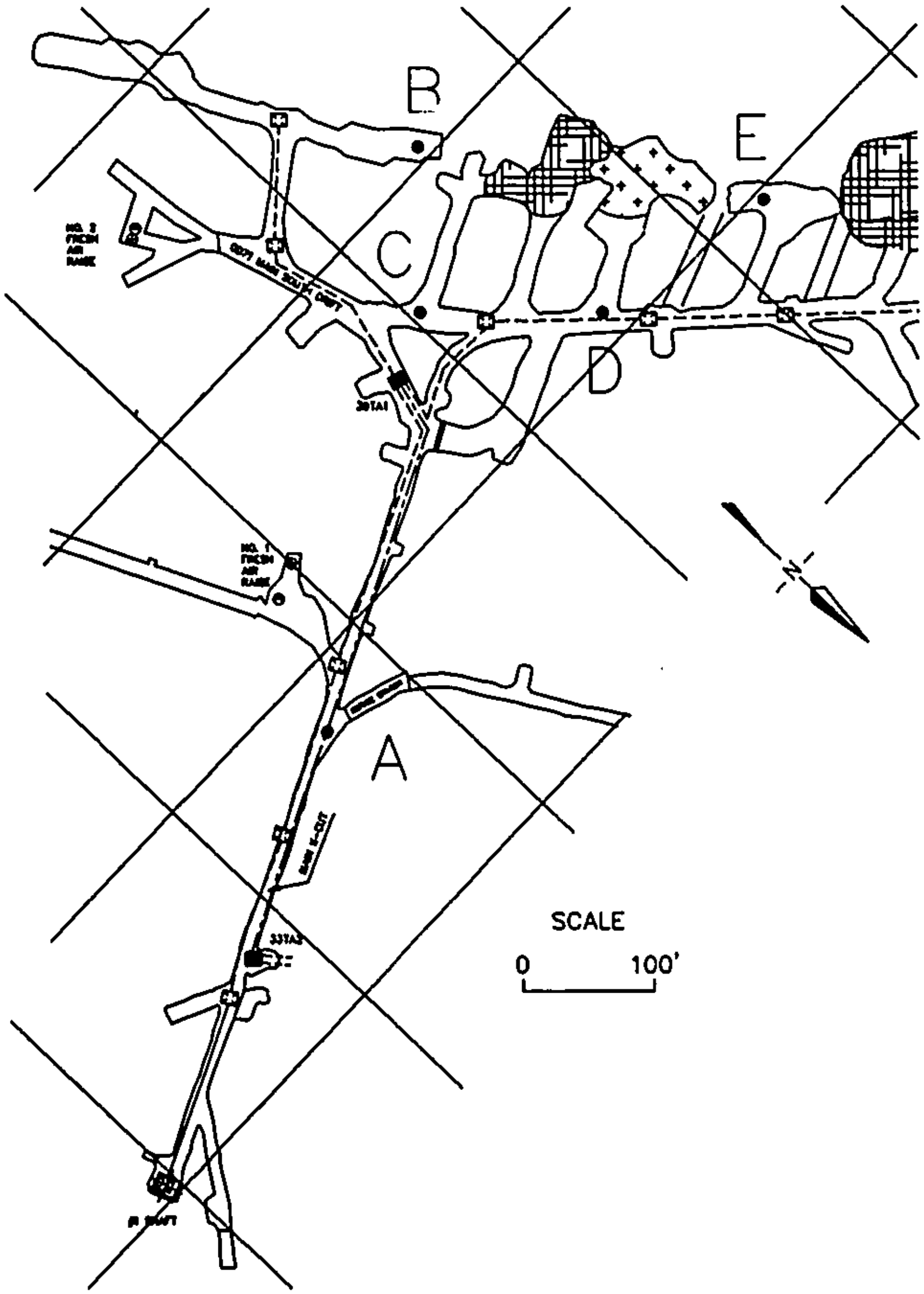

Figure 55 : Voice Radio Test Locations.

complicated due to dialling requirements. Therefore, work needed to be performed in this area to ease the use of the radios as telephones. This work was not attempted as part of the experiment as the radios used were far too expensive and would be simplified with further development if warranted.

Radio voice quality and signal consistency were determined to be very subjective to measure. Since the antenna system covered all areas on the level, the reception was proven to be provided everywhere on the level through testing and use of the system.

6.4.2.3 System Integration

The telephone and radio systems tested complemented each other in that a telephone outside the plant or on surface could communication directly with the radios underground. This will be a useful function in the future. One problem determined was the lack of full-duplex voice transmission. Conversations on a radio were difficult, as the push-to-talk used on radios caused a keying delay that broke up the continuity of the conversations. This must be an area for future development.

6.4.3 Data

The objective of this portion of the experiment was the development of a backbone data handling system as a platform for automated mining. In determining this platform many aspects of the mining organization had to be considered including :

* hardware
* software
* information flow
* maintenance

* expendability
* training

To handle the requirements of the operation, three information uses were determined: engineering, process control and corporate computing. This section reviews the systems developed or integrated and the results obtained.

6.4.3.1 System Hardware

The system hardware installed consisted of two servers, 15 workstations and various peripheral devices. The operating system used in the experiment was OS/2™ version 1.3. The network operating was the IBM™ LAN Server™ software.

OS/2™ version 1.3 was selected at North Mine over UNIX™. The reasons for this selection included the need to maintain information flow across the three information systems used in the operation; ease of system maintenance (all software and hardware were compatible); system expandability as support was for the largest software development group (DOS™ and OS/2™); the ability to move information dynamically across software systems; and training was simplified, as all personnel at the mine were already familiar with DOS™.

The computer hardware used was not an issue. IBM™ equipment was selected, as the risk to the experiment was high in many other areas and it was anticipated that this risk needed to be minimized. In the experiment this equipment proved to be of good quality, with some difficulty experienced with the network adapter boards. This boards were expected to meet IEEE 802.3 but did not, as IBM™ uses a proprietary 14 bit addressing scheme, where as IEEE 802.3 defined 16 bit addressing. Although this was an issue in the short term, it was not expected to be an issue in the longer term as the limited speed (2 mb/second) over such a large network would require the move to a non-contention based access protocol (token bus passing IEEE 802.4), or the network would become to be too busy for the transfer of the information.

6.4.3.2 Engineering Network

The information systems required for the mine operation were fully supported. The applications used in the mine network were:

* Wordperfect™ for word processing
* Autocad™ for surveying and mine design work
* Lotus™ 123™ for the accounting of material balances, production statistics, maintenance statistics, short range planning and long range planning.
* Rock Mechanics Numeric Modelling

These software systems were currently used in the operation and supported on the network. Although no engineering workstations existed below surface during this experiment, the facility installed supported the connection of the engineering office to the foremen in the field.

The software systems used by the engineering office were all based on relatively standard software systems. Some other operations use software such as "Data Mine™" as a mine modelling and design package, and some are starting to use numeric modelling packages to model the rock mass behaviour characteristics to determine optimum mine design.

Although all these software systems exist, they are all stand alone systems that will have difficulty supporting an automated mining operation. To fully support automated mining, significant improvement in the software systems for mine operations is required. The starting base technology, now that a network has been developed, is the selection of a database system which will support a complete mine model. This data model must include geological, design, development, process control and maintenance information which must be compatible with the main corporate information systems. As well, these data models must integrate easily with simulations for operations planning. Simulations in mine engineering offices must be used which the data model to ask "What If" questions in the mine design process. These types of systems are used extensively in manufacturing operations to predict product flows and resource requirements.

To make all the models used in engineering design valid, process information must be imported to improve the accuracy. Currently, little importing is done, as there are no models that are designed to function in this way.

6.4.3.3 Process Control Network

Two attempts were made to link mine engineering models with production: SCADA for process control, and the LHD Monitoring System. As data were gathered from the LHD, the expert system called "LHD Maintenance Assistant", was used to attempt diagnostics of the monitored LHD braking system.

A SCADA system existed at North Mine at the beginning of the experiment. The purpose of the experiment was not to develop a new SCADA system, but to expand its capabilities, to link SCADA to the engineering and corporate systems, to allow room to expand the development of SCADA type systems at the mine, and to support the integration of the PLCs throughout the operation.

A number of positive results were achieved in the SCADA development. The old SCADA system was converted to an OS/2™ based software called "FIX DMACS™" with system support for a development environment which was not restricted by the memory limitations of DOS™. Four SCADA nodes were installed in the operation (two full function nodes for SCADA development and two for viewing the operation). Ten PLCs were connected to the network using broadband modems emulating point-to-point RS232 lines.

The conversion of the SCADA system (two of the nineteen screens created are shown in figures 56 and 57) was accepted readily by the operators, as can be shown by the development of two new subsystems for control of the crusher on 3935 level using FIX DMACS™, and the video system described later in the section on video cameras, and a subsystem for water-spray control in the shaft. The full function SCADA nodes were used to develop the subsystems previously described. The view nodes were originally designed as a main SCADA in the control room and one for the Operating Shaft Boss (OSB); both were readily accepted by the operations personnel, although the screen manipulation was changed from touch screens to mouse driven at the request of the OSBs.

The experiment attempted to connect ten PLCs on the broadband. However, a problem surfaced when erroneous traffic on the network caused the translator to fail. Subsequent problem diagnosis identified particular MODEMs as the weak points.

A data collection system for the LHD monitoring system was included on the network. This system consisted of a software program developed during a previous research project[6] which displayed graphs of monitored parameters collected via the radio link between the broadband network and the LHD. These graphs will be discussed later in the section on LHD teleoperation.

6.4.3.4 Corporate Network

In order to achieve the final link in the flow of information, a connection method between the network and the corporate computing systems had to be established. This was done using an SDLC gateway running at 9600 baud line over telephone

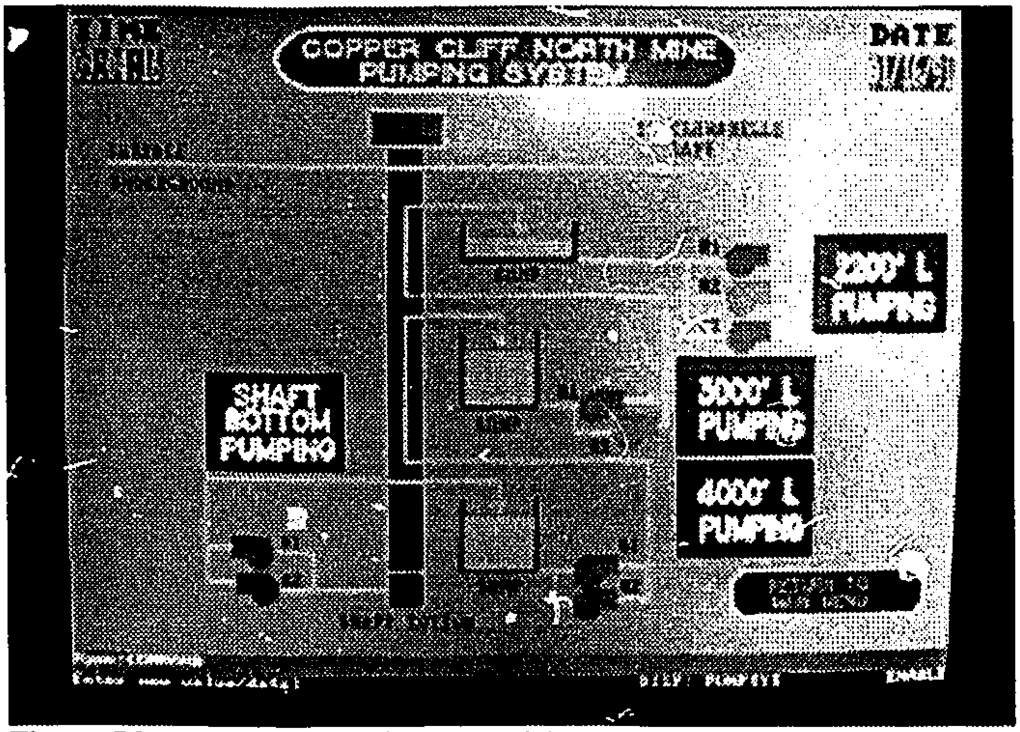

Figure 56 : Mine Dewatering Control Screen

lines to the IBM™ mainframe. A total of 64 workstations could be connected to the corporate databases via this link. All computers on the network had access to this facility. This link completed the requirements for a mine information system supporting the current levels at mining operations. It gives real-time access to the production information for corporate activities, such as:

* Accounting
* Safety
* Purchasing and Warehousing
* Time Keeping
* Marketing

6.4.3.5 Network Integration

The computer networks developed and installed at the mine for testing allow the integration of the engineering office with operations and the corporate computing

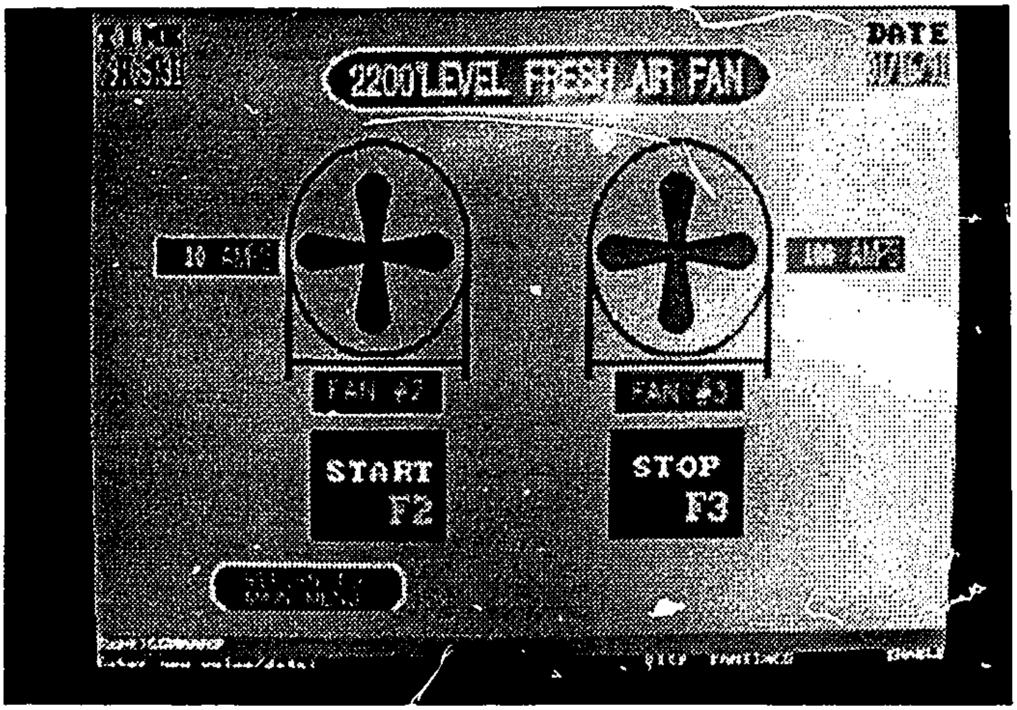

Figure 57 : 2200 Level Fresh Air Fan Control Screen

environment. Figure 58 is a computer screen showing windows of an Autocad™ mine drawing of 3400 level, the SCADA screen of the pumping system for process control and the Inco mainframe screen. This figure represents the ability to integrate the three main requirements of an operating mine. Therefore, the information flow path was demonstrated as part of this experiment.

The system developed as part of this research has significantly more capability than was exploited during this project. This will be discussed in the next chapter on Strategy for Automation.

6.4.4 Video

Four video cameras were installed in the operation. These cameras were installed to allow viewing from the control room of the crusher on 3935, the loading

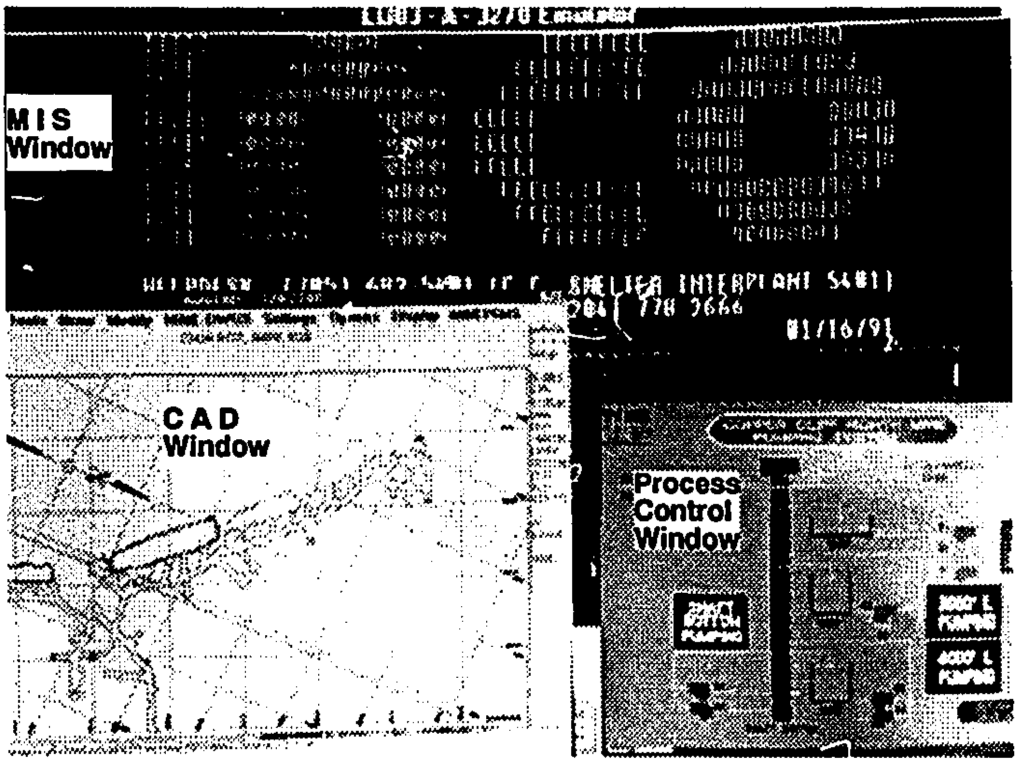

Figure 58 : Computer Screen showing Multi-function Capabiiity.

pockets and the skip dumps. A typical camera installation is shown in figure 59.

The units had the ability for zoom, pan and tilt which was operational from the control room on surface using the IBM™ PC based software "Quickview™". The real-time video achieved was clear and crisp as expected.

Following the installation of the system, the camera on 3935 at the crusher was used to perform tests on the remote operation of the crusher. The video proved instrumental since the crusher had to be viewed, due to the possibility of drill rods and timber in the feed to the crusher which could damage the jaws. Two days, production was crushed using the video system proving the viability of remote operation. Subsequently, the definition of requirements for the automation of the crusher could be determined.

Figure 59 : Typical Camera Installation

6.4.5 LHD Teleoperation

LHD monitoring and teleoperation were successfully accomplished using a Wagner ST8A LHD. The LHD had a data acquisition system, remote control unit and two cameras mounted as shown in figure 60 on the LHD located on 3000 level.

6.4.5.1 Mobile Data Acquisition

The mobile data acquisition system consists of two main components: the onboard data collection and network data collection. The onboard data collection system consisted of 34 sensors, a Sensor Interface Unit, an Operator Display Panel and an RF transmission unit. The network data collection system consisted of the leaky coax antenna system, DAT, RF data collection control board, broadband network and IBM™ PC running the mobile data acquisition control software.

The sensors installed on the machine are shown in table XIV. The table is broken down into the machine subsystem, sensor use, sensor type, sensor signal and sensor range. The sensors have been installed on a production LHD for six months with only minor maintenance required.

The sensors were wired to the Sensor Interface Unit (SIU). The SIU was located under the operator compartment in a specially designed enclosure as shown in figure 61. This installation occurred as a result of original experimentation with the first LHD monitoring system. The original LHD monitoring system failed for two reasons: the first was poor sensor installation, and the second was poor operator acceptance due to the location of monitoring equipment. These were corrected on this LHD, and subsequently, the sensing system has been reliable and the operators have accepted the equipment.

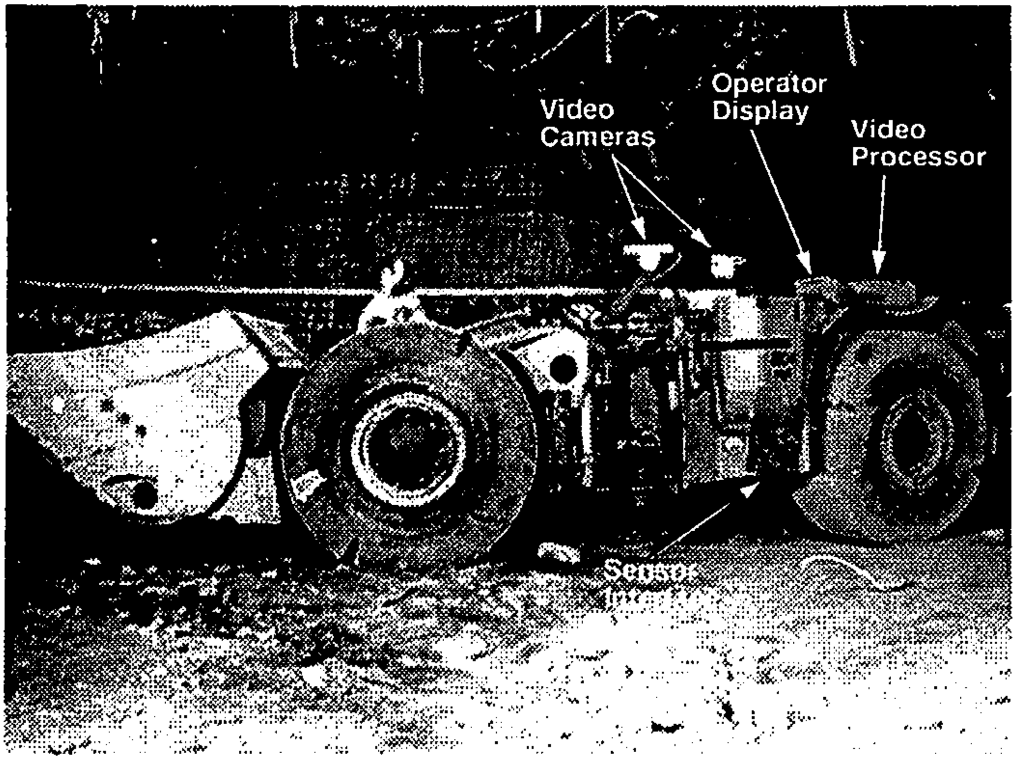

Figure 60 : Wagner ST8A LHD used in Teleoperation Experiment

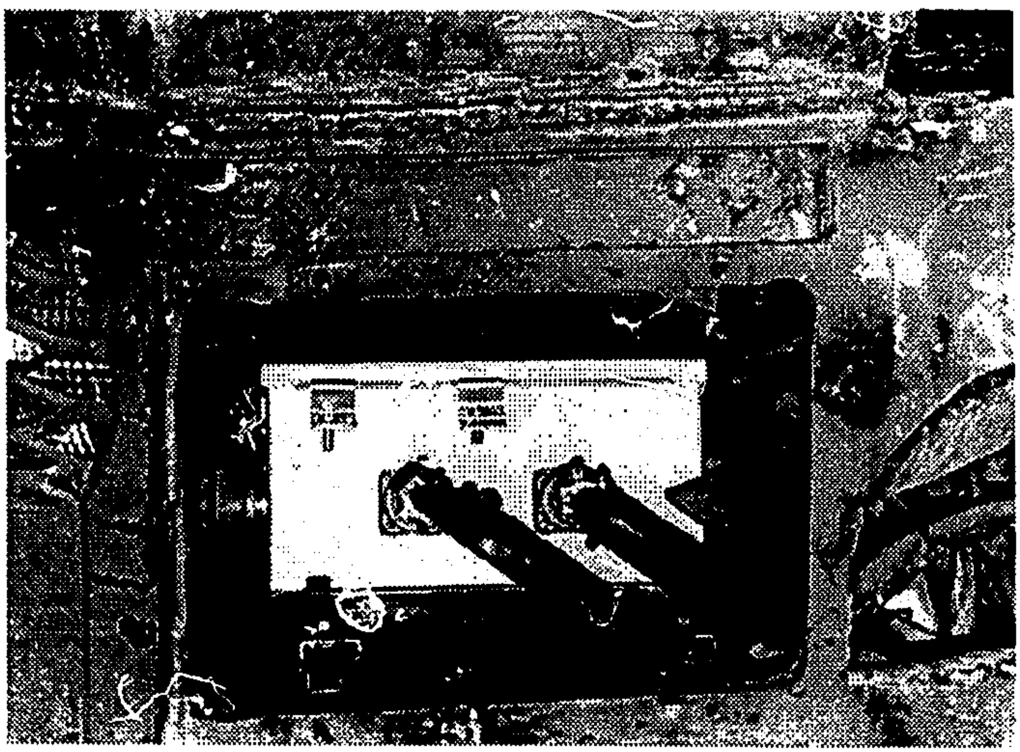

Figure 61 : Sensor Interface Unit

Table XIV : LHD Sensor System

Machine Subsystem	Sensor Use	Sensor Type	Req. #	Sensor Signal	Sensor Range
Engine	Oil	Pressure	1	Analog	250 PSI
	Oil	Temp	1	Analog	
	Oil	Level	1	Digital	
	Exhaust	Temp	2	Analog	
	Head	Temp	2	Analog	
	RPM	Tach	1	Digital	
	Air Filter	Pressure	2	Digital	
Brake	Line	Pressure	3	Analog	5000 PSI
	Accumulator	Pressure	3	Analog	2500 PSI
Hydraulic	Pump	Pressure	1	Analog	5000 PSI
	Oil	Temp	1	Analog	
	Oil	Level	1	Digital	
	Steering	Pressure	1	Analog	5000 PSI
	Lift	Pressure	1	Analog	5000 PSI
Transmiss	Oil	Pressure	1	Analog	500 PSI
	Oil	Temp	1	Analog	
	Oil	Level	1	Digital	
	Gear Posit.	Pressure	1	Digital	
Electrical	Battery	Voltage	1	Analog	
	Charging	Current	1	Analog	
Fuel	Use	Level	1	Analog	
Exhaust	Scrubber	Pressure	2	Analog	5 PSI
Orient	Pitch and Roll	Level	2	Digital	

The display panel on the LHD allowed the operator to view the parameters being monitored on the machine. This unit is shown in figure 62 above the current LHD dashboard. The RF radio was mounted below the seat in the cab of the LHD. The use of the display by the operator was limited, as it was to difficult to use. As testing went on, it became apparent that the display should not be provided to the operator unless it was an integral part of the machine dashboard.The network use of the information was more successful. Data from the LHD were collected on surface via the leaky coax, DAT, RF controller card in an IBM™ PC on the level and then finally via the PC network to a surface computers. Data were collected for a three hour period while the LHD was working on 3000 level. The tram consisted of reverse travel to the main haulage drift, a short wait while the second machine passed, continued reverse tram to the orepass, forward to dump, reverse out of orepass and forward to the drawpoint as shown in figure 63. Sample data from six sensor points are shown in the following series of graphs.

Figures 64 and 65 show two graphs representing gear position vs time. The upper graph has a time scale of three hours. The graph demonstrates a repeatable pattern representing the tramming cycle. A total of 22 loads were moved to the orepass. The lower graph drills in on a specific cycle between 9:00 am and 9:15. A complete cycle occurs from 9:02 until 9:09 am (7 minutes). To fully understand the cycle, this information must be overlaid with other parameters. However, this is extremely valuable information which could be used for machine design, time studies, production statistics and machine maintenance.

Figure 66 and 67 show engine oil temperature and right exhaust temperature versus time, respectively. With an understanding of the cycle that the LHD was working in, it can be seen that the temperature peaks during each tram cycle when travelling with a full bucket. This finding is similar for right exhaust temperature, although some loss of data occurred. Upon investigation, it was

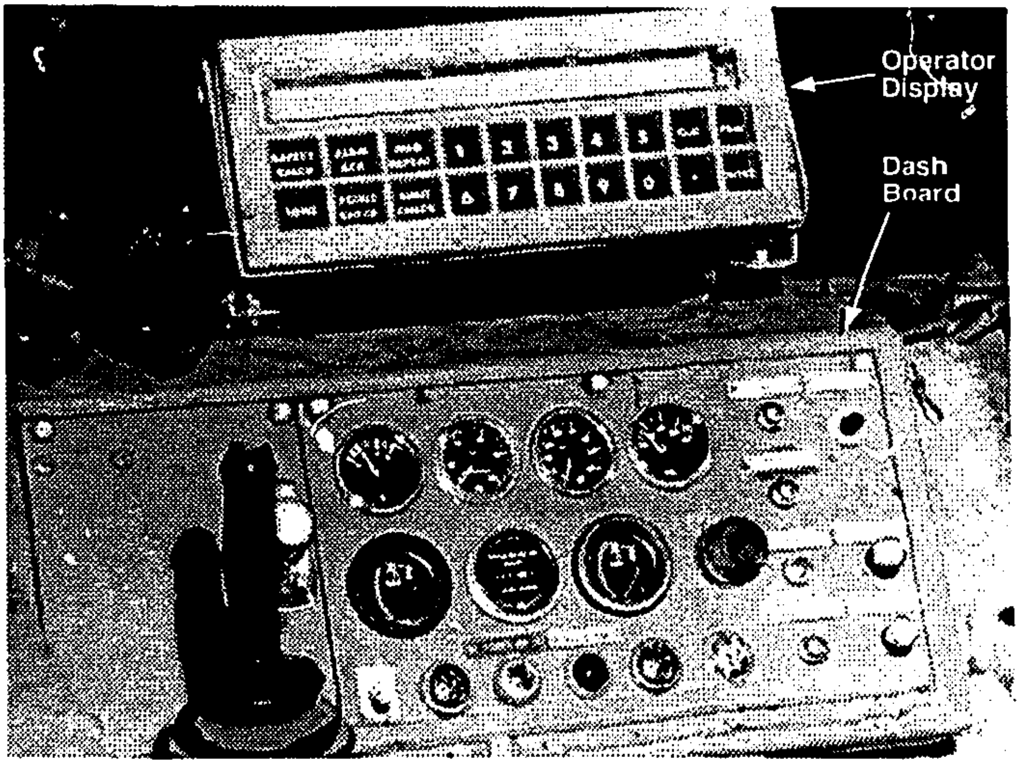

Figure 62 : Operator Display Panel Mounted above the LHD Dashboard.

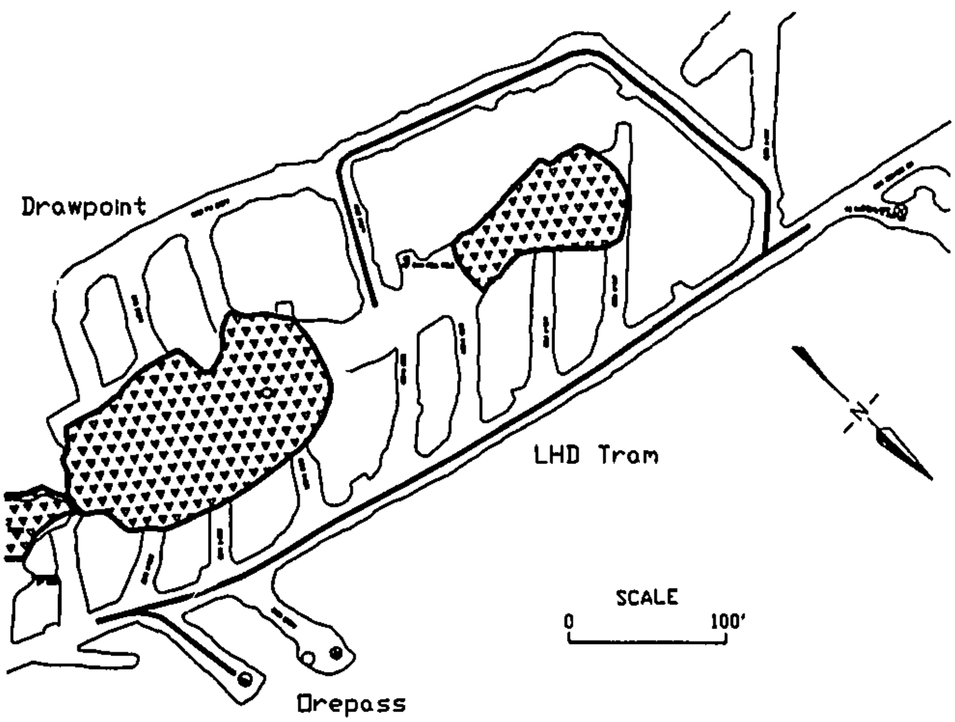

Figure 63 : 3000 Level LHD Tram during Monitoring.

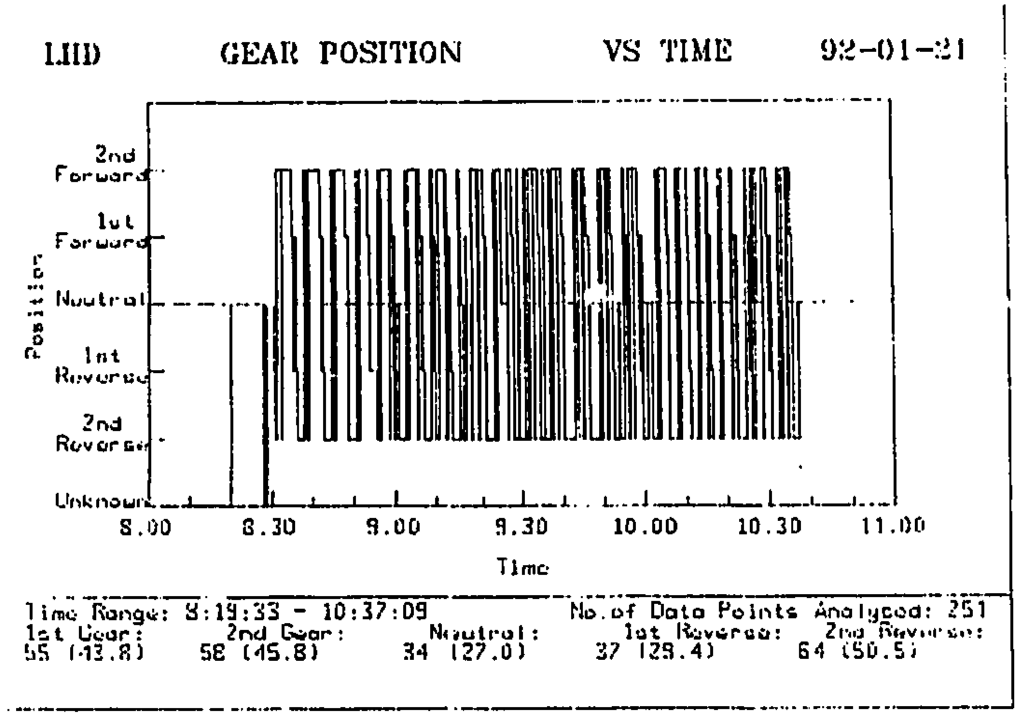

Figure 64 : LHD Gear Position vs Time

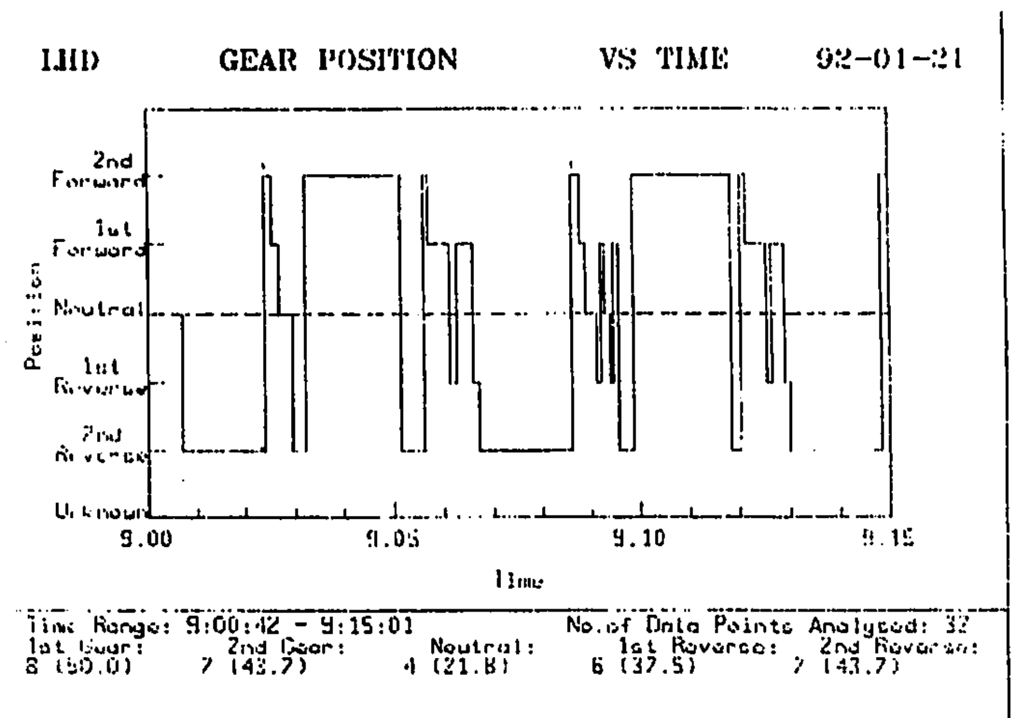

Figure 65 : Close up of Gear Position

noted that a section of radio antenna was missing. Therefore, the machine was out of RF contact until it returned to the main haulage drift. Since this particular sensor had a high scan rate (1/second), data were lost as the buffer was too small and the rate of communication too slow (1200 baud).

