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Load-Haul-Dump machine automation at Inco's Ontario Division

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements of the degree of
Master of Engineering.

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Dedication

This thesis is dedicated to my wife Karen and our sons Sean, Kevin and Jeff. Without their continual support and understanding, this project would not have succeeded.

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This document is based on both personal experience and research components. The author is grateful for the sharing and interaction with many in the mining industry. Two friends and associates encouraged the author to attempt this M. Eng. Program: it is with great thanks that I recognize Peter Golde and Greg Baiden who guided me into the program and then were so patient with my many questions. The author is especially grateful to his Thesis Supervisors, Malcolm Scoble and Hani Mitri, for their guidance and assistance offered during the studies.

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Abstract

This thesis is based upon field studies of automation research in Inco mines of the Ontario Division. It considers the advancement of technology and practice for underground hardrock mining automation, emphasizing the Load-Haul-Dump machine and its evolution and automation. It attempts to define the requirements for future mining processes, including the potential for extended teleoperation and autonomous operation of machines from safe vantage points.

Design issues including effective underground communications, automation amenable equipment, and process and workplace suitability are analyzed in detail and then related to solutions in design and practice.

This thesis concludes with discussions and recommendations towards solutions for future autonomous haulage for extreme long distance situations. Conclusions will highlight the successes the LHD has enabled in Canadian underground hardrock mines and its suitability to the task of optimizing automated haulage for use in safe, higher productivity automated processes that will optimize underground hardrock mining in Canada.

Résumé

Cette thèse est basée sur des études de chantier concernant la recherche en automatisation dans les mines de Inco- division d'Ontario. La thèse considère l'avancement de la technologie et la pratique de l'automatisation dans les mines souterraines de roche dure, en mettant l'accent sur le Load-Haul-Dump (LHD), son évolution et son automatisation. Dans cette thèse, on essaie de déterminer les besoins au future des processus miniers, incluant le potentiel d'élaborer la tele-opération et l'automatisation des équipements du point de vue de la sécurité.

Les issues de communication efficace souterraine, automatisation des équipements et de processus, ainsi que les conditions de chantier sont analysées en détail, puis reliées aux solutions pratiques.

Enfin, des discussions et recommandations visées vers des solutions pour le transport autonome des matériaux à très longues distances sont présentées. Les conclusions résument les succès que le LHD a déjà atteint dans les mines Canadiennes souterraines, de roches dure. Il est démontré que le LHD est idéal pour optimiser le transport des matériaux, et maximiser la productivité en gardant la sécurité des travailleurs dans les mines souterraines Canadiennes.

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1.0 INTRODUCTION AND BACKGROUND

1.1 Objectives

The force behind this thesis is the satisfaction of the final portion of a Masters of Engineering degree at McGill University. The organization of the material, and the topics covered are considered to be significant to the Canadian hardrock mining industry. The document provides a brief examination of the history of trackless machines and recent mining processes dependent on the LHD. Faced with the driving forces behind the Canadian hardrock underground mining industry, the document identifies issues and provides suggestions for a focused methodology for implementation of LHD automation.

Special emphasis is given to some of the significant enablers of automation underground.

This thesis focuses on the underground mining process. A case study, Inco's Stobie Mine, is offered as a typical bulk-mining example in the Sudbury area. The issues identified have been those of general concern and use rather than the specifics of a particular implementation. This is primarily based on the desire to offer a generic analysis of the process rather than focus on the specifics and minutia of a particular installation.

1.2 Contribution

The thesis is founded on an initial overview of the history of the LHD and comparison of the mining techniques that have affected the machine's evolution. This aims to provide an understanding of the factors, which shaped the design of the machine and its mode of utilization. The value of this exercise is considered to lie in the appreciation of the logic behind its functional design and characteristics.

This is felt to be a unique contribution at this stage in its development and integration into the next generation mining systems. This evolution is then extended into the application of the automated LHD and techniques that are applicable to its automation and remote operation in the underground workplace. This structured analysis of the issues and solutions towards mine automation is considered to be a unique contribution, which is aimed to contribute to the future competitiveness as well as health and safety of the Canadian mining industry. The LHD is the central node for future bulk mining

automation. This thesis should facilitate the taking stock of where and how its evolution should be guided

1.3 Methodology

The thesis is based on a literature review and practical experience gained in several underground mines. As well, information is presented that is a result of field studies by the author at the Stobie mine, in particular the implementation and assimilation of automation in its LHD fleet, starting with the initial installations in late 1995, through mid-1999. As an employee of Automated Mining Systems, the author has been in the position to "live" the implementation process. Many of the issues identified and solutions proposed will be solely based on these experiences and as such are offered without external reference.

1.4 Structure

Reviewers of this document are assumed to be comfortable with the fundamentals of bulk mining as implemented in Canadian underground hard-rock mines. It traces changes in some features of the LHD in its evolution to the format of machine currently used in Inco's mines. The operations of Inco are considered to be well representative of Canadian mining practice. Having established the nature of these machines, it continues by outlining some of the enablers of underground automation as well as some of the deterrents to the effective use of the process. Several sections are devoted to the techniques and requirements of both the machine as well as the workplace that effectively utilizes automated LHDs in the process. The analytical approach is reflected in the objective to identify issues and recommend solutions.

1.5 The team

The team assembled to research, develop and implement the automation and the communications strategies at the Stobie Mine included the following:

- Inco Mines Research supplied the mine related project management and original project initiatives. The central objective was to prove the safety and advantages of the savings associated with miners not being required to travel to the underground work location, coupled with the savings associated with one-man, multiple machine operation.
- Automated Mining Systems supplied the modifications to the machine communications equipment to allow the machine communications to become broadband compatible. As well, Automated Mining Systems supplied the ancillary hardware and software necessary to integrate the components into a cell of automation, capable of reporting to the central mine information systems.
- Mine personnel were made available to test functionality and then integrate the concept of remote control mining and automation into their operations.

1.6 Inco's Sudbury mines

Inco mines in the Sudbury Basin use various mining methods including sub-level cave, room and pillar, and vertical retreat mining. The challenge Inco faces is to utilize technology to increase safety and reduce costs to ensure mine profitability to and beyond the end of the decade. As a result of natural attrition, due in a large part to retirements, its employee base has reduced significantly over the last decade. The loss of experience and the knowledge base within the workforce can potentially be counterbalanced by the implementation of automation.

2.0 PRESSURES ENCOURAGING AUTOMATION IN THE MINING INDUSTRY

2.1 Economics

2.1.1 Issues of mining competitiveness

The economical mining of an orebody is based on a recovery of material that can be sold at a profit above the sum of the costs of acquisition, removal and conditioning for sale, including the extra burdens of environmental and social costs. The sale of metals is based on a world-economy pricing

scheme; pricing of metals is by supply and demand pressure. The following figure indicates one example of the variability of the sales and inventory levels for the London Metals Exchange over the last 14 years. It is notable that the price of nickel varied from below \$1.75 to over \$8.25 in US dollars, almost a factor of 5.

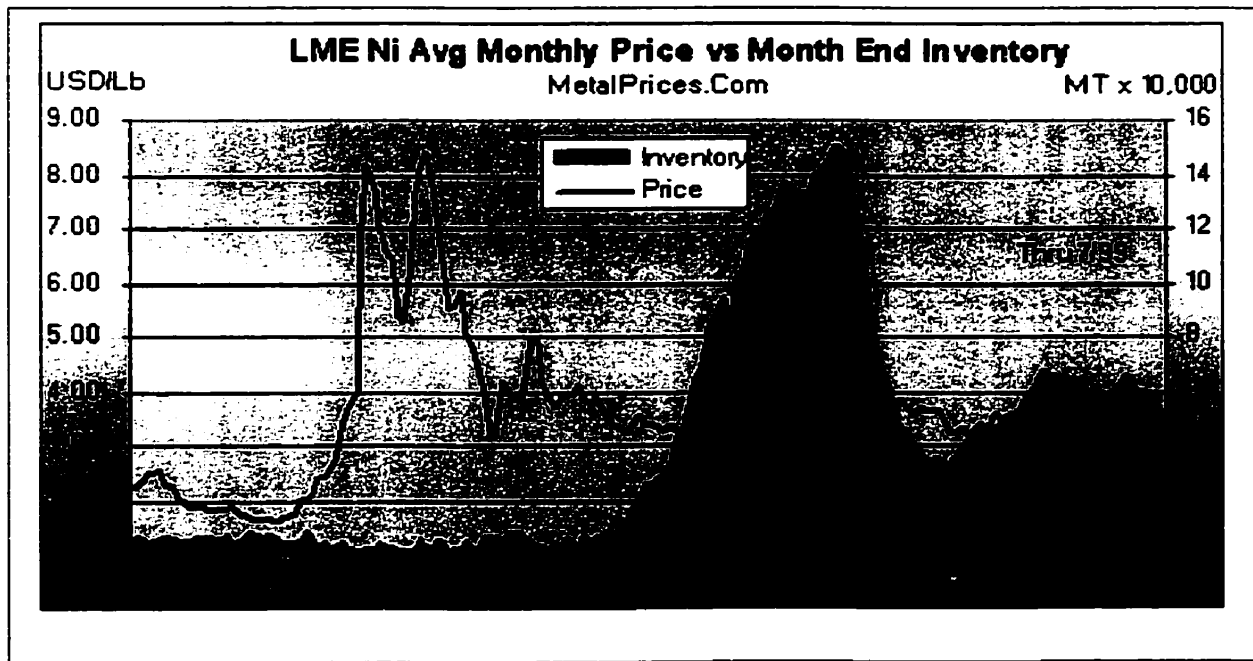


Figure 1: LME nickel price chart 14-year price vs. inventory¹

The effect of supply and demand in the metal mining industry removes a mining company's ability to control selling prices, unless they are responsible for a significant portion of the supply.

Mining companies are at the mercy of a global economy and they must suit their process to the externally set current or anticipated prices. The company must control their costs in order to maintain their profitability, within the constraints of regulatory, environmental and social factors.

An ore body usually can be mined, using several varied techniques, at a variety of costs per unit mined. These costs include all of the fixed costs (for example acquisition, exploration, development, head-office transfer charges and infrastructure installation costs) as well as the variable costs (such as infrastructure, labour, safety, dilution and mining method). Typically the mines are unable to adjust very much of the fixed costs around their operations. The variable costs including mining method and personnel costs are the primary cost-control methods available. Fortunately these costs are those that are most susceptible to adjustment using automation techniques. Once the mining method is chosen,

then the primary cost control issues driving automation will be those surrounding personnel and incremental infrastructure costs.

2.1.2 Underground mining method choice

Mining methods have changed with time and technology. Based on the ability to automate portions of the mining process, several new options have become available that allow the mines to accomplish tasks using a changed set of embedded costs and risks. Some of these changes have increased the effective mine output while reducing the worker's exposure to underground workplace hazards.

Methods such as VRM and sub-level caving are examples of bulk mining techniques that have become viable based on new equipment and automation enhancements. The use of these techniques allows mines to better utilize labour and machinery to reduce total mining costs.

2.1.3 Emergence of enabling technologies

Several technologies influenced the creation and implementation of the LHD in Canadian mines including the evolution of the LHD machine as well as updates and advances to the available mining infrastructure. Perhaps the most significant was the development of communications capabilities underground. The ability to pass data and control information between operator and machine was critical to the success of automation of underground processes. Once established, mine-wide communications supported all underground activities from personnel-intensive tasks through miner-less mining and automated mining cells.

2.1.4 Personnel issues

The underground mining workplace is a hazardous environment. The basic hostility of the site can be reduced by many methods, however the risks cannot be totally eliminated. The risks to personnel are best described as time related; the greater the amount of time underground, the greater the likelihood of problems with injury, immediate and long-term health issues. Most of these risks have direct costs associated with them, and reduction of the underground time will decrease the impact to the mine.