Figure 68 and 69 are representations of the rear and front brake accumulator pressures. The rear break exhibits a relatively constant pressure of 1900 psi, while the front shows a range between 1900 and 1600 psi. This finding led to the identification a leaking accumulator on the front of the LHD, which was later confirmed by mechanical work. This points out the value of such information for troubleshooting in the future.

The previous figures are included to demonstrate some of the achievements of the communication infrastructure, although to this point little analysis of the information has been will be performed since it is beyond the scope of this thesis work. However, it can be seen that very valuable information can be obtained when machines are monitored in real-time. This information will be critical to the future development of teleoperated and autonomous systems, both as virtual dashboards for equipment and in maintaining these systems.

The network movement of information of the sort collected in this experiment will allow the development of online maintenance systems for underground mining and the application of online expert systems for diagnostics. This is one of the goals of the network development. Online systems will require machine monitoring systems. The network tested successfully, allowing the polling of multiple machines.

6.4.5.2 Mobile Control Data

The network developed allowed the use of an open channel for remote control of

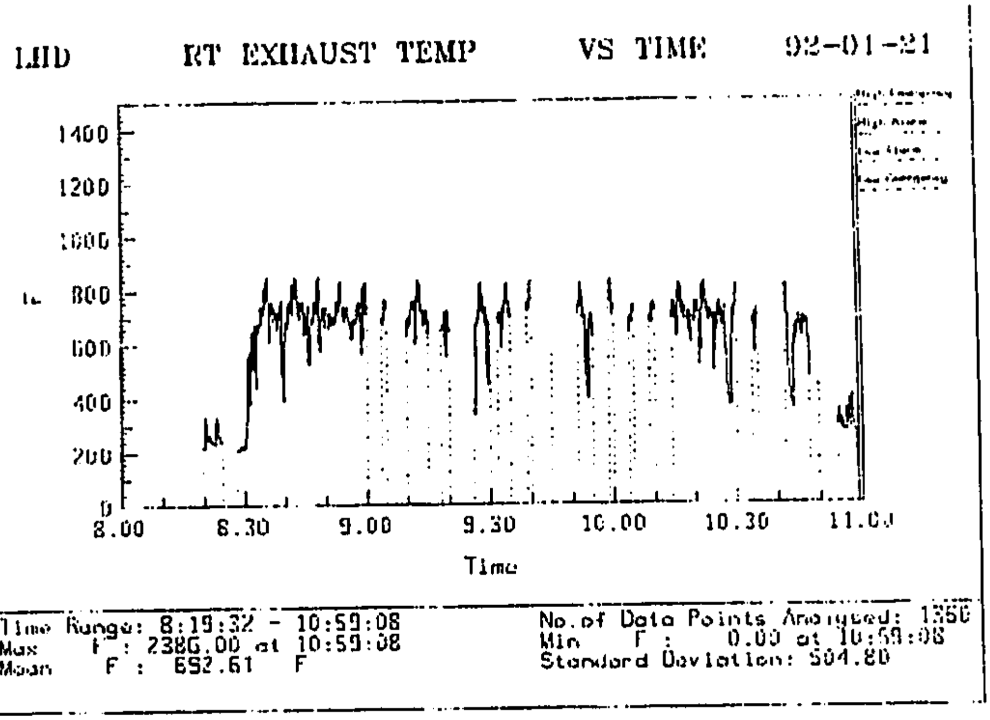

Figure 66 : Right Exhaust Temperature.

the LHD. The remote control used was a MOOG™ transmitter/receiver operating at 467.750 MHz. The unit was plugged into a broadband tap where the RF was translated via the headend then out through a data channel to leaky coax. The concept used basically extended the antenna on the transmitter out through the operation wherever leaky coax was connected to the broadband, allowing the receiver on the LHD to be activated. The control signal propagated showed no noticeable delay to the operation of the controls on the LHD from surface approximately 1300 metres away.

The propagation delay (PD) between the surface transmitter and the receiver on the machine was calculated using:

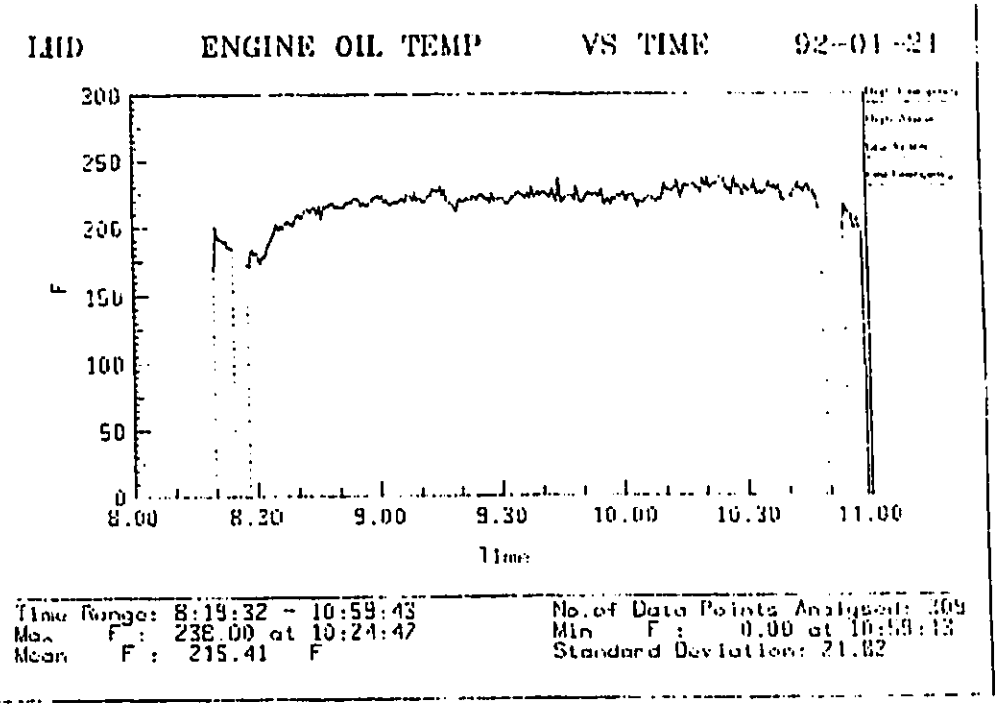

Figure 67 : LHD Engine Oil vs Time.

$$PD=\frac{d}{cf}$$

where

c = speed of light

f = velocity of propagation through foam dielectric as percent of the speed of light

d = distance between the transmitter and receiver

The propagation delay was 5.057 x 10^{-6} seconds for a foam dielectric constant of 81% and a transmitter/receiver distance of 1300 metres.

6.4.5.3 Mobile Video

Two mobile video cameras were mounted on the LHD on 3000 level to allow transmission to surface for control of the LHD. The equipment integrated onto

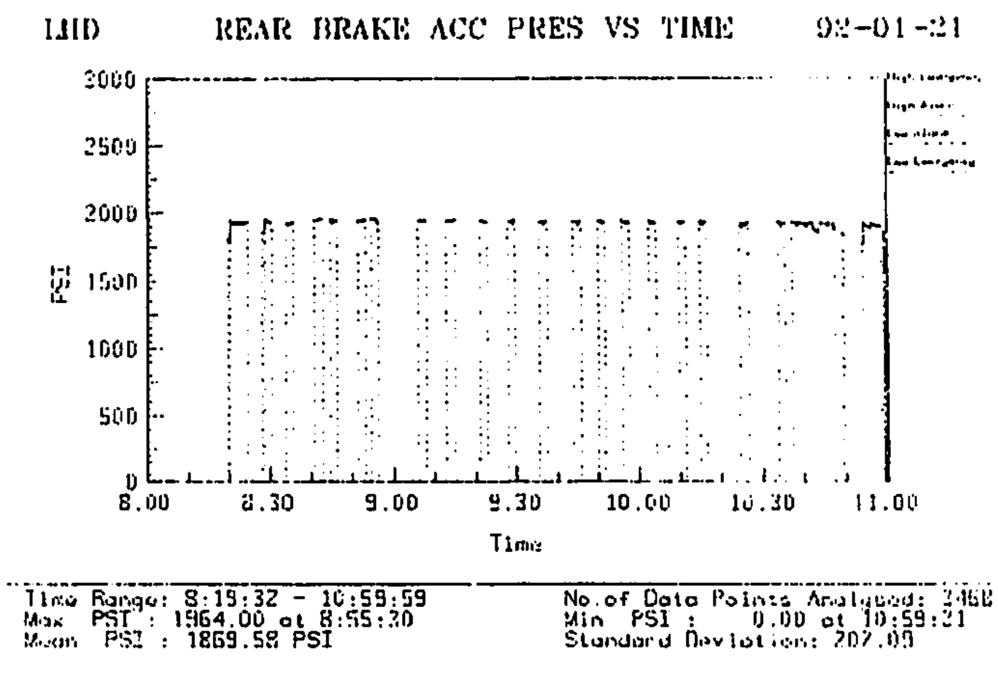

Figure 68 : Rear Brake Accumulator Pressure.

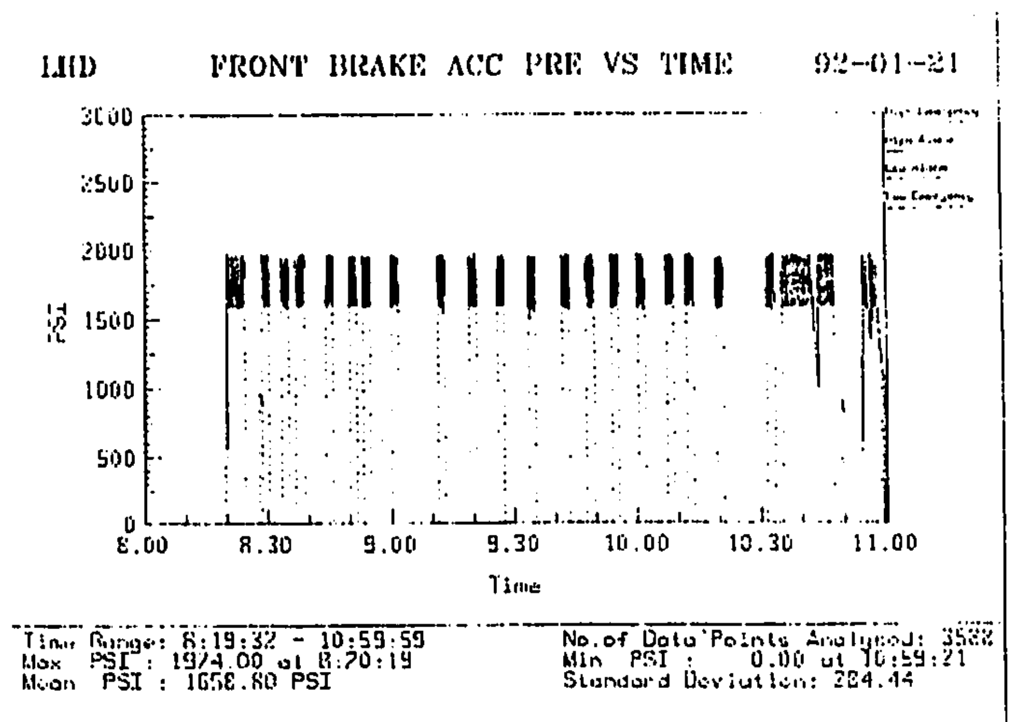

Figure 69 : Front Brake Accumulator Pressure.

the network consisted of two cameras, translator, microphone, radio transmitter and antennas.

The cameras were mounted on the LHD at central locations looking forward and reverse. The location tried to duplicate the operator view of the LHD while driving the machine. The cameras were switched between forward and reverse via a relay on the remote control receiver unit which controlled forward and reverse of the machine. The camera mounting is shown in figure 70.

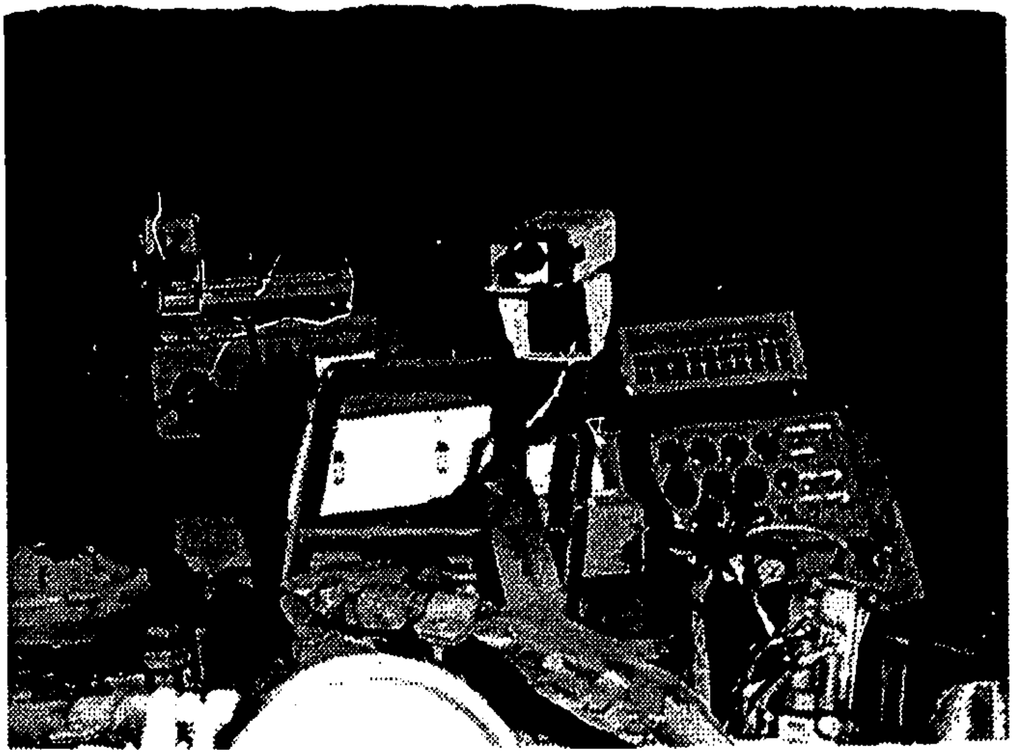

Figure 70 : Camera Mountings on LHD

The switching of the cameras on the machine allowed the operator to run the machine as if he were in the operator compartment. Some loss of visual quality was experienced due to multipathing. An attempt was made to correct this by adding a second antenna as shown in figure 71. A comparison of the two methods of transmission resulted in significant improvement in the reception, with half the dropouts in the LHD run. The double antenna allowed one antenna to achieve a strong signal even if the other was in a nulled area. A video tape of the operation of the machine is included as part of this thesis.

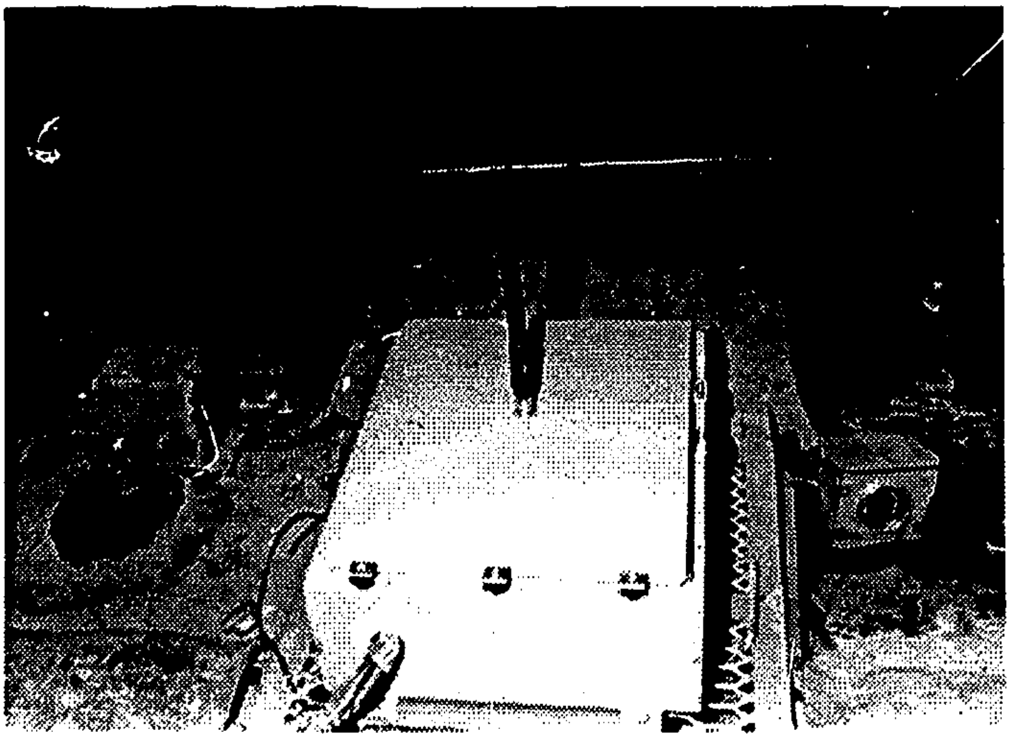

Figure 71 : Video Antenna Mounting

6.4.6 Teleoperation Testing

The experimentation with the machine consisted of four tests: machine control on 3000 level using all functions; control of motion from surface; control of mucking and hauling from surface; and control of the machine in unfamiliar area underground while operating from surface.

Control of the LHD on 3000 level consisted of setting up the electronic equipment in the electrical room on 3000 and running the machine in the adjacent drift. The first step, to allow the operator to become comfortable with the control was to allow him to operate without video but in sight of the moving machine. All functions were tested and had excellent response times. These were actually the most difficult from a communication point of view. The distance between the transmitter and the receiver was approximately 2750 metres, and since the signal had to be translated on surface, this doubled the distance compared to remote operation from surface.

The next step in experimentation controlled LHD motion from surface. Figure 72 shows the operator running the machine from the control room. On the advice of the operator, the drift was improved by adding a bright yellow tape, 10 cm wide, to the side walls that allowed the operator some depth perception, as shown in figure 73. The test area for mucking had pipes along the back, so four tapes were hung from the back so the operator could see when he could lift the bucket.

Before operating the machine from surface, a test run was completed on the level. Following this run, the electronic equipment was moved to the control room on surface. In the control room the transmitter was attached to the broadband via a translator. The video monitor was set to the appropriate channel for the LHD cameras and the operation was attempted.

During the initial part of the test it was recognized that audio feedback was missing. On the level the operator could hear the machine. However, on surface he could not, so testing was stopped and a microphone was installed. With the microphone in place the test was tried again the next day. The machine was started and the operator now had all the feedback required to attempt running the machine from surface.

The machine was moved up and down the drift with relative ease. Following the movement the machine was shut down and the site was prepared for the next test. The operator was questioned after the test to determine how he was driving the machine and what could be done to aid him in the operation of the machine. The first feedback from the operator was that there was:

* a lack of depth perception while driving the machine even with the tapes on the walls
* the audio installed was an absolute necessity for the operation of the machine from surface
* the method of driving the machine was to use the tires of the LHD as reference to the drift walls for operation
* the control system used needed significant rework to provide an ergonomic design in the joystick controi

Figure 72 : Teleoperation of LHD

The next experiment was performed to attempt mucking from surface. The area was prepared for mucking by moving ore to the area and checking the tape installation. The machine was then run from surface and attacked the muckpile. The mucking operation went smoothly and a full bucket was achieved. This was attempted a number of times and the same results occurred. Following the

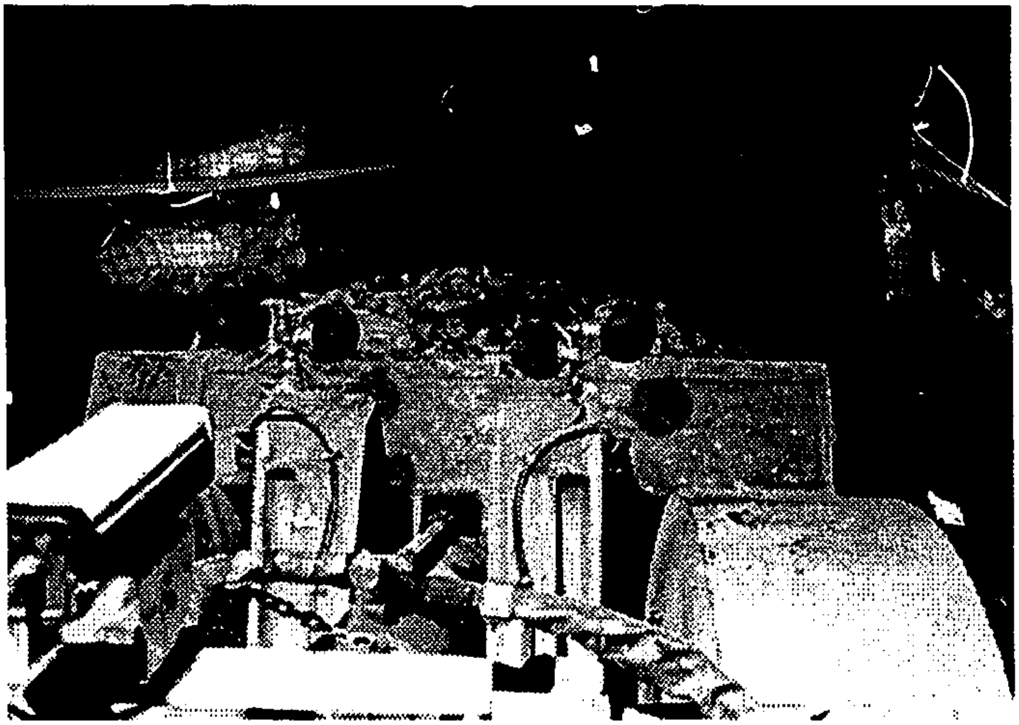

Figure 73 : Front Camera View showing Placement of Tape for Driving

experiment the operator was questioned again as to the suitability of the system. Depth perception became even more of a concern, with respect to effective handling of exceptions such as large muck; the operator was trying to "feel" his way around chunks. Other than this problem the mucking operation was relatively straightforward.

The final test was to put the machine in an unfamiliar area to drive the unit. During this test the operator ran the machine as before but he encountered a major difficulty, again due to the lack of depth perception. His inability to understand the depth to and from the walls and other open areas resulted in hitting the walls. All other functions operated as required.

Following the tests, it was determined that there was a significant need for some means of achieving depth perception. Three methods were considered: the addition of colour, or the addition of 3D video (requiring stereo vision), or both.

Operator ergonomics will be another important consideration if this is to become a viable tool. No action was taken as part of the research to achieve these enhancements. However, this work will be explored during the ongoing development at Inco. The amount of time require to train the operator was a pleasant surprise; he picked the operation of the LHD up within a few hours. With some minor enhancements, the system can be used as is for production operation.

6.5 Summary

The communications infrastructure required to automate an underground hardrock mine has been tested as part of this thesis work. The system has been in operation for 12 months at the time of writing this thesis with no difficulties from the underground mining environment point of view. The system is capable of supporting multichannel systems for :

* voice via telephone
* voice via radio
* data for computer networks
* data for process control
* data for mobile data acquisition
* data for mobile process control
* video from fixed locations
* mobile video via radio

The speed and capacity of the system are sufficient to allow all present communication requirements to be met for underground operation. As well, the system is capable of supporting future mine automation, as proved by the experimentation with the teleoperation of an LHD from surface.

A system such as the one developed as part of this work is sufficient to support the teleoperation of many pieces of mining equipment underground from anywhere in the operation. Moreover, the ability of the communication infrastructure to support many computer integrated facilities will dramatically enhance the future productivity and safety of many mining operations since personnel on surface will have instant access to a wide range of information from the mining process.

7 STRATEGY FOR AUTOMATION

The purpose of this chapter is to identify a strategy based on the telecommunications system proven in the previous chapter. This includes determining the components that are most sensitive to automation, to demonstrate, by modelling in chapter 8 the potential economic impact of mine automation. This is accomplished through the establishment of a mine system automation strategy through research and development assumptions. These assumptions are then used in chapter 8 to prove the economic viability of the communication system developed as part of this thesis work.

This chapter consists of two main parts. The first establishes a framework for future mine automation based on the communication system developed in this thesis. The second considers the detailed assumptions required to make the framework a reality including future directions anticipated in mine automation. This section is a precursor to the economic modelling analysis in the next chapter.

The data used in the next two chapters are given in Imperial units since these represent the nickel mining sector standard.

7.1 Strategy

The automation strategy developed in this work consists of the establishment of the telecommunications infrastructure followed by the development of remote control and automated mining systems that can be connected. From the perspective of mining systems this strategy first, simplifies the current mining process and then automates it. As new primary mining system developments occur these new unit processes must then be integrated into the mining process and telecommunication infrastructure allowing an evolutionary rather than revolutionary approach to mining automation.

7.2 Technology Research and Development

The National Science Foundation (U.S.) presented a graphic representation of the process of research and development, figure 74[70]. This figure represents the progress of science as it moves from initial exploration and discovery through the development of models. The process shown evolves through the collection of data, the clustering of data, the development of rules of thumb, the establishment of principles and finally the definition of laws.

Communication infrastructure, teleoperation and autonomous systems, may be classed together as "Intelligent Manufacturing Systems." This new field is reflected in the formation recently of the International Intelligent Manufacturing Systems (IMS) group[71] to perform research in this field. In mining systems most of the work is at the initial exploration phases of this R&D continuum. Advanced manufacturing technologies already developed offer immediate answers to nagging problems in the mining industry, specifically underground communication via broadband industrial networks, as shown in the previous chapter. Moreover, this enabling communication technology has the potential for high payback in the short term as for voice communication and stationary process control and as a foundation for future mining automation. Therefore, the technology justifies significant future R&D as it enables the development of applications which fit on the system allowing an evolutionary path to continuously improve the mining process. A collaborative approach in this area of research is necessary as the skills to pursue this goal are difficult to obtain. Moreover, a consortium approach is necessary to maximize the perspectives brought to bear and to reduce the cost burden.

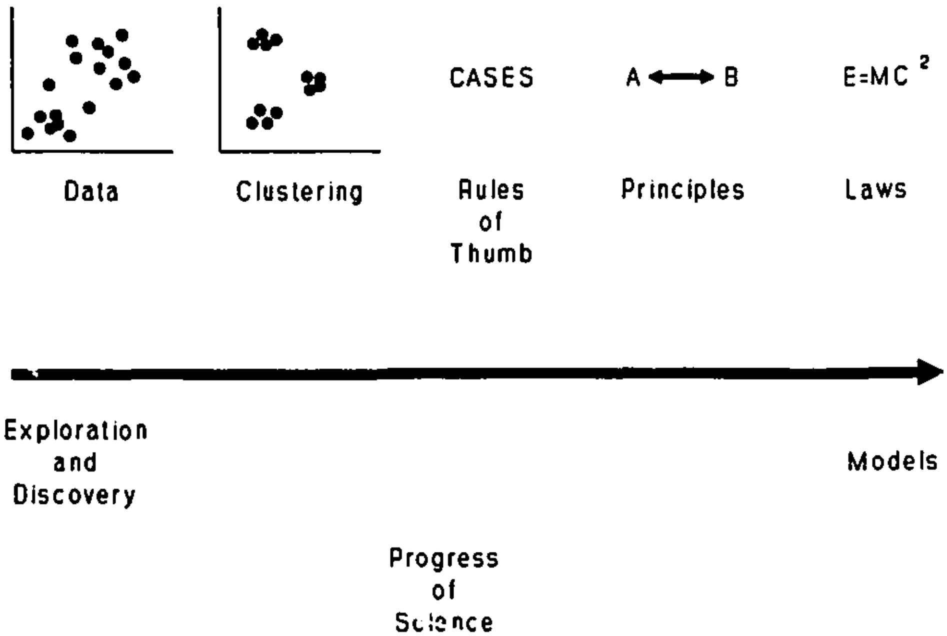

Figure 74 : Progress of Science, after 70.

The key to cost-effective automation in a mine is the minimization of the infrastructure necessary to run the operation. In a manufacturing facility, good engineering principles minimize the number of parts, reducing the complexity of the process and aiding in the assembly of components that comprise the product. When comparing this approach to mining, the key challenge will be to reduce the infrastructure required in the process. The rest of this chapter deals with the major areas of research related to infrastructure reduction and future mining systems. These include enhancement of the communication infrastructure, peripheral research and application development.

7.2.1 Communication Infrastructure Enhancement

The major R&D thrusts required in the enhancement of the communication infrastructure and the definition and building of individual mining systems are:

* DAT refinement and production

* development of diagnostic software for the communication infrastructure
* research into remote control systems, to be integrated with the communication system
* intelligent sensors to attach directly to the communication system
* expansion and testing of 3D video.

The next section on mining system architecture will discuss results achieved in the field experiment and make recommendations to improve the system to meet production objectives.

Mining System Architecture

The mining system architecture is based on the communication infrastructure and issues that include topologies, protocols, media, modulation and integrity. This section reviews these issues individually.

Topology

The topology used for the mine network should be a bus topology for hardwired systems and a star topology attached to the bus for the radio network as proven by the field experiment. This has been shown to allow the coexistence of hardwired and radio signals on the same communication system in the bandwidth required for automating mining from an engineering office through to underground equipment.

Technology existing on the market today, proven by the surface cable television industry, can form the backbone of the mine network. Therefore, the design techniques and equipment for amplification, splitting and tapping can be purchased cost effectively to supply distributed communication over the large geographical areas required underground. Since the cable television technology exists and is cost effective, this is a logical base for the backbone.

The flexibility inherent to mining systems requires a system that can support mobile voice, data and video transmission. Since the CATV systems can move these forms of data over a hardwired network then a logical extension for mining is the mapping of this transmission over the radio spectrum. Efficient mapping of the DAT was shown across radio and hardwired systems in the field experiment.

Protocol

Protocols to be adopted by the mining industry will be set by other industries, except for minor changes. The significant challenge will be the integration of these secondary technologies with the primary mining technologies. However, computer processors now on the market can be linked to many commercially available products and allow the minor customization required by the mining industry without too much need for development of specialized electronics specifically for mining. Three primary areas of protocol determination for mining are required: voice, data and video. The strategy leading to mine automation will require reference to the evolution of these primary areas.

Voice: The present requirements in terms of voice are the need to establish communication links between personnel. As work towards the automated mine progresses, fewer and fewer personnel will be operating equipment underground, and a growing proportion will be concentrating on maintaining it. Maintenance support will require more sophisticated communication. Where now there is a need for radio systems, in the future, there will be a slow deliberate evolution toward the underground mobile telephone system required by highly skilled technical employees.

Data: The physical geography of the mining environment will demand the application of protocols for the transmission of data based on the large distances to be covered. The research and experimentation done in this thesis have allowed the definition of a Noncontention based protocol - Token Bus (IEEE 802.4 or Manufacturing Automation Protocol (MAP)) for the mining operation. Ethernet or IEEE 802.3 CSMA/CD cannot support the volumes of transactions for mining, because the distances are too large and the volumes too high.

Video: The video transmission standards established by the cable television industry will allow the mining industry to follow their lead, avoiding costly development except where absolutely necessary. Operation of mobile video cameras will require a move to digital video. The digital video transmission will allow software techniques for picture quality enhancement and colour addition and, potentially in the future, "virtual reality." Virtual reality will allow the working environment to be improved, using software to enhance the video image of the production process. As well, teleoperation of equipment will require the use of 3D video systems to aid the operator in depth perception. This has been proven absolutely necessary in the underground experimentation undertaken to date.

Media

Although, in the experiment, coax was the medium of choice, for many good reasons (chapter 4), the protocols and topologies established will support the use of fibre optic cable for the backbone. For some time yet, however, coax will remain the medium of choice as it is easy to maintain, very inexpensive, and has multichannel capability. Fibre optics will not be usable until the following needs have been met for mining. First, the cost and skill-requirements for maintenance must be reduced. Second the conversion of light to electrical signals must become less expensive. And finally, the ability to modulate light must be developed. The work undertaken here is directly applicable to fibre optics once these shortcomings are overcome.

Modulation

Modulation methods to be used in the future mine communication systems can be variable, since the broadband spectrum can be supplied to underground mining over both hardwired and radio systems. The modulation used is broadband and ranges from AM, FM and Phase Modulation. A recently declassified radio technique called "Spread Spectrum" also offers many advantages for the mining operation. This method allows a high security system, as the signal is scrambled over many frequencies and unscrambled at the receiving device. This has the added advantage of reduced power requirements on any given frequency thus reducing the potential for premature blasting cap ignition.

Integrity

Maintaining system integrity will be a key consideration in the application of communication infrastructure to underground mining. The main aspects to be considered are reliability, durability, security and safety. Each will be discussed in this section.

Reliability: The reliability of the communication system in an automated mine will be important as the whole operation will be using the system for the movement of data around the operation. Therefore, a dual cable system with two separate paths to the same points will be an absolute necessity. With two paths to the same point, any damage to the cable system can quickly be rerouted or, in the worst case, the fault can be localized and contained. An important consideration for the equipment computer systems will be the immediate shutdown of all equipment upon the loss of communication signal.

Power outages can be handled easily by the installation of battery backup supplies around the operation at key points. These were established in the experiment and proved successful, allowing the system to run for six hours without external power.

Durability: Since the communication infrastructure will be the backbone of the automated mine, the system must be durable. The keys to durability are the components used in the system. The cables must be designed to last for the mining cycle in the particular area of mining and the mining process must take every precaution to protect the system. As well, the amplification systems should withstand high vibration from blasting, and should be waterproof.

Security: The application of computer systems to production mining will require the development of a security system for operations so there is no possibility of unauthorized personnel performing functions. This is more for safety than for the protection of information. No equipment underground should function without the operator knowing it is being operated.

Safety: As stated earlier, the system should be designed with dual cables to ensure redundancy and failsafe operation. As well, some of the equipment used was are already failsafe. For example, the amplifiers have a dual amplification system and ultimately can be reconfigured by software systems on surface.

To ensure safety, the establishment of a mining Special Interest Group (SIG) of the Manufacturing Automation Protocol (MAP) committee would help in allowing the industry some say in the standards being developed for all industry in terms of electronic systems.

Some accidents have already occurred in connection with dual remote control codes[72]. In a system such as the communication infrastructure experimented with in this work, care must be taken in the establishment of frequencies for the remote control of equipment so that similar accidents involving dual radio remote control do not happen.

A group for spectrum allocation should be established by the mining companies and RF equipment suppliers to insure safe operation of this equipment.

7.2.2 Peripheral Research

Peripheral research work should be directed at the radio frequency hazard associated with the use of blasting caps around the underground network. The experimentation performed as part of this thesis demonstrates the need for changes to the work undertaken by the "Franklin Institute"[73], the current authority in RF hazards and blasting caps. The main reason that change is needed is the use of multiple frequencies during transmission of radio waves underground over the network. Strictly speaking, the current experiment meets the Occupational Health and Safety Act of less than one watt of power/frequency. However, as more applications are developed, the spectrum will be filled, consuming frequencies for different applications with the potential for additive power to a particular frequency. The blasting cap research will take one of two forms: the first could result in changes to the initiation of the electric cap by isolation, or the second could change the initiation method entirely. This research is essential for increasing RF power levels underground so that colour video can eventually be transmitted.

7.2.3 Application Development Research

Application development research will relate to the systems to fit on the communication system. In mining, there are five major areas for process change due to technological improvements: process time improvements, remote control, teleoperation, autonomous operation and finally self deployment. Figure 75 represents these potential applications for development. Time efficiency improvements and the basic remote controls will be achieved in the short term probably through industrial engineering. Sophisticated remote control leading to multiple teleoperation is the current goal of most mining research. With the communication system reported in this work, the pace of developments for multiple teleoperation will be significantly accelerated as it can support the centralization of process operations. Sophisticated teleoperation, autonomy and self deployment are precompetitive research goals of the mining industry and will be the focus of research work in the domain of organizations such as PRECARN and HDRK.

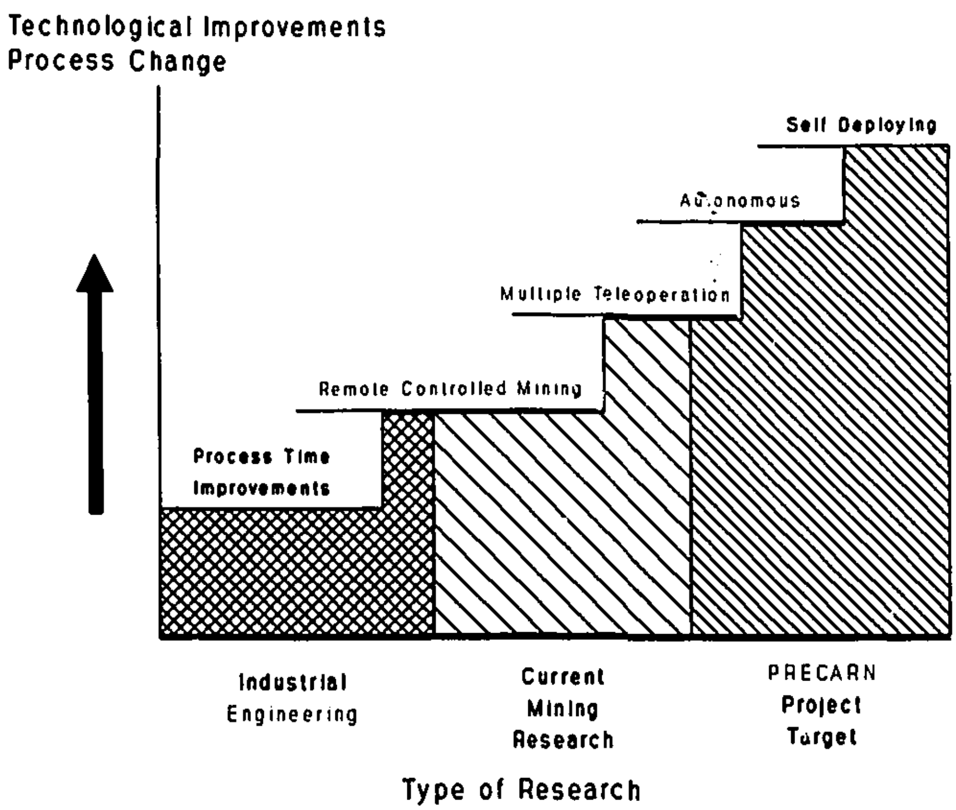

Figure 75 : Technological Change vs Research Type

The application research is outlined conceptually in the following figures. These represent delineation, development, production and overall support systems. Figure 76 illustrates a delineation robot interfaced to an intelligent geological model via the communication infrastructure. The development process, shown in figure 77, further builds on the orebody model from delineation. Automated engineering development models can supply information directly to robotic machines that can do the work. This cascading effect on the mine model will be carried on to the production process, figure 78, supplying information directly to the robots and ultimately reporting information back to the model. The device that will make this all happen will be a "Mining Robot Controller." The mining robot controller will be a parallel computing device linking the monitoring sensors to actuators for local control and an RF modem providing a communication path for control data, monitoring data, position data and video.

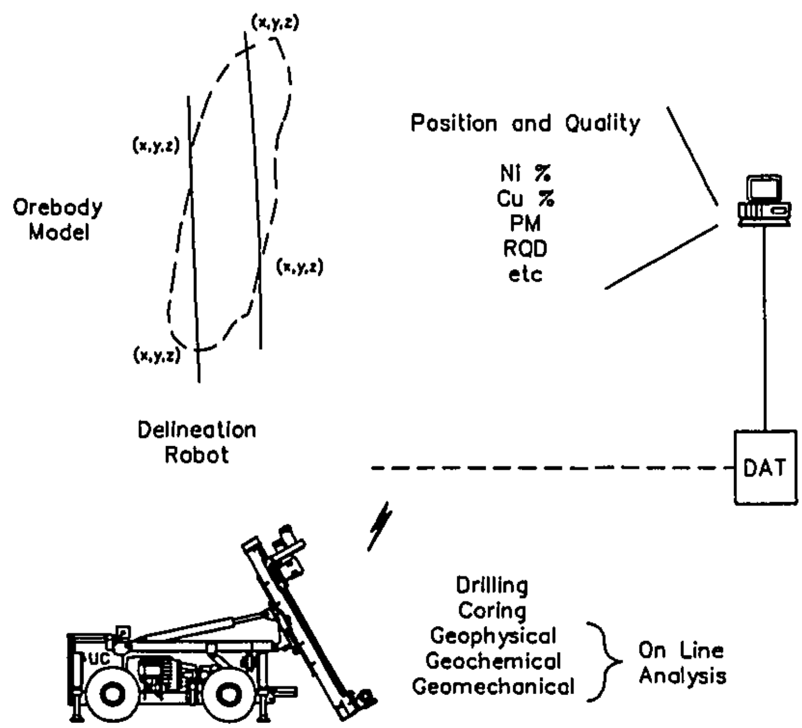

Figure 76 : Delineation Process

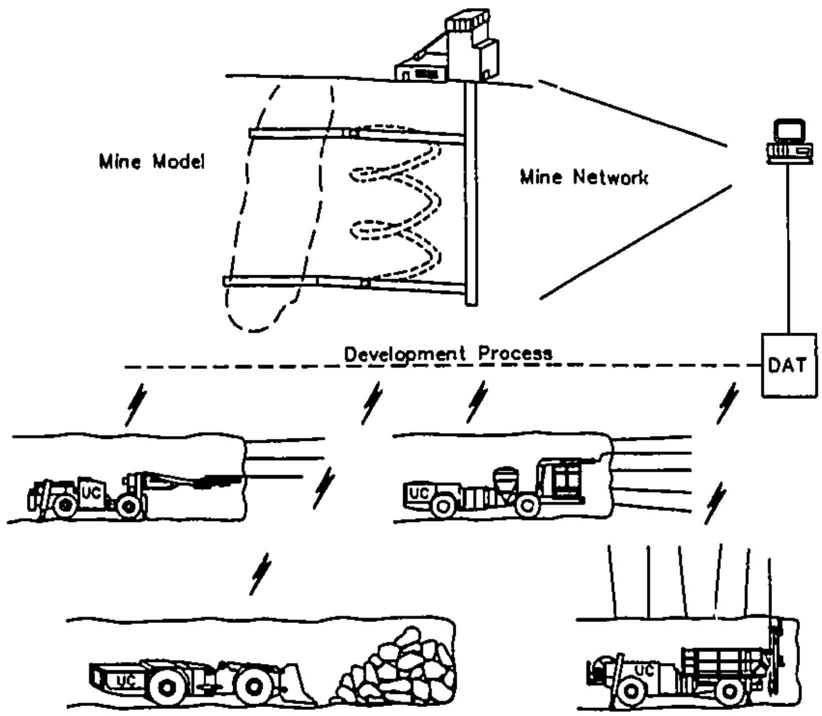

Figure 77 : Development Process

Another set of applications is the development of complete mine support systems in ventilation, pumping, ground control, power distribution, mine dewatering, compressed air and process water as shown in figure 79. Let us use ventilation as an example. Developments in the interface of sensors (e.g., for velocity, volume and air quality) to the communication infrastructure will report information from throughout the mine to a central control computer. This in turn could model the data and send signals back to remotely controlled fans and ventilation doors on various levels to direct the flow of air where it is needed. These will be key developments in the future as they can reduce the infrastructure and energy required to mine and ultimately the cost of operating.

With the development of the systems like those described in the last two paragraphs, several limitations in the types of orebodies that can be mined disappear such as mining at depth, mining in poor ground conditions, and mining

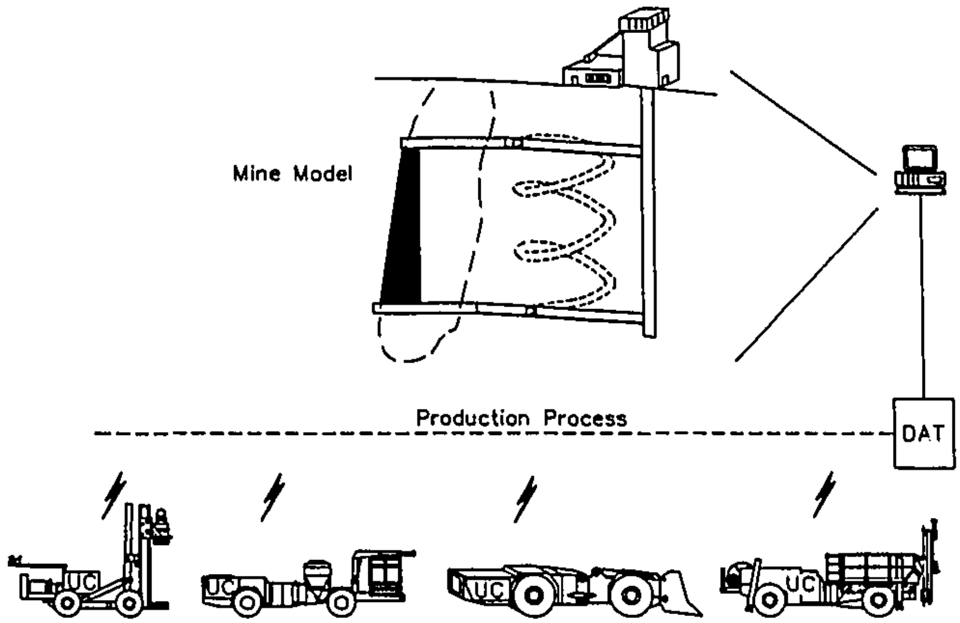

Figure 78 : Production Process

of radioactive ores. Potentially, the robots developed will provide valuable information toward the understanding of automated systems for operating in difficult conditions, such as undersea mining, toxic waste cleanup, and mining in space.

With the framework for future mining R&D defined, the assumptions must be detailed and then proven to be viable. The next sections detail the application development assumptions for automated mining in the future, based on the availability of the underground communication infrastructure and remote computer systems for individual mining systems.

7.3 Telecommunication Infrastructure

With the research and experimentation performed as part of this thesis work, the

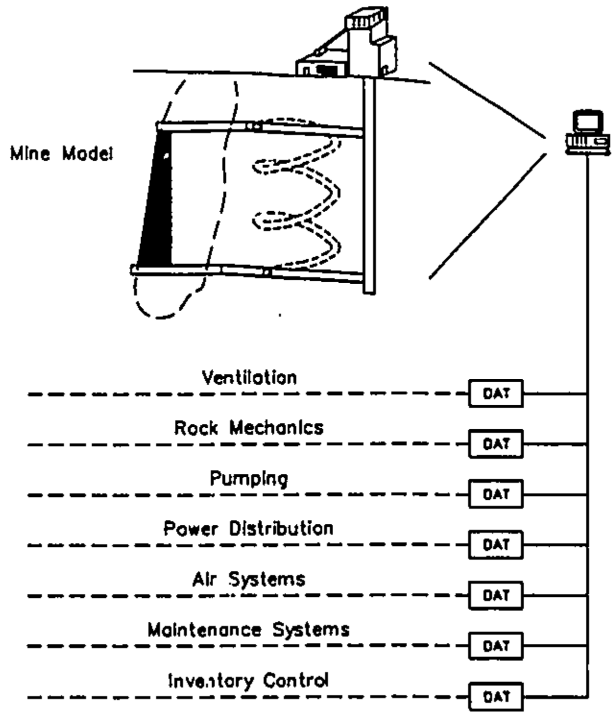

Figure 79 : Mining Support Systems

ability to move high bandwidth information throughout an underground hardrock mine has been proven. This capability enables the consideration of a completely automated mining facility as voice, data and video, to and from stationary and mobile locations, has been established. The system developed is easy to install, use and maintain. As well, the cost per unit bandwidth is extremely cheap in comparison to typical hardwired systems. This system includes the advantage of high bandwidth availability compared to current twisted pair and even fibre optical networks. Another major advantage is the potential improvement in process efficiency due to the elimination of the geographical constraints of mining, allowing equipment to be operated from anywhere in the operation. A further advantage is the ability to move information about the performance and costs of the process and about the environment instantaneously throughout the operation.

Current mining control cabling systems cost approximately $250/ft in the shaft and $25/ft on level runs; installation can double these costs. Maintenance is time consuming and expensive. The aim of the research experiment was to develop a system to support automation of hardrock mining at a cost, following R&D, of approximately $40/ft, dropping to $25/ft in the next few years as the technology matures.

Improved utilization can be achieved through the reduction of process allowance time and as automation increases the ability to maximize the utilization of equipment (e.g. operating three-shifts - seven-days per week). Process allowance time will be minimized as the communication system will eliminate the current geographical restrictions that make it impossible to use the resources to their full potential. Moreover, as the mining systems become automated, equipment availability can be maximized as machines can work alone monitored by their own process control systems for maintenance requirements and for failures.

The ability to move information instantaneously throughout the operation has the advantages of increasing productivity, adding value to the product and reducing process throughput time. These will be achieved through the provision of accurate and timely information to and from engineering and operations.

The next sections discuss the base assumptions that will prove these points in the next chapter.

7.4 Future Automated Mining Systems

To assess the economic potential of mine automation, the economic model developed will evaluate automation as it relates to the VCR mining method, the communication research performed as part of this work. Many of the assumptions about the automation of an underground VCR facility can be extrapolated or adopted to apply to other mining methods. The next sections give research directions based on the future needs for automated mining.

Before assessing a specific mining method there is a common process in underground mining methods and infrastructure that can be broken into the following list:

* Delineation
* Development
  - Drilling
  - Blasting
  - Gangue/ore Handling
  - Ground Support
  - Services
* Production
  - Drilling
  - Blasting
  - Gangue/ore Handling
  - Ground Support
  - Services
* Backfill
* Gangue/Ore Handling
* Supplies Handling
* Infrastructure Systems
  - Communication
  - Power
  - Ventilation
  - Ground Sensing
  - Dewatering
  - Water
  - Air
* Mine Engineering
  - Orebody Modelling
  - Production System Simulation
  - Supervisory Control and and Data Acquisition (SCADA)
* Mine Management
  - Logistics
  - Resource Allocation
  - Legal
  - Occupational Health & Safety
  - Market Condition
  - Process Monitoring & Control

The next sections discuss specifically the VCR mining process with explanations of how the individual subprocess are currently accomplished followed by a brief view of the future research directions anticipated.

7.4.1 Delineation Process

The delineation process currently consists of the diamond drilling of typically 500 foot holes one to four inches in diameter to retrieve rock core to determine the grade and quality of ore at a given point in space. A group of diamond drilled holes and the related information form the database for the modelling of the quality and quantity of ore in the orebody to be mined.

The process consists of worksite preparation, machine setup, drilling, core retrieval, core analysis and orebody modelling. Improvement of this process through future research will build on the following assumptions:

* delineation of an orebody is a separate activity from discovery-based exploration
* delineation drilling in the future will switch from diamond drills to a non-core-recovery system (i.e. destructive drilling) with sensing systems supplying information on-line to a geologic model integrated over the network developed
* a Position, Location and Navigation System (PLANS) will exist for mining equipment use.
* a computer system will be established on the delineation equipment in the mine.
* the turnaround time for delineation information will be cut to near real-time, resulting in increased holes in the same period with better geologic information to engineer both delineation and the mining operation.

7.4.2 Development

Development improvement will occur only with complete cycle automation (drilling, blasting, mucking and ground support or rock cutting). Focus in this work is on drilling, blasting, mucking and ground support. It is recognised that fundamental research in rock cutting is under way and positive results may refocus the automation effort in the future. The model developed is capable of dealing with this as it becomes reality.

Drilling: The current drilling process is performed by Jumbo drilling, typically 10-12 ft holes with little or no perimeter blasting being used. Research assumptions are:

- perimeter blasting is starting to be applied and with automation this work will be more consistently applied in the development process resulting in increased quality of the excavation.
- longitudinal grade control will be improved with the achievement of a PLANS (reduced surveying as PLANS system will replace this) and appropriate sensing on the booms of the machine.
- multiple machines per operator as the jumbo will only need to be moved upon completion of the drilling cycle.
- longer rounds (up to 20 ft) will be possible (due to improve mechanization and automation) resulting in reduced cycle time.

Blasting: Current method of blasting is pneumatically loaded ANFO with nonelectric initiation system. Research in the future will allow:

- blasting automation through the addition of a second boom on the drill jumbo that can load the holes after completion of the drilling cycle resulting in reduced time to load holes.
- initiation techniques for automation loading should be established.
- teleoperation of drill jumbo has already been described and loading

will also be teleoperated in the same manner.

* blasting automation is less effective and low priority as a stand alone function.

Gangue/Ore Handling: Material handling is currently performed using Load-Haul-Dump (LHD) machines. This practice will probably continue in the short term with possible use of Continuous Loading equipment in the future. The same fundamental techniques (e.g., PLANS and teleoperation, maintenance and sensing) are constant in both approaches. Future development systems will allow:

* LHD teleoperation combined with LHD guidance to allow the operation of one person/multiple machines.
* all LHD machines will be monitored for performance and maintenance improving process quality and machine availability and utilization.

Ground Support: Ground support currently uses rock bolts and screen; this is a quantitative method. With the arrival of ground sensing techniques, the method of ground support has the potential to become qualitative; bonded ground support, in combination with lining material in areas where personnel travel may become the norm. The research assumption is that ground support will become automated by the development of bonded ground support and blown-on linings (shotcrete or other material).

Services: Presently include power, air, water, communication, ventilation, ground sensing and fuelling systems. We assume that research will enable automated service installation and electric operation of all mining equipment and dry drilling. The basic infrastructure installation for an automated mine will be power and communication, with taps for sensing packs for ventilation and ground monitoring. No air and water systems will be required.

7.4.3 Production Process

The production process will probably remain drill, blast, muck, ground support and service installation for the foreseeable future. These subprocesses will be refined to improve the productivity, quality and process time.

Drilling: The current drilling process is performed by ITH drilling vertically, typically 100 to 200 ft holes, typically 4-8 inches in diameter. Future long-hole production drilling research directions are:

* hole information (location, grade, strength, impurities) must be monitored on-line for dilution and grade control increasing quality of the ore.
* machine setup will be improved with the achievement of a PLANS (reduced surveying as PLANS system in place) and appropriate sensing on the masts of the machine will improve hole location and direction quality.
* multiple machines per operator, as the ITH will need an operator only to be move it upon completion of the drilling cycle in the stope.
* faster more accurate drilling will result from improved mechanization and automation thus improving fragmentation and digability of the ore. Good fragmentation will also ease the task of automation of continuous loading systems.

Blasting: The current method of blasting is an emulsion-based explosive, with the emulsion added to vary the charge power, and a nonelectric initiation system. Automation research can be assumed to provide:

* blasting automation, through the introduction of explosives via the drill string. The benefit would be the time to load holes reduced.
* initiation techniques for loading automation.

* teleoperation of ITH drilling via PLANS, and teleoperation of loading.

Gangue/Ore Handling: Material handling is currently performed using Load-Haul-Dump (LHD) machines. This practice will probably continue in the short term with the possible use of Continuous Loading equipment. The longer term will probably see hardrock cutting equipment that can be automated fully. The same fundamental techniques (e.g., PLANS and teleoperation, maintenance and sensing) are constant in both approaches. Research directions:

* LHD teleoperation, combined with LHD guidance to allow one person to operate multiple machines.
* LHD monitoring for performance and maintenance, improving process quality, machine availability and utilization.

Ground Support: Ground support is currently done using rock bolts and screen. This is a quantitative method of ground support. With the advent of ground sensing techniques the method of ground support has the potential to become qualitative. If this potential is realized, bonded ground support in combination with lining material in personnel-travelled areas may become the norm. Ground support will become automated by the development of bonded ground support and blown-on linings (shotcrete or other material).

Services: Present requirements are power, air, water, communication, ventilation, ground sensing and fuelling systems. Future operations will require fewer services, since air, water and fuelling systems will be eliminated. The only potential service need is for local ventilation equipment (fans and tubing).

7.4.4 Backfill Process

Current mining methods include either no fill, rock fill, uncemented hydraulic fill, cemented hydraulic fill or paste fill. Each have advantages and disadvantages in given situations. Potential research will provide:

* LHD teleoperation for rock fill systems. Fill plant automation will allow the operation of fill systems at the stope area required with fewer operators and higher quality fills since the process will be more closely controlled.

7.4.5 Gangue/Ore Handling

The gangue/ore handling systems include any long haulage systems to the orepass followed by crushing, conveying, loading and hoisting systems. Future research will allow:

* automated truck systems and automated loading devices such as chutes or continuous loaders. Work to date at Inco has shown this capability.
* conveying systems with acoustic or thermal sensors and PLCs for control.
* crushing systems that are run as much as possible on off-peak power. Robot arms in combination with vision sensing will pick out tramp metal and wood for automated systems operation.
* hoisting of material will be performed through automated loading pockets and automated skip hoist systems. Hoisting will be performed as much as possible on off-peak power.

7.4.6 Supplies Handling

Current supplies handling systems are relatively unsophisticated where parts are delivered and shipped underground with little or no tracking of inventory. Research and proper monitoring and control of supplies will:

* enable computer-based-material handling systems to track supplies

underground. Barcoded supplies will be wanded in on each level and every part added to a machine will be wanded as it is installed and removed. This will cover parts and supplies inventory tracking in addition to maintenance tracking.

7.4.7 Infrastructure Systems

Current infrastructure systems consist of communication, power, ventilation, ground sensing, dewatering, water and air. In future, only basic energy and communication infrastructure will be required. Energy will be supplied through electrical power and communication will be high bandwidth based on broadband cable networks in combination with radio frequency communication systems. This relatively simple infrastructure will be easy to install probably as an integral part of drift development. The systems will provide basic energy for powering equipment and a connection capability to allow monitoring and control of mine-wide basic functions such as ventilation, ground sensing and dewatering. Compressed air systems will be eliminated in the future and the need for water should be eliminated or at least minimized.

Ventilation of the mining operations will be based on monitoring and control. The monitoring will take the form of sensor packs mounted underground in strategic locations to observe the process. Control of the system will occur through automatic fan and door control. All these control elements will be connected to the broadband for distributed control. Ground sensing can be performed with power and communication only. Radio or hardwired connection to sensor packs via broadband will ease and speed installations. All ground monitoring will be done from surface, or even remotely, eventually.

Dewatering PLC controlled pumping systems will be connected to the broadband with local water being reused in the process if it is necessary and the remainder treated for outflow (with on-line water quality monitoring). The need for additional water will be significantly reduced, due to dry drilling and teleoperation of loading.

Air hydraulic drilling will eliminate the need for compressed air systems and air lines. Local air systems will use power to generate any air required for bailing of cutting or maintenance.

7.4.8 Mine Engineering

Mine engineering is currently performed using either manual drafting and scheduling or slightly computerized drawings and schedules. Future directions will allow both geology and engineering to use a 3D, object-oriented, solid-modelling software. This will combine the information generated in the process for facility and production planning. This software base will be the equivalent of CAE/CAM software used in manufacturing.

7.5 Summary

This section has discussed a strategy for future mine automation based on the establishment of underground telecommunication infrastructure. The definition of the telecommunication backbone allowed the development of the strategy for mining systems in the future. Following this strategy development each mining process was discussed allowing a broad view of the mining process and the ability to assess the economic impact of automation on a hypothetical mining operation in the next Chapter.

8 MINE AUTOMATION ECONOMIC ANALYSIS

The purpose of this chapter is to assess the telecommunication system developed in chapter 6 combined with the automation strategy (chapter 7) to determine the impact of automation on productivity, waste/rework (quality) and throughput time to evaluate the benefits of mine automation. A constant dollar economic model was developed, specifically for this purpose, as a spreadsheet analysis of the revenue, costs, manpower, mining rates and maintenance costs. This model was populated with the data set developed in the study "Deep Mining Pre-Feasibility Study"[77] that uses a Cut-and-Fill mining method for a particular orebody. This study was prepared for Falconbridge Limited by J.S. Redpath Engineering Limited, and costs were developed for a series of hypothetical orebodies in the Sudbury area. A second data set for analysis was developed based upon the same approach and orebody. This data set was combined with actual 1990 costs and equipment requirements for Copper Cliff North Mine. This represented the basis for the main economic study, performed on bulk (VCR) mining to determine the economic viability of automation.

8.1 Mine Automation Cost Benefit Analysis

The benefits of mine automation need to be measured in the context of the mining business. The method chosen was benchmarking, followed by the establishment of measurement criteria and then assessment using a mine economic model. Benchmarking by reference to various business sectors could be undertaken, but based on the level of automation technology applied, manufacturing was seen to be the most suitable.

8.1.1 Manufacturing Automation Benchmark

With the base assumptions made in the previous sections, a comparison must be made of the effects of automation for mining. The manufacturing industry was selected as a benchmark to determine the impact and potential benefits of mine automation. This was seen to provide a framework to establish criteria for economic evaluation in the models developed in later sections. Benchmarking of processes is a technique where by different industrial operations are compared to establish what factors make some companies successful, and to allow other organizations to observe their strengths and weaknesses.

Automation in Germany was assessed as part of a benchmarking study by Rommel[74]. In this study, Rommel shows (figure 80) benchmarks for successful and less successful manufacturing companies in Germany. The effects of automation can be staggering when undertaken successfully, i.e.:

* 38% reduction in manufacturing cost
* 33% reduction in waste and rework

and * 30% reduction in total throughput time.

Even the less successful companies achieved:

* 15% reduction in manufacturing cost
* 3% reduction in waste and rework

and * 17% reduction in total throughput time.

To quote Rommel further,

> "Through systematic use of automation, the best companies have, since 1985, realized improvements in cost, time and quality of around 30%. These companies first simplify their structures and procedures before introducing computer-aided technologies. They do not use systems to control complexity."

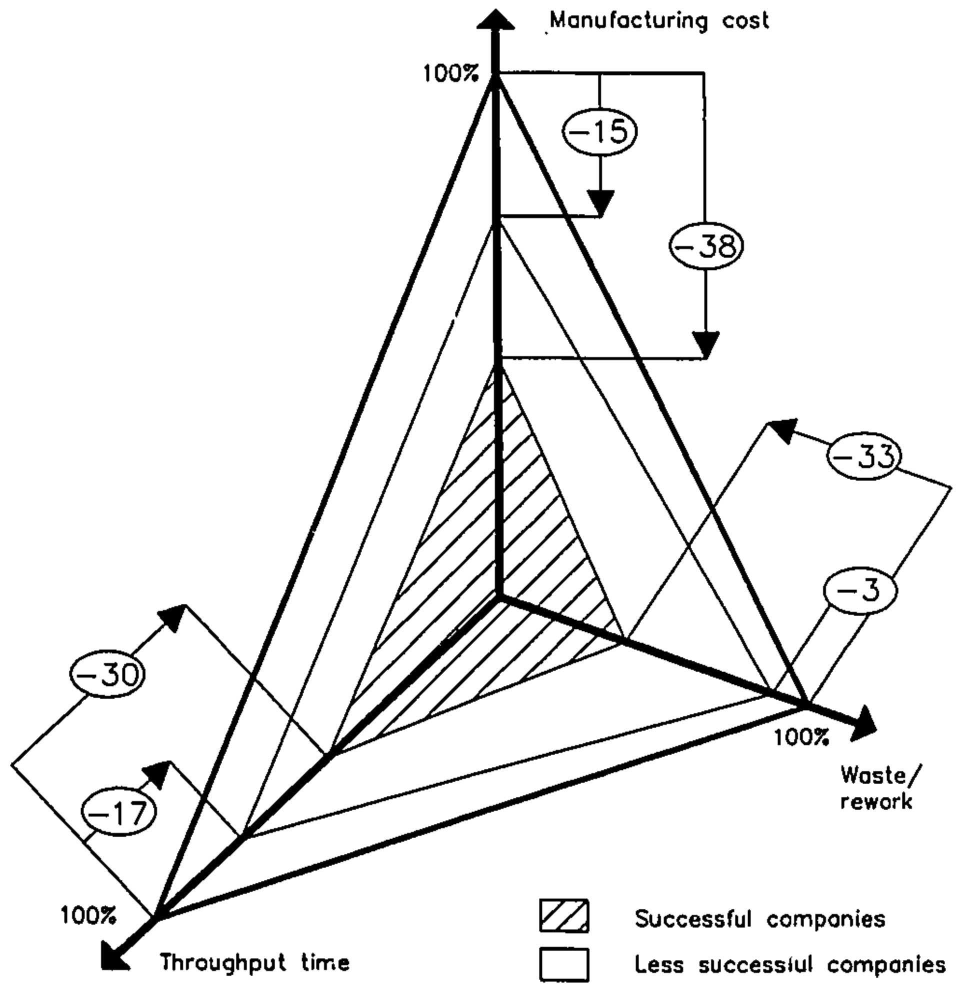

Figure 80 : Manufacturing Automation Benefits, after Rommel(74).

8.1.2 Mining Automation Measurement Targets

It was decided also to adopt the following key parameters to measure the business effects of automation:

* Manufacturing Cost
* Waste/Rework (Quality)
* Throughput Time

To establish the effect of these parameters on mining, specifically related to underground communication and automation, they must be translated into mining-related parameters that can be applied to economic models.

8.1.2.1 Mining Cost

The mining cost parameter consists of six main cost components: capital, management, engineering, labour, supplies and energy. Capital costs are not considered in this analysis as it is assumed that equipment costs will not change significantly, even though the level of automation will increase significantly the other parameters will be more affected by automation. Therefore, to evaluate the impact of automation on mining cost each of the remaining subparameters must be evaluated. Their relative contribution to operating costs for 1990 at the Copper Cliff North Mine were: management 11.6%, engineering 8.1%, labour 37.0%, supplies 30.1% and energy/infrastructure 13.2% see figure 81.

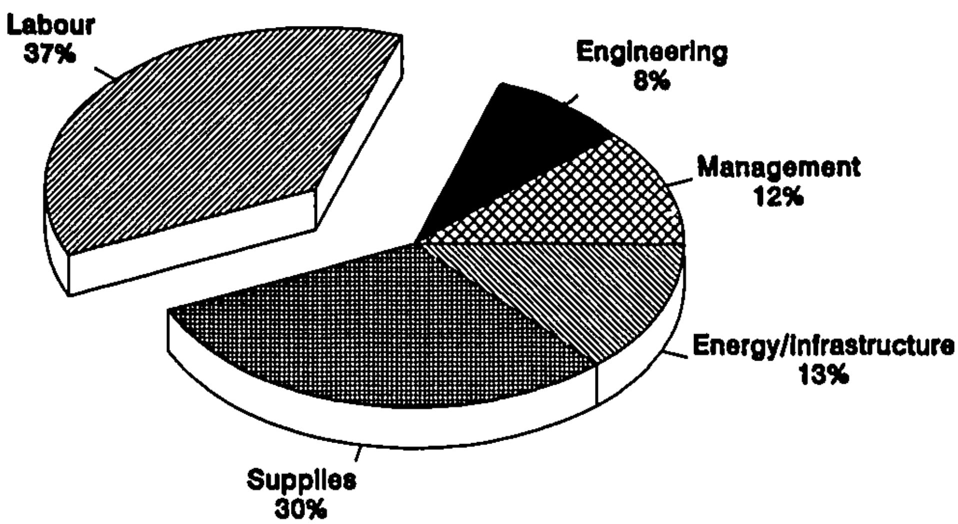

Figure 81 : Mining Cost Breakdown

Tables XV through XXIII show the detailed operating cost breakdowns.

Management cost reductions can be affected positively through provision of

Table XV : 1990 Costs for Delineation, Copper Cliff North Mine

Delineation	Labour	Total	Cost/Ton
Diamond Drilling	$218,400	$280,600	$0.43

accurate information and knowledge and the use of decision support systems. Moreover, since the current management style is based on managing labour, then as the labour component of costs is reduced then so too will management costs follow a similar trend. Engineering costs can be cut through the provision of tools which allow faster design and development, and superior analysis before implementation. Labour costs can be cut by automation, as shown in figure 82. This graph was developed to represent process productivity with process automation or the number of machines a single person can operate (e.g., LHDs). This graph was derived by increasing productivity through the reduction of labour involved in a process. Finally, the last two, supplies and energy/infrastructure, will have a relatively minor or neutral impact unless process quality is improved. In fact, an increase in consumption of supplies and energy can be expected, as utilization of equipment and systems increase. Therefore, analysis of the effect of automation on cost reduction will focus on management, engineering and labour.

8.1.2.2 Waste/Rework

This section attempts to quantify the impact of quality improvement through automation. Product quality is the act of maximizing the value of work done by a process, while process quality optimizes the process which creates the product. Some firms in the mining industry are currently pursuing Dr. Demming's statistical approaches to reducing rework/waste and improving quality[75]. This section deals with the impact of quality improvement on the mining process

Table XVI : 1990 Costs for Development, Copper Cliff North Mine

Development	Labour	Totals	Cost/Ton
Production Development	$575,500	$599,200	$0.91
LCD Drilling	$122,500	$124,200	$0.19
Raise Boring	$380,800	$665,900	$1.01
Bolts and Screen		$445,900	$0.68
Explosives		$102,719	$0.15
Short Hole Equipment Repair	$111,900	$217,300	$0.33
LCD Equipment Repair	$6,900	$67,700	$0.10
Total	$1,197,600	$2,222,919	$3.21

enabled by engineering planning and logistics, process operation and process output through automation.

A method for evaluating the impact of quality on the mining process must be determined. North American management styles have focused on product enhancement while the Japanese, through "lean production", have focused on process enhancement. By improving the process that improves the product the Japanese have become a world economic power in a relatively short time period. This concept was taught to them by North American management through people like Dr Demming and now this concept is being adopted by North American culture. This section attempts to assess the impact of process quality on the production of ore.

The effect of process quality must be measured through the impact on the individual processes: delineation, development, production, backfill, gangue/ore handling, supplies handling, energy/infrastructure systems, engineering and

Table XVII : 1990 Costs for Production, Copper Cliff North Mine

Production	Labour	Totals	Cost/Ton
ITH Drilling	$678,400	$706,900	$1.07
ITH Repair	$130,500	$957,500	$1.45
Blasting	$366,000	$552,600	$0.84
Explosives	-	$667,118	$1.01
Removal - Including Secondary Blasting	$776,700	$1,163,564	$1.76
Tramming Ore and Rock	$570,700	$598,600	$0.91
Mobile Equipment - Fuel & Oil	-	$13,800	$0.02
Mobile Load Equipment Repair	$678,700	$1,135,000	$1.72
Locomotive Repair	$131,200	$188,400	$0.29
Miscellaneous Equipment Repair	$10,900	$68,500	$0.10
Underground Upkeep	$147,300	$877,500	$1.33
Total Production	$3,490,400	$6,929,482	$10.50

management. Process quality is governed by the effectiveness of engineering planning and logistics, process operation and process output.

The measurement of the following processes is best performed relating the quality of the process to the worth of the product obtained. The study uses grades of 1.43% Ni and 0.75% Cu per ton of ore for the hypothetical orebody which are typical of the Sudbury area. The prices of nickel and copper used are $3.00 and $1.00 per pound respectively. Therefore, the value of the ore in the base case is $100.80 Can./ton. The quality is then assumed to improve through improving

Table XVIII : 1990 Costs for Material Handling, Copper Cliff North Mine

Material Handling	Labour	Total	Cost/Ton
Underground Crush, Pass and Conveying	$615,800	$770,700	$1.17
Hoisting	$1,614,300	$1,859,300	$2.82
Surface Ore and Rock Handling	$131,200	$219,900	$0.33
Total Material Handling	$2,361,300	$2,849,900	$4.32

the grade of the ore being mined. As quality increased this would improve the value of the ore through improved selectivity in stoping.

Delineation: Delineation drilling builds on the exploration drilling process. Drill holes are planned on this basis and are attempting to define the orebody further. Quality in this process can be measured through the accuracy of information in terms of grade and quantity. As well, secondary information on the strength and competency of the rock mass can be derived. The automation of information retrieval will cut the process time significantly, and support informed decisions more quickly, increasing the ability to drill more holes and/or better place the holes. This will determine the characteristics of the orebody more accurately improving knowledge and reducing risk with the potential to reduce dilution and improve the grade. The process cost may increase or may result in better pattern layouts that could actually reduce the process cost while obtaining the information required.

Development: The development process has six major subprocesses: planning,

Table XIX : 1990 Costs for Backfilling, Copper Cliff North Mine

Backfilling	Labour	Total	Cost/Ton
Main Fill System	$267,900	$1,536,700	$2.33

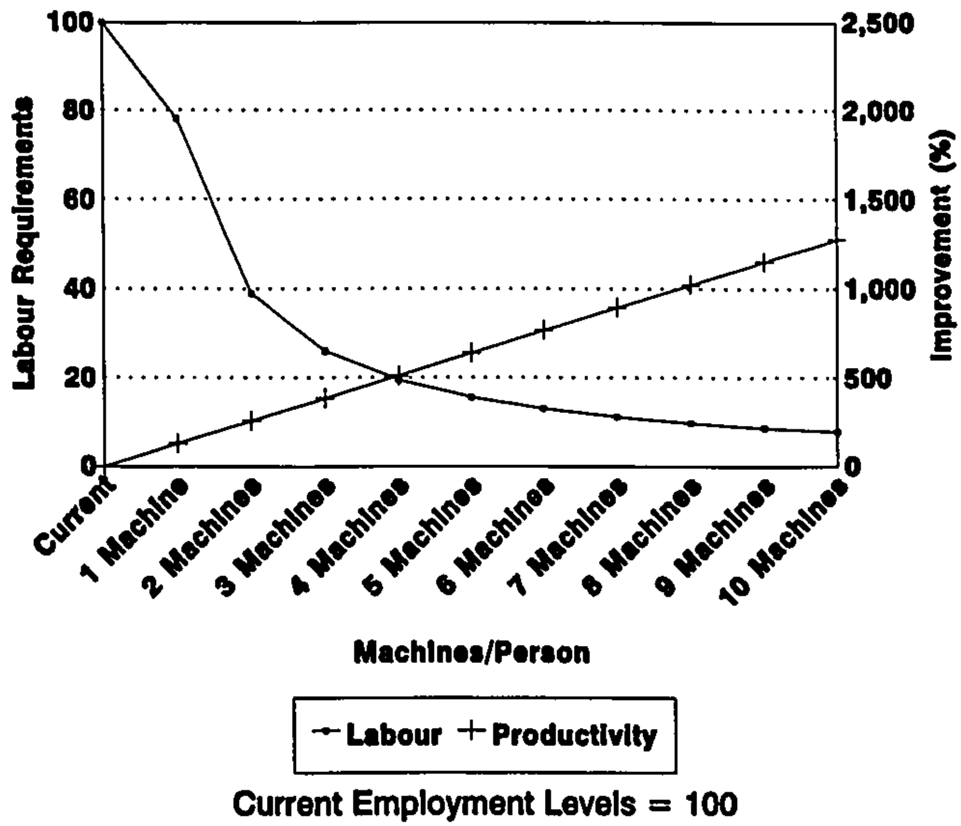

Figure 82 : Indexed Labour Productivity Improvements with Process Automation

drilling, blasting, material handling, ground support and service installation. Quality in this process can be regarded according to the subprocesses.