The most significant cost that can be reduced with the removal of the miner from the mining area is the cost of maintaining the environment in a condition safe for workers. There is a lot of effort that needs

to be made to manufacture and maintain an underground opening. Such areas are often inherently unstable and require reinforcement and support to keep them from failing. There is a minimum amount of support that needs to be provided to maintain the stability of the opening, and over and above this, is the extra work necessary to eliminate hazards to the miners. These hazards consist of smaller rock falls, ventilation and rock stability issues that are significant to humans but not as significant to machines and equipment. To be in a position to reduce the additional infrastructure costs while maintaining production levels dramatically adjusts the profitability of the mining area.

Some of the issues that affect the number of miners underground are social issues. One issue that increases the desire for miner-less mining is the overall undesirability of the profession. It is infrequent that a miner indicates that he “likes” the job. Rather the words relate to the income from the position and premium available for the underground work. Miners never say “I’ve been working underground for 40 years and I hope that my children join me at the face”. Rather, the miners would hope that their children stay on surface and get the appropriate training to assist mining companies from a safe and healthy vantage point.

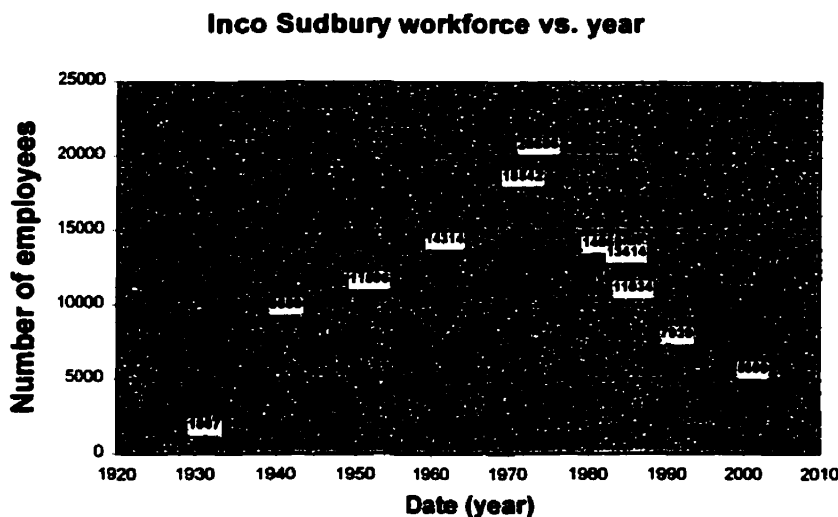


Figure 2: The growth and decline in Inco's Ontario Division workforce²

Another issue is the availability of suitable underground workers. Over the past decade the number of employees at the mine-site, assisted by increased productivity, has gradually decreased. This decrease is also prompted by the physical locations of the mining camps and the relative isolation of these locations. While the location of mine usually

creates a community in the immediate area, often the number of workers is insufficient to make up the “critical mass” necessary to sustain a community at that location. Examination of the areas of significant mining shows mining to be in areas that are remote and therefore less desirable, than the

locations of the large communities. Unfortunate location, and the inherent life cycle of mining related activities, usually reduces the likelihood that the community will grow and prosper without diversification.

A final point, that has recently emerged, is the impact of disease on some offshore mining communities. Mining is one of the last occupations where workers can expect to achieve a better than average income and life style, with a very modest educational and social requirement for the worker. Natural attrition and career mobility to supporting industries have reduced the impact of the changes in the Canadian mining industry. This is very different from developing nations such as South Africa, where the health, community organization and social infrastructure issues are not as well developed. In Canada we have attempted to increase the level of automation to allow the number of workers to gradually reduce. In developing nations, the skills are not available and the mining must proceed, emphasizing manual labour and appropriate technology. However, this is jeopardized by anticipated wide spread illness and death from diseases such as AIDS. "AIDS has now exceeded mine accidents as a hazard to miners" according to Gencor Ltd.'s chairman. "The affected population is now estimated at 2 million."³ Issues such as AIDS are likely to cripple the South African mining industry unless steps are taken to reduce the dependence on large amounts of unskilled labour and increase automation alternatives to keep the mining levels constant.

2.2 Worker health

Other issues that are significant to the miner underground are the long-term effects of operating in close association with the machines found at the face. These machines are often physically hostile to the miner, causing immediate and long-term physical discomfort and damage. The issues of noise, vibration, dust, emissions and humidity are hazards that are immediately evident. These are immediate hazards but also are potential sources of pain, discomfort and reduced quality of life that result from long-term exposure to the environment and machines.

2.2.1 LHDs and operator back problems

Back problems are common among LHD operators. The high shock and vibration environment is transferred to the operator through the poorly sprung seat. These shocks are magnified by the effort

that the operator expends to keep fairly upright while driving a machine that tilts and rolls as a result of the poor road conditions. These strains, combined with the cross-seated operator forced to continually twist neck and torso, add to the likelihood for back problems. The continual jostling is just part of the issue for the operator. Other issues also contribute to the back injuries such as accidents mounting and dismounting the LHDs. The large spacing, poor lighting and slippery hand and foot holds on the vehicle all contribute to create an accident-prone scenario.

LHD operators, "because of the bouncing, they are beginning to have trouble... (but) they put up with it because there is good money in the job. A guy that's run about three to four years on a scooptram probably has got a bad back, just by virtue of the bouncing and bashing he is getting from being on that machine.⁴" In spite of the potential for back problems, as the quote illustrates, there are still volunteers, and it is the long term issues including the compensation and disability issues that eventually cause the costs to shift to future liability issues. The issues of back-related injury are the most frequent injury that the LHD operator experiences.

2.2.2 Respiratory hazards and the LHD

Another source of problems for the underground workforce is the issue of the respiratory environment. In general it is impractical to totally remove all of the contaminants from the underground work place. Instead, it is more usual to attempt to increase the flushing air that is delivered to the work area. Quantification of these issues is sketchy at best; the tools to accurately analyze the environment are ill suited to widespread deployment underground. As early as the late 1970s, machine diesel emissions were suspected of being a problem. There were suspicions that ventilation conditions at the time of the LHD introduction were inadequate and chronic bronchitis, asthma and other breathing conditions might be anticipated in the future. Unfortunately it is hard to quantify the air requirements. The results of investigations, based on chest x-rays, was that "there has been no indication among our miners of a health problem resulting from the use of diesels underground"⁵. More current information indicates that "whole diesel exhaust can be regarded as a potential occupational carcinogen" and "occupational exposure to diesel exhaust is associated with an increased risk of lung cancer"⁶. Given the popularity and proliferation of the LHD, this issue is one that will require a solution, whether by removing the operator or eliminating the hazard by changing the power plant.

It is difficult to effectively monitor and model the airflow through most mines. The myriad of paths and variables make most of the efforts at measurement and control a poor science, with overcompensation attempted as a resolution to measurement inaccuracies. The result is an environment that is adjusted based on ventilation by horsepower in the area rather than specific measurements. Whereas the standards are now becoming available, (recommended an interim exposure level of 1.5 mg/m³ for respirable combustible dust (RCD)⁶) these limits are difficult to monitor and measure on a widespread basis underground. Further the studies indicate "LHD operators are generally exposed to the highest levels"⁶. Overall the choice is to reduce the number of man-hours at the face wherever possible. Automation will be key to success in this reduction.

2.2.3 Other operator health issues

The current LHD has not been manufactured to suit the operator; rather the significant features are driven by output related criteria. Evolution of the machine has been guided primarily to assist the machine with increasing output ability and not to be more amenable to the operator. Many of the listed machine problems are responsible for operator injury and body stress. These problems become magnified as the operator copes with poor lighting, machine heat and variable environmental conditions. Even with the use of cab structures on the LHD the reduction still leaves a lot to be desired for proper operator comfort. As the MAPAO report concludes, overall "the machines are still not man suited"⁷. The ability to avoid the operator being subjected to these stresses, through the application of automation techniques, will eventually create better long-term working conditions and career development for LHD operators.

2.3 Worker safety

As suggested in the Hatch report to Industry Canada, "although automation has the potential to improve the safety conditions of a mine, primarily by removing the equipment operators from potentially dangerous areas, the implementation of different procedures and equipment can create new and unanticipated hazards"⁸. As the level of automation increases then some of the tasks that previously were part of the operator's duties have been altered to be part of another's job.

Tasks such as fueling and lubrication are already known skills. However, the basic operation and rudimentary servicing previously fulfilled by the LHD operator are issues that often fall to untrained supervisors and nearby mine personnel. These are additional multi-tasking requirements added to the already stretched personnel. This definitely creates problems that will increase as automation intensifies, until such time as the supply of trained “underground technicians and technologists” matches the underground requirements.

Other issues, such as complacency, are problems that are starting to be evident. “Familiarity breeds contempt” appears to be the problem as workers take short-cuts and chances with automated machinery. In contrast with typical fixed automation installations, trackless vehicles are more hazardous since the length and speed of movements is much greater. It appears that the operators, in the event of complacency, may forget that the machines are controlled and actuated by man-made electronics, in an incredibly hostile environment. Failures in a seventy-ton machine that is able to move down the drift at speeds in excess of 25 Km/h is not as trivial as the “blue screen of death” on the home computer. Inexperience and trust that the machines will behave logically is probably going to be one of the biggest challenges to overcome in the future. This issue and similar will be addressed in sections 6.0 (Workplace issues) and 8.0 (Mining process changes) later in the thesis.

In summary, automation has the possibility to decrease the safety hazards to the LHD operator who is transferred to a remote site for control. There are, however, still hazards to the “generalist” underground worker who may be less trained in many tasks requiring action. It is these workers that will face the safety challenges and be exposed to new risks. These employees will need to achieve high safety awareness. It will be necessary to remove the current negative safety outlook of many of today's miners. As the Australian mining article Death by Mining states, “such a culture traditionally views risk taking and unsafe practices as proof of manhood and evidence of a person's courage”⁹.

2.4 Machine safety

In addition to the issues surrounding the operator, there are many benefits to the automation of the LHD in terms of the health and safety of the machine. Most of the issues that affect the safety of the machine involve the reduction of damage and inadvertent abuse to the machine from operator error and aggressiveness. Several of these issues may be controlled through the use of monitoring of the

machine's actions through use of an on-board computer to assess the operator's instructions and relax or reduce the efforts that are relayed to the hydraulic systems.

Another instance where automation can reduce repair costs is in the monitoring functions that may be implemented to watch over the operating parameters and observe for impending failures and system difficulties. Often these problems are accompanied by a signature that can be used to predict impending failures and therefore be in the position to either alert the operator or interfere with the operator's commands to safeguard the machine.

Other possibilities that are available as a result of the automation of the tramming process are the reduction of the damage that can occur as a result of drift wall impacts. Since the first of the automation efforts have been to remove some of the tedious tramming effort from the operator and rely on the machine for tramming guidance, the automation promises to be an aid to reducing the damage from tramming impacts. It is anticipated that the automation changes will provide significant savings to mining companies in terms of reduced machine damage and repairs.

3.0 HISTORY OF THE LHD

3.1 Introduction

The development of the modern LHD took underground hardrock mining from a single miner moving one shovel-full at a time, to 25 cubic meters per bucket-full. The evolution of the LHD with which we are familiar was shaped by many factors. This chapter outlines some of the factors that affected the features of the LHD. It will also identify how the evolution of this machine was tied to changes of mining methods. These ties are so interrelated that it is almost a "chicken and egg" situation as to which came first, the machine or the mining method changes. The LHD revolution was not just a larger stick; it was also a catalyst for methods change. As well, a brief review of some of the North American LHD manufacturers products, with a comparison of their products will accompany a photographic review of some of these early machines.

3.2 Background

This section focuses on the automation and application of LHDs in the underground bulk-mining environment. It is acknowledged that there were many parallel technologies explored as the LHD evolved. Two are significant in the manner that they supplemented the larger LHD in other mining operations.