Development drilling is performed using a drill jumbo which may consist of multiple booms and may operate in single or multiple headings. Planning and logistics require the definition of the engineering which will determine direction

Table XX : 1990 Costs for Infrastructure, Copper Cliff North Mine

Infrastructure	Labour	Totals	Cost/Ton
Drainage and Pumping	$251,900	$969,200	$1.47
Mine Ventilation System	$131,400	$419,500	$0.64
Electric Power System	$217,100	$1,166,700	$1.77
Water Supply System	-	$19,900	$0.03
Compressed Air System	$185,900	$244,300	$0.37
Heating System	$12,900	$193,300	$0.29
Total Infrastructure	$799,200	$3,012,900	$4.57

and slope of the drift, while logistics will insure the correct infrastructure and supplies are in place to perform the process. Drilling will create the holes which are loaded with explosives for blasting. If care is not taken at the drilling phase of the process, the perimeter of the drift will be overbroken and the longitudinal portion of the drift will not have the correct characteristics. This cascades to increased consumption of explosives and poor breaking of the material. The over-broken perimeter of the drift may likely require additional bolting and screening. Finally, the installation of services such as power, water, communication and air will become more difficult. From a more global perspective, the longitudinal characteristics of the drift, the slope and side-slope, while not seeming to be a problem for the 10 foot round, will, if not corrected, make for difficult operation of machines. In the worst cases the drift may not serve its desired purpose of creating an opening for travel between two points.

While these points do not seem to relate to the quality of the product the impact of poor quality in these areas affects the entire down-stream processes. For example a poor floor will:

Table XXI : 1990 Costs for Supplies Handling, Copper Cliff North Mine

Supplies Handling	Labour	Total	Cost/Ton
Material and Personnel Handling	$249,700	$566,500	$0.86
General Surface Services	$637,500	$921,300	$1.40
Total Supplies Handling	$887,200	$1,487,800	$2.25

* reduce LHD material handling efficiency
* increase LHD maintenance
* increase capital costs
* increase energy costs
* increase labour requirements
* increase management costs

in both the development and subsequent down-stream processes. An example of just this result was recently reported[76]. The installation of the Automatic Haulage Truck at Little Stobie mine required a concrete roadbed to allow high speed operation of the truck. This roadbed proved to be successful and was repeated on the 1800 level for the LHDs which would feed the truck. The productivity of the LHDs, increased eliminating the need for one of three LHDs and saving $500,000 in capital cost. Fuel consumption was reduced as one less machine was required. There was less rolling resistance. Labour requirements were reduced by two people, as the third machine would have been run on a two-shift basis; this would ultimately translate into a management cost reduction, as fewer people require less supervision. These arguments demonstrate the effect of quality on reducing the process cost and this will ultimately translate into reduced product cost.

Table XXII : 1990 Costs for Management and Engineering, Copper Cliff North Mine

Management and Engineering	Labour	Total	Cost/Ton
Mine Management	$749,100	$1,589,700	$2.41
Maintenance Overhead	$619,700	$711,200	$1.08
Safety and Pint Prot.	$65,100	$337,500	$0.51
Engineering	$478,900	$1,851,700	$2.81
Total Management and Engineering	$1,912,800	$4,490,100	$6.81

To compare the effects of quality through automation, the most practical ideal scenario for development must be used as a target. Tunnel boring is ignored in this argument although it may be practical in the long term for underground hardrock mining. This section deals only with the current development process of plan, drill, blast, material handling and service installation. The ideal scenario would be the one described in the assumptions section.

Production: The production process consists of planning, drilling, blasting, material handling, ground support and service installation. The impact of quality should be measured according to each subprocess.

Planning is the act of ensuring that the engineering and logistics for performing the process are in place. With planning and the development process complete, then establishing the worksite and the process can begin. In VCR mining, long-hole drilling starts the process which consists of machine travel, setup, drilling

Table XXIII : 1990 Total Costs, Copper Cliff North Mine.

Summary of Process Costs	Labour	Total	Cost/Ton
Delineation	$218,400	$280,600	$0.43
Development	$1,197,600	$2,222,919	$3.21
Production	$3,490,400	$6,929,482	$10.50
Material Handling	$2,361,300	$2,849,900	$4.32
Backfilling	$267,900	$1,536,700	$2.33
Infrastructure	$799,200	$3,012,900	$4.57
Supplies Handling	$887,200	$1,487,800	$2.25
Management and Engineering	$1,912,800	$4,490,100	$6.81
Total Process Cost	$11,134,800	$22,810,400	$31.60
Division Overhead	-	$9,565,500	$14.49
Total Process Cost including Division Overhead	$11,134,800	$32,375,900	$46.09

and process monitoring and control. Following the drilling of all holes in the stope then the explosive loading process is initiated. With the completion of explosive introduction the blast is initiated and the material handling process is underway. This process ends with the ore entering the orepass.

Drilling quality refers to optimizing the drilling of holes for the introduction of explosives in the material (ore) to be fragmented to achieve good material value and fragmentation while drilling is minimized. Blasting quality minimizes the explosives used in the drilled hole while achieving the maximum value and fragmentation.

Backfill: The backfill process consists of planning, site preparation, filling and stope curing. In most operations hydraulically placed backfill is the norm with large upfront capital costs and then relatively large operating costs. The objective of the backfill process is to fill open stopes underground to support the mine structure and improve ore recoveries.

Fill quality minimizes the cost of the backfill product, while placing it in the shortest possible time so it can reach the maximum strength, to allow optimization of production process and to maximize the recoveries.

The impact of backfill quality is beyond the scope of this thesis work other than the optimization of the backfill product through process monitoring and control. Therefore, the impact in terms of quality is ignored.

Gangue/Ore Handling: Gangue/ore handling is the process of material handling following the actual production process. This includes tramming and trucking systems supplying orepasses to crushing, conveying and hoisting systems. The objective of the process is to move the maximum amount of material in the shortest time to meet the schedule while minimizing energy and labour costs.

Several quality aspects can be assessed in this cascade of processes but at this point in the process the value of the ore has been established and utilization becomes an overriding consideration. The only real quality measure is the optimization of the process minimizing the down-time. The impact of these processes from a quality point of view is measured by maximizing process availability and minimizing energy requirements to perform the process.

Supplies Handling: Supplies handling is defined as the process of moving maintenance and consumable supplies to the workplace for keeping the processes operating. This includes the planning, receiving, tracking and delivery of supplies.

Quality in this process is the minimization of the supplies required through planned maintenance and the optimization of the supply receiving, tracking and delivery. Quality in this process is extremely difficult to measure and is not attempted in this analysis.

Energy/Infrastructure Systems: Energy/infrastructure systems consist of communication, power, ventilation, ground monitoring, water, air and dewatering. These are the pieces of infrastructure required to support current mining practices.

Quality in these processes can be measured through the maximizing the availability of these systems while minimizing the energy and infrastructure required. In other words, the effective use of the energy and infrastructure for mining.

Engineering: Engineering is the process of planning and logistics to provide the process with the information required to perform the tasks. With the correct information the process will be optimized and organized before it begins allowing the optimum utilization of the production systems.

Engineering quality can be measured as the most effective planning and logistics for process optimization. Therefore, quality in the engineering process is the maximization of the information to perform the process and the utilization of the systems.

Management: Management from a quality perspective is the most effective utilization of resources to achieve the desired result. With the correct resource in the right place the most significant impact can be attained.

The measurement of quality in management is effectively using the resource to attain the desired result. This is very difficult to measure in a cost model and is not attempted as part of this research work.

8.1.2.3 Throughput Time

Total throughput time will ultimately be reduced as automation will reduce travel time and increase utilization within the process. Thus the efficiency of the individual processes will be enhanced. These reductions and improvements can be categorized as improved utilization due to increased available time and mine process rate increases. To assess improved utilization the impacts of surface teleoperation, increased working hours and the combination of these alternatives. The mining process rate improvements will be assessed through increased individual process rates.

Delineation: The current delineation process is approximately eight weeks long for a 500 foot diamond drill hole. The components of this time are 1-2 days for machine setup, 1 week to drill the hole, 5 weeks to analyze the core and 3-4 days to model the information. The major problem in this process is the length of time required to process information. A great deal of time is spent in transferring core and in lab analysis.

The previous arguments discuss the future use of destructive delineation drilling. This technique once developed would provide a turnaround time of about 1 week as the information would be collected and modelled on-line. This provides a significant time reduction and an information quantity improvement. Therefore, the definition of the orebody would be enhanced and quality would be improved.

For purposes of the cost model, this process would see increases in the rate of consumption of supplies and energy used with the same or less capital equipment, as utilization rates would increase. Taking this process from 8 weeks to 2 weeks would see a four-fold improvement in utilization. Consumed supplies and energy would have a corresponding four-fold increase with the same equipment levels.

Development: The development process consists of drilling, blasting, material handling, ground support and service installation. Currently, this process achieves a rate of 10 feet/24 hours. Table XXIV breaks down the process time into the component times. To improve this process, an individual component cannot be improved in isolation; the entire process must be improved.

Table XXIV : Development Process Time Break Down

Process	Time (hours)
Drilling	3
Blasting	2
Material Handling	3
Ground Support	7
Service Installation	2
Unused Time	7
Total Process	24

From the table it can been seen that the two largest components of time in the process are ground support and idle time, at 7 hours each. Reducing the time to perform ground support will have a major impact. As for idle time, operating the equipment from surface will increase the utilization of the machines for development by reducing travel time to the work site.

Production: Production as a process consists of long hole drilling in VCR, blasting, material handling, ground support and service installation. The total process time for a typical stope (25 ft. x 100 ft. x 200 ft.) is 150 days. Table XXV breaks down this process into its component times for analysis.

The largest proportion of the time in the production process is spent handling ore to the orepass. When analyzing this process the critical path of the process must be determined. Drilling must be accomplished before blasting and material handling can proceed. Therefore, to impact this process two aspects must again be considered: first, the improvement in equipment utilization, and second the individual improvements in the subcomponents of the process.

The impacts of these parameters can be assessed through the cost model used later in this chapter. Operation from surface is shown to provide a 21.8% improvement in utilization and thus in the production rate. Process improvement can be measured as a sensitivity analysis on improving the production process rate between 0% and 50%.

Backfill: Backfill in the mining process is very dependent on the local characteristics of the rock. Some potential backfill requirements for mining are no backfill, uncemented backfill and cemented backfill. The issue in this process when backfill is required is to place the fill a quickly as possible in the quality required. Current placement rates are approximately 800 tons/shift for uncemented or cemented. The logistics of set up is more significant than placement rates.

Optimum control and continuous placement from surface will result again in a 21.8% improvement in utilization. As well, the correct control system will provide throughput process rate improvements. While this is particularly difficult to measure a sensitivity analysis can be performed which ranges between 0% and

Table XXV : Production Process Time Break Down

Production Process Components	Process Time (days)
Long Hole Drilling	60
Blasting	30
Material Handling	90
Ground Support	5
Service Installation	5
Process Total Time	150

50%.

Gangue/Ore Handling: Gangue/Ore handling is the process of moving the material around the operation and ultimately to surface in the case of ore and back into the stope in the case of gangue. In most mines this process is relatively continuous once the operations personnel are deployed. Therefore, the majority of the benefit will be making this operation continuous gaining the 21.8% benefit of running the operation from surface. Example of continuous material handling processes already at work are the Automatic Haulage Truck at Inco Limited, automated conveying systems and automated hoisting systems. To assess this impact using the cost model it is assumed that these processes are optimized reasonably well and the main benefit is a 21.8% utilization gain.

Supplies Handling: Supplies handling is the process of providing the equipment and systems with the maintenance supplies and consumable supplies to operate. The process time required to get these supplies to the worksite is extremely difficult to measure although it merits some discussion. The components of this process are different for maintenance supplies and consumable supplies.

The maintenance supply process consists of problem recognition, obtain parts, repair problem and rework component supplies if necessary. The consumable process consists of planning work, get consumable and perform work. While both processes are different they require similar systems to improve throughput times. The systems consist of ordering systems, shipping and inventory planning and tracking.

While it is recognized that these types of system will improve throughput time this cannot be measured in the level of cost model detailed in this thesis. Therefore, no attempt has been made to quantify this type of benefit.

Energy/Infrastructure Systems: Energy/Infrastructure systems are a significant cost to the mining process consisting of power, communication, air, water, ventilation and pumping. The efficient use of energy in mining is required to minimize cost in this area.

Several assumptions need to be made in this section as outlined below:

* hydraulic systems will replace pneumatic systems bringing the energy utilization down as the main use for pneumatics is underground drilling. This will eliminate the need for pneumatic systems consisting of electrically driven compressors, piping networks and local compressors which are ultimately 3% efficient as a system.
* water systems will be reduced as the main purposes for water in the mine are for drilling and dust suppression. Therefore, if dry drilling and teleoperation of material handling equipment are used, water will not be needed except in limited locations.

The switching from pneumatic to hydraulic systems will reduce the power requirements and the requirements for capital and operating dollars for compressors, piping and the associated maintenance.

Ventilation system efficiency can be improved significantly through the reduction in personnel underground and the development of monitoring and control systems to support real-time operation. Energy consumption will be reduced as it can be tied to the personnel actually in the mine through transponders which could control the ventilation to the operation. To assess the impact a sensitivity analysis ranging between 0% and 50% improvement in energy is performed.

Engineering: Engineering, with the advent of computer aided engineering design tools will become more efficient and the design process will provide significant savings throughout the entire process. The main impacts in this area are accounted for in almost every aspect of the previous sections. The implementation of these systems depends completely on the engineering design work done before implementation. New tools including sophisticated process simulation and mining engineering design will improve the efficiency of the mine design.

Model impacts have already been accounted for in the section on cost, waste/rework and throughput time. Therefore, no model impacts for this section are warranted that has not already been accounted for.

Management: Management at the mine level presently involves a great deal of moving around the operation by foot or jeep. As communications infrastructure is implemented, the information required to run the operation will be more readily available, not only to the management but also to the engineering, operations and maintenance staff. Therefore, the concentration of the information and personnel on surface will result in significant improvements in the efficiency of managing a mining operation.

Based on the previous arguments time savings of 21.8% can be assumed although this has already been accounted for in the first analysis on productivity improvement and the process of managing the operation will enhanced. The management enhancement can be measured as a sensitivity analysis between 0% and 50%.

8.2 Assumptions

The hypothetical orebodies originally developed in the "Deep Mining Pre-Feasibility Study" report consider four different mining scenarios between 4500 and 6500 levels of a mine, based on post pillar cut-and-fill mining in the Onaping area. One scenario was chose for the model as shown on the plan and section, figure 83 and 84 respectively. The orebodies consist of three zones with a strike length of 2300 feet and a total of 15 million tons. The value of the ore is about $100/ton CAN. Characteristics of the zones are shown in table XXVI.

Table XXVI : Model Orebody Zone Characteristics

Characteristics	Zone 1	Zone 2	Zone 3
Dip (degrees)	45	40	60
Dip Length (ft.)	1050	340	265
Average Mining Width (ft.)	40	35	30
Vertical Height (ft.)	742	218	230

Many assumptions were used in the development of the model. They include:

* specific gravity is 3.5 or 9.75 ft^3 per short ton
* all shaft sinking, ventilation and ore pass raising, and preproduction ramping and drifting use schedules and costs based on contractor performances. Costs are calculated over a 350-day year.

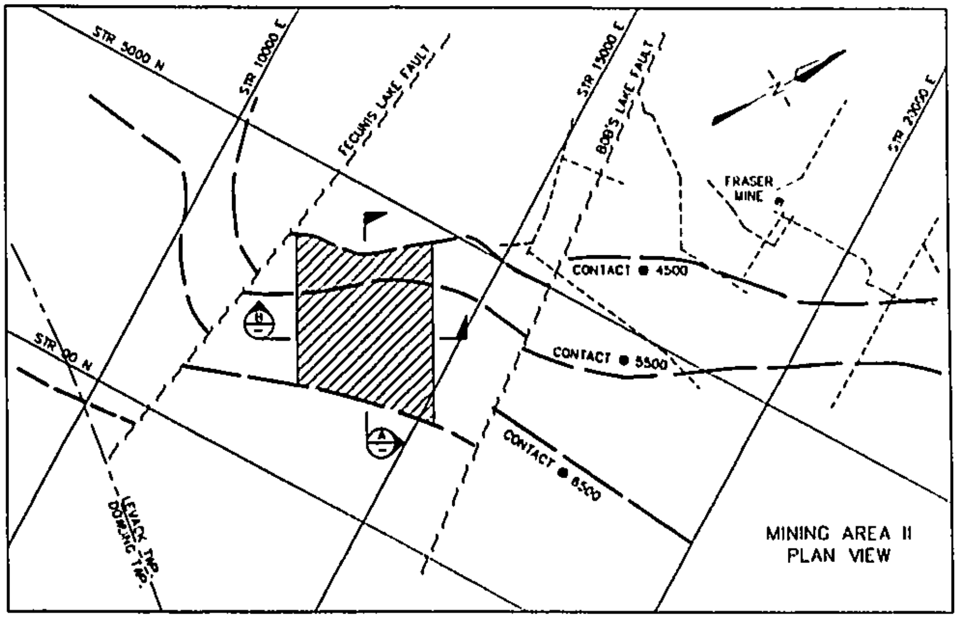

Figure 83 : Model Orebody in Plan.

* ongoing diamond drilling and stope development are based on company performance and costs for normal operating years of 220 days with three-shift operation.
* power cost is 3.14 cents per horsepower hour.

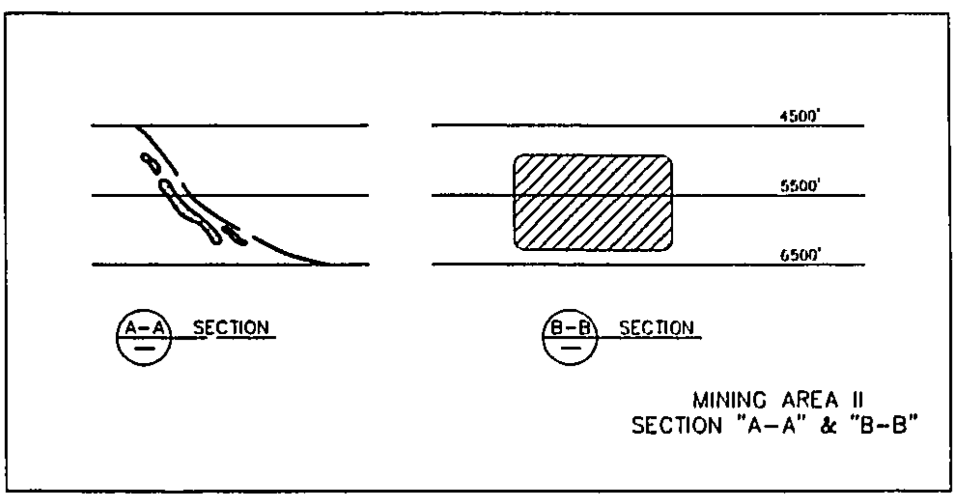

Figure 84 : Model Orebody in Section.

* preproduction development costs include all indirect charges.
* stoping and stope preparation costs do not include indirect charges.
* drift headings are 16.5 ft. x 16.5 ft. (5m x 5m) with arched back, supported by rockbolts on 4 ft. x 4 ft. patterns.
* all raises are circular and consist of rebar on a 3 ft. x 3 ft. pattern.
* historically, 40% of development waste is used for backfill.
* the backfill rate is 800 tons/shift using 0.45 tons of fill per ton of ore. An expected availability of 75% is expected.
* in narrow ore, definition diamond drilling is required at 41 ft. (12.5 m) sections. In wider ore, use 25 m (82 ft. spacing).
* maximum ventilation velocity in a smooth lined dedicated ventilation shaft or raise is 4000 ft. per minute. In unlined dedicated airways it is 2000 ft. per minute.
* refrigeration will not be required.
* ventilation was calculated to require 1 c.f.m. air per ton/year of ore, or 1.2 million c.f.m. per 1.2 million tons/year. This factor has been used in designing ventilation.
* all pumps are standard construction and have a spare base on each pump station with one spare pump.
* vertical settlers will be used for sludge removal below the 6500 level.
* an extra 10% of development has been allowed for turns and turnoffs, in calculating the slope distance of ramps at 15%.
* an extra 15% of development has been allowed for in calculating the length of sublevels, to compensate for irregularities.
* all costs are in 1990 dollars.

8.3 Modelling Methodology

An economic model was developed using Lotus 123G^{tm} to emulate the original

Falconbridge cost infrastructure. The structure of the model relates to yearly cashflow distributed over the life of the mining project. Components of the model include a summary, parameter inputs, detailed capital cost, direct detailed operating costs, distributable operating costs, manpower-breakdown and finally production rates and costs, including equipment lists and maintenance costs. This model is included in Appendix A.

The summary section consists of year by year summaries of capital cost, operating cost, combined capital and operating cost, revenue and cashflow. This is followed by total project costs for capital, operating, total cost, revenue and cashflow in constant and discounted dollars. The discounted dollars are calculated based on three rates: effective cost of capital, the consumer price index to inflate or deflate wages and supplies, and price inflation or deflation based on metal price indices.

With the input section of the model the modeller can adjust financials, orebody grades and value, productivity, quality and throughput time factors. The financial parameters include effective cost of capital, effective consumer price index and a metal price inflation or deflation rate. The input section on orebody grade allows the input of grade and value per pound to decide the value per ton. Another section on effective grade is included to show the grade used if the quality of the process results in grade improvement. Productivity factors are input for management, engineering and labour. A second column permits the division of the productivity by this integer factor based on the automation level (e.g. one person/three machines, "3" would be input). The rework/waste or quality section allows input of value improvement parameters and process quality refinement factors. The final input section enables the study of process utilization based on percentage improvements, and of the process rate improvement based on refinement of the process subcomponents.

Capital requirements for a mining operation are detailed in the next section. It starts with a brief summary of total capital charges for the categories of permanent development, and property, plants and equipment, distributed over the life of the project. Permanent development costs are summarized from the section on production rates near the end of the spreadsheet. The detailed property, plant and equipment charges directly follow the summary.

Following capital costs are the direct operating cost charges broken down according to the process: delineation, horizontal and vertical development, production and backfill. Each process is further subdivided into a cost for labour, supplies, maintenance labour and maintenance supplies distributed over the life of the project.

Distributable or indirect operating costs follow direct operating charges. These costs are distributed over the life of the project and consist of: ore handling system, mine services and utilities, mine engineering, mine administration and supervision, plant services and electrical and instrumentation followed by a summary of total distributables.

The next section is labour-breakdown which is again subdivided into direct and distributable components. This table is generated based on a labour cost of $70,000 per person for labour and $80,000 for mine administration, supervision and engineering. Direct labour is subdivided into delineation, horizontal and vertical development, production and backfill. Mine distributables are subdivided into ore handling system, mine services and utilities, mine engineering, mine administration and supervision, plant services and electrical and instrumentation. The totals are summarized with 10% absenteeism included.

Production rates and costs follow the labour section. This section is subdivided into production rates consisting of development in ore and actual mining production. Delineation production rates follow mining production rates (in feet/year, cost/foot and total cost). Next are development rates (in feet/year, cost/foot and total cost) followed by mining costs/ton and concluded by backfilling cost/ton. This section is the main cost generation area used to complete the remaining portions of the spreadsheet.

The final section is the equipment list that comprises the number of pieces of different equipment along with estimated maintenance costs based on a 35/65 ratio of labour and material distribution, respectively. Costs were generated based on estimated cost/hour, total hours/year, and production-rate.

8.4 Input Data Sets

Two data sets were developed for a selective (Cut-and-Fill) and a bulk mining method (VCR)for use within the model. Both sets were developed based on 1990 Canadian dollars.

The actual costs for Cut-and-Fill were supplied by Falconbridge through interviews[78] and the "Deep Mining Prefeasibility Study"[77] (completed model Appendix B). The data set applied to the model was only developed to prove the functioning of the mine economic model. This selective mining model although developed had no analysis performed on it for automation. This was considered to be beyond the bounds of the thesis study.

The data for the VCR model were based on the main Cut-and-Fill data set with appropriate changes in equipment levels, mine development requirements, mine production requirements and actual 1990 costs from Copper Cliff North Mine (as shown previously in tables XV through XXIII). For analysis in this thesis only the VCR model was used. A copy of this model is included in Appendix A.

8.5 Analysis

This section reports the results of savings from productivity improvements, reduction in waste/rework or quality and reduction in process throughput time. The need for communication-infrastructure is inherent in achieving the productivity improvements shown in figure 82. This communication infrastructure is also required to improve quality and reduce the total throughput time. Three basic cost assumptions are made throughout all modelling work:

* the new communication infrastructure cost is $4 million over the life of the mine (based on $50/foot in the shaft, $40/foot for the rest of the coverage, $50,000 per DAT and $100,000 for the headend equipment).
* the cost of automation of the individual pieces of equipment is the same as the purchase of current mining equipment and systems.
* the cost of communication-infrastructure currently being used over the life of the mine is removed from the mining cost ($5.5 million based on $500/foot in the shaft and $50/foot to cover the rest of the operation including terminations).

The next sections report the results of the improvements achievable concerning mining cost (productivity), waste/rework (quality) and throughput time.

8.5.1 Mining Cost

The effects of automation on mining costs was assessed by varying the main cost components: capital, management, labour, engineering, supplies and energy/infrastructure according to productivity improvements. Subsequent analysis deals with quality and throughput time improvements. The situations to be assessed were input into a series of cases and the impact of the particular variation was found relative to the base case (Appendix C).

In this analysis, capital was assumed to be constant. The same types and numbers of equipment were assumed to be required to achieve the production rates. The cost was assumed to be more or less unchanged because, in the work reported on the "Automatic Haulage Truck"[8], it was found that if the automation system is embedded in the equipment, the actual cost of automated machinery is competitive in price with labour operated vehicles.

Mining cost savings were based on productivity improvements in management and labour. The productivity gains used are shown in table XXVII with operating labour improvements based on the level of automation. Management productivity gains followed operating labour and are calculated to be based on 2/3 of the labour productivity gains. This consideration assumes that the management style will evolve from a labour-based management to a technology-based management.

Engineering productivity rationale was based on the application of "Computer Aided Engineering" or CAE tools. Inco Limited and Noranda Inc. have been developing "Computer Aided Design" or CAD tools that may show productivity improvements in the rework of mine planning drawings. This will probably account for 10-50% productivity gains. Falconbridge Limited has been taking a different approach with their "Computer Aided Mine Planning System" or CAMPS, which is based on solids modelling capability. CAMPS type systems offer the large potential for engineering productivity improvements of 100-200%, as engineering planning would need fewer engineers and no draftspeople.

The productivity rationale for supplies is not accounted for in this section on productivity as it is really a throughput time issue or an increase in utilization that will be dealt with in a different analysis. This rationale is also used for the increases expected in energy/infrastructure due to increased utilization.

The application of the above rationale to the economic model was performed in

Table XXVII : Percent Productivity Gains Modelled

Automation Level (Machines\Person)	Management	Operating Labour
Case 1 - Base Model	0	0
Case 2 - 1 Machine	128	128
Case 3 - 2 Machines	171	256
Case 4 - 3 Machines	256	384
Case 5 - 4 Machines	341	512
Case 6 - 5 Machines	427	640
Case 7 - 6 Machines	512	768
Case 8 - 7 Machines	597	896
Case 9 - 8 Machines	683	1024
Case 10 - 9 Machines	768	1152
Case 11 -10 Machines	853	1280

10 successive case studies (Appendix D) based on the previous table XXVII that yielded results in employment reduction, cashflow increases and total return improvements in constant 1990 dollars.

The productivity improvement analysis is based on automation levels ranging from one person operating one machine from surface through to one person operating 10 machines. Ten machines was chosen as an upper limit as the cycle time of the Automatic Haulage at Little Stobie mine was 10 minutes and the actual involvement of the operator is one minute. Therefore, the current situation would allow one operator to supervise nine machines. Figure 85 shows the reduction in employment level through the case studies. It should be noted that the greatest effect can be seen at one person operating three machines where the employment level dropped to 103 people from the base of 313, i.e. a 304% improvement. It also happens that one person operating three machines is practically achievable and has been proven through testing underway at Inco Limited. This testing demonstrates productivity improvements by combining LHD teleoperation with vehicle guidance[76]. Results achieved to date have already proven the practicality of one person operating two LHDs over the communication system at Copper Cliff North Mine. Employment reductions correspond to increased cashflows over the life of the project as shown in figure 86. Again it can be seen that most of the benefit in cashflow are achieved by one person operating three machines from surface. As well, total cashflow (figure 87) of the project increases significantly as the level of automation expands.

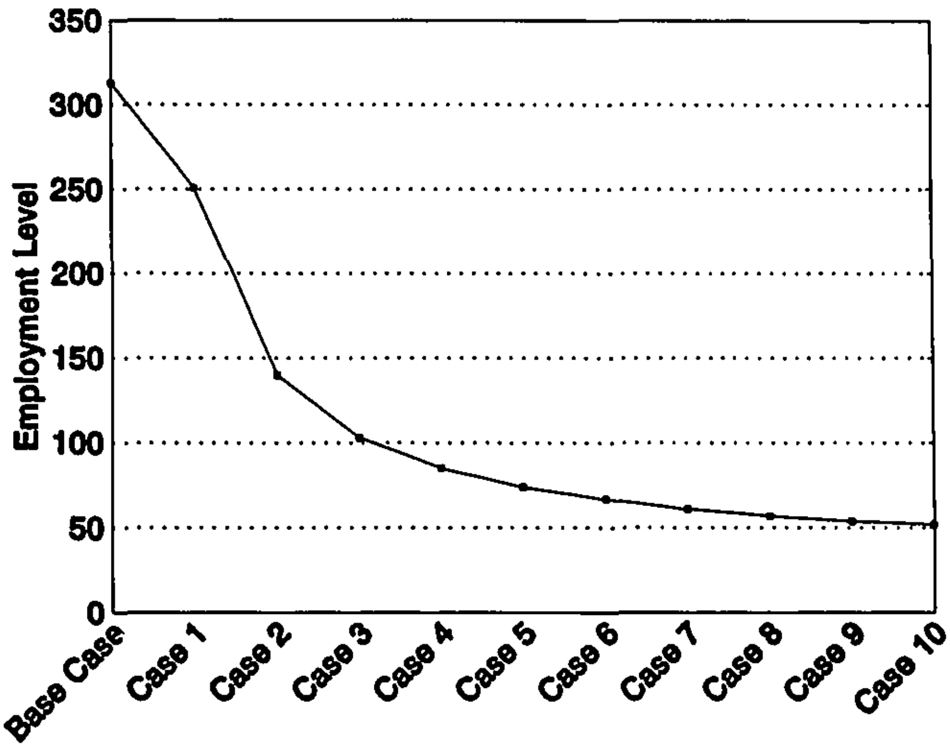

Figure 85 : Employment Level as Automation Increases

Engineering productivity improvements was considered to occur through the application of two particular computer assist tools, CAD and CAE. As stated earlier, both offer productivity improvements: CAD provides time saving on drawing rework, while CAE offers much larger productivity gains. The impact

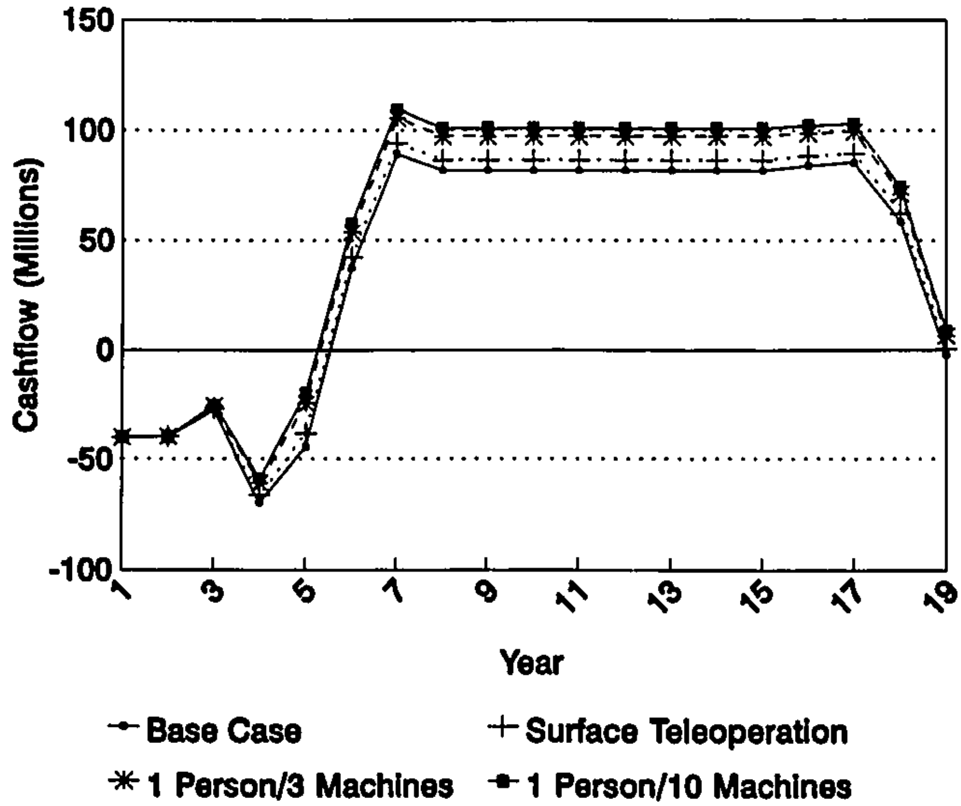

Figure 86 : Cashflow Case Studies for varied Productivity Levels achieved through Automation.

of engineering productivity was assessed by developing cashflow curves for engineering productivity increases ranging from 0-200% (Appendix E), which is within the range achieved by successful manufacturing companies. Improvements in productivity of engineering do not significantly effect the cashflow of the operation as shown in figure 88. In fact, a reduction in personnel in this area will probably impact negatively as the needed analysis to optimize the productivity, quality, availability and utilization would not be performed. Therefore, the objective in engineering productivity should be to maximize the productivity of the engineering personnel to optimize the operation design.

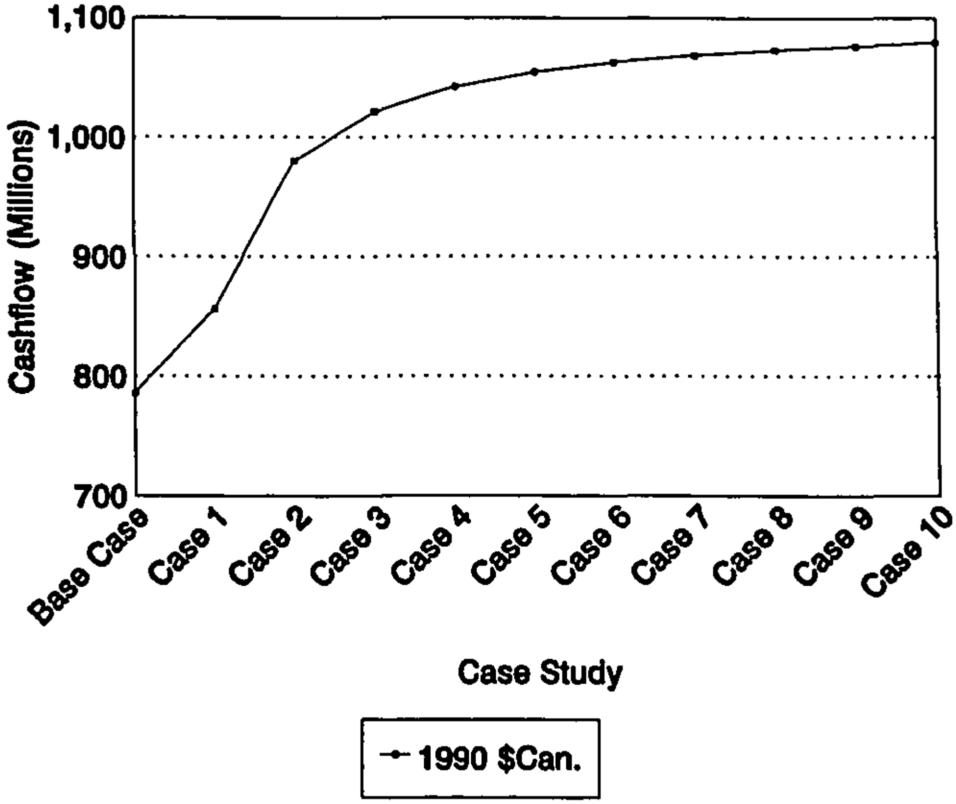

Figure 87 : Total Cashflow as Productivity Level increases through Automation

8.5.2 Waste/Rework (Quality)

Waste/rework costs (or quality) can be significantly improved through the application of automation as machines can achieve far higher levels of quality than people. This argument holds true particularly when people are maintaining the process system as opposed to being critical components in the process. The effect of quality is twofold: first, the process will be optimized, and second, the value of the product will increase. Optimization of the process is difficult to measure but it is attempted in this analysis by measuring the cost reduction of the process (not including labour). Value improvement is measured in terms of its effect on the grade produced. Since each function in the process contributes to an increase in grade, an attempt was therefore made to categorize this through

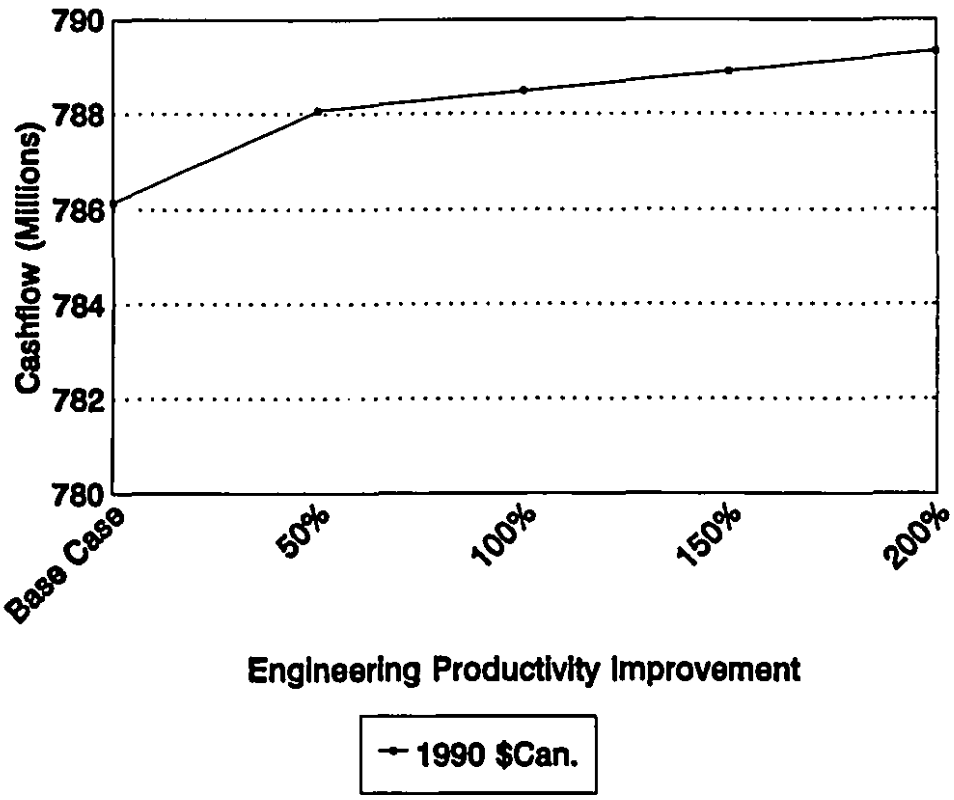

Figure 88 : Cashflow Improvements Resulting from the Application of Engineering Productivity Tools.

percentage improvements in grade as contributed by individual processes.

The impact of process quality improvement on cashflow was analyzed with the model (Appendix F) and the results are shown in figure 89. In this graph, process quality was measured against cashflow in constant dollars. To effect this in the model the quality was improved using a reduction in process cost. Therefore, if the process quality was improved by 15% the supplies costs for performing the process would fall by 15%, thus simulating a 15% reduction in rework or waste. The results show that the upper limit of potential savings in this area is 100% or about $80 million. While this appears to be excessively large it should be recognised that a more realistic goal is in the range of 0 to 50%, since 100% implies zero supplies cost. Therefore, the maximum potential savings available are approximately $40 million.

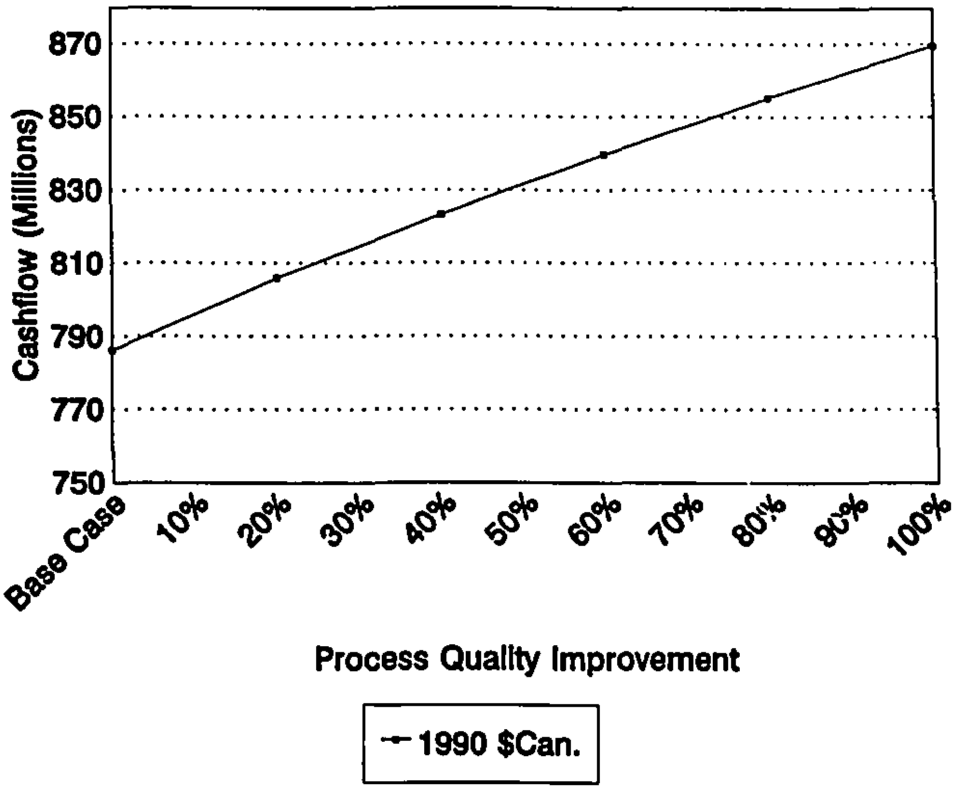

Figure 89 : Impact of Process Quality Improvement on Cashflow

The impact of increasing the value of the product through process improvement was also measured (Appendix G) and the results are shown in figure 90. This graph shows the impact of quality improvement by increasing value. Value impacts the cashflow of the operation dramatically. A 20% improvement in grade achieves about a $400 million improvement in cashflow. A 20 % improvement in grade is the change from 1.43% nickel and 0.75% copper to 1.72% nickel and 0.90 copper. The graph continues through 40, 80 and 120 percent improvement so the impact of grade on mining cashflow can be seen. This analysis proves that improved value of product has a significant impact.

The two quality factors compared (figures 89 and 90) show that product quality improvement has the single biggest impact. Therefore, R&D should prioritize to work on mining systems that will improve grade, and focus less on process improvement. In actual fact, targeting grade improvement will probably also lead to the process quality improvements.

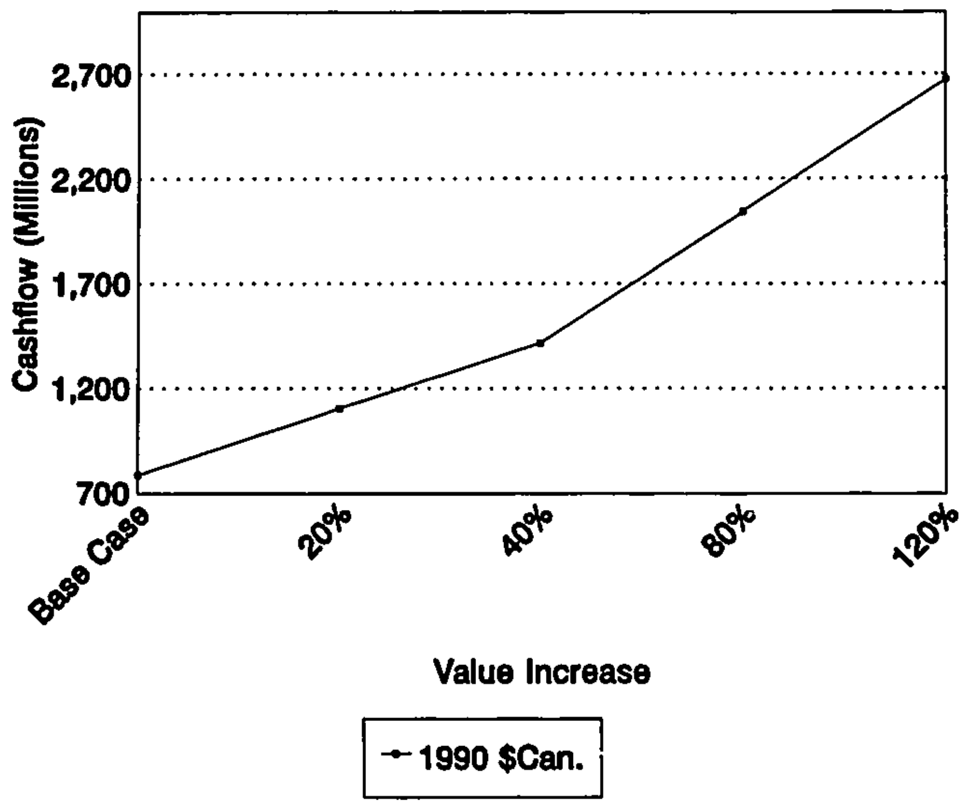

Figure 90 : Impact of Process Improvement which enhances Product Value on Cashflow.

8.5.3 Throughput Time

Throughput time will be improved with automation because of increased utilization of the mining system and ultimately an increase in the mining rate with the same equipment levels. The impact of these points was measured in the economic model by increasing utilization by 21.8% corresponding to the elimination of process allowance time (shown in figure 91) for operation from surface. The estimate of current productive time of 375 minutes in a shift is extremely conservative; it is actually closer to 250 minutes. The next analysis is based on moving from a three-shift with five-day per week operation to a three-shift with seven-day per week operation or a process utilization increase of 28.6%. This leads to process time improvements ranging from 50-100% as a result of process cycle time reductions as process automation increases.

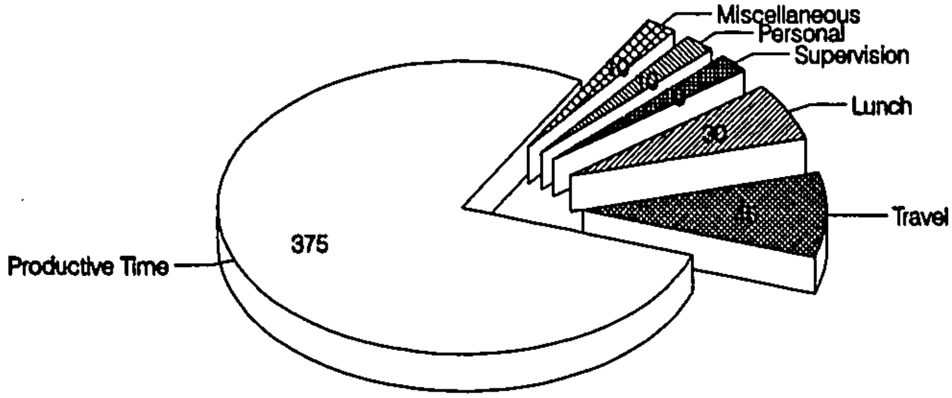

Figure 91 : Current Total Shift including Process Allowance Time

To discover the benefits of operation from surface, the first case shows 21.8% utilization improvements and a corresponding 21.8% productivity improvement with only teleoperation capability of all mining processes. Another two cases adding individual process time improvements of 50 and 100 percent were investigated. The cashflow results of these three cases (Appendix H) are shown in figure 92. Teleoperation of mining equipment from surface adds cashflow of about $110 million. If the mining rate is improved the impact on cashflow is another $40 million for a 50% increase and a further $20 million for a 100% increase. Therefore, the maximum benefit will be achieved through teleoperation of machines from surface, followed by diminishing returns as the mining rate is increased.

The next investigation shows the improvement in total cashflow of a move from

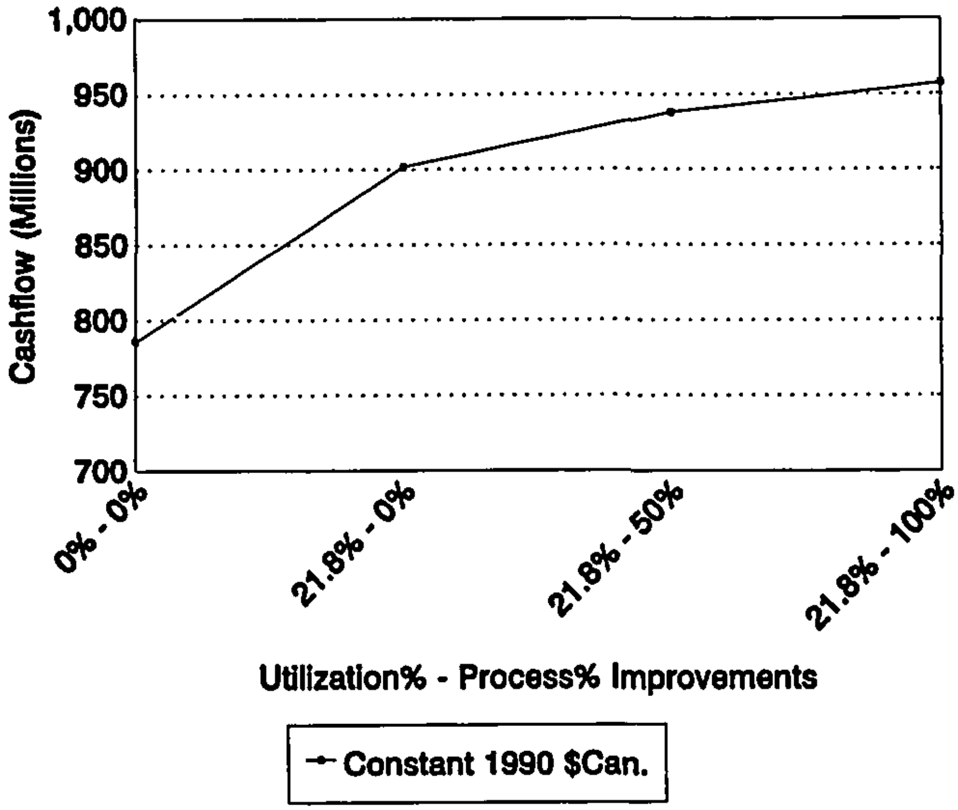

Figure 92 : Teleoperation from Surface Combined with Process Time Improvements on Cashflow.

three-shift - five-day per week to a three-shift - seven-day per week operation, without and then with 50 and 100 percent mining rate improvements. Figure 93 shows the results obtained in this analysis (Appendix I). As the available time is increased the personnel required to perform the jobs would need to increase. Therefore, the graph shows a slight decrease in cashflow due to staffing up. Increases in mining rate are only sufficient to bring the cashflow back to the value it started at 50%, and improve it only slightly at 100%.

These two investigations are then combined to show a three-shift - seven-day per week operation from surface while varying the degree of automation between 50 and 100 percent. The total cashflow improvements (Appendix J) in the operation are shown in figure 94. As expected the graph, shows an increase in cashflow

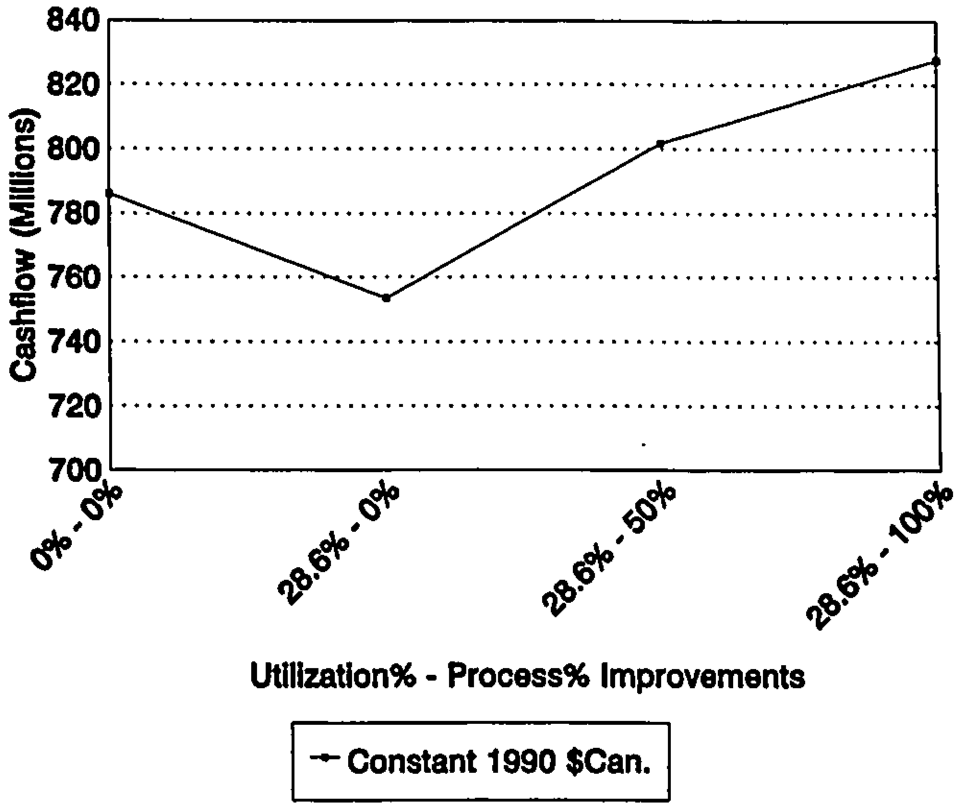

Figure 93 : Effects of Three Shift - Seven Days per Week Operation Combined with Process Time Improvements on Cashflow.

of $60 million which is somewhat less than what could be achieved if the operation remained three-shift - five-day per week. Mining rate increases add another $40 million for each 50% increase in mining rate. Based on these graphs the maximum benefit would be obtained by surface teleoperation with mining increases, as staffing would not have to increase to support three-shift - seven-day per week operation.

8.5.4 Potential Total Mine Operation Improvement

This final section investigates the impact of combining reasonable improvements achievable in mining cost, waste/rework (quality) improvement and process throughput time improvements. This study will allow an assessment of the impact

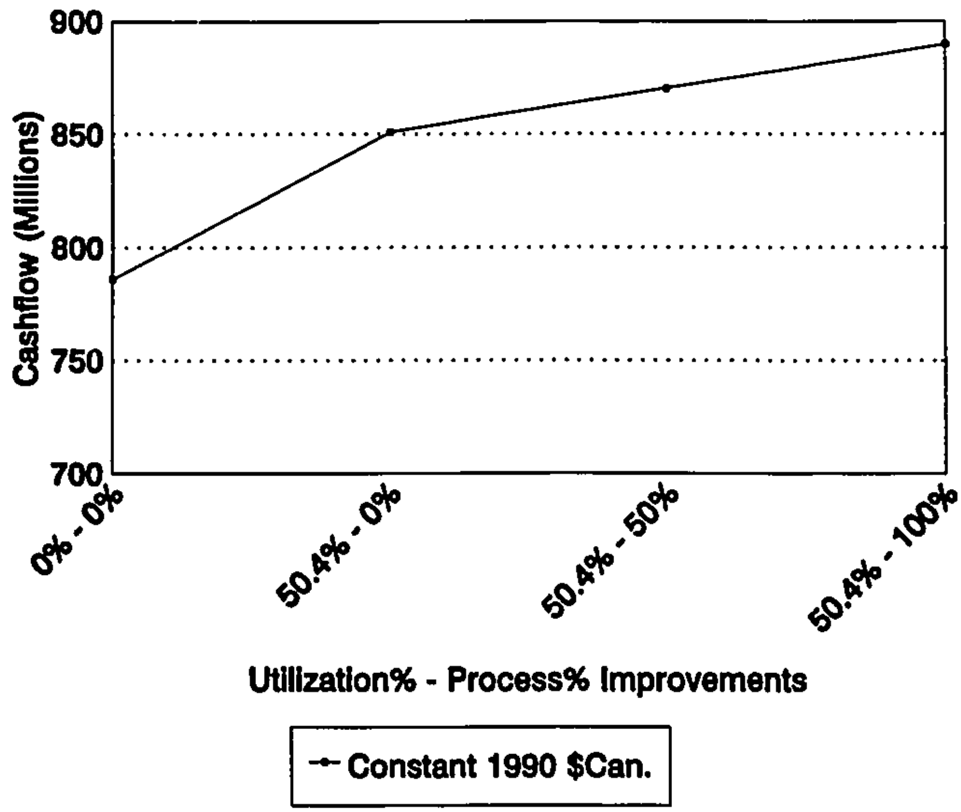

Figure 94 : Effects of Surface Teleoperation Combined with Three Shift - Seven Day per Week Operation with Process Time Improvements on Cashflow.

of automation based on reasonable targets that can be achieved through mining process automation.

Mining cost improvements will be based on a level of automation allowing one person to operate three machines. This has already been experimented with at Inco Limited and is a reasonable assumption. Waste/rework (quality) improvement of 20% in total value addition and 15% in cost reduction is assumed as this was achieved by even the less-successful German manufacturing organizations. And last, the operation runs three shifts - seven days per week, from surface, with 50% improvement in process time. These parameters are included with the model results in Appendix K.

A comparison of cashflows for the base case with the combined factor case described above is shown in figure 95. The results show that the cashflow level yearly is significantly improved and the total length of the mining project is reduced from 19 to 12 years, a 36.8% improvement. The complete economic picture for the project is also enhanced as can be seen in table XXVIII in 1990 constant Canadian dollars. The analysis shows a slight increase in capital cost of 4.0% because of the communication system purchase and installation. Operating cost improvements of 62.5% due to productivity, waste/rework reduction and throughput time improvements and a revenue increase of 20%. As expected this resulted in a 78.3% improvement in cashflow.

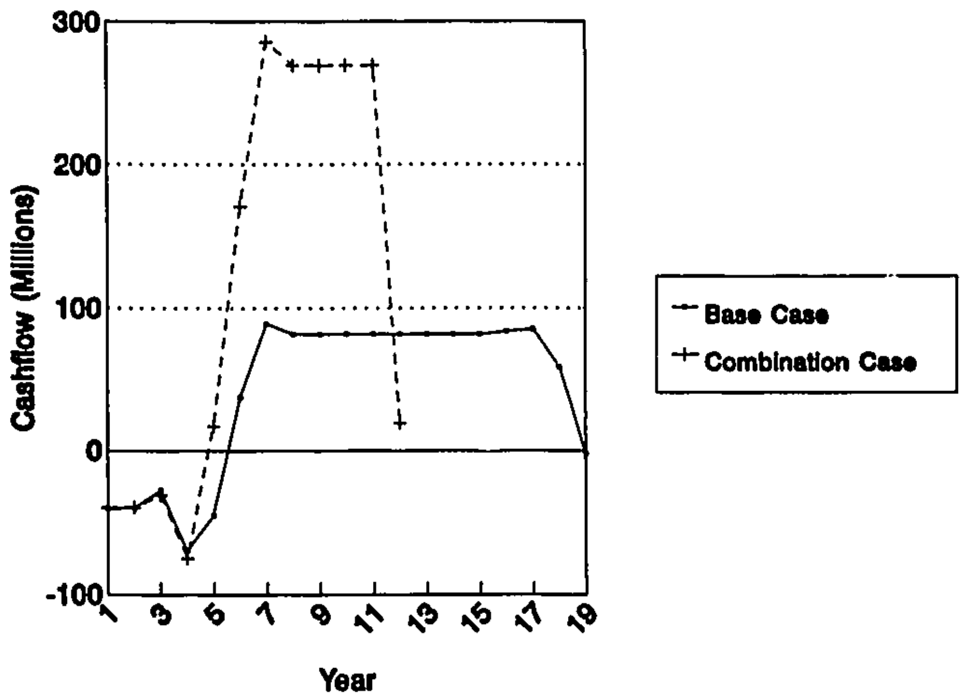

Figure 95 : Comparison of Cashflows for Base Case and Combined Factor Case.

A final graph on labour requirements for the comparison of the two cases is shown in figure 96. As can be seen in this graph, the total employment level is lower for the combined factor case. Moreover, that level does not have to be

Table XXVIII : Comparison of Base Case to Combined Parameter Improvement Case (all values in 1990 $CAN.)

	BASE CASE	COMBINED PARAMETER IMPROVEMENT CASE	PERCENT IMPROVEMENT
Total Capital Cost	$197,849,400	$206,175,696	-4.0%
Total Operating Cost	$586,984,817	$276,805,691	112.1%
Total Cost	$784,834,217	$482,981,387	62.5%
Total Revenue	$1,572,480,000	$1,886,976,000	20.0%
Total Cashflow	$787,645,783	$1,403,994,613	78.3%

maintained for as long a period of time,as the total mining project is reduced by seven years.

8.6 Model Discussion

The potential improvements in cashflow to the mining process are summarized in table XXIX. This reviews the results obtained in the previous section with respect to mining cost (productivity), process quality improvements, product value improvements, process utilization improvements and process rate increases. The table illustrates the finding that the highest impact on cashflow can be attained by focusing on product value improvement ($400 million) through increasing grade. While this should be a primary focus, the impact of process productivity improvements when combined with utilization improvements can also produce significant results ($220 million and $110 million). Based on these findings the

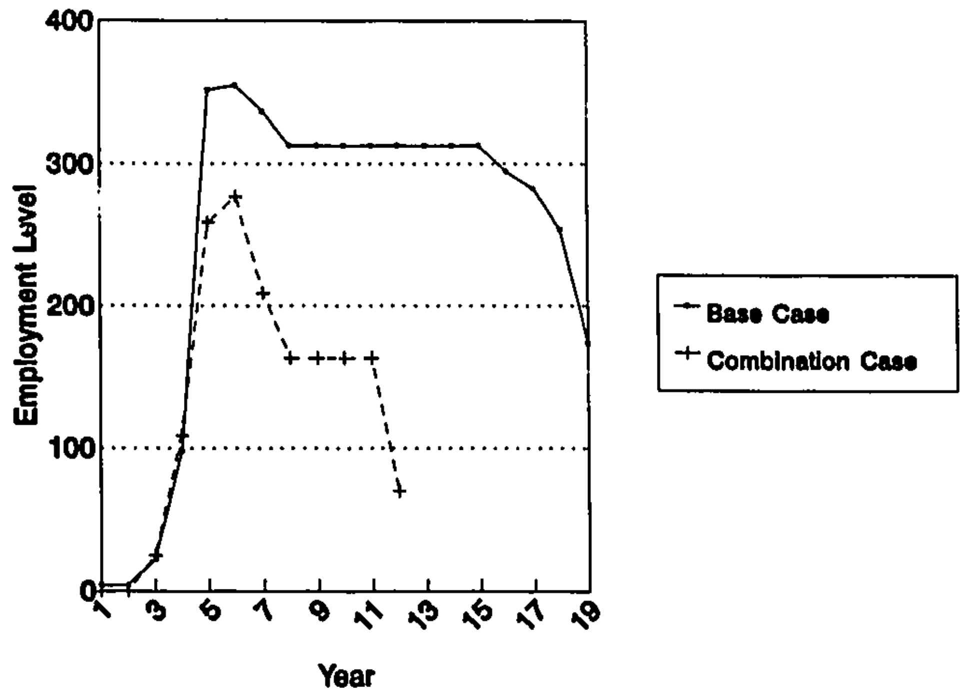

Figure 96 : Employment Level Comparison between the Base Case and the Combined Factor Case.

focus of research and development, as well as automation, should be on improving grade (reduced dilution), optimizing process productivity and maximizing utilization.

The economic viability of mining automation has also been clearly demonstrated by the results obtained in the previous sections which are illustrated in figure 97 based on the combined case model. Productivity would be enhanced dramatically, a 30% improvement in cashflow, with relatively practicable teleoperation combined with limited autonomy for the mining equipment. Utilization would be improved through a project life reduction of 37%. Based on the combined-factor model, quality would be improved resulting in a 42% improvement in cashflow. These combined improvements would result in a corresponding reduction in labour, engineering and management personnel to perform the same level of work with improved quality and increased utilization. The reduced personnel levels

Table XXIX : Summary of Results

Cashflow	Improvement (millions)
Process Productivity	$220
Engineering Productivity	$1
Product Value	$400
Process Quality	$40
Surface Teleoperation	$110
Three-shifts - Seven-days per week	$-35
Mining Rate	$70

combined with automation would improve safety performance as there would be fewer people exposed to the operation for less time. As well, the information gathered about the technical performance of the operation would provide useful information to assess the impacts of the operating environment on people and machines. The reduced personnel with a higher skill level will enable the transition from labour-based management to a technically-based management style, empowering the workforce. In terms of cost, the improvements would be realized in adding value to the ore being mined, keeping capital costs relatively constant, and reducing operating costs. These factors will all aid in improving cashflows and reducing project lives that would enhance the competitiveness of mining operations.

The model developed is a conservative strategy for mine automation, where only the current "drill, blast, muck, ground support cycle" is automated. No radical ideas are considered in this analysis and the improvements possible are dramatic. Now that this type of model has been established, more sophisticated mining methods can be analyzed for their impact on future mining operations, to establish the impact of new equipment and future research directions.

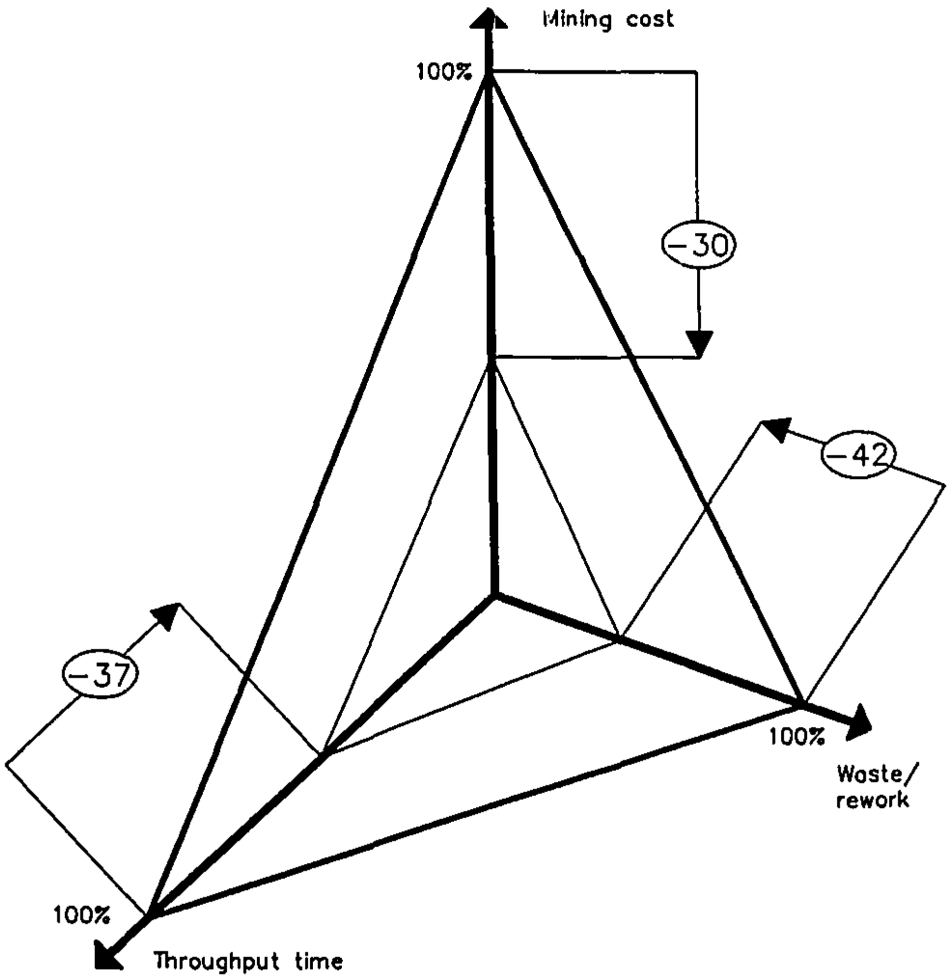

Figure 97 : Mining Automation Potential Benefits based on the Economic Analysis

This model offers many potential uses besides proving the viability of automation. New methods of delineation, development, production, backfill, gangue/ore handling, supplies handling, energy/infrastructure, engineering and management can be assessed to find out their impact from an operation perspective. Some aspects that have not been included in the model but should be in the future are:

* labour compensation rate changes
* supplies cost and utilization changes

* capital cost and utilization changes
* process changes
* energy cost and utilization changes
* maintenance practice changes
* management and engineering changes

As the models were being created, the difficulty of getting reliable costing data was observed. This is the result of cost accounting systems designed for paying bills and not to improve the process. Many manufacturing companies have changed their cost accounting systems to direct cost accounting or activity based accounting based on reliable process data. This form of accounting system enables assessment of the process in order to improve it continuously, and should be implemented in the mining industry. This model, while not an activity-based costing system, can be used as a basis to establish the requirement for this type of accounting system, to assist in process improvement.

The model and recent experiments[76] demonstrate the improvements in productivity and machine utilization that can be achieved when the mining geographical constraints are removed by the communication system. Productivity increases of 256% for one person operating three machines are achievable. Utilization improvements of 50.6% can be achieved through operating from surface and increasing the operating time to three-shifts - sevens-days per week. These indicate dramatic potential for automation built on the communication system.

The information generated through the modelling work also allows a comparison of mining and manufacturing. In a typical manufacturing operation, the labour component of the cost accounts for 5-6% of manufacturing cost. The mining industry labour component typically consumes 50-60% of the total mining cost. Therefore, the impact of automation will be much more significant in mining, as automation reduces the labour component of cost. As the mining operations become more automated, the labour component of cost will drop, and other aspects of the production cost will become relatively more important (i.e. waste/rework and throughput time).

8.7 Summary

This section studied the strategy developed in the previous Chapter by creating a model to assess the impact of an automated bulk mining system. The analysis considered background based on the measurement criteria used by the manufacturing industry as an aid to the establishment of mining improvements. The criteria established was manufacturing cost, rework/waste or quality improvement and throughput time improvements. The impact of automation was assessed and the potential economic contribution of mining automation based on the communication system developed in this thesis work was demonstrated. The potential savings in mining costs are significant.

9 CONCLUSIONS

This thesis follows the view that automation of hardrock underground mining in Canada is necessary if these operations are to survive in the future. In order to achieve automation it has proven the need for a high bandwidth, high speed telecommunication system. The strategy which has been developed is based on the view that an evolutionary approach will be most appropriate in order to achieve the benefits the mining industry requires in order to survive in the future. Finally, the magnitute of the economic benefits have clearly been shown to be significant.

This thesis resolved a number of issues related to the automation of a hardrock underground mine. It has:

* defined and analyzed research underway in automation and communication systems to establish the criteria for hardrock mine automation;
* established the requirements for system developments from a management point of view;
* formulated the requirements and priorities for information technology development;
* successfully defined and developed a mine-wide communication infrastructure capable of supporting voice, data and video communications in an underground hardrock mine, to and from stationary and mobile locations;
* successfully developed a strategy which will allow mining sub-systems to be integrated in the future, as proved by the capability to teleoperate underground mobile equipment, specifically an LHD, from surface;
* formulated a first-principles economic model to assess the impacts

of mining cost, waste/rework reduction and throughput time improvements;

* developed a plan for the direction of future underground hardrock mining research and development;
* clearly demonstrated the economic viability of the communication infrastructure and the potential of mine automation.

As a result of the resolution of these issues, it is evident that remote control and automated techniques can be used to achieve a significantly automated hardrock underground mine in the future.

The main impact of the communication technology tested here has proven to be a significant improvement in productivity when used to support teleoperated and autonomous systems. Improvements in safety will also arise, as a result of fewer personnel at the face and improved data on ground conditions and support performance. Cost savings will accrue from improvements in productivity. Mining will be more efficient, with improved recovery and reduced dilution arising from the accompanying increase in quality and timeliness of information available on grade distribution, orebody morphology, ground behaviour and production tonnage and grade.

Psychologically, the system offers the potential to change fundamentally the way that a mine and mining company are managed, by providing the right information to the right place at the right time. Management and the workforce will have to adapt dramatically as a result of this technology. The need for enhanced technical skills will escalate if the technology is to be effective and the desired improvements in productivity, cost and safety are to be attained.

The automation of an underground hardrock mine will require the establishment of a high capacity, high speed computer network that transmits signals over radio to the equipment required to operate the process. This strategy absolutely requires the integration of engineering planning models directly with equipment used in the process. It also necessitates the minimization of infrastructure required to operate the facility. This strategy is incremental rather than revolutionary, and it will probably require many years to realize the full potential of the automated mine. Although no changes to the mining methods have been analyzed, this thesis has proposed and examined changes that will make very significant contributions towards changing underground mining into a process-based operation.

10 RECOMMENDED FUTURE WORK

The development of an effective and efficient communication infrastructure has been accomplished as part of this thesis work. Several new areas of mining engineering and robotics can be researched now that an infrastructure is established which will support information technology and teleoperation of equipment. To follow through on this technology, there is a critical need to get more people involved by forming strategic alliances. One such alliance would be the adoption by CCARM of this architecture so mining related systems can be developed for future use in Canadian mines. The PRECARN process is a tool to form such alliances with CCARM, in a strategic project, which will allow the work to continue as precompetitive research developing applications in Artificial Intelligence and Robotics for underground hardrock mining.

This research should be collaborative in nature and allow the university and government community to understand the directions the mining companies are taking to be more competitive in the future. The development of applications for the mining information infrastructure should be able to attract the high-tech industry toward mining. The mining industry can now be regarded as ready for the application of technology from the space program to the underground environment. Some specific areas of research needs which were discovered as a result of the experimentation were:

* depth perception for operational control
* basic information flow on which mining is dependent, i.e. the type, nature, volume and timeliness of information fundamental to the decision-making underlying mine management and control.

These needs require the application of 3D video, using stereo vision systems developed for CANARM control, by the space program, and fundamental research into the basic information required to operate a mining facility. These are only two particular research areas and many more will need to be examined to automate underground hardrock mining. In fact, a project has already been initiated at Copper Cliff North Mine to test the suitability of a new 3D video monitor which will provide the operator with depth perception in the next set of teleoperation tests.

As well, the introduction of this kind of sweeping technology change in mining requires considerable work on the economic and social implications to the mining industry as the old ways of evaluating mining productivity, production costs, safety and even the very nature of industrial relations will be modified.

In fact, the very nature of managing a mining company will need to be revisited as the game is now radically different with the application of information technology to mining.

Two particular areas of future research will be required: information engineering, and management and control. Both these topics are discussed in more detail in this chapter to stimulate some foresight into the application of these techniques to underground mining.