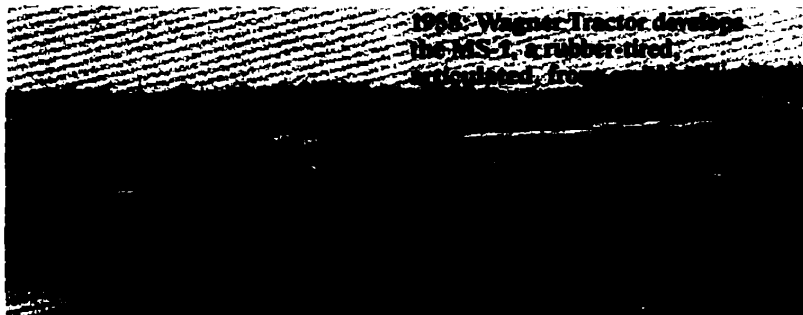


Figure 3: Wagner MS-1 front-end loader¹⁰

The use of the Front End Loader (FEL) is still a popular option in many mines; however, their application is usually in

applications that involve primarily loading and dumping. This differentiates the FEL application from the LHD because of the reduced haulage component. As well, neither the capacity nor the geometry of the FEL has specialized to the same manner as the LHD, especially in terms of the low machine profile and capacity and breakout force.



Figure 4: Tamrock Microscoop 100 LHD¹¹

Another important machine that has continued to change with time is the microscoop. This machine represents the other end of the haulage spectrum: a machine that is as small as possible while still able to carry significant loads. These machines have evolved to assist with the mining of materials that occur in narrow veins or where access requires unusual agility.

In both of the preceding cases the machines make a valuable contribution to the applicable mining environments. The basis of the following discussions has been limited to the use of LHDs in bulk mining processes and the larger mining zones, with a significant haulage requirement.

3.3 Motivation for the LHD

The modern LHD has allowed modifications of mining methods and the alteration of the mining cycle in all types of underground mining. The LHD has changed with time in response to pressures from the mining industry. Each of these pressures has affected different aspects of the machines evolution. Not just a progressively bigger shovel, the LHD has progressed from rudimentary air-powered sub-cubic-meter loaders to huge automated creations with 25 cubic-meter buckets. With these changes, a solution has been created for many mining issues. The ability also to mine using techniques previously impossible, is allowing the methods needed by modern bulk mining to evolve and stabilize. This section will deal with a few of the pressures of the mining industry, as an introduction to the evolution of the LHD.

3.3.1 Mining methods pressure

The initial need for the LHD was based on the mechanical advantage that such a machine offered over manual labour. As early as the late 1960's, the stresses on the mining community were already starting to be felt in terms of the availability and cost of the labour pool required for underground mining. Just prior to the introduction of the LHD, the mining community had optimized existing mining

methods. With the methods and equipment optimized, the changes required to increase mining productivity could only come from new equipment and methods.

The ability to increase productivity and safety underground required a change in equipment to be able to alter the productivity of the process. Prior to the LHD, the movement of the rock underground was primarily based on track haulage, assisted by cable-operated machines, such as slushers. The costs surrounding the infrastructure and development required to suit the relatively rudimentary mechanical assists were high. To be able to avoid these costs and reduce the quantity of development required the agility of a machine that could move materials larger distances with a reduced amount of development. The LHD, with its inherent agility, was immediately appreciated. Of particular note were the increased speed, greater traction and reliability available using rubber tires, as compared to crawler tracks or tracked vehicles.

The mining methods in vogue, at the time of the introduction of the first LHD, were blast hole, block caving and shrinkage stope methods. Table 1 compares some of the features of these methods and outlines some of their similarities.

Method	Drilling	Loading	Drawbacks	Features
Shrinkage stoping	Driller stands on broken ore, works upwards	Pull from underside of broken ore, similar to sub-level caving	Not suitable for rich pyrite/pyrrhotite ore: would have oxidization problems, drillers in hazardous area, requires continued drilling as part of process	First of methods that allow the direct loading of mine cars
Block caving	Not required except for initial development	Multiple finger raises	Rock must be suited to process, undercutting must give natural caving and fragmentation, hard to control cave reliably	Higher secondary fragmentation requirements, suited to large uniform orebodies
Blast hole	Depends on accurate initial holes and spacings to minimize oversize production	Loading from raises	Very sensitive to fragmentation,	Relatively constant loading positions

Table 1: Brief overview of mining methods prior to the LHD creation

The common feature across all of these methods was the ability to install simple infrastructure to allow mechanization of some portion of the ore movement. These methods all avoided the teams of shovellers and hand tramming that historically were part of the mining process by guiding the fragmented rock to a predicted location.

3.3.2 Labour cost pressure

With the rock "delivered" to a specific area, mechanical units assisted the interim movement from the drawpoint to the ore pass raise. Often these assists were relatively simple winches and cables that allowed the muck to be drawn or scraped to the chute.



Figure 5: Slusher in use at Creighton Mine³¹

The slusher, implemented in the mines starting in the 1930s, reduced the input labour from a shoveling crew of 3-5 men, to two men operating a slusher.⁴ The slusher operation was one in which the skill level of the miner would affect the amount and quality of the material moved. The skilled operator could move many more times more ore than the novice. Skill was a significant factor in this time of craft in the mines. These skills, and the requisite training required to maintain operators with specialized skills, were challenged by reductions in the underground workforce, required to keep mining costs down.

3.3.3 Infrastructure cost pressure

The labour savings as the slusher gained popularity were accompanied by reduced development costs as the number of ore passes was reduced, from as frequent as every 6 to 7 meters, to one to two per stope. The chute at the base of the ore passes was used to control and load the rail haulage on a level below the mining level. The loaded rail cars were then pulled by locomotive to the load-out point at the main ore pass or crusher.

While these techniques were efficient for the period, there were many disadvantages. The most significant was the amount of mine development required to create the multiple horizons in the ore zones. Each of the areas being mined required an access on the level. Since the drilling technology was not available for long accurate holes, the sub-levels were very close: sub-level separations of 10

meters were common, for example in sublevel caving. (Drilling capability was also a constraint to the increase of sub-level spacing. As drills evolved from percussive to rotary-percussive, the ability to drill increasingly longer holes became possible, at a reasonable cost, with acceptable deviation.¹²⁾

The small inter-level spacing was also accompanied by an increased number of ore chutes. Each slusher was set up to drag the ore to a chute that eventually loaded the rail tram, carrying the ore to the ore pass. The number of chutes was very costly since the installation and maintenance costs were very high. These chutes, in spite of their being placed in the ore of the mining area, were significantly more expensive to create and maintain than the production removal of the ore using LHDs to the ore passes. Overall the slusher / chute process, while increasing the output of the production miner, was still less efficient and less safe than the output subsequently using the LHD.

3.3.4 The rail system

The other part of the ore haulage system was usually a rail tram. The rail system, on a main haulage level below the active mining area, had several unique features that also increased the cost of the haulage. The most significant cost was that associated with the installation. The rail lines were time consuming to lay and required a straight and level drift. Once installed, rail trams worked fairly well, but quickly became a maintenance nightmare as the system aged. Acidic water, the stress on the lines by overloaded cars, careless operation and the lack of organized preventative maintenance all took their toll. These costs were multiplied by the fact that the rail trams often were installed for relatively brief periods in each mining area, before removal and re-installation in another mining area.

Several other issues are involved with the implementation of rail trams underground. Some of the more significant are summarized in table 2 below:

Feature	LHD	Rail tram
Tram use	Loads at stope then carries	Carries only, loaded by others
Process use	Development and production	Usually production only
Tram function	Usually standalone	Usually requires other interim loading techniques
Installation requirements	No infrastructure required	Usually requires air, electrical for chutes, signals, track controls
Installation duration	Suits frequent changes	Extensive installation, long term solution
Crew size	Single operator	Usually at least 2 in crew
Load-outs	Suits frequent load-out changes, primary ore mover	Typically loaded at chutes, significant installation efforts
Drift criteria	Agile, tight corners possible, can follow the ore boundaries	Must be straight track
Drift size	Larger than rail tram	Can use older drifts
Fuel requirements	Can go to centralized fuel bays	Must have fuel or battery charging on level
Drift drainage	Based on operator comfort	Required to maintain rail traction
Garages	Can use centralized facilities	Must have repairs on level
Ventilation features	Frequently in blind headings requiring ventilation	Seldom in areas without constant ventilation
Mechanical complexity	Engines similar to other vehicles	Many items unique to rail needs
Shaft transit	Very large, requires significant re-assembly time	Heavy but smaller size

Table 2: Comparison of the features of LHD and rail haulage systems

Another issue, similar to that experienced in the slusher mining process, was the difficulty associated with handling oversize rock. The appearance of oversize in the slusher trench or ore pass finger or chute could often stall the production until it was further fragmented by secondary blasting. The whole haulage process could be stalled by the arrival of oversize, with little means of speedy relief. This created an additional safety hazard associated with the further effort necessary to break or blast the offending oversize.

Beyond the maintenance and installation issues, the labour associated with the running of a rail system was large. In addition to the engineer and the chute operator(s), there were various support

and maintenance personnel. The number of employees to move the rock to the pass system was large and the implementation of LHDs in the process had the ability to eliminate many of these positions.

The reduction of the craft skills of the 1940's such as that associated with the slusher was beneficial to the mining industry. With the advent of the LHD the operator's skill required to achieve reasonable productivity was less significant. Even the miners themselves recognized "scooptram operators ... have much less control over the productivity of their machines. In fact, the greatest control they can exert is to keep the machine operating by preventing its breakdown."⁴ The machinery set the pace and the productivity of the worker / machine couple was usually affected only by failure avoidance. The higher the automation level, the less the operator could affect the productivity.

Fortuitously, there were three North American suppliers manufacturing equipment that could be adjusted and modified to suit the emerging technology. These companies, encouraged by the existence of several large mining customers, such as Inco and Falconbridge, were able to justify the designs and modifications to their equipment. As well, the pressures to cost reduce and increase safety provided the incentive to the mining companies to assist and sponsor changes to the equipment customized to their evolving process.

3.4 The early LHD

3.4.1 Precursors to the LHD

The development of the LHD was not accomplished in one step. In the process there were many other machines with features that were meshed into the final product. The experience of the other smaller machines provided valuable technical information as well as providing interim value to the mining companies.

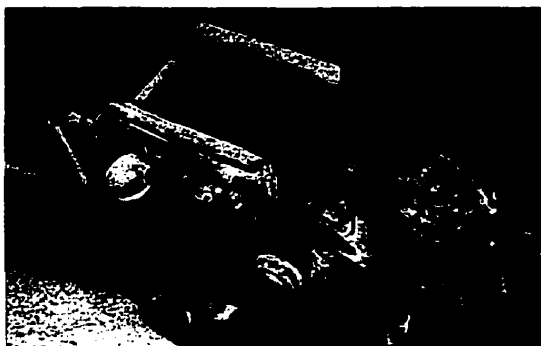


Figure 6: LM36 autoloader¹³



Figure 7: Cavo 310 loader, late 1960's¹⁴

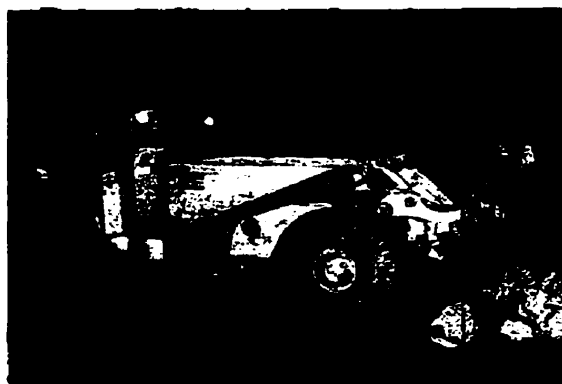


Figure 8: Cavo 710 diesel loader¹³

Figures 6-8 are pictures of a sampling of loaders that lead into the development of the LHD. Table 3 illustrates a selection of various machines that were part of this evolution as well as some of the significant features of each. It is interesting to note the dimensions of the drifts required to accommodate these machines.¹³ For comparison purposes some current machines are included.