10.1 Information Engineering

The information systems supporting mining operations are currently disjointed and typically stand alone. Based on this work, the communication infrastructure has been developed to support wide use of information systems for underground operations. Now equipment can report on its status and, with the aid of decision support and expert system technology, online diagnostics and ordering of parts for repair of automated machines, along with detailed monitoring of costs, are a reality.

In order to perform these functions, a major development effort in computer systems is required using a process called "Information Engineering" (IE). IE has been defined as:

> "The application of an interlocking set of formal techniques for the planning, analysis, design and construction of information systems on an enterprise basis or across a major sector of the enterprise.[79]"

The achievement of a sophisticated information system for mine automation will require automated software development tools as part of what is termed "Computer Aided Software Engineering" or CASE. CASE tools have been defined as:

> "An interlocking set of automated techniques in which enterprise models, data models and process models are built up in a comprehensive knowledge base and are used to create and maintain data processing systems.[80]"

The ultimate goal of IE is:

> "An organization-wide set of automated disciplines for getting the right information to the right people at the right time.[81]"

The IE process consists of four stages:

- A Information Strategy Planning
- B Business Area Analysis
- C System Design
- D Construction

The four stages of IE require the development of applications based on the process used by the enterprise. In adopting an Information Engineering approach, the enterprise structure must be defined using enterprise models, process models and finally data models. This approach is based on a common database format used by all software systems and automatic code generation. There are many benefits to an IE approach for a mining organization including:

* new technology opportunity assessment,
* assessment of how the company should be strategically changed to compete,
* new technology competitive threat assessment,
* the development of a strategic business plan which will be based on five year technology trends,
* establishment of critical success factors (CSF),
* development of information systems, decision support systems and expert systems to met CSFs,

The main component in information engineering is the encyclopedia or information repository. The encyclopedia constantly accumulates information on planning, analysis, design, construction and the maintenance of systems. The data models, process models, and planning information are stored in the encyclopedia, along with facts, rules, and policies governing the enterprise. The encyclopedia contains many rules relating to knowledge about the organization. These rules are stored and processed using rule processing, an Artificial Intelligence (AI) technique. Thus the encyclopedia is a knowledge base constantly being updated within the organization.

The development of an information strategy plan for an automated mining operation will require the development of a model and goals of the enterprise, an assessment of CSFs, technology impact, and finally a vision for strategic systems. A model of the organization consists of the development of a number of matrices relating organization units, geographical location, function of the unit and entities of the unit (information about the unit). Once this model is established, CSFs must be determined. For example, CSFs can be defined as :

"the limited number of areas in which satisfactory results will ensure competitive performance for the individual, department, or organization.

CSFs are the few key areas where "things must go right" for the business to flourish.[82]"

Along with the CSFs, a technology impact analysis must be performed to assess the opportunities and the potential competitive threats. With all the information gathered a strategic systems vision must be developed.

Following the establishment of a strategy, business area analysis (BAA) should be performed. BAA establishes the detailed framework for the information systems of an enterprise. Several objectives should be accomplished in the BAA, including:

* a clear understanding of the business and how activities interrelate,
* definition of an architectural framework for information systems,
* definition of a standard approaches to information systems so that the individual systems can interrelate,
* rethinking enterprise procedures in the context of desktop computers, information networks and flexible databases,
* prioritizing applications to be developed.

As part of the BAA, initial system design begins by developing process models using tools such as data models, process decomposition diagrams, entity/process matrix and process dependency diagrams.

With the institution of the information strategy and the BAA, system design and construction would begin. Design and construction would be performed using an I-CASE tool. The I-CASE tool is similar to a CAD system for engineering design that is focused on the development of software systems. Several sub-tools are included in an I-CASE development system:

* Decomposition diagrammer
* Action diagrammer

* Structure chart tool
* Data flow diagrammer
* Data model diagrammer
* Database code generator
* Screen painter
* Dialog generator
* Report generator
* Code generator
* Ability to run code
* Test data generator

These tools can be used to design and develop information systems with the flexibility to run in the desktop computer environment as well as the corporate environment while reducing time the produce finished systems and allowing the information system to grow with the organization.

The advent of this communication infrastructure will support these integrated CASE tools for mining to facilitate the development of the business systems for the future mine. A selection of a suitable database format is required. Once a database format is selected, teams of personnel need to be focused on enterprise and business areas to establish a consistent set of tools which can support the combination of information systems and automated equipment for all functional areas of the mining organizations. The need for integrated mining software is great today as little work has been done in this area by the mining companies, except in the traditional software areas of accounting, payroll and purchasing. The major computer based organizations have not seen mining as a large enough market to undertake this work to date.

To develop the enterprise and business models for an automated mining operation many functional areas in the companies require software systems. These must be developed so that information systems for payroll, inventory and purchasing, and budget and costs can be integral parts of the overall systems developed for the enterprise. As this information is established in an integrated model the best information about the operation can be provided to the management of the organization, mine operating personnel and the robotic equipment doing the mining.

10.2 Mine Management and Control Systems

This section discusses mine management and control systems by first reviewing production methods, discussing the application of these systems to mining and finally the benefits of the technology from a local and global perspective.

10.2.1 Agile Production

The systems developed as part of this thesis offer the platform for real-time closed-loop control on quality. The development and implementation of communication infrastructure in combination with the introduction of electronic and software systems for individual mining subprocesses will start a movement toward "Agile Production". The next few sections discuss the changes in the production process that relate to the automobile industry and ultimately could occur in the mining industry due to the work undertaken in this thesis.

Production technologies have evolved from craft production through mass production and lean production and the main catalyst for this change has been a need for improved quality.

To understand the change, a brief historical review of the these production improvements will be useful. In the late 1800s, craft production was the main form of business. This type of production as it relates to the automobile industry[83] was characterized by:

* A work force that was highly skilled in design, machine operations, and fitting. Most workers progressed through an apprenticeship to a full set of craft skills. Many could hope to run their own machine shops, becoming self-employed contractors to assembler firms.
* Organizations that were extremely decentralized, although concentrated within a single city. Most parts and much of the vehicle's design came from small machine shops. The system was coordinated by an owner/entrepreneur in direct contact with everyone involved - customers, employers, and suppliers.
* The use of general purpose machine tools to perform drilling, grinding, and other operations on metal and wood.
* A very low production volume - 1,000 or fewer automobiles a year, only a few of which (fifty or fewer) were built to the same design. And even among those fifty, no two were exactly alike since craft techniques inherently produced variations.

This type of production suffered from two main drawbacks. First, high production costs that remained constant with the volume produced, and second, since each unit was a prototype, the consistency and reliability were difficult to obtain.

In 1908, Henry Ford initiated the mass production age based on:

> "the complete and consistent interchangeability of parts and the simplicity of attaching them to each other.[84]"

or standardization. This type of production, as it matured, resulted in large yields at low cost. But, as the Japanese eventually noticed, it also resulted in wastage and poor quality. It also served to demotivate the workforce as they became as interchangeable as the parts they were assembling. Little skill or training was required and there was no goal to be achieved, as in craft production, where the worker achieved satisfaction and pride from the completion of an entire vehicle.

The Japanese, specifically through Toyota, noticed these disadvantages in the mass production system and developed a new system called "lean production". The concept was simple: combine mass production with the craft production techniques. Instead of producing massive amounts of parts, the process was changed so that the batches were smaller and the assembly time quicker, resulting in deviations in quality being noticed faster and allowing continuous improvement of the process through the careful implementation of a statistically-based quality control philosophy implemented by people like Demming[85]. As well, the Japanese noticed that the North American workforces were unskilled and demotivated. They decided that, if Toyota was to be successful, the workforce must be highly skilled and highly motivated. This required massive training and profit sharing. The implementation of this approach across a wide range of manufacturing enterprises resulted in an extremely successful industry as demonstrated today by the current Japanese economic situation.

Agile production has been promoted as the next step in this progression of production methods[86]. This production method combines craft production with information technology and robotic equipment to produce a custom product in low volumes at the same or less cost as lean production. Quality in the agile production system is based on real-time closed-loop monitoring of the process which requires the broadband communication demonstrated in the earlier work of this thesis.

The development of the infrastructure presented in this thesis could allow mining companies to move to agile production methods. The implementation of these methods have a need for change in three main areas: production technologies, managerial techniques and workforce skill level.

Agile enterprises require production technologies which will support the integrated organization where information flows freely between production, engineering, marketing, purchasing, finance, inventory, sales and research departments. In this integrated organization the "not-invented-here" syndrome is replaced by a cooperative effort in the performance of the organization due to the sharing of information and a collaborative responsibility for success. The only means by which this will happen is the strict adherence to universal data exchange standards in communication infrastructure and information systems. The strict adherence to universal exchange standards will facilitate the vertical and horizontal integration of mining organizations from the mining face to finished product.

The openness of information requires significant change in the managerial techniques used in an organization. With this openness, management, labour, suppliers and consultants will interact in a "virtual" company intertwined by an electronic infrastructure. Therefore, any proprietary attitudes about information must be eliminated to create an effective team. As well, the mining organization of the future must apply techniques that promote work force initiative at the operational level and performance measures for project teams that are self-directed and cross the enterprise as a whole.

A knowledgeable work force is a key element in the implementation of the agile enterprise as continuous innovation will be synonymous with competitive advantage. The workforce, i.e. managers, production workers and technical professionals, must continuously improve educational levels and production quality. As well, the involvement of scientists and engineers in strategic planning and operations is crucial to the success of the agile enterprise. The characteristics of the agile enterprise differ from current mass production philosophies as adversarial relationships must be eliminated to be successful. Social contracts need to be established where employees and the company are mutually tied together through long term benefits and loyalty to each party.

10.2.2 Mining Implementation

Today many industries including the mining companies are applying "Total Quality Improvement" (TQI)[75]. The infrastructure developed in this work will allow operations to attain accurate real-time information and use it to determine process problems and remedy them with the aid of information generated by the process. This will allow the provision of this information directly from the process underground into statistical representations for problem solving. The information provided will allow a significant improvement in management as now information can be provided in real-time so that corrective action can be taken quicker.

The communication infrastructure allows the application of more than real-time TQI. It also allows the application of automation moving toward "Agile Production". The question is, to what degree. Figure 99 represents the degree of automation vs the variable to be optimized. The variables to be considered are:

* automation development cost
* operational cost
* human risk
* resistance to adaption.

The degree of automation starts at mechanization with the human operating the machine, and moves on to teleoperation, autonomy and finally self-deploying systems. The general trends of each variable are shown on the graph along with a composite of all four variables. The development cost of particular mining equipment and systems is high for keeping an operator on the machine. However, as the human is removed from the machine, the issues of maintaining an area on the machine for the operator disappear, reducing the cost.

Teleoperation seems to provide the best pay-back as the cost of control system design becomes more complex when the level of automation increases. A good example of this point is the premium that LHD manufacturers pay in structural integrity and cost for maintaining the operator cab on the machine. As well, a comparison of underground haulage trucks shows significantly more space available for material in Inco's Automatic Haulage Truck vs the same dimensionally sized trucks, such as the Wagner 39-Ton and the Kiruna 50-Ton trucks, as a result of not needing to maintain a human operator's compartment. The operational costs are high for the human operated machine as there is typically, in mining, a minimum of one operator per machine. As the level of automation increases then the need for human involvement is reduced and the machine is better controlled reducing premature failures and improving quality of the process. Human risk is significantly reduced moving through the levels of automation, especially in mining, as the exposure is reduced through the application of control systems. The resistance to adaption increases through the levels of automation as the skill level required to operate the devices increases thus increasing the difficulty of operation. Finally, the composite shows that teleoperation and autonomy provide the most chance for application and the highest pay-back. This graph was developed specifically for mining but derived from a similar one from a NASA presentation[87] on space construction using robotics.

The application of the communication infrastructure in combination with information systems would result in two fundamental changes to the management of a mining organization. First, since data is collected by the system then a reduction in middle management would also result, and thus, the hierarchal control of the organization would change to an "Adhocracy"[88] as shown in Figure 100. And second, with timely information, decision making would be quickened and the companies should become more market driven since there would be no lag in the time required to manage the company.

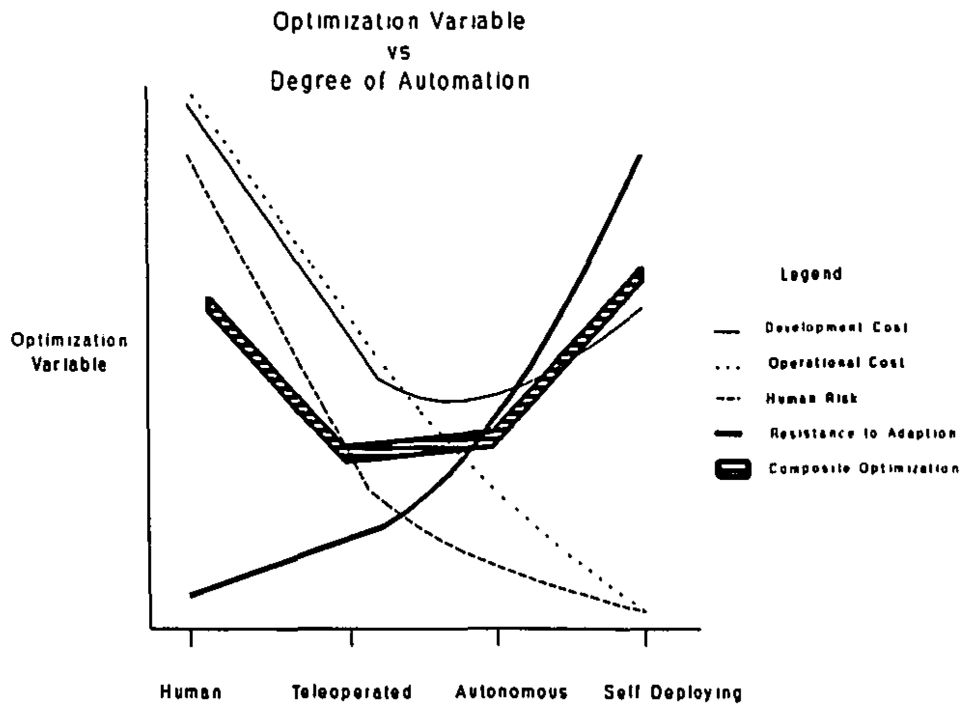

Figure 98 : Optimization Variable vs Type of Control System(83).

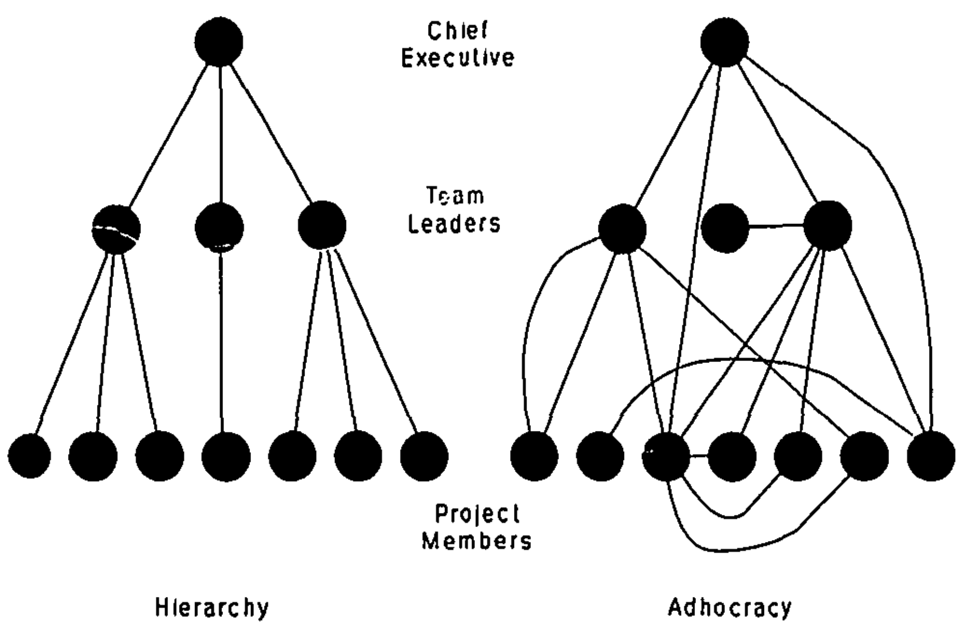

Figure 99 : Computerized Firms Organizational Structure Changes(88).

With all the positive influences on the mining companies there are some negatives implications. There is a large potential for misuse of the system by management. For example, the "big brother" of the company could be watching and using the information for the wrong purposes. As well, with the improvements in technology, a corresponding reduction in the workforce will result. This would be a continuing trend as since the early 1970s a reduction of production workers has been reported by Chaywkosksi[89] as a result of technological improvement. Although these negatives exist, if the global pressures continue it will probably be the only way that some operations will survive.

As these technologies are brought to maturity, then the philosophy of the mining organizations will need to change from a grade competitive to a technologically competitive environment. These organizations will need to become horizontally diversified and not so dependant on the currently higher grade orebodies. Canadian mining organizations could evolve by diversifying into mining technology and manufacturing business in the mode of the Swedes and the Finns, as their deposits became depleted over the last decades. This technology offers a large opportunity not only for the mining companies but also for Canada since its development would allow the building of a stable secondary industry, based on the current strength of the resource sector in the economy, instead of a satellite industry based on a parent foreign company.

10.3 Summary

This section summarizes recommended future work and discusses two important areas for consideration: information engineering and management and control. The technology associated with this thesis has demonstrated immediate application. The development of software systems which get the right information to the right place at the right time will, following their development and deployment, have significant impact on the bottom line of mining organizations. Agile production techniques will likely be the most effective for mining companies in the future as the pressures on management to provide higher quality product with fewer and fewer resources escalate.

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Appendix A - VRM Cost Model

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	22,866	53,438	45,349	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,915	1,915	4,730	15,179	39,359	42,954	41,887	39,027	39,027	39,027	39,027	39,027	39,027	39,027	39,027	36,931	35,606	32,091	22,203
COST (CAPITAL and OPERATING)	40,194	39,832	27,596	68,618	84,708	42,954	41,887	39,027	39,027	39,027	39,027	39,027	39,027	39,027	39,027	36,931	35,606	32,091	22,203
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20,160
CASHFLOW	(40,194)	(39,832)	(27,596)	(68,618)	(44,388)	37,686	89,153	81,933	81,933	81,933	81,933	81,933	81,933	81,933	81,933	84,029	85,354	58,629	(2,043)
TOTAL MANPOWER ALLOCATION	4	4	23	98	352	355	337	313	313	313	313	313	313	313	313	295	283	254	174

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	197,849	175,144
TOTAL OPERATING COST	586,985	658,020
TOTAL COST	784,834	833,164
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	787,646	739,316

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	0.00%	1
Engineering	0.00%	
Labour	0.00%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
COST DETAIL BREAKDOWN																			
CAPITAL COSTS																			
Capital Charges Total	38,279	37,917	22,866	53,438	45,349	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Permanent Development	22,430	34,132	10,014	33,068	29,525														
Property, Plant and Equipment Total	15,849	3,785	12,852	20,371	15,824	0	0	0	[illegible]	0	0	0	0	0	0	0	0	0	0
Facilities	7,680	3,785	3,785																
Delineation					400														
Development																			
Drill Jumbo				810	1,215														
Blast				158	238														
LHD				1,000	1,500														
Trucks				0	0														
Bolting Equipment				410	616														
Miscellaneous Equipment				0	0														
Mining Ore																			
Drill				480	720														
Blast				80	120														
LHD				1,600	2,400														
Trucks				752	1,128														
Bolting Equipment				1,660	2,489														
Miscellaneous Equipment				666	998														
Backfill				10,330	3,000														
Material Handling	5,669		6,297	425															
Ventilation			1,950																
Power Distribution	2,500																		
Mine Dewatering			820	1,000															
Miscellaneous Installations				500	500														
Communications Infrastructure				500	500														
OPERATING COSTS																			
Direct Charges																			
DELINEATION - DIAMOND DRILLING																			
Labour	0	0	0	0	437	218	71	71	71	71	71	71	71	71	71	62	0	0	0
Supplies	0	0	0	0	180	90	29	29	29	29	29	29	29	29	29	26	0	0	0
Maintenance Labour	0	0	0	0	36	18	6	6	6	6	6	6	6	6	6	5	0	0	0
Maintenance Supplies	0	0	0	0	67	34	11	11	11	11	11	11	11	11	11	10	0	0	0

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
HORIZONTAL DEVELOPMENT																			
Development Drilling																			
Labour	0	0	171	513	1,037	1,037	519	388	388	388	388	388	388	388	388	226	131	131	0
Supplies (bits & steel)	0	0	142	755	725	655	328	245	245	245	245	245	245	245	245	143	83	83	0
Maintenance Labour	0	0	108	583	612	565	283	211	211	21	211	211	211	211	211	123	71	71	0
Maintenance Supplies	0	0	201	1,082	1,136	1,050	525	392	392	392	392	392	392	392	392	229	133	133	0
Development Blasting																			
Labour	0	0	103	308	622	622	311	233	233	233	233	233	233	233	233	136	79	79	0
Explosives & Blasting Supplies	0	0	142	755	725	655	328	245	245	245	245	245	245	245	245	143	83	83	0
Maintenance Labour	0	0	22	117	122	113	57	42	42	42	42	42	42	42	42	25	14	14	0
Maintenance Supplies	0	0	40	216	227	210	105	78	78	78	78	78	78	78	78	46	27	27	0
Development Material Handling (Mucking)																			
Labour	0	0	111	333	674	674	337	252	252	252	252	252	252	252	252	147	85	85	0
Maintenance Labour	0	0	152	816	856	792	396	296	296	296	296	296	296	296	296	173	100	100	0
Maintenance Supplies	0	0	282	1,515	1,590	1,470	735	549	549	549	549	549	549	549	549	320	186	186	0
Development Ground Support																			
Labour	0	0	402	1,206	2,438	2,438	1,219	911	911	911	911	911	911	911	911	531	308	308	0
Supplies	0	0	125	660	635	573	287	214	214	214	214	214	214	214	214	125	72	72	0
Maintenance Labour	0	0	102	548	575	532	266	199	199	199	199	199	199	199	199	116	67	67	0
Maintenance Supplies	0	0	189	1,018	1,068	987	494	369	369	369	369	369	369	369	369	215	125	125	0
Development Services																			
Labour	0	0	68	205	415	415	207	155	155	155	155	155	155	155	155	90	52	52	0
Supplies	0	0	125	660	635	573	287	214	214	214	214	214	214	214	214	125	72	72	0
Maintenance Labour	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maintenance Supplies	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VERTICAL DEVELOPMENT																			
Raise Boring																			
Labour	0	0	0	1,138	1,884	390	80	48	48	48	48	48	48	48	48	48	48	0	0
Supplies	0	0	0	1,018	1,686	349	71	43	43	43	43	43	43	43	43	43	43	0	0
Maintenance Labour	0	0	0	239	397	82	17	10	10	10	10	10	10	10	10	10	10	0	0
Maintenance Supplies	0	0	0	599	992	205	42	25	25	25	25	25	25	25	25	25	25	0	0

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
MINING ORE																			
Production Drilling																			
Labour	0	0	0	0	194	389	631	583	583	583	583	583	583	583	583	583	583	437	97
Supplies (Bits & Steel)	0	0	0	0	8	16	26	24	24	24	24	24	24	24	24	24	24	18	4
Maintenance Labour	0	0	0	0	29	59	96	88	88	88	88	88	88	88	88	88	88	66	15
Maintenance Supplies	0	0	0	0	189	377	613	566	566	566	566	566	566	566	566	566	566	424	94
Production Blasting																			
Labour	0	0	0	0	105	210	342	315	315	315	315	315	315	315	315	315	315	237	53
Supplies (Explosives & Blasting)	0	0	0	0	244	489	794	733	733	733	733	733	733	733	733	733	733	550	122
Maintenance Labour	0	0	0	0	25	51	83	76	76	76	76	76	76	76	76	76	76	57	13
Maintenance Supplies	0	0	0	0	47	94	154	142	142	142	142	142	142	142	142	142	142	106	24
Production Material Handling (Mucking)																			
Labour	0	0	0	0	505	1,009	1,640	1,514	1,514	1,514	1,514	1,514	1,514	1,514	1,514	1,514	1,514	1,135	252
Maintenance Labour	0	0	0	0	193	387	628	580	580	580	580	580	580	580	580	580	580	435	97
Maintenance Supplies	0	0	0	0	359	718	1,167	1,077	1,077	1,077	1,077	1,077	1,077	1,077	1,077	1,077	1,077	808	179
Production Ground Support																			
Labour	0	0	0	0	22	44	71	65	65	65	65	65	65	65	65	65	65	49	11
Supplies	0	0	0	0	218	436	709	655	655	655	655	655	655	655	655	655	655	491	109
Maintenance Labour	0	0	0	0	61	122	198	183	183	183	183	183	183	183	183	183	183	137	30
Maintenance Supplies	0	0	0	0	113	226	368	340	340	340	340	340	340	340	340	340	340	255	57
Production Services																			
Labour	0	0	0	0	22	44	71	65	65	65	65	65	65	65	65	65	65	49	11
Supplies	0	0	0	0	218	436	709	655	655	655	655	655	655	655	655	655	655	491	109
Maintenance Labour	0	0	0	0	42	84	136	126	126	126	126	126	126	126	126	126	126	94	21
Maintenance Supplies	0	0	0	0	78	156	253	234	234	234	234	234	234	234	234	234	234	175	39
TOTAL MINING ORE																			
TOTAL LABOUR	0	0	0	0	848	1,695	2,755	2,543	2,543	2,543	2,543	2,543	2,543	2,543	2,543	2,543	2,543	1,907	424
TOTAL SUPPLIES	0	0	0	0	689	1,378	2,239	2,067	2,067	2,067	2,067	2,067	2,067	2,067	2,067	2,067	2,067	1,550	345
TOTAL MAINTENANCE LABOUR	0	0	0	0	351	702	1,141	1,053	1,053	1,053	1,053	1,053	1,053	1,053	1,053	1,053	1,053	790	176
TOTAL MAINTENANCE SUPPLIES	0	0	0	0	786	1,572	2,554	2,358	2,358	2,358	2,358	2,358	2,358	2,358	2,358	2,358	2,358	1,768	353

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Backfill Underground																			
Labour	0	0	0	0	1,200	2,400	3,900	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	2,700	600
Supplies	0	0	0	0	812	1,624	2,639	2,436	2,436	2,436	2,436	2,436	2,436	2,436	2,436	2,436	2,436	1,827	406
Direct Charges - Total																			
Labour	0	0	855	2,565	7,671	9,501	9,319	8,152	8,152	8,152	8,152	8,152	8,152	8,152	8,152	7,335	6,798	5,263	1,024
Supplies	0	0	534	2,829	4,402	5,549	6,136	5,450	5,450	5,450	5,450	5,450	5,450	5,450	5,450	5,064	4,614	3,688	751
Maintenance Labour	0	0	384	2,063	2,552	2,722	2,148	1,807	1,807	1,807	1,807	1,807	1,607	1,607	1,807	1,495	1,306	1,043	176
Maintenance Supplies	0	0	713	3,832	4,874	5,323	4,424	3,758	3,758	3,758	3,758	3,758	3,758	3,758	3,758	3,178	2,828	2,238	393
Total Direct	0	0	2,485	11,289	19,499	23,094	22,027	19,167	19,167	19,167	19,167	19,167	19,167	19,167	19,167	17,071	15,746	12,231	2,343
Mine Distributables																			
Ore Handling Systems																			
Labour	0	0	0	0	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170
Supplies	0	0	0	0	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Mine Mechancical Supplies	0	0	0	0	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900
Total Ore Handling Systems	0	0	0	0	3,120	3,120	3,120	3,120	3,120	3,120	3,120	3,120	3,120	3,120	3,120	3,120	3,120	3,120	3,120
Mine Services & Utilities																			
Labour	0	0	0	0	1,610	1,610	1,610	1,610	1,610	1,610	1,610	1,610	1,610	1,610	1,610	1,610	1,610	1,610	1,610
Supplies	0	0	0	0	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400
Mine Mechancical Supplies	0	0	0	0	700	700	700	700	700	700	700	700	700	700	700	700	700	700	700
Electric Power	990	990	1,320	2,750	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300
Fuels (included in direct supply cost)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Heating Plant/Fuel	150	150	150	250	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
Compressed Air	150	150	150	250	310	310	310	310	310	310	310	310	310	310	310	310	310	310	310
Water Supply	35	35	35	50	70	70	70	70	70	70	70	70	70	70	70	70	70	70	70
Total Mine Services & Utilities	1,325	1,325	1,655	3,300	6,690	6,690	6,690	6,690	6,690	6,690	6,690	6,690	6,690	6,690	6,690	6,690	6,690	6,690	6,690
Mine Engineering																			
Operating Labour	210	210	210	210	1,540	1,540	1,540	1,540	1,540	1,540	1,540	1,540	1,540	1,540	1,540	1,540	1,540	1,540	1,540
General Supplies & Expenses	0	0	0	0	800	800	800	800	800	800	800	800	800	800	800	800	800	800	800
Outside Services(Contractor/Consult.)	100	100	100	100	120	[illegible]	120	120	120	120	120	120	120	120	120	120	120	120	120
Mine Geology Charges	0	0	0	0	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
Industrial Eng. Charges	0	0	0	0	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Ground Control Charges	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Total Mine Engineering	310	310	310	310	2,780	2,780	2,780	2,780	2,780	2,780	2,780	2,780	2,780	2,780	2,780	2,780	2,780	2,780	2,780

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Mine Administration & Supervision																			
Operating Labour	80	80	80	80	1,680	1,680	1,680	1,680	1,680	1,680	1,680	1,680	1,680	1,680	1,680	1,680	1,680	1,680	1,680
General Supplies & Expenses	100	100	100	100	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
Business Administration Expenses	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Outside Services(Contractor/Consult.)	50	50	50	50	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
Equipment Repair	0	0	0	0	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Building Repairs	50	50	50	50	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Total Mine Administration	280	280	280	280	2,250	2,250	2,250	2,250	2,250	2,250	2,250	2,250	2,250	2,250	2,250	2,250	2,250	2,250	2,250
Plant Services																			
Stationary Maintenance																			
Operating Labour	0	0	0	0	2,240	2,240	2,240	2,240	2,240	2,240	2,240	2,240	2,240	2,240	2,240	2,240	2,240	2,240	2,240
General Supplies & Expenses	0	0	0	0	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
Mine Mechanical Supplies	0	0	0	0	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
Total Stationary Maintenance	0	0	0	0	2,840	2,840	2,840	2,840	2,840	2,840	2,840	2,840	2,840	2,840	2,840	2,840	2,840	2,840	2,840
Electrical/Instrumentation																			
Operating Labour	0	0	0	0	980	980	980	980	980	980	980	980	980	980	980	980	980	980	980
General Supplies & Expenses	0	0	0	0	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350
Electrical Supplies	0	0	0	0	450	450	450	450	450	450	450	450	450	450	450	450	450	450	450
Outside Electrical Charges	0	0	0	0	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400
Total Electrical & Instrumentation	0	0	0	0	2,180	2,180	2,180	2,180	2,180	2,180	2,180	2,180	2,180	2,180	2,180	2,180	2,180	2,180	2,180
Total Distributables	1,915	1,915	2,245	3,890	19,860	19,860	19,860	19,860	19,860	19,860	19,860	19,860	19,860	19,860	19,860	19,860	19,860	19,860	19,860
MANPOWER BREAKDOWN																			
Direct Manpower																			
DELINEATION - DIAMOND DRILLING																			
Labour	0	0	0	0	6	3	1	1	1	1	1	1	1	1	1	1	0	0	0
Maintenance	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HORIZONTAL AND RAMP DEVELOPMENT																			
Labour																			
Drilling	0	0	2	7	15	15	7	6	6	6	6	6	6	6	6	3	2	2	0
Blasting	0	0	1	4	9	9	4	3	3	3	3	3	3	3	3	2	1	1	0
Mucking	0	0	2	5	10	10	5	4	4	4	4	4	4	4	4	2	1	1	0
Ground Support	0	0	6	17	35	35	17	13	13	13	13	13	13	13	13	8	4	4	0
Services	0	0	1	3	6	6	3	2	2	2	2	2	2	2	2	1	1	1	0

MINE COST INPUT SHEET(1990 $CAN)   TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Maintenance																			
Drilling	0	0	2	8	9	8	4	3	3	3	3	3	3	3	3	2	1	1	0
Blasting	0	0	0	2	2	2	1	1	1	1	1	1	1	1	1	0	0	0	0
Mucking	0	0	2	12	12	11	6	4	4	4	4	4	4	4	4	2	1	1	0
Ground Support	0	0	1	8	8	8	4	3	3	3	3	3	3	3	3	2	1	1	0
Services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
VERTICAL DEVELOPMENT																			
Labour	0	0	0	16	27	6	1	1	1	1	1	1	1	1	1	1	1	0	0
Maintenance	0	0	0	3	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0
PRODUCTION																			
Labour																			
Drilling	0	0	0	0	3	6	9	8	8	8	8	8	8	8	8	8	6	6	1
Blasting	0	0	0	0	2	3	5	5	5	5	5	5	5	5	5	5	5	3	1
Mucking	0	0	0	0	7	14	23	22	22	22	22	22	22	22	22	22	22	16	4
Ground Support	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0
Services	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0
Maintenance																			
Drilling	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0
Blasting	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0
Mucking	0	0	0	0	3	6	9	8	8	8	8	8	8	8	8	8	8	6	1
Ground Support	0	0	0	0	1	2	3	3	3	3	3	3	3	3	3	3	3	2	0
Services	0	0	0	0	1	1	2	2	2	2	2	2	2	2	2	2	2	1	0
BACKFILL																			
Labour	0	0	0	0	17	34	56	51	51	51	51	51	51	51	51	51	51	39	9
Total Direct Labour	0	0	12	53	137	141	134	117	117	117	117	117	117	117	117	105	98	75	15
Total Direct Maintenance	0	0	5	33	42	40	31	26	26	26	26	26	26	26	26	21	19	15	3
Total Direct Manpower	0	0	18	86	179	181	165	143	143	143	143	143	143	143	143	127	117	90	17
Absenteeism @ 10%	0	0	2	9	18	18	17	14	14	14	14	14	14	14	14	13	12	9	2
Total Direct Manpower	0	0	19	94	197	199	182	157	157	157	157	157	157	157	157	140	128	99	19

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Distributable																			
Mine Administration & Supervision																			
Mine Manager	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
U/G/Project Superintendent	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mine Captain - Production	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Mine Captain - Services	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Production Supervisors	0	0	0	[illegible]	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Services Supervisors	0	0	0	0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Electrical Supervisor	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Plant Supr./Master Mechanic	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Loss Control	0	0	0	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Mine Secretary	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sub-Total	1	1	1	1	21	21	21	21	21	21	21	21	21	21	21	21	21	21	21
Mine Engineering & Geology																			
Mine Engineer	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Production Engineer	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Project Engineer	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Planning Engineer	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Planning Tech./Scheduler	1	1	1	1	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Surveyors/Instrum.	0	0	0	0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Ventilation Tech.	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Ground Control Engineer	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Ground Control Technologist	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Mine Geologist	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Beat Geologist	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Clerk	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sub-Total	3	3	3	3	22	22	22	22	22	22	22	22	22	22	22	22	22	22	22
Ore Handling Systems																			
Cage Tender/Deckmen	0	0	0	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Hoistmen	0	0	0	0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Shaft Crew	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Haulage Truck Op.	0	0	0	0	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Crusher Op.	0	0	0	0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Labourers	0	0	0	0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Sub-Total	0	0	0	0	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Mine Services																			
Dry/Lamp/Tool Men	0	0	0	0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Yard Crew	0	0	0	0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Construction Crew	0	0	0	0	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Fill Plant Operators	0	0	0	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Labourers	0	0	0	0	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Sub-Total	0	0	0	0	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23
Electrical/Instrumentation																			
Electricians - Surface	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Electricians - U/G	0	0	0	0	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Instrumentation	0	0	0	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Sub-Total	0	0	0	0	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14
Stationary Maintenance																			
Hoist Mechanics	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Industrial Mechanic - U/G	0	0	0	0	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
Industrial Mechanic - Surface	0	0	0	0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Welders	0	0	0	0	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Sub-Total	0	0	0	0	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32
Total Dist. Manpower	4	4	4	4	143	143	143	143	143	143	143	143	143	143	143	143	143	143	143
Absenteeism @ 10%					12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
Total	4	4	4	4	155	155	155	155	155	155	155	155	155	155	155	155	155	155	155
GRAND TOTAL MANPOWER	4	4	23	98	352	355	337	313	313	313	313	313	313	313	313	295	283	254	174
PRODUCTION RATES AND COSTS																			
Ore Development Production Rate (1000's	0	0	0	0	400	400	200	100	100	100	100	100	100	100	100	100	100	0	0
Stope Production Rate (1000's tons/yr)	0	0	0	0	0	400	1,100	1,100	1,100	1,100	1,100	1,100	1,100	1,100	1,100	1,100	1,100	900	200
Production Rate (1000's tons/yr)	0	0	0	0	400	800	1,300	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200	1,200	900	200
Delineation (ft/yr)	0	0	0	0	48,000	24,000	7,800	7,800	7,800	7,800	7,800	7,800	7,800	7,800	7,800	6,800	0	0	0
Delineation ($/ft)	$15																		
Delineation ($/yr)	0	0	0	0	720	360	117	117	117	117	117	117	117	117	117	102	0	0	0

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Production Shaft (ft/yr)	2,300	3,500	1,100																
Ventilation Shafts (ft/yr)	2,530	3,850	120	2,860	1,640														
Ramp (ft/yr)			733	14,638	2,229														
Vertical Development Footage/yr				5,987	9,918	2,050	420	250	250	250	250	250	250	250	250	250	250	0	0
Horizontal Development (ft/yr)			4,500	13,500	27,300	27,300	13,650	10,200	10,200	10,200	10,200	10,200	10,200	10,200	10,200	5,950	3,450	3,450	0
Miscellaneous (ft/yr)			700	3,300	700														
Production Shaft ($/ft)	$5,440																		
Ventilation Shaft ($/ft)	$3,920																		
Ramp ($/ft)	$600																		
Vertical Development ($/ft)	$500																		
Horizontal Development ($/yr)	$600																		
Miscellaneous ($/ft)	$600																		
Production Shaft ($ x 1000)	$12,512	$19,040	$5,984	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ventilation Shafts ($x1000)	$9,918	$15,092	$470	$11,211	$6,429	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Ramp ($x1000)	$0	$0	$440	$8,783	$1,337	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Vertical Development ($x1000)	$0	$0	$0	$2,994	$4,959	$1,025	$210	$125	$125	$125	$125	$125	$125	$125	$125	$125	$125	$0	$0
Horizontal Development ($x1000)	$0	$0	$2,700	$8,100	$16,380	$16,380	$8,190	$6,120	$6,120	$6,120	$6,120	$6,120	$6,120	$6,120	$6,120	$3,570	$2,070	$2,070	$0
Miscellaneous ($x1000)	$0	$0	$420	$1,980	$420	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Total Ramp & Horizontal Development Co	$600																		
Direct Labour ($/ft)	$190																		
Drilling Supplies ($/ft)	$70																		
Blasting Supplies ($/ft)	$40																		
Ground Support Supplies ($/ft)	$35																		
Service Supplies ($/ft)	$35																		
Maintenance ($/ft)	$230																		
Total Vertical Development Cost ($/ft)	$500																		
Direct Labour ($/ft)	$190																		
Drilling Supplies ($/ft)	$170																		
Maintenance Labour ($/ft)	$40																		
Maintenance Supplies ($/ft)	$100																		
Total Mining Cost ($/ton)	$10.65																		
Labour ($/ton)	$4.96																		
Drilling Materials ($/ton)	$1.00																		
Explosives ($/ton)	$1.96																		
Support Materials ($/ton)	$1.16																		
Equipment Maintenance ($/ton)	$1.17																		

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Backfill Cost/ton		$5 03																		
Labour		$3 00																		
Fill Materials		$2 03																		

EQUIPMENT LISTS	Labour - Material Distribution =					35%	65%
	#	$/hr	hr/yr	$/yr	$/ft	Labor $/ft	Mat. $/ft
Delineation							
Diamond Drill	2						
Development							
Drill Jumbo	5	$50	2,180	$545	$59.17	$20.71	$38.46
Bulk Loader	2	$25	2,180	$109	$11.63	$4.14	$7.69
LHD	5	$70	2,180	$763	$82.84	$29.00	$53.85
Truck	0	$50	2,180	$0	$0.00	$0.00	$0.00
Sissor Truck	6	$30	2,180	$392	$42.61	$14.91	$27.69
Scaler	0	$30	1,450	$0	$0.00	$0.00	$0.00
Cable Bolter	0	$30	1,450	$0	$0.00	$0.00	$0.00
Personnel Carrier	0	$30	2,180	$0	$0.00	$0.00	$0.00
Grader	0	$20	2,180	$0	$0.00	$0.00	$0.00
Fork Lift	0	$25	2,180	$0	$0.00	$0.00	$0.00
Jacklegs	20		3,000	$60	$6.51	$2.28	$4.23
Stopers	20		3,000	$60	$6.51	$2.28	$4.23
				$1,929	$209.49		
Production							
Drill	6	$50	2,180	$654	$0.55	$0.07	$0.47
Bulk Loader	4	$25	2,180	$218	$0.18	$0.06	$0.12
LHD	8	$70	2,180	$1,221	$1.02	$0.36	$0.66
Truck	4	$50	2,180	$436	$0.36	$0.13	$0.24
Sissor Truck	4	$30	2,180	$262	$0.22	$0.08	$0.14
Scaler	3	$30	1,450	$131	$0.11	$0.04	$0.07
Cable Bolter	3	$30	1,450	$131	$0.11	$0.04	$0.07
Personnel Carrier	4	$30	2,180	$262	$0.22	$0.08	$0.14
Grader	1	$20	2,180	$44	$0.04	$0.01	$0.02
Fork Lift	1	$25	2,180	$55	$0.05	$0.02	$0.03
Jacklegs	0		3,000	$0	$0.00	$0.00	$0.00
Stopers	0		3,000	$0	$0.00	$0.00	$0.00
				$3,411	$2.84		

Appendix B - Cut & Fill Cost Model

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (CUT & FILL) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
TOTAL CAPITAL COST	38,279	37,917	22,917	54,289	39,636	0	0		0	0	0	0	0	0	193,037
TOTAL OPERATING COST	1,915	1,915	4,995	15,201	27,740	36,871	41,859	4[illegible]	49,131	49,131	49,131	49,131	45,961	44,133	466,745
TOTAL COST (CAPITAL and OPERATIN	40,194	39,832	27,912	69,490	67,376	36,871	41,859	49,629	49,131	49,131	49,131	49,131	45,961	44,133	659,782
REVENUE (ore value $100/ton)	0	0	0	0	0	40,000	80,000	120,000	120,000	120,000	120,000	120,000	120,000	120,000	960,000
CASHFLOW	(40,194)	(39,832)	(27,912)	(69,490)	(67,376)	3,129	38,141	70,371	70,869	70,869	70,869	70,869	74,039	75,867	300,218
TOTAL MANPOWER ALLOCATION	4	4	25	93	251	304	342	407	402	402	402	402	375	360	
COST DETAIL BREAKDOWN															
CAPITAL COSTS															
Capital Charges Total	38,279	37,917	22,917	54,289	39,636	0	0	0	0	0	0	0	0	0	193,037
Permanent Development	22,430	34,132	10,065	31,757	20,321										118,705
Property, Plant and Equipment Total	15,849	3,785	12,852	22,532	19,315	0	0	0	0	0	0	0	0	0	74,333
Facilities	7,680	3,785	3,785												15,250
Delineation					400										400
Development															
Drill Jumbo				972	1,458										2,430
Blast				158	238										396
LHD				1,200	1,800										3,000
Trucks				0	0										0
Bolting Equipment				398	597										995
Miscellaneous Equipment				0	0										0
Mining Ore															
Drill				1,944	2,916										4,860
Blast				317	475										792
LHD				2,400	3,600										6,000
Trucks				752	1,128										1,880
Bolting Equipment				1,852	2,777										4,629
Miscellaneous Equipment				284	426										710
Backfill				10,330	3,000										13,330
Material Handling	5,669		6,297	425											12,391
Ventilation			1,950												1,950
Power Distribution	2,500														2,500
Mine Dewatering			820	1,000											1,820
Miscellaneous Installations				500	500										1,000

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (CUT & FILL) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
OPERATING COSTS															
Direct Charges															
DELINEATION - DIAMOND DRILLING															
Labour	0	0	0	0	373	373	373	373	71	71	71	71	0	0	1,776
Supplies	0	0	0	0	154	154	154	154	29	29	29	29	0	0	732
Maintenance Labour	0	0	0	0	31	31	31	31	6	6	6	6	0	0	147
Maintenance Supplies	0	0	0	0	57	57	57	57	11	11	11	11	0	0	273
HORIZONTAL DEVELOPMENT															
Development Drilling															
Labour	0	0	174	430	454	591	371	350	350	350	350	350	131	0	3,903
Supplies (bits & steel)	0	0	253	1,229	625	653	410	387	387	387	387	387	145	0	5,250
Maintenance Labour	0	0	132	645	353	387	243	229	229	229	229	229	86	0	2,990
Maintenance Supplies	0	0	245	1,198	655	718	450	425	425	425	425	425	159	0	5,553
Development Blasting															
Labour	0	0	105	258	273	355	222	210	210	210	210	210	79	0	2,342
Explosives & Blasting Supplies	0	0	144	702	357	373	234	221	221	221	221	221	83	0	3,000
Maintenance Labour	0	0	22	108	59	64	40	38	38	38	38	38	14	0	498
Maintenance Supplies	0	0	41	200	109	120	75	71	71	71	71	71	27	0	925
Development Material Handling (Mucking)															
Labour	0	0	113	280	295	384	241	228	228	228	228	228	85	0	2,537
Maintenance Labour	0	0	185	903	494	541	340	321	321	321	321	321	120	0	4,186
Maintenance Supplies	0	0	344	1,677	917	1,005	631	596	596	596	596	596	223	0	7,774
Development Ground Support															
Labour	0	0	409	1,011	1,068	1,389	871	823	823	823	823	823	308	0	9,171
Supplies	0	0	126	614	313	327	205	194	194	194	194	194	72	0	2,625
Maintenance Labour	0	0	97	476	260	285	179	169	169	169	169	169	63	0	2,205
Maintenance Supplies	0	0	181	884	483	530	332	314	314	314	314	314	118	0	4,096
Development Services															
Labour	0	0	70	172	182	236	148	140	140	140	140	140	52	0	1,561
Supplies	0	0	108	527	268	280	176	166	166	166	166	166	62	0	2,250
Maintenance Labour	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maintenance Supplies	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (CUT & FILL) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
VERTICAL DEVELOPMENT															
Raise Boring															
Labour	0	0	0	1,138	1,884	390	80	48	48	48	48	48	0	0	3,729
Supplies	0	0	0	1,018	1,686	349	71	43	43	43	43	43	0	0	3,336
Maintenance Labour	0	0	0	239	397	82	17	10	10	10	10	10	0	0	785
Maintenance Supplies	0	0	0	599	992	205	42	25	25	25	25	25	0	0	1,963
MINING ORE															
Production Drilling															
Labour	0	0	0	0	0	303	606	909	909	909	909	909	909	909	7,271
Supplies (Bits & Steel)	0	0	0	0	0	408	816	1,224	1,224	1,224	1,224	1,224	1,224	1,224	9,792
Maintenance Labour	0	0	0	0	0	153	305	458	458	458	458	458	458	458	3,662
Maintenance Supplies	0	0	0	0	0	283	567	850	850	850	850	850	850	850	6,802
Production Blasting															
Labour	0	0	0	0	0	227	454	682	682	682	682	682	682	682	5,454
Supplies (Explosives & Blasting)	0	0	0	0	0	560	1,120	1,680	1,680	1,680	1,680	1,680	1,680	1,680	13,440
Maintenance Labour	0	0	0	0	0	25	51	76	76	76	76	76	76	76	610
Maintenance Supplies	0	0	0	0	0	47	94	142	142	142	142	142	142	142	1,134
Production Material Handling (Mucking)															
Labour	0	0	0	0	0	505	1,010	1,515	1,515	1,515	1,515	1,515	1,515	1,515	12,119
Maintenance Labour	0	0	0	0	0	265	529	794	794	794	794	794	794	794	6,348
Maintenance Supplies	0	0	0	0	0	491	982	1,474	1,474	1,474	1,474	1,474	1,474	1,474	11,789
Production Ground Support															
Labour	0	0	0	0	0	1,338	2,676	4,014	4,014	4,014	4,014	4,014	4,014	4,014	32,115
Supplies	0	0	0	0	0	760	1,520	2,280	2,280	2,280	2,280	2,280	2,280	2,280	18,240
Maintenance Labour	0	0	0	0	0	143	286	429	429	429	429	429	429	429	3,432
Maintenance Supplies	0	0	0	0	0	266	531	797	797	797	797	797	797	797	6,374
Production Services															
Labour	0	0	0	0	0	151	303	454	454	454	454	454	454	454	3,636
Supplies															0
Maintenance Labour	0	0	0	0	0	42	84	126	126	126	126	126	126	126	1,007
Maintenance Supplies	0	0	0	0	0	78	156	234	234	234	234	234	234	234	1,870

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (CUT & FILL) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
TOTAL MINING ORE															
TOTAL LABOUR	0	0	0	0	0	2,525	5,050	7,574	7,574	7,574	7,574	7,574	7,574	7,574	60,595
TOTAL SUPPLIES	0	0	0	0	0	1,728	3,456	5,184	5,184	5,184	5,184	5,184	5,184	5,184	41,472
TOTAL MAINTENANCE LABOUR	0	0	0	0	0	628	1,255	1,883	1,883	1,883	1,883	1,883	1,883	1,883	15,060
TOTAL MAINTENANCE SUPPLIES	0	0	0	0	0	1,165	2,331	3,496	3,496	3,496	3,496	3,496	3.496	3,496	27,969
Backfill Underground															
Labour	0	0	0	0	0	1,200	2,400	3,600	3,600	3,600	3,600	3,600	3,600	3,600	28,800
Supplies	0	0	0	0	0	812	1,624	2,436	2,436	2,436	2,436	2,436	2,436	2,436	19,488
Direct Charges - Total															
Labour	0	0	871	2,150	2,646	7,053	9,677	13,299	12,996	12,996	12,996	12,996	11,830	11,174	110,685
Supplies	0	0	632	3,072	1,717	4,327	6,258	8,741	8,617	8,617	8,617	8,617	7,982	7,620	74,817
Maintenance Labour	0	0	437	2,131	1,196	1,936	2,087	2,670	2,645	2,645	2,645	2,645	2,166	1,883	25,087
Maintenance Supplies	0	0	811	3,958	2,221	3,595	3,876	4,959	4,913	4,913	4,913	4,913	4,023	3,496	46,590
Total Direct	0	0	2,750	11,311	7,780	16,911	21,899	29,669	29,171	29,171	29,171	29,171	26,001	24,173	257,180
Mine Distributables															
Ore Handling Systems															
Labour	0	0	0	0	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170	21,700
Supplies	0	0	0	0	50	50	50	50	50	50	50	50	50	50	500
Mine Mechancical Supplies	0	0	0	0	900	900	900	900	900	900	900	900	900	900	9,000
Total Ore Handling Systems	0	0	0	0	3,120	3,120	3,120	3,120	3,120	3,120	3,120	3,120	3,120	3,120	31,200
Mine Services & Utilities															
Labour	0	0	0	0	1,610	1,610	1,610	1,610	1,610	1,610	1,610	1,610	1,610	1,610	16,100
Supplies					400	400	400	400	400	400	400	400	400	400	4,000
Mine Mechancical Supplies					700	700	700	700	700	700	700	700	700	700	7,000
Electric Power	990	990	1,320	2,750	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	39,050
Fuels (included in direct supply cost)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Heating Plant/Fuel	150	150	150	250	300	300	300	300	300	300	300	300	300	300	3,700
Compressed Air	150	150	150	250	310	310	310	310	310	310	310	310	310	310	3,800
Water Supply	35	35	35	50	70	70	70	70	70	70	70	70	70	70	855
Total Mine Services & Utilities	1,325	1,325	1,655	3,300	6,690	6,690	6,690	6,690	6,690	6,690	6,690	6,690	6,690	6,690	74,505

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (CUT & FILL) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
Mine Engineering															
Operating Labour	210	210	210	210	1,540	1,540	1,540	1,540	1,540	1,540	1,540	1,540	1,540	1,540	16,240
General Supplies & Expenses					800	800	800	800	800	800	800	800	800	800	8,000
Outside Services(Contractor/Consult.)	100	100	100	100	120	120	120	120	120	120	120	120	120	120	1,600
Mine Geology Charges					200	200	200	200	200	200	200	200	200	200	2,000
Industrial Eng. Charges					20	20	20	20	20	20	20	20	20	20	200
Ground Control Charges					100	100	100	100	100	100	100	100	100	100	1,000
Total Mine Engineering	310	310	310	310	2,780	2,780	2,780	2,780	2,780	2,780	2,780	2,780	2,780	2,780	29,040
Mine Administration & Supervision															
Operating Labour	80	80	80	80	1,680	1,680	1,680	1,680	1,680	1,680	1,680	1,680	1,680	1,680	17,120
General Supplies & Expenses	100	100	100	100	200	200	200	200	200	200	200	200	200	200	2,400
Business Administration Expenses					100	100	100	100	100	100	100	100	100	100	1,000
Outside Services(Contractor/Consult.)	50	50	50	50	200	200	200	200	200	200	200	200	200	200	2,200
Equipment Repair					50	50	50	50	50	50	50	50	50	50	500
Building Repairs	50	50	50	50	20	20	20	20	20	20	20	20	20	20	400
Total Mine Administration	280	280	280	280	2,250	2,250	2,250	2,250	2,250	2,250	2,250	2,250	2,250	2,250	23,620
Plant Services															
Stationary Maintenance															
Operating Labour	0	0	0	0	2,240	2,240	2,240	2,240	2,240	2,240	2,240	2,240	2,240	2,240	22,400
General Supplies & Expenses					300	300	300	300	300	300	300	300	300	300	3,000
Mine Mechanical Supplies					300	300	300	300	300	300	300	300	300	300	3,000
Total Stationary Maintenance	0	0	0	0	2,840	2,840	2,840	2,840	2,840	2,840	2,840	2,840	2,840	2,840	28,400
Electrical/Instrumentation															
Operating Labour	0	0	0	0	980	980	980	980	980	980	980	980	980	980	9,800
General Supplies & Expenses					450	450	450	450	450	450	450	450	450	450	4,500
Electrical Supplies					450	450	450	450	450	450	450	450	450	450	4,500
Outside Electrical Charges					400	400	400	400	400	400	400	400	400	400	4,000
Total Electrical & Instrumentation	0	0	0	0	2,280	2,280	2,280	2,280	2,280	2,280	2,280	2,280	2,280	2,280	22,800
Total Distributables	1,915	1,915	2,245	3,890	19,960	19,960	19,960	19,960	19,960	19,960	19,960	19,960	19,960	19,960	209,565

MINE COST INPUT SHEET(1990 $CAN)   TYPICAL SUDBURY OPERATION MINING COST MODEL (CUT & FILL) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
MANPOWER BREAKDOWN															
Direct Manpower															
DELINEATION - DIAMOND DRILLING															
Labour	0	0	0	0	5	5	5	5	1	1	1	1	0	0	
Maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
HORIZONTAL AND RAMP DEVELOPMENT															
Labour															
Drilling	0	0	2	6	6	8	5	5	5	5	5	5	2	0	
Blasting	0	0	1	4	4	5	3	3	3	3	3	3	1	0	
Mucking	0	0	2	4	4	5	3	3	3	3	3	3	1	0	
Ground Support	0	0	6	14	15	20	12	12	12	12	12	12	4	0	
Services	0	0	1	2	3	3	2	2	2	2	2	2	1	0	
Maintenance															
Drilling	0	0	2	9	5	6	3	3	3	3	3	3	1	0	
Blasting	0	0	0	2	1	1	1	1	1	1	1	1	0	0	
Mucking	0	0	3	13	7	8	5	5	5	5	5	5	2	0	
Ground Support	0	0	1	7	4	4	3	2	2	2	2	2	1	0	
Services	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
VERTICAL DEVELOPMENT															
Labour	0	0	0	16	27	6	1	1	1	1	1	1	0	0	
Maintenance	0	0	0	3	6	1	0	0	0	0	0	0	0	0	
PRODUCTION															
Labour															
Drilling	0	0	0	0	0	4	9	13	13	13	13	13	13	13	
Blasting	0	0	0	0	0	3	6	10	10	10	10	10	10	10	
Mucking	0	0	0	0	0	7	14	22	22	22	22	22	22	22	
Ground Support	0	0	0	0	0	19	38	57	57	57	57	57	57	57	
Services	0	0	0	0	0	2	4	6	6	6	6	6	6	6	

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (CUT & FILL) BASE CASE

MINE SUMMARY	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
Maintenance																
Drilling		0	0	0	0	0	2	4	7	7	7	7	7	7	7	
Blasting		0	0	0	0	0	0	1	1	1	1	1	1	1	1	
Mucking		0	0	0	0	0	4	8	11	11	11	11	11	11	11	
Ground Support		0	0	0	0	0	2	4	6	6	6	6	6	6	6	
Services		0	0	0	0	0	1	1	2	2	2	2	2	2	2	
BACKFILL																
Labour		0	0	0	0	0	17	34	51	51	51	51	51	51	51	
Total Direct Labour		0	0	12	47	65	106	139	191	186	186	186	186	169	160	
Total Direct Maintenance		0	0	6	34	23	29	30	38	38	38	38	38	31	27	
Total Direct Manpower		0	0	19	81	87	135	169	229	224	224	224	224	200	187	
Absenteeism @ 10%		0	0	2	8	9	14	17	23	22	22	22	22	20	19	
Total Direct Manpower		0	0	21	89	96	149	186	252	247	247	247	247	220	205	
Distributable																
Mine Administration & Supervision																
Mine Manager						1	1	1	1	1	1	1	1	1	1	
U/G/Project Superintendent		1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Mine Captain - Production						2	2	2	2	2	2	2	2	2	2	
Mine Captain - Services						1	1	1	1	1	1	1	1	1	1	
Production Supervisors						6	6	6	6	6	6	6	6	6	6	
Services Supervisors						4	4	4	4	4	4	4	4	4	4	
Electrical Supervisor						1	1	1	1	1	1	1	1	1	1	
Plant Supr./Master Mechanic						1	1	1	1	1	1	1	1	1	1	
Loss Control						3	3	3	3	3	3	3	3	3	3	
Mine Secretary						1	1	1	1	1	1	1	1	1	1	
Sub-Total		1	1	1	1	21	21	21	21	21	21	21	21	21	21	

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (CUT & FILL) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
Mine Engineering & Geology															
Mine Engineer					1	1	1	1	1	1	1	1	1	1	
Production Engineer					2	2	2	2	2	2	2	2	2	2	
Project Engineer	2	2	2	2	1	1	1	1	1	1	1	1	1	1	
Planning Engineer					1	1	1	1	1	1	1	1	1	1	
Planning Tech./Scheduler	1	1	1	1	6	6	6	6	6	6	6	6	6	6	
Surveyors/Instrum.					4	4	4	4	4	4	4	4	4	4	
Ventilation Tech.					1	1	1	1	1	1	1	1	1	1	
Ground Control Engineer					1	1	1	1	1	1	1	1	1	1	
Ground Control Technologist					1	1	1	1	1	1	1	1	1	1	
Mine Geologist					1	1	1	1	1	1	1	1	1	1	
Beat Geologist					2	2	2	2	2	2	2	2	2	2	
Clerk					1	1	1	1	1	1	1	1	1	1	
Sub-Total	3	3	3	3	22	22	22	22	22	22	22	22	22	22	
Ore Handling Systems															
Cage Tender/Deckmen					8	8	8	8	8	8	8	8	8	8	
Hoistmen					4	4	4	4	4	4	4	4	4	4	
Shaft Crew					2	2	2	2	2	2	2	2	2	2	
Haulage Truck Op.					9	9	9	9	9	9	9	9	9	9	
Crusher Op.					4	4	4	4	4	4	4	4	4	4	
Labourers					4	4	4	4	4	4	4	4	4	4	
Sub-Total	0	0	0	0	31	31	31	31	31	31	31	31	31	31	
Mine Services															
Dry/Lamp/Tool Men					4	4	4	4	4	4	4	4	4	4	
Yard Crew					4	4	4	4	4	4	4	4	4	4	
Construction Crew					6	6	6	6	6	6	6	6	6	6	
Fill Plant Operators					3	3	3	3	3	3	3	3	3	3	
Labourers					6	6	6	6	6	6	6	6	6	6	
Sub-Total	0	0	0	0	23	23	23	23	23	23	23	23	23	23	

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (CUT & FILL) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
Electrical/Instrumentation															
Electricans - Surface					2	2	2	2	2	2	2	2	2	2	
Electricans - U/G					9	9	9	9	9	9	9	9	9	9	
Instrumentation					3	3	3	3	3	3	3	3	3	3	
Sub-Total	0	0	0	0	14	14	14	14	14	14	14	14	14	14	
Stationary Maintenance															
Hoist Mechanics					2	2	2	2	2	2	2	2	2	2	
Industrial Mechanic - U/G					18	18	18	18	18	18	18	18	18	18	
Industrial Mechanic - Surface					4	4	4	4	4	4	4	4	4	4	
Welders					8	8	8	8	8	8	8	8	8	8	
Sub-Total	0	0	0	0	32	32	32	32	32	32	32	32	32	32	
Total Dist. Manpower	4	4	4	4	143	143	143	143	143	143	143	143	143	143	
Absenteeism @ 10%					12	12	12	12	12	12	12	12	12	12	
Total	4	4	4	4	155	155	155	155	155	155	155	155	155	155	
GRAND TOTAL MANPOWER	4	4	25	93	251	304	342	407	402	402	402	402	375	360	
PRODUCTION RATES AND COSTS															
Production Rate (1000's tons/yr)	0	0	0	0	0	400	800	1,200	1,200	1,200	1,200	1,200	1,200	1,200	9,600
Delineation (ft/yr)	0	0	0	0	41,000	41,000	41,000	41,000	7,800	7,800	7,800	7,800	0	0	195,200
Delineation ($/ft)	$15														
Delineation ($/yr)	0	0	0	0	615	615	615	615	117	117	117	117	0	0	2,928
Production Shaft (ft/yr)	2,300	3,500	1,100												6,900
Ventilation Shafts (ft/yr)	2,530	3,850	120	2,860	1,640										11,000
Ramp (ft/yr)			733	14,638	2,229										17,600
Vertical Development Footage/yr				5,987	9,918	2,050	420	250	250	250	250	250	0	0	19,625
Horizontal Development (ft/yr)			4,584	11,316	11,960	15,554	9,758	9,216	9,216	9,216	9,216	9,216	3,452	0	102,704
Miscellaneous (ft/yr)			700	3,300	700										4,700
Production Shaft ($/ft)	$5,440														
Ventilation Shaft ($/ft)	$3,920														
Ramp ($/ft)	$600														
Vertical Development ($/ft)	$500														
Horizontal Development ($/yr)	$600														

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (CUT & FILL) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
Miscellaneous ($/ft)	$600														
Production Shaft ($ x 1000)	$12,512	$19,040	$5,984	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0	$37,536
Ventilation Shafts ($x1000)	$9,918	$15,092	$470	$11,211	$6,429	$0	$0	$0	$0	$0	$0	$0	$0	$0	$43,120
Ramp ($x1000)	$0	$0	$440	$8,783	$1,337	$0	$0	$0	$0	$0	$0	$0	$0	$0	$10,560
Vertical Development ($x1000)	$0	$0	$0	$2,994	$4,959	$1,025	$210	$125	$125	$125	$125	$125	$0	$0	$9,813
Horizontal Development ($x1000)	$0	$0	$2,750	$6,790	$7,176	$9,332	$5,855	$5,530	$5,530	$5,530	$5,530	$5,530	$2,071	$0	$61,622
Miscellaneous ($x1000)	$0	$0	$420	$1,980	$420	$0	$0	$0	$0	$0	$0	$0	$0	$0	$2,820
Total Ramp & Horizontal Development Co	$600														
Direct Labour ($/ft)	$190														
Drilling Supplies ($/ft)	$70														
Blasting Supplies ($/ft)	$40														
Ground Support Supplies ($ft)	$35														
Service Supplies ($/ft)	$30														
Maintenance ($/ft)	$235														
Total Vertical Development Cost ($/ft)	$500														
Direct Labour ($/ft)	$190														
Drilling Supplies ($/ft)	$170														
Maintenance Labour ($/ft)	$40														
Maintenance Supplies ($/ft)	$100														
Total Mining Cost ($/ton)	$16.53														
Labour ($/ton)	$6.31														
Drilling Materials ($/ton)	$1.02														
Explosives ($/ton)	$1.40														
Support Materials ($/ton)	$1.90														
Equipment Maintenance ($/ton)	$4.48														
Miscellaneous Materials ($/ton)	$1.42														
Backfill Cost/ton	$5.03														
Labour	$3.00														
Fill Materials	$2.03														

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (CUT & FILL) BASE CASE

EQUIPMENT LISTS	Labour - Material Distribution =					35%	65%
	#	$/hr	hr/yr	$/yr	$/ft	Labor $/ft	Mat. $/ft
Delineation							
Diamond Drill	2						
Development							
Drill Jumbo	6	$50	2,180	$654	$71.01	$24.85	$46.16
Bulk Loader	2	$25	2,180	$109	$11.83	$4.14	$7.69
LHD	6	$70	2,180	$916	$99.41	$34.79	$64.62
Truck	0	$50	2,180	$0	$0.00	$0.00	$0.00
Sissor Truck	6	$30	2,180	$392	$42.61	$14.91	$27.69
Scaler	0	$30	1,450	$0	$0.00	$0.00	$0.00
Cable Bolter	0	$30	1,450	$0	$0.00	$0.00	$0.00
Personnel Carrier	0	$30	2,180	$0	$0.00	$0.00	$0.00
Grader	0	$20	2,180	$0	$0.00	$0.00	$0.00
Fork Lift	0	$25	2,180	$0	$0.00	$0.00	$0.00
Jacklegs	15		3,000	$45	$4.89	$1.71	$3.18
Stopers	15		3,000	$45	$4.89	$1.71	$3.18
				$2,161	$234.64		
Production							
Drill	12	$50	2,180	$1,308	$1.09	$0.38	$0.71
Bulk Loader	4	$25	2,180	$218	$0.18	$0.06	$0.12
LHD	12	$70	2,180	$1,831	$1.53	$0.53	$0.99
Truck	4	$50	2,180	$436	$0.36	$0.13	$0.24
Sissor Truck	12	$30	2,180	$785	$0.65	$0.23	$0.43
Scaler	3	$30	1,450	$131	$0.11	$0.04	$0.07
Cable Bolter	3	$30	1,450	$131	$0.11	$0.04	$0.07
Personnel Carrier	4	$30	2,180	$262	$0.22	$0.08	$0.14
Grader	1	$20	2,180	$44	$0.04	$0.01	$0.02
Fork Lift	1	$25	2,180	$55	$0.05	$0.02	$0.03
Jacklegs	30		3,000	$90	$0.08	$0.03	$0.05
Stopers	30		3,000	$90	$0.08	$0.03	$0.05
				$5,379	$4.48		

Appendix C - Base Case

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10
CAPITAL COST	38,279	37,917	22,866	52,938	44,849	0	0	0	0	0
OPERATING COST	1,915	1,915	4,730	15,179	39,359	42,954	41,887	39,027	39,027	39,027
COST (CAPITAL and OPERATING)	40,194	39,832	27,596	68,118	84,208	42,954	41,887	39,027	39,027	39,027
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960
CASHFLOW	(40,194)	(39,832)	(27,596)	(68,118)	(43,888)	37,686	89,153	81,933	81,933	81,933
TOTAL MANPOWER ALLOCATION	4	4	23	98	352	355	337	313	313	313

MINE SUMMARY Year	11	12	13	14	15	16	17	18	19
CAPITAL COST	0	0	0	0	0	0	0	0	0
OPERATING COST	39,027	39,027	39,027	39,027	39,027	36,931	35,606	32,091	22 203
COST (CAPITAL and OPERATING)	39,027	39,027	39,027	39,027	39,027	36,931	35,606	32 091	22 203
REVENUE	120,960	120,960	120,960	120,960	120,960	120,960	120 960	90 720	20,160
CASHFLOW	81,933	81,933	81,933	81,933	81,933	84,029	85,354	58 629	(2 043
TOTAL MANPOWER ALLOCATION	313	313	313	313	313	295	283	254	174

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4 0%
CONSUMER PRICE INDEX INCREASE	-1 0%
EFFECTIVE PRICE DEFLATION RATE	0 0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	196,849	174,305
TOTAL OPERATING COST	586,985	658,020
TOTAL COST	783,834	832,326
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	788,646	740,154

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	0.00%	1
Engineering	0.00%	
Labour	0.00%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

Appendix D

Mining Cost - Management and Labour Productivity Improvements

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	22,620	51,888	43,686	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,898	1,898	4,490	14,407	35,216	38,233	37,070	34,523	34,523	34,538	34,523	34,523	34,523	34,523	34,523	32,630	31,424	28,357	19,677
COST (CAPITAL and OPERATING)	40,176	39,815	27,110	66,295	78,902	38,233	37,070	34,523	34,523	34,538	34,523	34,523	34,523	34,523	34,523	32,630	31,424	28,357	19,677
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20,160
CASHFLOW	(40,176)	(39,815)	(27,110)	(66,295)	(38,582)	42,407	93,970	86,437	86,437	86,422	86,437	86,437	86,437	86,437	86,437	88,330	89,536	62,363	483
TOTAL MANPOWER ALLOCATION	4	4	20	85	287	288	271	251	251	251	251	251	251	251	251	236	226	202	137

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	194,391	172,234
TOTAL OPERATING COST	521,498	584,411
TOTAL COST	715,889	756,645
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	856,591	815,835

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	21.60%	1
Engineering	0.00%	
Labour	21.60%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	22,180	49,108	40,704	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,866	1,866	4,058	13,023	27,785	29,764	28,430	26,446	26,446	26,488	26,446	26,446	26,446	26,446	26,446	24,916	23,923	21,659	15,146
COST (CAPITAL and OPERATING)	40,145	39,783	26,238	62,131	68,489	29,764	28,430	26,446	26,446	26,488	26,446	26,446	26,446	26,446	26,446	24,916	23,923	21,659	15,146
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20,160
CASHFLOW	(40,145)	(39,783)	(26,238)	(62,131)	(28,169)	50,876	102,610	94,514	94,514	94,472	94,514	94,514	94,514	94,514	94,514	96,044	97,037	69,061	5,014
TOTAL MANPOWER ALLOCATION	3	3	15	52	170	168	153	140	140	141	140	140	140	140	140	130	123	109	70

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	188,187	167,014
TOTAL OPERATING COST	404,044	452,388
TOTAL COST	592,231	619,401
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	980,249	953,079

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	21.80%	2
Engineering	0.00%	
Labour	21.80%	2

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	22,033	48,181	39,710	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,856	1,856	3,914	12,561	25,308	26,942	25,550	23,753	23,753	23,805	23,753	23,753	23,753	23,753	23,753	22,344	21,423	19,426	13,635
COST (CAPITAL and OPERATING)	40,134	39,773	25,947	60,742	65,018	26,942	25,550	23,753	23,753	23,805	23,753	23,753	23,753	23,753	23,753	22,344	21,423	19,426	13,635
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20,160
CASHFLOW	(40,134)	(39,773)	(25,947)	(60,742)	(24,698)	53,698	105,490	97,207	97,207	97,155	97,207	97,207	97,207	97,207	97,207	98,616	99,537	71,294	6,525
TOTAL MANPOWER ALLOCATION	3	3	13	55	131	128	114	103	103	104	103	103	103	103	103	95	89	78	47

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INCEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	186,119	165,274
TOTAL OPERATING COST	364,892	408,380
TOTAL COST	551,011	573,653
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	1,021,469	998,827

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	21.80%	3
Engineering	0.00%	
Labour	21.80%	3

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10
CAPITAL COST	38,279	37,917	21,959	47,718	39,212	0	0	0	0	0
OPERATING COST	1,851	1,851	3,842	12,330	24,070	25,530	24,110	22,407	22,407	22,463
COST (CAPITAL and OPERATING)	40,129	39,768	25,801	60,048	63,282	25,530	24,110	22,407	22,407	22,463
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960
CASHFLOW	(40,129)	(39,768)	(25,801)	(60,048)	(22,962)	55,110	106,930	98,553	98,553	98,497
TOTAL MANPOWER ALLOCATION	3	3	12	51	112	108	94	85	85	86

MINE SUMMARY Year	11	12	13	14	15	16	17	18	19
CAPITAL COST	0	0	0	0	0	0	0	0	0
OPERATING COST	22,407	22,407	22,407	22,407	22,407	21,059	20,172	18,309	12,880
COST (CAPITAL and OPERATING)	22,407	22,407	22,407	22,407	22,407	21,059	20,172	18,309	12,880
REVENUE	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20,160
CASHFLOW	98,553	98,553	98,553	98,553	98,553	99,901	100,788	72,411	7,280
TOTAL MANPOWER ALLOCATION	85	85	85	85	85	77	72	63	36

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	185,085	164,404
TOTAL OPERATING COST	345,316	386,376
TOTAL COST	530,401	550,780
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	1,042,079	1,021,700

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	21.80%	4
Engineering	0.00%	
Labour	21.80%	4

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10
CAPITAL COST	38,279	37,917	21,915	47,440	38,914	0	0	0	0	0
OPERATING COST	1,848	1,848	3,799	12,192	23,327	24,683	23,246	21,599	21,599	21,658
COST (CAPITAL and OPERATING)	40,126	39,765	25,714	59,632	62,241	24,683	23,246	21,599	21,599	21,658
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960
CASHFLOW	(40,126)	(39,765)	(25,714)	(59,632)	(21,921)	55,957	107,794	99,361	99,361	99,302
TOTAL MANPOWER ALLOCATION	3	3	11	48	100	96	82	74	74	75

MINE SUMMARY Year	11	12	13	14	15	16	17	18	19
CAPITAL COST	0	0	0	0	0	0	0	0	0
OPERATING COST	21,599	21,599	21,599	21,599	21,599	20,287	19,422	17,640	12,427
COST (CAPITAL and OPERATING)	21,599	21,599	21,599	21,599	21,599	20,287	19,422	17 640	12 427
REVENUE	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90 720	20,160
CASHFLOW	99,361	99,361	99,361	99,361	99,361	100,673	101,538	73,080	7,733
TOTAL MANPOWER ALLOCATION	74	74	74	74	74	67	62	54	30

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1 0%
EFFECTIVE PRICE DEFLATION RATE	0 0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	184,465	163,882
TOTAL OPERATING COST	333,571	373,173
TOTAL COST	518,035	537,055
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	1,054,445	1,035,425