Model	Bucket capacity cu. Yd. (Cu. m)	Body capacity cu. Yd. (Cu. m)	Drift height in. (m.)	Drift width in. (m.)	Comments power/style
Cavo 310	.16 (.13)	1.31 (1)	95 (2.42)	103 (2.62)	air, tires
Cavo D710	1.3 (1)	6.55 (5)	118 (3.0)	118 (3.0)	diesel, tires
Cavo 320	.39 (.3)	-	117 (2.97)	104 (2.64)	air, rail
Cavo 520	.77 (.6)	-	148 (3.75)	121 (3.07)	air, rail
LM36	.19 (.14)	-	85 (2.16)	68 (1.715)	air, rail
LM250	.78 (.6)	-	126 (3.2)	91 (2.29)	air, rail
ST-8B ¹⁵	8.5 (6.5)		101 (2.59)	109 (2.79)	current
Toro 450 ¹⁶	7.8 (6.0)		100 (2.54)	106 (2.7)	current

Table 3: Chart comparing equipment used for loading and hauling

3.4.2 The merits of the early LHD

The mining industry could take advantage of the larger capacity of the LHD as a process assist. In addition to the greater capacity of the LHD than the smaller mucking machines, the ability also existed

to move oversize out of the mining area to a location more suited to secondary fragmentation. As LHDs became available, there were several side issues that became evident. The LHD soon became a "jack-of-all-trades" in the mining process, while being a "master of none". The movement of materials underground, previously a very labour intensive task, was facilitated by the agility of this vehicle. Installation and repairs to the basic environment were also made easier since the machine could carry incoming materials into new headings and remove scrap from older areas. Installation and servicing of back-mounted fans, screening, piping and many other tasks were all simplified by the availability of the LHD.

These side tasks for the LHD made the miner's life easier. Mining requires several small tasks be accomplished as the process proceeds. The ability to quickly make these changes was immediately recognized. These abilities however, inadvertently reduced the yield of the LHD, since rock movement was no longer the sole job. With the availability of underground scoops these tasks were often vying for machine time. Frequently the rock movement slowed while installations in the area used the available LHD. Even more common were delays to the small tasks. No longer would a team arrive with ladders to do a task that might be accomplished easier using a nearby LHD. All of these issues diffused the application and reduced the apparent effectiveness of the LHD underground.

Overall the creation and use of the LHD was a progressive step in the mining cycle. In spite of the significant cost of the machine, its agility and general applicability to a multitude of underground tasks sped up all of the mines processes. Useful in development through production and backfill processes, the LHD was a quick and economical alternative to other methods. The convenience and ease with which secondary tasks could be accomplished, using a single operator rather than team of miners, easily made the LHD a cost effective solution to many mining tasks.

3.5 Mining changes

3.5.1 Mining changes facilitated by the LHD: personnel-free mining

Several mining goals encourage the use of LHDs in modern mining. As the LHD and the processes in which it is used evolved, the features associated with being able to remotely control these machines became evident. The first remote operations were lead by research, but this quickly changed with the

realization of the mining method changes that could be made if the operator were not present on the machine. Whereas this is one of the features that makes VRM methods possible, it is these miner-less approaches that makes some mines viable.

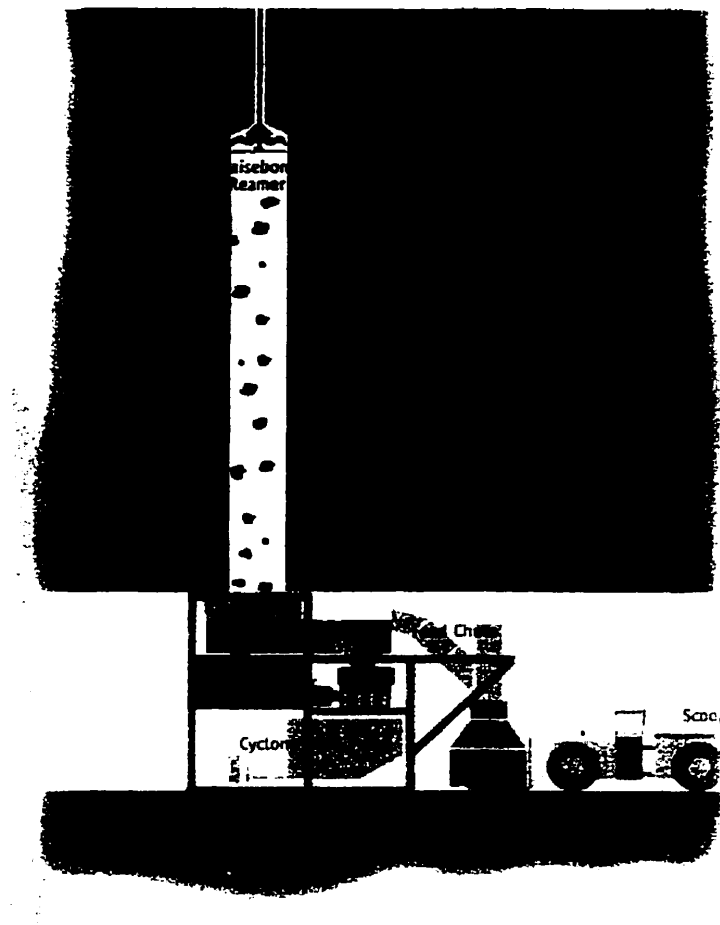


Figure 9: Raise mining at Cameco¹⁷

camera and can be operated manually, line-of-sight tele-remotely".¹⁷ The use of the LHD is just one of the essential technologies that made this mine possible.

3.5.2 Mining changes facilitated by the LHD: bulk mining

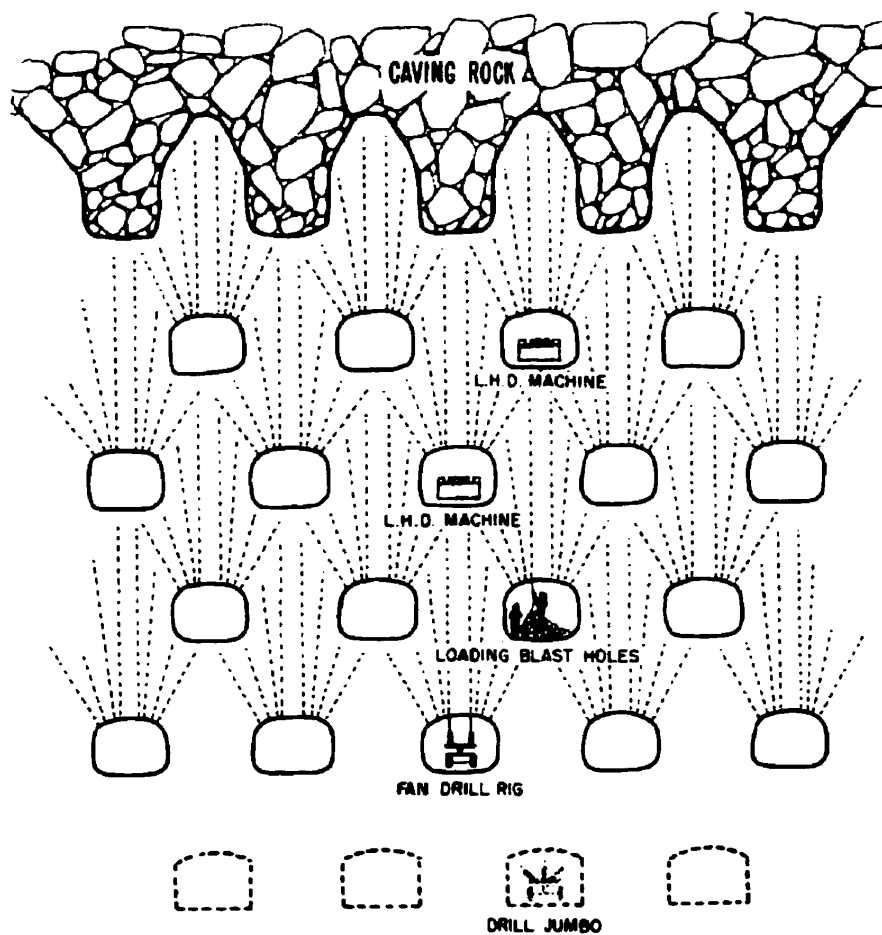
As the LHD became more popular, the mining methods of choice tended to focus on bulk-mining and mining mobility. Whereas the LHD could be used effectively in selective mining areas, bulk-mining methods obtained the best leverage from the relatively large capacity of the LHD. Failures of the bulk mining process, however, created many new and unusual difficulties. One example is poor

One example is Cameco's MacArthur River uranium mine. This mine is the third application that Cameco has made of a "non-entry system of mining" in Canada. Previous successes at Cigar Lake and Eagle Point have refined their mining process to the dependability necessary for MacArthur River. The high grade of this particular mine has challenged technology in many areas and the process has been developed based on radiation protection.¹⁷

"Personnel are kept safely separated from the ore by using remote controls and shielding ... the ore will be channeled into a Transportable Mining Unit ... the TMU will be transported by an LHD that is equipped with a

fragmentation of ore in the mining zones. While resulting from many diverse factors, the net effect is oversize rock requiring movement.

The previous haulage methods were very sensitive to the rock size. Slushers and other conveying methods were unable to manage or accommodate oversize in-situ. The appearance of a large oversize block in the slusher trench often stalled work in the area until the crew managed to manoeuvre the block into a suitable position for secondary cracking. This often significantly reduced the production from that area. After the implementation of the LHD, the oversize could be conveniently removed to another area, to be blasted by another crew. This meant the rock could continue to flow in spite of the oversize, without stalling the process. It also encouraged safety and efficiency, as the underground workers became specialists and more differentiated in their skills.



Drawing by Orest Andrew

Two mining methods that were made possible due to the abilities of the LHD were Sub-Level Cave (SLC) and Vertical Retreat Mining (VRM). Each of these methods depends on features of the LHD that were not available in the era of slusher and scrapers. Table 4 assesses some of the features of various methods and the hazards that are avoided with LHDs.

Figure 10:SLC method¹⁸

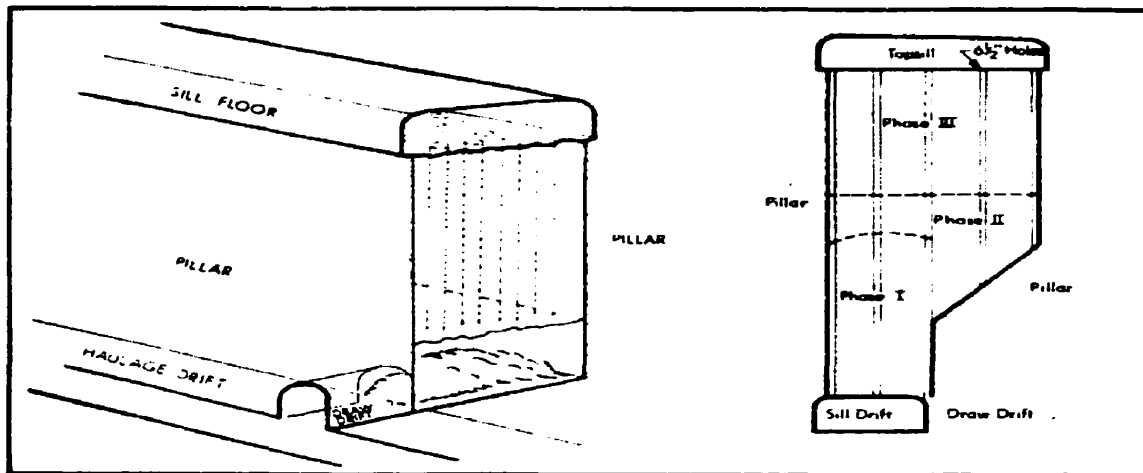


Figure 11:VRM method¹⁹

Method	Drilling	Load-out	Drawbacks	Features
Sublevel cave	From protected area, upward fans, from access drift below ore	Pull ore from access drift, retreat to foot wall drift as fans are mucked out, multiple headings via ramps encourage direct transport to pass	Sensitive to oversize, cave progress, costs may be high: up to 15% of ore removed in development crosscut installations	Allows multiple mining areas to be processed simultaneously, since drilled & blasted not as sensitive to natural cave progress
Vertical retreat mining	From protected area above stope	Pull ore from drawpoint, then stope entry, LHD frequently under unprotected ground	Depends on drilling accuracy for fragmentation, radio remote control is mandatory, Some ores may degrade if left in stope after blasting due to oxidization causing milling and hard digging.	Allows multiple mining headings, good, controllable process, little development
Uranium: raise mining	Raise machine in area of relative safety	Ore chips fall, are caught, transported in man-free zones; containers carried by LHDs	Not safe for miners in mining areas	Possible only using effective remote control techniques

Table 4: Comparison of newer mining methods

Analysis of table 4 reviews the reasons that the various bulk mining methods could develop based on the technology of the LHD.

In the case of Sub-level cave operations, the mining areas change very frequently and are usually blind headings. This made the typical slusher installation impossible since the far end where the pulley or engine would be located would be inaccessible after the first cut. And, in addition to the impediments to the use of the slusher, the agility of the LHD made it possible to pull from several drawpoints at the same time. This allowed both the cave to proceed smoothly and the opportunity to utilize another stope if the current location was blocked by oversize. In spite of the inefficiency, at least production could continue, and the equipment could continue to be used elsewhere while waiting for the secondary blasting crew to clear the offending oversize. A further benefit was that the LHD operator was able to remain in an area where the danger could be minimized through appropriate ground support.

The LHD was one of the prime enablers of the Vertical Retreat Mining (VRM) method. After fragmentation by the blasting process, slices of the back fall into the stope. The LHD starts in the drawpoint and clears the fragmented ore until the pile stops flowing into the drawpoint. (It is generally desirable to take the next cut prior to the brow opening to minimize the blast damage to the mining area and infrastructure nearby.) Once the final blast has been taken, the last stage of material removal is the pile that resides in the stope. This material is recovered using radio remote control of the LHD since the area is unsupported ground and therefore inaccessible to miners. This is a mining method that could not have been accomplished with pre-LHD techniques.

3.6 Remote control of the LHD

As the LHD gained popularity, the ability to move away from the tracks that defined rail trams and into areas newly developed, were strong assists to the mining process. As the experience and comfort with the LHD increased, and electronics implementation on underground machines became more pervasive, operator location began to change. Initially the LHD was under on-board operator control. This confined the machine to areas that were safe for the human operator. As remote control techniques became more popular on surface (crane, rail, factory automation etc.), the application to underground machinery accelerated. The LHD, previously on-board operator controlled, became a

target of remote control, and more amenable to use in areas that were unsuitable to the human operator.



Figure 12: Wired remote control of LHD circa 1978²⁰

Remote control allowed unsupported areas, areas of poor ventilation and other undesirable features, to become accessible earlier in the mining cycle. This allowed more options in mining sequence, as well as reduced or eliminated some of the non-productive efforts required for the onboard operator. Development could be accelerated and miner safety was increased. As more remote control became possible, also came the ability to send the machine further into areas unsafe for men.

Unsupported and unscreened areas, such as new headings, could now be mucked out prior to the evaluation and installation of screening and bolting, streamlining the development and mining processes.

With the experience gained from the use of remote control, several mining method changes were made possible. The development of the VRM mining method was totally dependent on the remote control of the LHD. Unsafe for on-board operators, the use of remote control allowed the operator to be located in a safe area and the hazard exposure to be confined to the mucking equipment only.

3.7 The Evolution of the LHD

3.7.1 LHD power sources

3.7.1.1 Compressed air power



Figure 13: Cavo 511 loader¹³

In spite of the wide spread use of diesel engines in the current underground mining industry, this was not the only power method used. The power source for the initial LHDs was based on the infrastructure that was in place in the mining areas. Frequently there was a source of compressed air that could be tapped for equipment power. This was ideal for some of the smaller overshot (rocker shovel) loaders, especially the units that were used in the loading of the rail cars directly since the source air was already available for use with the rail system. Figure 13 illustrates such

a loader.

As diesel engines became popular, the machine electric systems were very rudimentary. Initial machines often used compressed air to power the starter motor used to start the diesel engine. The mine compressed air system air was often used as a source of this energy. It is interesting to note that the use of air-power for starting many LHD models extended into recent times. This allowed the weight of the machine to be reduced, capitalized on energy widely available, while minimizing the complexity of the electrical system on-board. The downside of the use of air for starting is that the LHD must have an air line available in the event that the air accumulators become discharged through use or leakage. The LHD is then connected to the air system for starting purposes. This requirement is an added safety hazard, as well as difficult to accommodate during remote control use of LHDs.

Most current machines use electric start systems where the energy required is more appropriately stored in batteries, allowing a greater number of start cycles.

3.7.1.2 Electrical power

Electrical power was not as popular with the first LHDs. This was probably due to the low level of electric motor and power distribution underground. Prior to the wide spread use of electricity underground, mines used compressed air for supplementary fans, hoists and automation controls.

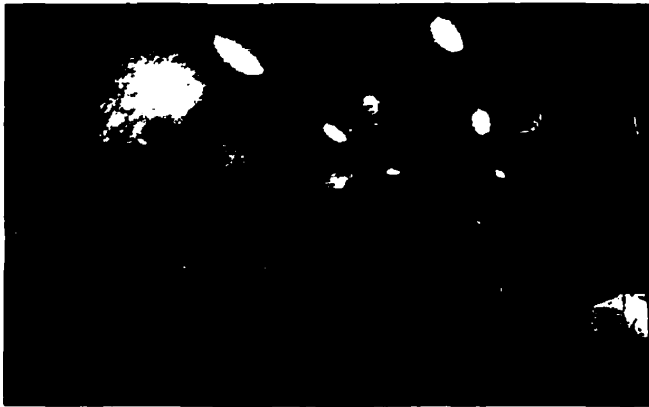


Figure 14: Tamrock 2500 electric LHD

As electricity use matured, the mining industry increased the number of electrically operated units. This allowed the electric LHD to become available and create its own niche of popularity. Electric units were suitable for implementation in areas of short repetitive trips where the same path was short and well enough defined to enable the use of the requisite umbilical cable and associated handling facilities. Such trips were frequently found, and a parallel

evolution of LHD power-plant using electric motors developed.

The use of electricity as a power source is very attractive. The reduction of emissions is frequently able to encourage their use in spite of the increased infrastructure and consumables costs. In addition to the physical constraints of the cable and reel, the cable tethered the machine into an area. This meant that one of the initial motivators of the LHD; the ability to move readily from area-to-area was hampered.

3.7.1.3 Battery power

As an alternative to either diesel or electrical power, the use of batteries was not popular. This was due to the immaturity of battery technology. Size and weight are both drawbacks to the use of secondary cells underground.



Figure 15: Battery powered UNA loader²¹

Since the primary use of LHDs is to lift and haul, over frequently inclined paths, the requirements for battery capacity would be great.

(However, battery use developed in the coal industry where the use

of diesels was more difficult, the loading effort is lower and the hauls tend to be level.)²¹ The UNA loader shown in figure 15 is an example of such a machine.

3.7.1.4 Air-cooled diesel engine evolution

One of the most significant issues regarding the underground use of diesel-powered machinery is the exhaust system emission. The introduction of the LHD underground was made possible by the evolution of diesel engines and the reduction of exhaust contaminants. This was primarily a result of research and development of on-surface air-cooled machines. By the mid 1960s, manufacturers of the diesel engines had created a power plant with reduced emissions. Using scrubbers and various other techniques, the amount of exhaust contamination could be reduced to the point that it was "reasonable" for use underground. However, diesel engines were still a major source of air borne contaminants and pollution. As diesel machines were proposed for underground use, the means of dealing with the diesel exhaust, and the remaining contaminants still needed to be addressed. Since the underground workplace is confined with respect to the airborne contaminants, the most obvious method to manage these exhaust problems depended on increased ventilation in the area.

Ventilation of the underground work place is primarily defined by the quantity of diesel engine exhaust. At the time that the diesels first made their appearance underground, tools to evaluate the effect of engine emissions were not available.

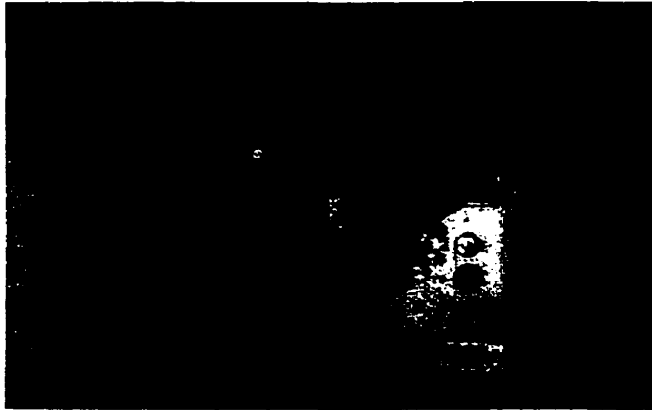


Figure 16: Air cooled, ST-8B at Stobie Mine

In spite of the lack of accurate measurement techniques, the industry developed rules and techniques that related the number of horsepower in an area to the flushing ventilation. Whereas this made the implementation of diesels underground possible, there was a drawback in the process since ventilation (and heating) were increased significantly, frequently becoming the largest of the common infrastructure costs.

3.7.1.5 Water cooled engines

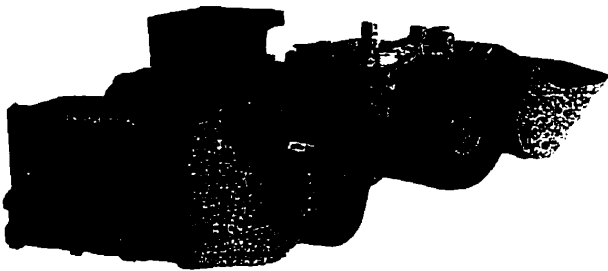


Figure 17: DDEC, Water cooled, Elphinstone R1600²²

The development of engines used by the surface industries continued at a faster pace than those destined for underground use. One of the main attributes that was refined was the reduction of emissions present in the exhaust. To accomplish this goal,

the engine was equipped with many sensors and actuators installed for the purposes of "fine-tuning" the variables of the engine. The accurate control of engine temperature, fuel, timing and air components creates a more efficient combustion cycle for the engine. Also, the system is able to adjust to accommodate wear of components as well as changing environmental conditions. This produces an emission contamination level that can be optimally controlled.

In addition to the emissions that may be better controlled, there are other attributes that are useful as more electronics and sensors proliferate on the engine. Many of the variables that are monitored are necessary for the emissions reductions. The support electronics for these sensors is quite sophisticated. Based on the existence of this support, the addition of a few more sensors is easily accomplished. These sensors are available to be used to monitor the engine for other operating

parameters and potential failures. Standard serial communications and protocols are available that allow the mechanic to verify the integrity of the engine operating parameters and its recent operating history.²³ With this data available, it is frequently possible to predict or anticipate failures and then identify the events that lead to the failure. This allows the engine to be shutdown or output reduced prior to its destruction, in many cases.

Another benefit of the electronics being installed on the current engines is that it allows the identification of problems to be made over a serial communications network on the engine. Standard protocols such as SAE J1587 and J1922 allow the engine to be a part of the overall LHD system. The open standard availability of the communications between power plant and system will also allow simpler remote control, and more ability to safeguard the engine, from distant control stations, while allowing accurate problem and failure analysis to be made.

For the reasons of better emissions and better ability to monitor the wear and operating parameters of the LHD engine, electronically-controlled water-cooled engines are becoming the standard power plant for LHDs in the underground mines. These intelligent engines, with their communications capabilities, will be more amenable to integration into the future "Digital Mine"²⁴ support system.

3.7.1.6 Evolving technologies: the fuel cell

The diesel engine and its associated emissions are a continuous problem for underground mines. Ventilation is mandated according to the horsepower rating of underground diesel engines. With the use of diesel fuel there is also a requirement for a distribution network for that fuel. Diesel fuel, although relatively benign, is still a hazardous material with precautions that must be observed to keep operators safe. The excess heat produced by the engines is also a problem. Current research is very active into alternate sources of energy that would avoid some of these risks and hazards. The fuel cell technology is a technology that shows promise in terms of its future use underground.