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	21.80%	5
Engineering	0 00%	
Labour	21.80%	5

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0 0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0 0%	0.0%
Production	0.0%	0 0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10
CAPITAL COST	38,279	37,917	21,686	47,254	38,715	0	0	0	0	0
OPERATING COST	1,845	1,845	3,770	12,100	22,831	24,119	22,670	21,061	21,061	21,122
COST (CAPITAL and OPERATING)	40,124	39,762	25,656	59,354	61,547	24,119	22,670	21,061	21,061	21,122
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960
CASHFLOW	(40,124)	(39,762)	(25,656)	(59,354)	(21,227)	56,521	108,370	99,899	99,899	99,838
TOTAL MANPOWER ALLOCATION	3	3	11	47	92	88	74	67	67	68

MINE SUMMARY Year	11	12	13	14	15	16	17	18	19
CAPITAL COST	0	0	0	0	0	0	0	0	0
OPERATING COST	21,061	21,061	21,061	21,061	21,061	19,773	18,922	17,193	12,125
COST (CAPITAL and OPERATING)	21,061	21,061	21,061	21,061	21,061	19,773	18,922	17,193	12,125
REVENUE	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20,160
CASHFLOW	99,899	99,899	99,899	99,899	99,899	101,187	102,038	73,527	8,035
TOTAL MANPOWER ALLOCATION	67	67	67	67	67	60	55	47	25

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	184,051	163,534
TOTAL OPERATING COST	325,740	364,372
TOTAL COST	509,792	527,906
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	1,062,688	1,044,574

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	21.80%	6
Engineering	0.00%	
Labour	21.80%	6

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	21,865	47,122	38,573	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,844	1,844	3,749	12,034	22,477	23,716	22,259	20,676	20,676	20,738	20,676	20,676	20,676	20,676	20,676	19,406	18,565	16,874	11,909
COST (CAPITAL and OPERATING)	40,123	39,761	25,614	59,156	61,051	23,716	22,259	20,676	20,676	20,738	20,676	20,676	20,676	20,676	20,676	19,406	18,565	16,874	11,909
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20,160
CASHFLOW	(40,123)	(39,761)	(25,614)	(59,156)	(20,731)	56,924	108,781	100,284	100,284	100,222	100,284	100,284	100,284	100,284	100,284	101,554	102,395	73,846	8,251
TOTAL MANPOWER ALLOCATION	3	3	11	46	87	82	69	61	61	62	61	61	61	61	61	55	50	43	22

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	183,756	163,285
TOTAL OPERATING COST	320,147	358,085
TOTAL COST	503,903	521,370
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	1,068,577	1,051,110

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	21.80%	7
Engineering	0.00%	
Labour	21.80%	7

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	21,849	47,023	38,467	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,843	1,843	3,734	11,984	22,212	23,413	21,950	20,388	20,388	20,451	20,388	20,388	20,388	20,388	20,388	19,130	18,297	16,635	11,747
COST (CAPITAL and OPERATING)	40,121	39,760	25,583	59,007	60,679	23,413	21,950	20,388	20,388	20,451	20,388	20,388	20,388	20,388	20,388	19,130	18,297	16,635	11,747
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20,160
CASHFLOW	(40,121)	(39,760)	(25,583)	(59,007)	(20,359)	57,227	109,090	100,572	100,572	100,509	100,572	100,572	100,572	100,572	100,572	101,830	102,663	74,085	8,413
TOTAL MANPOWER ALLOCATION	3	3	10	45	82	78	65	57	57	58	57	57	57	57	57	51	46	40	20

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	183,534	163,099
TOTAL OPERATING COST	315,952	353,370
TOTAL COST	499,487	516,469
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	1,072,993	1,056,011

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	21.60%	8
Engineering	0.00%	
Labour	21.60%	8

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	21,837	46,946	38,384	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,842	1,842	3,722	11,946	22,005	23,178	21,710	20,163	20,163	20,227	20,163	20,163	20,163	20,163	20,163	18,916	18,089	16,449	11,621
COST (CAPITAL and OPERATING)	40,121	39,759	25,559	58,891	60,389	23,178	21,710	20,163	20,163	20,227	20,163	20,163	20,163	20,163	20,163	18,916	18,089	16,449	11,621
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20,160
CASHFLOW	(40,121)	(39,759)	(25,559)	(58,891)	(20,069)	57,462	109,330	100,797	100,797	100,733	100,797	100,797	100,797	100,797	100,797	102,044	102,871	74,271	8,539
TOTAL MANPOWER ALLOCATION	3	3	10	44	79	74	61	54	54	55	54	54	54	54	54	48	44	37	18

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	183,362	162,954
TOTAL OPERATING COST	312,690	349,703
TOTAL COST	496,052	512,656
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	1,076,428	1,059,824

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	21.80%	9
Engineering	0.00%	
Labour	21.80%	9

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	21,827	46,884	38,318	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,841	1,841	3,712	11,915	21,840	22,990	21,518	19,984	19,984	20,048	19,984	19,984	19,984	19,984	19,984	18,744	17,922	16,300	11,521
COST (CAPITAL and OPERATING)	40,120	39,758	25,540	58,799	60,158	22,990	21,518	19,984	19,984	20,048	19,984	19,984	19,984	19,984	19,984	18,744	17,922	16,300	11,521
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20,160
CASHFLOW	(40,120)	(39,758)	(25,540)	(58,799)	(19,838)	57,650	109,522	100,976	100,976	100,912	100,976	100,976	100,976	100,976	100,976	102,216	103,038	74,420	8,639
TOTAL MANPOWER ALLOCATION	3	3	10	44	77	72	59	52	52	53	52	52	52	52	52	46	41	35	16

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	183,224	162,838
TOTAL OPERATING COST	310,080	346,769
TOTAL COST	493,304	509,606
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	1,079,176	1,062,874

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	21.80%	10
Engineering	0.00%	
Labour	21.80%	10

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

Appendix E

Mining Cost - Engineering Productivity Improvements

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	22,866	53,438	45,349	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,810	1,810	4,625	15,074	39,359	42,954	41,887	39,027	39,027	39,027	39,027	39,027	39,027	39,027	39,027	36,931	35,606	32,091	22,203
COST (CAPITAL and OPERATING)	40,089	39,727	27,491	68,513	84,708	42,954	41,887	39,027	39,027	39,027	39,027	39,027	39,027	39,027	39,027	36,931	35,606	32,091	22,203
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20,160
CASHFLOW	(40,089)	(39,727)	(27,491)	(68,513)	(44,388)	37,686	89,153	81,933	81,933	81,933	81,933	81,933	81,933	81,933	81,933	84,029	85,354	58,629	(2,043
TOTAL MANPOWER ALLOCATION	3	3	22	97	352	355	337	313	313	313	313	313	313	313	313	295	283	254	174

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	197,849	175,144
TOTAL OPERATING COST	586,565	657,590
TOTAL COST	784,414	832,734
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	788,066	739,746

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	0.00%	1
Engineering	50.00%	
Labour	0.00%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	22,866	53,438	45,349	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,705	1,705	4,520	14,969	39,359	42,954	41,687	39,027	39,027	39,027	39,027	39,027	39,027	39,027	39,027	36,931	35,606	32,091	22 203
COST (CAPITAL and OPERATING)	39,984	39,622	27,386	68,408	84,708	42,954	41,687	39,027	39,027	39,027	39,027	39,027	39,027	39,027	39 027	36 931	35,606	32,091	22 203
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20.160
CASHFLOW	(39,984)	(39,622)	(27,386)	(68,408)	(44,388)	37,686	89,153	81,933	81,933	81,933	81,933	81,933	81,933	81,933	81,933	84,029	85,354	58,629	(2 043
TOTAL MANPOWER ALLOCATION	1	1	20	95	352	355	337	313	313	313	313	313	313	313	313	295	283	254	174

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4 0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	197,849	175,144
TOTAL OPERATING COST	586,145	657,159
TOTAL COST	783,994	832,303
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	788,486	740,177

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	0.00%	1
Engineering	100.00%	
Labour	0.00%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10
CAPITAL COST	38,279	37,917	22,866	53,438	45,349	0	0	0	0	0
OPERATING COST	1,600	1,600	4,415	14,864	39,359	42,954	41,887	39,027	39,027	39,027
COST (CAPITAL and OPERATING)	39,879	39,517	27,281	68,303	84,708	42,954	41,887	39,027	39,027	39,027
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960
CASHFLOW	(39,879)	(39,517)	(27,281)	(68,303)	(44,388)	37,686	89,153	81,933	81,933	81,933
TOTAL MANPOWER ALLOCATION	(1)	(1)	19	94	352	355	337	313	313	313

MINE SUMMARY Year	11	12	13	14	15	16	17	18	19
CAPITAL COST	0	0	0	0	0	0	0	0	0
OPERATING COST	39,027	39,027	39,027	39,027	39,027	36,931	35,606	32,091	22 203
COST (CAPITAL and OPERATING)	39,027	39,027	39,027	39,027	39,027	36,931	35,606	32,091	22,203
REVENUE	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20 160
CASHFLOW	81,933	81,933	81,933	81,933	81,933	84,029	85,354	58,629	(2,043:
TOTAL MANPOWER ALLOCATION	313	313	313	313	313	295	283	254	174

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1 0%
EFFECTIVE PRICE DEFLATION RATE	0 0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	197,849	175,144
TOTAL OPERATING COST	585,725	656,728
TOTAL COST	783,574	831,872
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	788,906	740,608

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0 75%	$1.00	0.75%
Value ($/Ton)	$100 80		

PRODUCTIVITY IMPROVEMENTS		
Management	0 00%	1
Engineering	150 00%	
Labour	0 00%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0 0%	0.0%
Development	0 0%	0 0%
Production	0 0%	0 0%
Backfill	0 0%	0 0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0 0%	0 0%
Development	0 0%	0 0%
Production	0 0%	0 0%
Backfill	0 0%	0 0%

Appendix F

Rework/Waste (Quality) - Process Quality Improvement

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10
CAPITAL COST	38,279	37,917	22,380	50,537	42,335	0	0	0	0	0
OPERATING COST	1,915	1,915	4,565	14,304	38,355	41,870	40,979	38,256	38,256	38,256
COST (CAPITAL and OPERATING)	40,194	39,832	26,945	64,841	80,690	41,870	40,979	38,256	38,256	38,256
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960
CASHFLOW	(40,194)	(39,832)	(26,945)	(64,841)	(40,370)	38,770	90,061	82,704	82,704	82,704
TOTAL MANPOWER ALLOCATION	4	4	23	98	352	355	337	313	313	313

MINE SUMMARY Year	11	12	13	14	15	16	17	18	19
CAPITAL COST	0	0	0	0	0	0	0	0	0
OPERATING COST	38,256	38,256	38,256	38,256	38,256	36,279	35,022	31,630	22,122
COST (CAPITAL and OPERATING)	38,256	38,256	38,256	38,256	38,256	36,279	35,022	31,630	22,122
REVENUE	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20,160
CASHFLOW	82,704	82,704	82,704	82,704	82,704	84,681	85,938	59,090	(1,962
TOTAL MANPOWER ALLOCATION	313	313	313	313	313	295	283	254	174

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	191,447	169,754
TOTAL OPERATING COST	575,000	644,720
TOTAL COST	766,447	814,474
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	806,033	758,006

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	0.00%	1
Engineering	0.00%	
Labour	0.00%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	20.0%
Development	0.0%	20.0%
Production	0.0%	20.0%
Backfill	0.0%	20.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	21,893	47,636	39,320	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,915	1,915	4,429	13,583	37,500	40,919	40,138	37,535	37,535	37,535	37,535	37,535	37,535	37,535	37,535	35,655	34,456	31,186	22,040
COST (CAPITAL and OPERATING)	40,194	39,832	26,322	61,219	76,820	40,919	40,138	37,535	37,535	37,535	37,535	37,535	37,535	37,535	37,535	35,655	34,456	31,186	22 040
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20,160
CASHFLOW	(40,194)	(39,832)	(26,322)	(61,219)	(36,500)	39,721	90,902	83,425	83,425	83,425	83,425	83,425	83,425	83,425	83,425	85,305	86,504	59 534	(1,880
TOTAL MANPOWER ALLOCATION	4	4	23	98	352	355	337	313	313	313	313	313	313	313	313	295	283	254	174

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1 0%
EFFECTIVE PRICE DEFLATION RATE	0 0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	185,045	164,364
TOTAL OPERATING COST	564,013	632,508
TOTAL COST	749,059	796,871
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	823,421	775,609

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	0.00%	1
Engineering	0.00%	
Labour	0.00%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	40.0%
Development	0.0%	40.0%
Production	0.0%	40.0%
Backfill	0.0%	40.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	21,407	44,735	36,306	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,915	1,915	4,322	13,017	36,794	40,103	39,365	36,864	36,864	36,864	36,864	36,864	36,864	36,864	36,864	35,061	33,907	30,758	21,959
COST (CAPITAL and OPERATING)	40,194	39,832	25,729	57,752	73,100	40,103	39,365	36,864	36,864	36,864	36,864	36,864	36,864	36,864	36,864	35,061	33,907	30,758	21,959
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20,160
CASHFLOW	(40,194)	(39,832)	(25,729)	(57,752)	(32,780)	40,537	91,675	84,096	84,096	84,096	84,096	84,096	84,096	84,096	84,096	85,899	87,053	59 962	(1,799
TOTAL MANPOWER ALLOCATION	4	4	23	98	352	355	337	313	313	313	313	313	313	313	313	295	283	254	174

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	178,643	158,974
TOTAL OPERATING COST	554,026	621,383
TOTAL COST	732,669	780,357
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	839,811	792,123

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	0.00%	1
Engineering	0.00%	
Labour	0.00%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	60.0%
Development	0.0%	60.0%
Production	0.0%	60.0%
Backfill	0.0%	60.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10
CAPITAL COST	38,279	37,917	20,920	41,834	33,292	0	0	0	0	0
OPERATING COST	1,915	1,915	4,245	12,606	36,236	39,421	38,659	36,243	36,243	36,243
COST (CAPITAL and OPERATING)	40,194	39,832	25,165	54,440	69,527	39,421	38,659	36,243	36,243	36,243
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960
CASHFLOW	(40,194)	(39,832)	(25,165)	(54,440)	(29,207)	41,219	92,381	84,717	84,717	84,717
TOTAL MANPOWER ALLOCATION	4	4	23	98	352	355	337	313	313	313

MINE SUMMARY Year	11	12	13	14	15	16	17	18	19
CAPITAL COST	0	0	0	0	0	0	0	0	0
OPERATING COST	36,243	36,243	36,243	36,243	36,243	34,496	33,375	30,347	21 878
COST (CAPITAL and OPERATING)	36,243	36,243	36,243	36,243	36,243	34,496	33,375	30,347	21,878
REVENUE	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20 160
CASHFLOW	84,717	84,717	84,717	84,717	84,717	86,464	87,585	60,373	(1,718
TOTAL MANPOWER ALLOCATION	313	313	313	313	313	295	283	254	174

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	172,241	153,584
TOTAL OPERATING COST	545,037	611,346
TOTAL COST	717,278	764,930
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	855,202	807,550

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	0.00%	1
Engineering	0.00%	
Labour	0.00%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	80.0%
Development	0.0%	80.0%
Production	0.0%	80.0%
Backfill	0.0%	80.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	20,434	38,932	30,277	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,915	1,915	4,196	12,350	35,827	38,873	38,019	35,673	35,673	35,673	35,673	35,673	35,673	35,673	35,673	33,960	32,859	29,954	21,797
COST (CAPITAL and OPERATING)	40,194	39,832	24,630	51,282	66,104	38,873	38,019	35,673	35,673	35,673	35,673	35,673	35,673	35,673	35,673	33,960	32,859	29,954	21,797
REVENUE	0	0	0	0	40,320	80,640	131,040	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	120,960	90,720	20,160
CASHFLOW	(40,194)	(39,832)	(24,630)	(51,282)	(25,784)	41,767	93,021	85,287	85,287	85,287	85,287	85,287	85,287	85,287	85,287	87,000	88,101	60,766	(1,637
TOTAL MANPOWER ALLOCATION	4	4	23	98	352	355	337	313	313	313	313	313	313	313	313	295	283	254	174

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	165,839	148,194
TOTAL OPERATING COST	537,047	602,398
TOTAL COST	702,886	750,591
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	869,594	821,889

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	0.00%	1
Engineering	0.00%	
Labour	0.00%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	100.0%
Development	0.0%	100.0%
Production	0.0%	100.0%
Backfill	0.0%	100.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

Appendix G

Rework/Waster (Quality) - Product Value Addition

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10
CAPITAL COST	38,279	37,917	22,866	53,438	45,349	0	0	0	0	0
OPERATING COST	1,915	1,915	4,730	15,179	39,359	42,954	41,887	39,027	39,027	39,027
COST (CAPITAL and OPERATING)	40,194	39,832	27,596	68,618	84,708	42,954	41,887	39,027	39,027	39,027
REVENUE	0	0	0	0	48,384	96,768	157,248	145,152	145,152	145,152
CASHFLOW	(40,194)	(39,832)	(27,596)	(68,618)	(36,324)	53,814	115,361	106,125	106,125	106,125
TOTAL MANPOWER ALLOCATION	4	4	23	98	352	355	337	313	313	313

MINE SUMMARY Year	11	12	13	14	15	16	17	18	19
CAPITAL COST	0	0	0	0	0	0	0	0	0
OPERATING COST	39,027	39,027	39,027	39,027	39,027	36,931	35,606	32,091	22,203
COST (CAPITAL and OPERATING)	39,027	39,027	39,027	39,027	39,027	36,931	35,606	32,091	22,203
REVENUE	145,152	145,152	145,152	145,152	145,152	145,152	145,152	108,864	24,192
CASHFLOW	106,125	106,125	106,125	106,125	106,125	108,221	109,546	76,773	1,989
TOTAL MANPOWER ALLOCATION	313	313	313	313	313	295	283	254	174

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	197,849	175,144
TOTAL OPERATING COST	586,985	658,020
TOTAL COST	784,834	833,164
TOTAL REVENUE	1,886,976	1,886,976
TOTAL CASHFLOW	1,102,142	1,053,812

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.72%
Cu	0.75%	$1.00	0.90%
Value ($/Ton)	$120.96		

PRODUCTIVITY IMPROVEMENTS		
Management	0.00%	1
Engineering	0.00%	
Labour	0.00%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	5.0%	0.0%
Development	5.0%	0.0%
Production	5.0%	0.0%
Backfill	5.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	22,866	53,438	45,349	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,915	1,915	4,730	15,179	39,359	42,954	41,887	39,027	39,027	39,027	39,027	39,027	39,027	39,027	39,027	36,931	35,606	32,091	22,203
COST (CAPITAL and OPERATING)	40,194	39,832	27,596	68,618	84,708	42,954	41,887	39,027	39,027	39,027	39,027	39,027	39,027	39,027	39,027	36,931	35 606	32,091	22 203
REVENUE	0	0	0	0	56,448	112,896	183,456	169,344	169,344	169,344	169,344	169,344	169,344	169,344	169,344	169,344	169,344	127,008	28 224
CASHFLOW	(40,194)	(39,832)	(27,596)	(68,618)	(28,260)	69,942	141,569	130,317	130,317	130,317	130,317	130,317	130,317	130,317	130,317	132,413	133,738	94,917	6 021
TOTAL MANPOWER ALLOCATION	4	4	23	98	352	355	337	313	313	313	313	313	313	313	313	295	283	254	174

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0 0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	197,849	175,144
TOTAL OPERATING COST	586,985	658,020
TOTAL COST	784,834	833,164
TOTAL REVENUE	2,201,472	2,201,472
TOTAL CASHFLOW	1,416,638	1,368,308

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	2.00%
Cu	0.75%	$1.00	1.05%
Value ($/Ton)	$141.12		

PRODUCTIVITY IMPROVEMENTS		
Management	0.00%	1
Engineering	0.00%	
Labour	0.00%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	10.0%	0.0%
Development	10.0%	0.0%
Production	10.0%	0.0%
Backfill	10.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	22,866	53,438	45,349	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,915	1,915	4,730	15,179	39,359	42,954	41,887	39,027	39,027	39,027	39,027	39,027	39,027	39,027	39,027	36,931	35,606	32,091	22,203
COST (CAPITAL and OPERATING)	40,194	39,832	27,596	68,618	84,708	42,954	41,887	39,027	39,027	39,027	39,027	39,027	39,027	39,027	39,027	36,931	35,606	32,091	22 203
REVENUE	0	0	0	0	72,576	145,152	235,872	217,728	217,728	217,728	217,728	217,728	217,728	217,728	217,728	217,728	217,728	163,296	36 288
CASHFLOW	(40,194)	(39,832)	(27,596)	(68,618)	(12,132)	102,198	193,985	178,701	178,701	178,701	178,701	178,701	178,701	178,701	178,701	180,797	182,122	131,205	14 085
TOTAL MANPOWER ALLOCATION	4	4	23	98	352	355	337	313	313	313	313	313	313	313	313	295	283	254	174

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	197,849	175,144
TOTAL OPERATING COST	586,985	658,020
TOTAL COST	784,834	833,164
TOTAL REVENUE	2,830,464	2,830,464
TOTAL CASHFLOW	2,045,630	1,997,300

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	2.57%
Cu	0.75%	$1.00	1.35%
Value ($/Ton)	$181.44		

PRODUCTIVITY IMPROVEMENTS		
Management	0.00%	1
Engineering	0.00%	
Labour	0.00%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	20.0%	0.0%
Development	20.0%	0.0%
Production	20.0%	0.0%
Backfill	20.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	22,866	53,438	45,349	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,915	1,915	4,730	15,179	39,359	42,954	41,887	39,027	39,027	39,027	39,027	39,027	39,027	39,027	39,027	36,931	35,606	32,091	22,203
COST (CAPITAL and OPERATING)	40,194	39,832	27,596	68,618	84,708	42,954	41,887	39,027	39,027	39,027	39,027	39,027	39,027	39,027	39,027	36,931	35,606	32,091	22 203
REVENUE	0	0	0	0	88,704	177,408	288,288	266,112	266,112	266,112	266,112	266,112	266,112	266,112	266,112	266,112	266,112	199,584	44 352
CASHFLOW	(40,194)	(39,832)	(27,596)	(68,618)	3,996	134,454	246,401	227,085	227,085	227,085	227,085	227,085	227,085	227,085	227,085	229,181	230,506	167,493	22,149
TOTAL MANPOWER ALLOCATION	4	4	23	98	352	355	337	313	313	313	313	313	313	313	313	295	283	254	174

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	197,849	175,144
TOTAL OPERATING COST	586,985	658,020
TOTAL COST	784,834	833,164
TOTAL REVENUE	3,459,456	3,459,456
TOTAL CASHFLOW	2,674,622	2,626,292

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	3.15%
Cu	0.75%	$1.00	1.65%
Value ($/Ton)	$221.76		

PRODUCTIVITY IMPROVEMENTS		
Management	0.00%	1
Engineering	0.00%	
Labour	0.00%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	30.0%	0.0%
Development	30.0%	0.0%
Production	30.0%	0.0%
Backfill	30.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

Appendix H

Throughput Time Improvement - Surface Operation

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	23,343	55,592	46,366	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,943	1,943	5,028	16,406	38,182	42,724	41,307	38,205	38,205	38,221	38,205	38,205	38,205	32,483	31,471	28,537	0	0	0
COST (CAPITAL and OPERATING)	40,222	39,860	28,371	71,998	84,548	42,724	41,307	38,205	38,205	38,221	38,205	38,205	38,205	32,483	31,471	28,537	0	0	0
REVENUE	0	0	0	0	49,110	98,220	159,607	147,329	147,329	147,329	147,329	147,329	147,329	140,213	135,052	106,304	0	0	C
CASHFLOW	(40,222)	(39,860)	(28,371)	(71,998)	(35,438)	55,496	118,299	109,124	109,124	109,109	109,124	109,124	109,124	107,730	103,581	77,767	0	0	0
TOTAL MANPOWER ALLOCATION	4	4	25	103	320	321	302	278	278	279	278	278	278	233	226	204	0	0	0

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	201,497	178,245
TOTAL OPERATING COST	469,273	518,352
TOTAL COST	670,770	696,596
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	901,710	875,884

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	21.80%	1
Engineering	-21.80%	
Labour	21.80%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	21.8%	0.0%
Development	21.8%	0.0%
Production	21.8%	0.0%
Backfill	21.8%	0.0%

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	25,361	61,369	54,670	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,943	1,943	6,406	19,872	48,457	55,270	53,145	48,393	40,372	38,406	38,390	38,390	26,136	0	0	0	0	0	0
COST (CAPITAL and OPERATING)	40,222	39,860	31,767	81,241	103,127	55,270	53,145	48,393	40,372	38,406	38,390	38,390	26,136	0	0	0	0	0	0
REVENUE	0	0	0	0	73,665	147,329	239,410	220,016	202,578	202,578	202,578	202,578	81,749	0	0	0	0	0	0
CASHFLOW	(40,222)	(39,860)	(31,767)	(81,241)	(29,462)	92,060	186,265	171,623	162,205	164,172	164,187	164,187	55,612	0	0	0	0	0	0
TOTAL MANPOWER ALLOCATION	4	4	35	142	394	414	393	356	293	278	278	278	186	0	0	0	0	0	0

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	217,596	191,802
TOTAL OPERATING COST	417,124	452,991
TOTAL COST	634,720	644,793
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	937,760	927,687

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	21.80%	1
Engineering	-21.80%	
Labour	21.80%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	21.8%	50.0%
Development	21.8%	50.0%
Production	21.8%	50.0%
Backfill	21.8%	50.0%

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	27,379	67,146	62,285	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,943	1,943	7,784	23,338	58,732	67,816	47,533	45,310	45,310	45,325	37,414	0	0	0	0	0	0	0	0
COST (CAPITAL and OPERATING)	40,222	39,860	35,163	90,484	121,016	67,816	47,533	45,310	45,310	45,325	37,414	0	0	0	0	0	0	0	0
REVENUE	0	0	0	0	98,220	196,439	275,265	270,104	270,104	270,104	192,246	0	0	0	0	0	0	0	0
CASHFLOW	(40,222)	(39,860)	(35,163)	(90,484)	(22,797)	128,623	227,732	224,794	224,794	224,779	154,832	0	0	0	0	0	0	0	0
TOTAL MANPOWER ALLOCATION	4	4	45	181	465	512	347	330	330	330	271	0	0	0	0	0	0	0	0

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	233,006	204,793
TOTAL OPERATING COST	382,446	411,656
TOTAL COST	615,452	616,449
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	957,028	956,031

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	21.80%	1
Engineering	-21.80%	
Labour	21.80%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	21.8%	100.0%
Development	21.8%	100.0%
Production	21.8%	100.0%
Backfill	21.8%	100.0%

Appendix I

Throughput Time Improvement - Three Shifts - Seven Days/Week

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	24,299	60,596	52,296	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,998	1,998	5,901	19,053	50,120	56,689	55,478	51,271	51,271	51,251	51,271	51,271	45,559	42,272	42,272	27,756	0	0	0
COST (CAPITAL and OPERATING)	40,277	39,915	30,200	79,649	102,415	56,689	55,478	51,271	51,271	51,251	51,271	51,271	45,559	42,272	42,272	27,756	0	0	0
REVENUE	0	0	0	0	51,852	103,703	168,517	155,555	155,555	155,555	155,555	155,555	149,748	142,592	142,592	35,703	0	0	0
CASHFLOW	(40,277)	(39,915)	(30,200)	(79,649)	(50,564)	47,014	113,040	104,284	104,284	104,304	104,284	104,284	104,189	100,320	100,320	7,947	0	0	0
TOTAL MANPOWER ALLOCATION	5	5	35	145	502	502	485	448	448	447	448	448	396	367	367	242	0	0	0

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	213,386	188,245
TOTAL OPERATING COST	605,429	668,198
TOTAL COST	818,815	856,443
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	753,665	716,037

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	-28.60%	1
Engineering	-28.60%	
Labour	-28.60%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	28.6%	0.0%
Development	28.6%	0.0%
Production	28.6%	0.0%
Backfill	28.6%	0.0%

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	26,795	67,807	61,881	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,998	1,998	7,687	23,656	63,788	73,642	71,825	60,894	52,017	51,997	52,017	52,017	24,335	0	0	0	0	0	0
COST (CAPITAL and OPERATING)	40,277	39,915	34,482	91,463	125,670	73,642	71,825	60,894	52,017	51,997	52,017	52,017	24,335	0	0	0	0	0	0
REVENUE	0	0	0	0	77,777	155,555	252,776	221,044	213,888	213,888	213,888	213,888	9,778	0	0	0	0	0	0
CASHFLOW	(40,277)	(39,915)	(34,482)	(91,463)	(47,892)	81,912	180,951	160,151	161,871	161,891	161,871	161,871	(14,557)	0	0	0	0	0	0
TOTAL MANPOWER ALLOCATION	5	5	50	205	609	651	627	531	451	450	451	451	213	0	0	0	0	0	0

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	232,679	204,507
TOTAL OPERATING COST	537,869	583,900
TOTAL COST	770,548	788,407
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	801,932	784,073

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	-28.60%	1
Engineering	-28.60%	
Labour	-28.60%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	28.6%	50.0%
Development	28.6%	50.0%
Production	28.6%	50.0%
Backfill	28.6%	50.0%

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	29,291	75,018	71,233	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	1,998	1,998	9,473	28,258	77,457	86,481	61,761	61,761	61,761	61,741	40,232	0	0	0	0	0	0	0	0
COST (CAPITAL and OPERATING)	40,277	39,915	38,765	103,276	148,690	86,481	61,761	61,761	61,761	61,741	40,232	0	0	0	0	0	0	0	0
REVENUE	0	0	0	0	103,703	201,600	285,183	285,183	285,183	285,183	126,444	0	0	0	0	0	0	0	0
CASHFLOW	(40,277)	(39,915)	(38,765)	(103,276)	(44,987)	115,119	223,422	223,422	223,422	223,442	86,211	0	0	0	0	0	0	0	0
TOTAL MANPOWER ALLOCATION	5	5	65	265	714	764	534	534	534	534	350	0	0	0	0	0	0	0	0

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	251,739	220,577
TOTAL OPERATING COST	492,922	530,550
TOTAL COST	744,661	751,127
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	827,819	821,353

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	-28.60%	1
Engineering	-28.60%	
Labour	-28.60%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	28.6%	100.0%
Development	28.6%	100.0%
Production	28.6%	100.0%
Backfill	28.6%	100.0%

Appendix J

Throughput Time Improvement

Surface Operation Three Shifts - Seven Days/Week

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	24,776	60,993	53,507	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	2,026	2,026	6,199	19,550	49,673	56,459	54,898	50,449	50,449	50,445	43,926	40,880	40,880	37,996	0	0	0	0	0
COST (CAPITAL and OPERATING)	40,305	39,943	30,974	80,542	103,180	56,459	54,898	50,449	50,449	50,445	43,926	40,880	40,880	37,996	0	0	0	0	0
REVENUE	0	0	0	0	60,641	121,283	197,084	181,924	181,924	181,924	171,279	166,764	166,764	142,894	0	0	0	0	0
CASHFLOW	(40,305)	(39,943)	(30,974)	(80,542)	(42,539)	64,824	142,186	131,475	131,475	131,479	127,353	125,883	125,883	104,898	0	0	0	0	0
TOTAL MANPOWER ALLOCATION	6	6	36	147	460	470	452	414	414	414	359	333	333	309	0	0	0	0	0

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	215,471	190,004
TOTAL OPERATING COST	505,857	553,136
TOTAL COST	721,329	743,140
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	851,151	829,340

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	-6.80%	1
Engineering	-50.40%	
Labour	-6.80%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	50.4%	0.0%
Development	50.4%	0.0%
Production	50.4%	0.0%
Backfill	50.4%	0.0%

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	27,510	68,864	63,781	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	2,026	2,026	8,120	24,455	64,232	74,411	61,951	51,043	51,043	51,038	51,043	24,346	0	0	0	0	0	0	0
COST (CAPITAL and OPERATING)	40,305	39,943	35,630	93,319	128,013	74,411	61,951	51,043	51,043	51,038	51,043	24,346	0	0	0	0	0	0	0
REVENUE	0	0	0	0	90,962	181,924	269,821	250,145	250,145	250,145	250,145	29,192	0	0	0	0	0	0	0
CASHFLOW	(40,305)	(39,943)	(35,630)	(93,319)	(37,051)	107,513	207,870	199,102	199,102	199,107	199,102	4,846	0	0	0	0	0	0	0
TOTAL MANPOWER ALLOCATION	6	6	52	208	568	621	509	416	416	416	416	197	0	0	0	0	0	0	0

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	236,351	207,606
TOTAL OPERATING COST	465,736	503,089
TOTAL COST	702,086	710,697
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	870,394	861,783

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.60		

PRODUCTIVITY IMPROVEMENTS		
Management	-6.80%	1
Engineering	-50.40%	
Labour	-6.80%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	50.4%	50.0%
Development	50.4%	50.0%
Production	50.4%	50.0%
Backfill	50.4%	50.0%

MINE COST INPUT SHEET(1990 $CAN) TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
CAPITAL COST	38,279	37,917	30,245	76,735	74,055	0	0	0	0	0	0	0	0	0	0	0	0	0	0
OPERATING COST	2,026	2,026	10,041	29,361	78,791	68,408	61,206	61,206	61,206	50,990	0	0	0	0	0	0	0	0	0
COST (CAPITAL and OPERATING)	40,305	39,943	40,286	106,096	152,846	68,408	61,206	61,206	61,206	50,990	0	0	0	0	0	0	0	0	0
REVENUE	0	0	0	0	121,283	201,600	333,527	333,527	333,527	249,016	0	0	0	0	0	0	0	0	0
CASHFLOW	(40,305)	(39,943)	(40,286)	(106,096)	(31,563)	133,192	272,321	272,321	272,321	198,026	0	0	0	0	0	0	0	0	0
TOTAL MANPOWER ALLOCATION	6	6	67	268	675	569	499	499	499	416	0	0	0	0	0	0	0	0	0

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	257,230	225,211
TOTAL OPERATING COST	425,262	455,919
TOTAL COST	682,492	681,130
TOTAL REVENUE	1,572,480	1,572,480
TOTAL CASHFLOW	889,988	891,350

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.43%
Cu	0.75%	$1.00	0.75%
Value ($/Ton)	$100.80		

PRODUCTIVITY IMPROVEMENTS		
Management	-6.80%	1
Engineering	-50.40%	
Labour	-6.80%	1

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	0.0%	0.0%
Development	0.0%	0.0%
Production	0.0%	0.0%
Backfill	0.0%	0.0%

THROUG^PUT TIME IMPROVEMENTS	Utilization	Process
Delineati.n	50.4%	100.0%
Development	50.4%	100.0%
Production	50.4%	100.0%
Backfill	50.4%	100.0%

Appendix K

Combined Factor Improvement Case

MINE COST INPUT SHEET(1990 $CAN) **TYPICAL SUDBURY OPERATION MINING COST MODEL (VERTICAL CRATER RETREAT) BASE CASE**

MINE SUMMARY Year	1	2	3	4	5	6	7	8	9	10
CAPITAL COST	38,279	37,917	24,876	56,744	50,366	0	0	0	0	0
OPERATING COST	1,653	1,653	5,853	18,037	41,559	47,067	37,875	30,923	30,923	30,968
COST (CAPITAL and OPERATING)	39,932	39,570	30,730	74,781	91,925	47,067	37,875	30,923	30,923	30,968
REVENUE	0	0	0	0	109,154	218,309	323,786	300,174	300,174	300,174
CASHFLOW	(39,932)	(39,570)	(30,730)	(74,781)	17,229	171,242	285,911	269,252	269,252	269,207
TOTAL MANPOWER ALLOCATION	0	0	25	109	259	277	209	163	163	164

MINE SUMMARY Year	11	12	13	14	15	16	17	18	19
CAPITAL COST	0	0	0	0	0	0	0	0	0
OPERATING COST	30,923	15,571	0	0	0	0	0	0	0
COST (CAPITAL and OPERATING)	30,923	15,571	0	0	0	0	0	0	0
REVENUE	300,174	35,030	0	0	0	0	0	0	0
CASHFLOW	269,252	19,459	0	0	0	0	0	0	0
TOTAL MANPOWER ALLOCATION	163	70	0	0	0	0	0	0	0

INTEREST RATES	
EFFECTIVE COST OF CAPITAL RATE	4.0%
CONSUMER PRICE INDEX INCREASE	-1.0%
EFFECTIVE PRICE DEFLATION RATE	0.0%

	1990 $	DISCOUNTED
TOTAL CAPITAL COST	208,183	183,881
TOTAL OPERATING COST	293,003	316,201
TOTAL COST	501,186	500,082
TOTAL REVENUE	1,886,973	1,886,976
TOTAL CASHFLOW	1,385,790	1,386,894

PRODUCT VALUE	GRADE	$/lb	Effective Grade
Ni	1.43%	$3.00	1.72%
Cu	0.75%	$1.00	0.90%
Value ($/Ton)	$120.96		

PRODUCTIVITY IMPROVEMENTS		
Management	-6.80%	3
Engineering	100.00%	
Labour	-6.80%	3

REWORK/WASTE (QUALITY) IMPROVE	Value	Cost
Delineation	5.0%	15.0%
Development	5.0%	15.0%
Production	5.0%	15.0%
Backfill	5.0%	15.0%

THROUGHPUT TIME IMPROVEMENTS	Utilization	Process
Delineation	50.4%	50.0%
Development	50.4%	50.0%
Production	50.4%	50.0%
Backfill	50.4%	50.0%