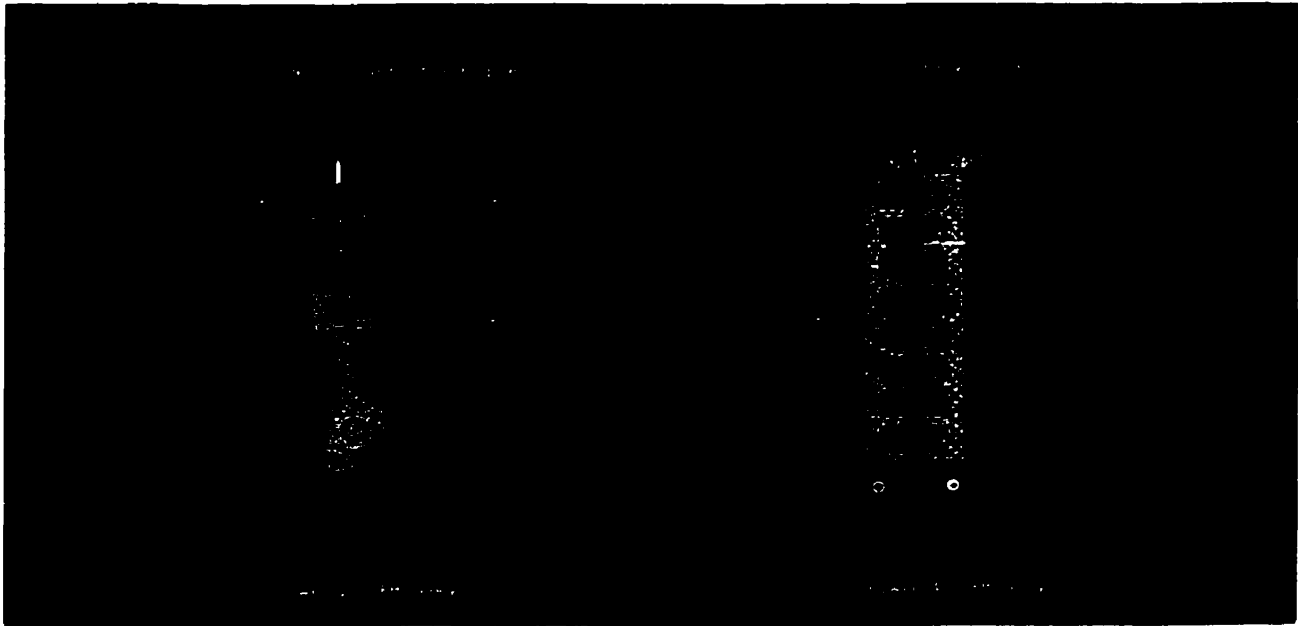


Figure 18: Comparison between fuel cells and internal combustion engine²⁵

Fuel cells have been used in many applications in the recent past. As this technology has evolved, the operating conditions and materials have been changing. The graphics in Figure 18 describe some of the significant features of the two technologies, revealing the merit of the fuel cell as a replacement for the internal combustion engine as a power source. Current technology, while expensive, appears to have some of the attributes that will make it amenable to underground use in terms of operating temperatures, fuels and materials. Although not ready for large-scale use in the mines, the first trials are being initiated now, and results in the near future will show whether this technology has matured to the point of suitability for underground LHDs.

3.8 Continuous loaders

One of the potential challenges to the increased use of LHDs underground was the development of the Continuous Mucking/Crushing/Conveying system (continuous loader). The continuous loader was designed to handle run-of-muck mining ore that included moderately large lumps, with in-line loading to maintain a continuous flow operation. Such a system would therefore be a likely candidate for automation and wide spread implementation.

Most mining methods are based on separate cycle components such as drill, blast, muck and support. Each of these components are unique in the manpower and equipment and do not readily support a continuous process. The continuous miner was proposed to integrate the mucking, crushing and conveying into a unit that could be located immediately at the drawpoint and output conditioned muck, ready to be conveyed to the surface.

During the 1985 – 1988 period Inco spent considerable efforts in the development and trials of a continuous mining machine. Inco's efforts included background research into previous equipment and technologies amenable for inclusion into a new continuous loader of their own manufacture. A summary of some of the significant efforts in the history of the continuous loader is shown in table 5:

1895	in-line manually loader conveyor	Minnesota Iron Mining
1897	moveable scraper ramp, pneumatic	Bunker, Hill & Sullivan
1908	mobile mechanical bucket, electric	Meyers - Whaley
1914	reciprocating Hoe feeder, pneumatic	Billings & Middlemiss
1917	orbital path gathering arms	Joy
1917	steam shovels converted to pneumatics & electric	various
1919	inline overhead bucket loader, pneumatic	Butler
1927	shaking pan / conveyor troughs	Jigger Digger
1931	in-line overhead bucket	Finlay & Royle
1940	in-line overhead bucket + belt or chain conveyor (rail or crawler), pneumatic or electric	Eimco 40
1950	in-line overhead bucket loader (crawler), diesel	Eimco 104
1952	front end bucket loader, diesel	Allis Chalmers HD9
1953	In-line overhead bucket loader (crawler), diesel	Eimco 105
1960	self-loading bucket/hopper pair, bottom discharge, rubber tired, diesel	Joy Transloader
1962	low profile front end loader, rubber tired, diesel or electric,	Wagner
1970	in-line digging, arm loader, (rail, crawler or rubber tired), pneumatic or electric	Hagglund

Table 5: Milestones in continuous loader evolution (prior to 1985)²⁶

The decision by Inco to develop a continuous loader was made in the early 1980s. The goals included 2000 tons per shift (approximately twice the 100 tons per hour available from a 6 cubic-meter class machine, with 80% availability).²⁷

The most important focus for the Inco designed continuous loader was the ability to integrate the ore removal, sizing and transport to moderate distances, in a continuous process. In addition, the machinery would need to handle all sizes of material that could be anticipated below a properly implemented bulk mining stope. The concept of larger and fewer stopes in "concentrated mining" grew in response to the apparent feasibility of continuous loading.

Initial tests included the CL-1000 Oscilloader at the head of the system. This portion of the system was capable in some cases of 500 tons per hour of muck moved.²⁷ After various successes with the installation of Oscilloaders the addition of an in-line portable crusher made by Eagle was successfully tested at the Copper Cliff Clarabelle Open Pit. The final portion of the system was the addition of an extensible and bendable conveyor system made by D.M. Enterprises of Saskatoon (D.M.E.). This complete system allowed the mining process to continuously load, crush and convey sized material into ore passes or bins up to 450 feet from the face in the tests at Copper Cliff South Mine.



Figure 19: Continuous loader in use at Copper Cliff South Mine²⁸

The results that were achieved at South Mine using the above array of equipment in a production environment were impressive. Using a two-man crew, the system moved an average of 185 tons per hour between September and November 1987.²⁹

This success confirmed that the system could work effectively in cases of well-fragmented rock.

The system worked well in the initial site but could be prone to failure in areas with oversize, with secondary fragmentation difficult to organize with the system in-situ. As with other new technology, the make or break of a process is dependent on the operator's acceptance and their desire to accommodate technology with change to their processes. Some inherent resistance to change at the mine may also have been responsible for the decision not to re-implement this technology after completion of the demonstration stopes mucked at South Mine. In addition, other technical difficulties with the deviation of the long blast holes and

unanticipated backfill related issues also assisted with the decision to discontinue the continuous loader tests.

Another reason for the lack of support for continuous mining systems at Inco was likely based on the capital cost of the system. In spite of the speed with which the system was able to move rock, the overall price in the \$3M range challenged the implementation of these machines in the majority of mines. The apparent failure to get a champion for the technology and high initial cost stopped further implementations at Inco. It is anticipated that other hard rock mines would face similar challenges. (These responses are in spite of the strong successes and experiences of other mining groups such as coal and potash companies.) "The current cost alone is prohibitive for many smaller mines" and "if a mine has only one continuous miner and something happens to that machine, production could be disrupted significantly until the problem is corrected."³⁰

3.9 The proliferation of the LHD



Figure 20: First ST-4 in use at Frood Mine³¹

"The first diesel-power machine used in underground mining operations at Inco was a 145 hp Scooptram. This load-haul-dump unit was put in service in March 1966 in a block of cut-and-fill stopes at Frood Mine."³¹ Table 6 illustrates how the growth of underground horsepower at Inco's Ontario division changed from the initial use of the LHD to the mid 1970s when the changes in mining methods stabilized. Over a period of less than a

decade, the number of machines using diesel underground has grown significantly.

Date	# diesel LHDs
March 1966	1 ⁵
August 1968	50 ³²
1969	98 ⁵
1972	192 ⁴
1977	314 ³³
1994	341 ³⁴

Table 6 and figure 21 demonstrate the acceptance that the LHD has enjoyed since its introduction. The growth in the number of machines accompanied a reduction of underground personnel allowing the tons per man-shift to increase steadily over the period.

Table 6: Number of LHDs in use in underground mining at Inco's Ontario division

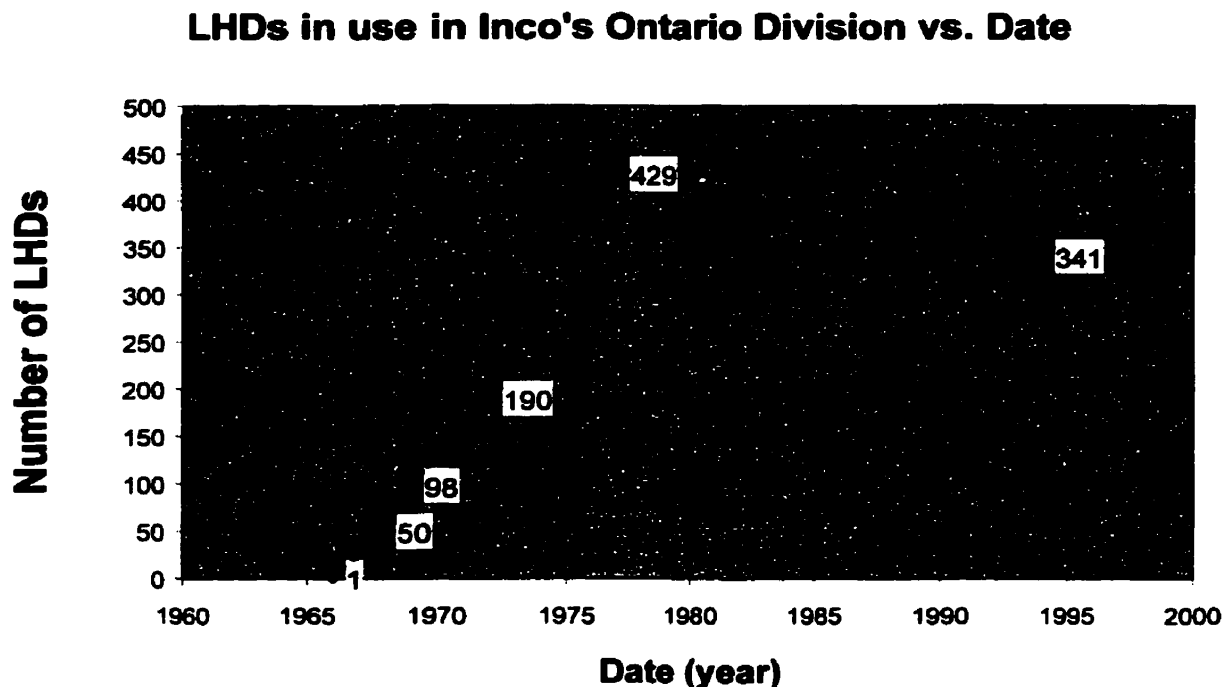


Figure 21: Graph of number of LHDs vs. time in Inco's Ontario Division

Figure 22 outlines the horsepower and capacity distribution of the diesel powered units in use underground by Inco's Ontario Division in 1972 and 1994. The number of machines increased steadily, peaking in the late 1970's. The gradual reduction that can be observed to the 1990's was the result of several factors including:

- The reliability and reliance on the LHD in the mining process increased during this period.
- The mining methods in use included more bulk mining techniques, with higher productivity stopes. This reduced the number of work sites required, and therefore reducing the number of LHDs used in the process.
- The end of life closure of several mines reduced the number of mines in the region.

Size distribution of underground diesel vehicles at Inco Sudbury mines

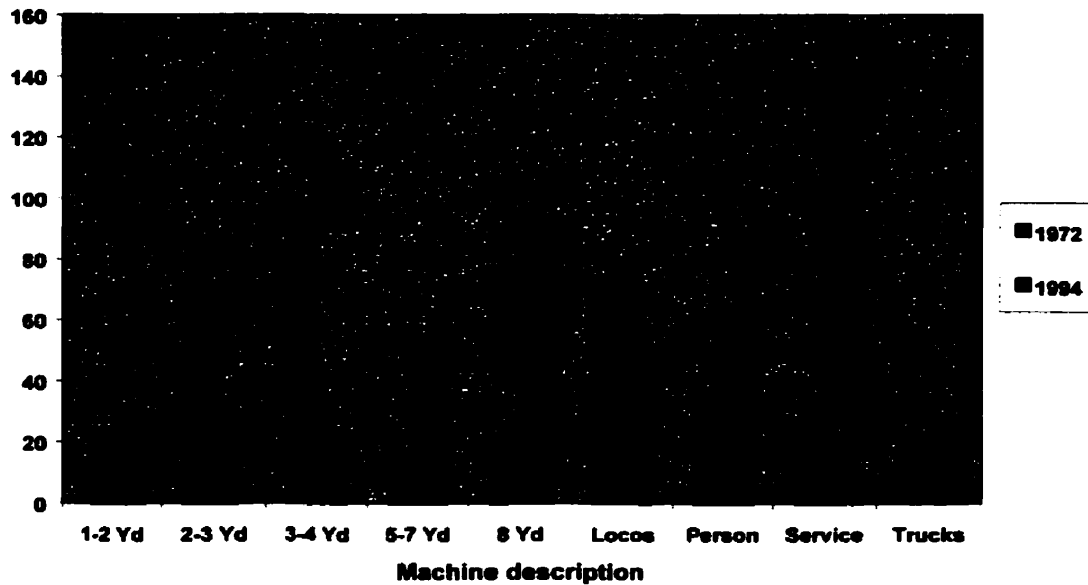


Figure 22: Diesel machine usage underground in 1972⁵ vs. 1994³⁴

Several issues are evident when this comparison is made:

- The number of LHDs in both years is approximately the same (192 vs. 194)
- The acceleration of the number of diesel operated vehicles continued into recent history.
- The number of mid-sized units dropped significantly during the period. This would imply that some specialization of LHD use has taken place. The needs therefore have been refined to a process that utilizes either the large or smaller machine size. This would support the view that mining methods have changed, causing a change in machine size distribution.
- It can also be extrapolated that the increased number of larger machines illustrates the emphasis on larger carrying capacity requirements, reflective of the increased dependence on bulk mining methods and economies of scale.

3.10 The LHD of the 1990s

The current LHD has evolved to become the workhorse of the underground materials handling system. It is used in all aspects of underground mining from the initial development processes such as drift driving, removal of both ore and waste in the mining process, through the installation of the backfill and scrap removal. In spite of the specialization of the capabilities of the LHD it has continued to retain its uses as a versatile haulage “jack of all trades”.

As the LHD has evolved, several tasks have been removed from the operator’s direct control and have been automated on the machine. Currently, even the most basic machines have interlocks that stop the machine in case of hydraulic fluid loss, engine oil loss or excessive engine temperature. These changes are essential since the operator’s attention to the instrument panel is often difficult and infrequent.

Power plant monitoring techniques have started to be formalized in the standard engine control packages that are supplied with current engines. Manufacturers such as Detroit Diesel have started to supply packages such as the DDEC (Detroit Diesel Engine Control) that implement a control system for the machine power plant and keep it operating within a safe operating area. With packages like the DDEC the engine output is de-rated if there are problems with cooling, fluid levels and other critical operating parameters.

Technology has increased the capacity as well as the longevity of the machines that are used in hardrock mines. These changes, however, have been at the expense of the simplicity of the initial machine. Rather than the simple diesel engine and most basic electrical system dedicated to engine controls and lighting, the newer machines have added complexity. These systems supplement the operator’s onboard senses and protect against inadvertent damage. The resulting machine has the rudiments of self-monitoring, used to safeguard the machine from the more major faults such as fire, brake failures and fluid losses.

With the need to support technology on the machines, several key issues have arisen as follows:

- Are the technologists & engineers available to design the machines?
- Is the industry contributing the effort to transform the integration of the technology and the machines into a total system?

- Do the mines have the staff and training to maintain such systems?
- Are the issues of the engine and host rock as sources of heat being recognized and addressed in the areas of automation?
- Have the fire suppression systems been enhanced to protect against unsupervised onboard fires, and does the automation system respond appropriately in response to the activation of these systems?
- Do the ergonomics of the machine suit the needs of the onboard operator, or the remote operator, and, is there a reason to differentiate between their needs? Have the onboard operator's visibility or comfort on an automated machine been compromised by the remote-required equipment too badly to be suitable?
- Are the necessary standards being developed and maintained to optimize the interoperability and cross-communications between machine controls, supervisory, automation and production systems?

The preceding issues are examples of questions that require examination and evaluation prior to the installation and acceptance of technology, especially in the underground environment. The resulting answers and discussions will provide insights into how well the implemented systems can be expected to perform.

3.10.1 Modifications defined by automation

Several modifications have been attempted to create LHD machines that are more amenable to teleoperation and full automation. These changes increase the amount of time that the machine is able to operate without direct supervision. Some of these are dictated by machine health issues, such as disabling the machine in the event of excessive temperature, fluid loss etc. Other issues are concerned with keeping the machine operating effectively and productively.

Table 7 outlines some of the automation assists that have been discussed and in some cases implemented.

System	Modification	Reason required
Supplementary lighting	Better lighting to front and rear to accommodate the use of video cameras for the off-board operator	Poor lighting conditions are stressful to tele-operators, shadows can be helpful if appropriately applied
Audio feedback	To allow the operator to "listen" to the engine and hydraulics on the machine	Real time information of the engine sounds are easier to assimilate if provided as audio cues, engine loading is easily monitored by audio cues
Fire suppression	Detonates fire suppression system if specific strategic areas suffer damage or excessive heat.	Fundamental requirement for a machine that will not be under operator observation continuously.
Auto lube system	Provide lubrication to all required locations on a continuous as-needed basis	Previous systems depended on short shifts to schedule lubrication opportunities.
Operator cab removal	Elimination or reduction of the cab for the operator.	To take advantage of the area formerly used by the operator for other uses
Machine battery contactor installation	Installation of a power contactor in the battery circuit to allow the machine to be "disabled" by remote control.	Allows the machine to be put into a safe mode wherein the battery consumption and hazards are minimized.
Fuel system augmentation	Addition of supplementary fuel tanks and support	Allows the machine to remain in production longer than the standard shift cycle. Needed in the case that the machine is in automated production on a continuous 8 hours available per 8 hour shift
Monitoring systems	Addition of equipment and techniques to collect and monitor operating and production data	To assist with the identification and prediction of faults based on measured parameters on-board

Table 7: Machine modifications to accommodate automation

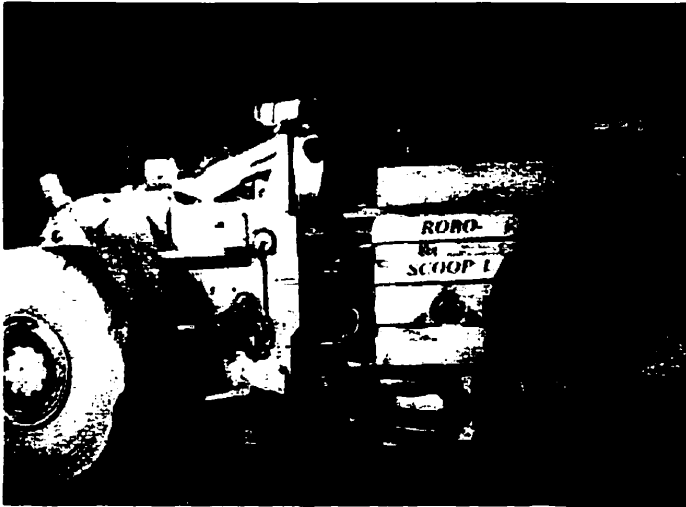


Figure 23: LHD16 after modification replacing operator's cab with extra fuel capacity

The application of these automation assists has met with varied successes. One interesting case was the removal of the operator controls in their entirety from a Wagner ST8-B LHD at the Stobie mine in 1995. In place of the operator's compartment a supplementary fuel tank was added. This additional fuel supply meant that the LHD would have the necessary fuel for double the operating hours. This experiment was successful in allowing longer time between fuel stops

and "showing the mine" an example of future changes likely to machines. As a solution to future automation needs, however, the test was not fully successful. The reduction of fuel truck visits was not possible since the fuel truck operator was also the person that performed some of the lubrication to areas of the machine that were not auto-lubricated. Another difficulty was that the machine became distinctly difficult to manoeuvre underground since the movements had to be accomplished using line of sight radio remote control methods. This necessitated the operator be in a jeep behind the LHD and another LHD in front (in case of runaway) whenever the machine was trammed down ramp to the garage facilities, requiring 2 additional operators and 2 additional pieces of equipment to make minor movements. This interesting group of events was not predictable at the outset of the experiment.

3.10.2 A Vision of the future machine

The future LHDs will likely be manufactured as an "automation-ready machine" ready to be customized for the specific needs at the customer's mine. The base machine will contain a comprehensive set of sensors and reporting systems that will monitor the safety of the machine as well as report production data, tools that will be useful in all modes of operation. These features will be implemented by significant revisions to the wiring and hydraulics systems suited to the simplification and integration of fundamental automation techniques.

Primarily focused towards remote operation applications (increased safety and productivity), the future machine will be better equipped for determining predictive failure analysis and productivity optimization. These results will be more accurate since they will be based on the true history of the machines work, rather than time intervals and paper reports. The end result will be LHDs that will be more reliable and available for use in both remote and manual operation.

4.0 COMMUNICATIONS: AN ENABLER OF AUTOMATION

4.1 Communication Issues

Underground mines are at a communications disadvantage compared to surface manufacturing plants. On surface it is relatively straightforward to link areas for automation purposes since there are few physical barriers. On the contrary, underground all connections require specific installation excavation or the use of existing drifts and holes. In addition, surface plants have the further ability to take advantage of the radio permeability of the construction materials. This is contrasted with the radio energy shielding properties of the host rock in the underground hardrock mining work places.

Whereas mines and surface factories have similar processes, it is more difficult to link portions of the underground plant together in the same manner that the surface industries enjoy. The communications links are the enabler of automation on surface. The equivalent ability is required to enable underground mining automation.

4.1.1 Communication systems status

Various communications systems were in use at the time Inco launched its automation efforts, installed mainly on an "ad hoc" basis, with little regard to future automation needs. These systems were oriented towards providing voice communications to the underground areas, supplementing the telephone systems that were also installed. Initiatives were focused on increasing the availability and effectiveness of the underground workers and their supervision. The capacity of installed voice systems evolved with time, from single channel systems (circa 1985), to more modern offerings providing in excess of 8 channels (circa 1994). As well as voice communications, the initial glimpses of the requirements for data underground were first evident in the commercial marketplace by 1988. This was the status of communications at the point that Inco approached industry for support to research communications systems to enable underground automation (Baiden and Scoble, 1991)³⁵.

4.1.2 Communications requirements

Understanding the need for rugged, reliable and affordable communications to allow automation efforts to be deployed underground, Inco outlined a plan for the ideal communications network. This network

would remove the physical constraints of location, and allow the communications to be as effective for underground areas as for surface operations. Factories were wired with the anticipation that a single-cable backbone services all network needs. Mines were wired based on a wire per service. Prior to Baiden's initiative at Inco, additions to information transfer frequently required sizeable additions to the wiring infrastructure. The desire was to reduce these cables to a consolidated single cable based system and makes the changes to the system as simple as "plugging in a television". In addition to the single cable aspects of the system, additional criteria that suppliers were given for solutions to Inco's needs were:

- create systems so all locations on the backbone would be equal in terms of information and bandwidth available
- use industry standard protocols, techniques and software systems wherever economically possible
- utilize components and support systems created for surface factory applications to take advantage of the higher commercial manufacturing volumes
- administer the users of the system in a cellular fashion such that the backbone bandwidth is re-allocated in an agile manner between users, reducing the effect of fixed allocations
- organize the use of the radio environment so as to be able to reuse radio channels in non-adjacent areas, in order to be able to optimize the radio spectrum usage
- create the concept of evaluation of costs based on cost per bandwidth availability.

4.1.3 The AMS solution

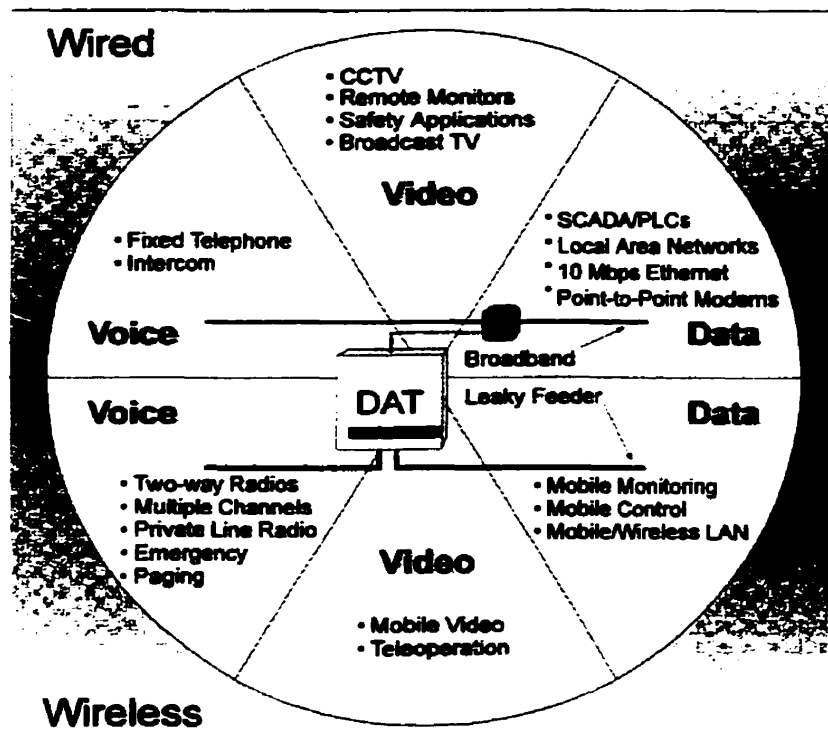


Figure 24: Graphic depicting services available using DAT architecture³⁶

The AMS system (Automated Mining Systems Inc.), developed to meet Inco's needs, is based on a broadband communications plant being used as the backbone of the communications installation. The initial installations used a broadband cable system similar to cable television installations on surface. This was chosen for its cost-effectiveness, robustness and ease of installation in the underground environment. In the case of Inco Sudbury Division

installations, the main trunk cable servicing the mine runs down the shaft and is accessed at all of the active levels. From these access points further distribution of the signals to the various mining zones is accomplished by cabling along the drifts and through a network of boreholes. Once commissioned, the broadband distribution system is available for both fixed and mobile equipment communications purposes. Figure 24 illustrates graphically some of the applications that typically use the mine-wide communications system. In Inco's Sudbury mines wired (non-mobile) applications include:

- PLC / PLC communications (ModBus, ModBus Plus over broadband modems)
- PLC communications to automation effectors (point-to-point RS232 communications @ 1,200 to 9,600 baud)
- PLC communications to automation effectors (simple control systems)
- surveillance video applications

- point-to-point telephone communications over the broadband
- computer LANs including Ethernet
- communications to the DATs (see later) located for purposes of voice radio communications via the radio system
- communications to the DATs, for operator's console to mobile machine communications via the radio system.

4.1.3.1 Media

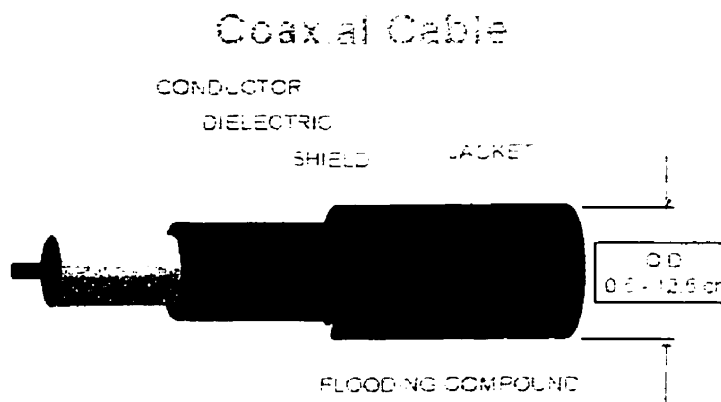


Figure 25: Physical description of coaxial wire³⁷

Basing current systems on coaxial media based cable plant is advantageous because connections, repairs and changes can be made in the field by the mining and electrical departments with standard tools and skills. (It is anticipated that the glass fiber industry will evolve techniques offering a similar ease of termination and splitting capability, in order to allow the full services to become available along a fiber

in the same manner as a coaxial cable. At that point the cost effectiveness of the media interface

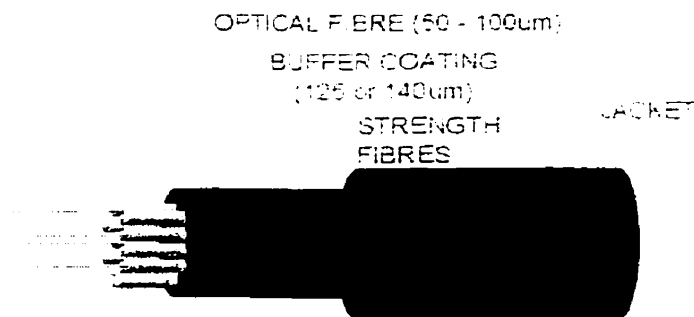


Figure 26: Physical description of fiber optic cable³⁷

connections will determine which media is chosen.) A second reason the coax cable-based system was chosen over optical cabling was to avoid the termination difficulties and fragility associated with fiber optics, especially in mining zones. Where cables are installed in the underground areas, they are sheltered wherever possible from the actual mining

activities in order to avoid damage. A coaxial-based cable system when impacted or crushed will usually continue to function, all-be-it at a deteriorated level, unless the cable is completely severed. By contrast, impacts, in the case of fiber, will often sever the fibers and result in cancellation of the carried services. Figures 25 and 26 demonstrate the physical characteristics of both cable types.

The large bandwidth of the installed broadband system provides a path for in excess of 30 video channels in each direction, towards and away from, the surface head-end equipment. Several of these video channels are used for other purposes, by virtue of the ability to utilize sub-channels in a given 6 Mhz video channel. RS232 communications (60 full-duplex, 9600 baud links), ModBus Plus Networks (1 network per channel) and telephone modems (more than 100 per channel) are examples of alternate uses found in video channels at Inco's mines.

Another significant technical reason why the coaxial-based system was chosen was to take advantage of the wide-band nature of the media. The system is designed to allow the full complement of signals and information to be available at all locations. This technique makes the concept of mobility of applications trivial. Since all taps are equal, the new location needs only the availability of a broadband tap to complete the installation of the equipment. Movement of equipment becomes as trivial as moving a television on surface. The coax-based broadband system makes the connection of fixed applications simple. Also, due to the fundamental equality of signals over the plant, it allows relocation and setup of equipment easily in various areas, without changing the basic communications network.

4.1.3.2 The DAT (Distributed Antenna Translator)

The DAT is a bi-directional interface system that modifies signals located on a broadband system and presents them for radio distribution, and it receives signals from the radio system and modifies them for connection to a broadband system. The DAT is the innovation that is fundamental to the Inco/AMS system. These radio signals are then re-distributed using attached antenna system(s), usually consisting of slotted coaxial cable antennas.

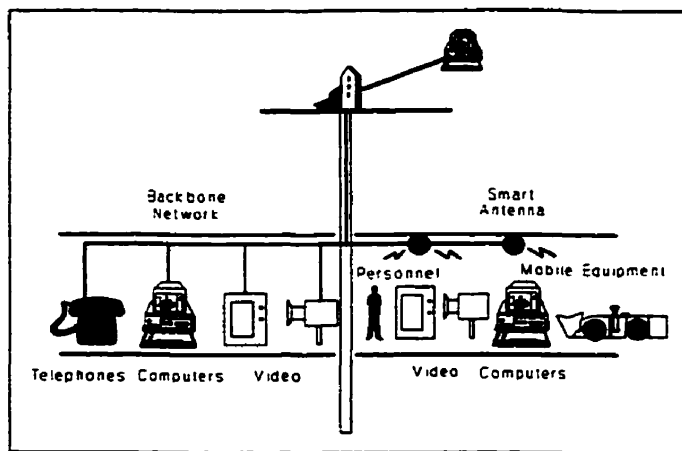


Figure 27: Integrated mine-wide communications³⁸

The broadband coax backbone is integrated with the underground radio network, using DAT technology, into a reliable utility suitable for current and future underground automation needs (Hackwood and Poole, 1994³⁹). A DAT is installed wherever the need to pass the signals to the radio environment is required. Since mining zones are usually physically challenging to electronics and communications equipment, it was desirable that the DAT be capable of

being located in areas of relative safety. The net result is a DAT located at the center of a star of communications antenna segments. This allows the electronics to be located in areas of relative physical safety. Each DAT is the hub for a star of up to 4 antenna segments, each up to 2000 feet long. Directional couplers are used to attach supplementary branches for covering intersecting crosscuts and specific areas of interest. The resulting coverage is a customized communications cell, with the appropriate communications abilities matching the needs of the users in that area.

The distance covered by a given antenna segment is governed by the capability of the cable and the bandwidth of the signals to be transmitted. Most of the Sudbury installations have used 7/8-inch diameter "Radiax" cable. The use of this cable has been justified in this application based on the superiority and uniformity of propagation and low loss per unit length. This is a premium quality cable and lesser quality cables have been used where the needs of the area are well defined and future expansion is not likely.

When designing the mine communications topology, the DATs are placed in such a way that each DAT is at the center of a mining zone. This is ideal, since it allows wide-band signals such as video sources to be effectively carried back to the DAT over distances of up to 2000 feet. In the event that there are areas that require services of lesser bandwidth, the length of the cable from the DAT is increased significantly, to the extent that the 7/8" Radiax cable can provide useable voice-radio

coverage to up to 4000 feet from the DAT. With the DAT at the center of the mining zone it is able to service voice needs for a significant area of the mine around the mining zone.

4.2 Communications standards

Fundamental to the underground communications architecture is the desire for adherence to world standards. It is logical to observe, therefore, that the underground needs should follow the surface standards wherever possible. In the case of underground communications, the use of standards simplifies the implementation underground of the solutions from surface communications and computer vendors.

Standards make connections easier and more reliable. The market for underground communications services is small in comparison to that of the surface automation arena. The ease with which one can import tools, products and applications is increased if the interfaces are made in a well-defined manner. As an example, it is only the standards associated with the North American phone and power grids that make appliance and phone installations trivial. Similarly, other countries such as Britain have standards within their respective countries that ease installations. The two groups of standards are different, but they are both formalized and recognized standards, with the result that the interface between both are available products.

The use of standards assured that the interface between underground devices and between underground and surface is as logical and straightforward as possible. Whenever standards are used, the reliability and robustness of the system is improved. The behavior of the component parts may be well defined, and a design based on standards based interfaces for the interaction between parts ensures a predictable and uniform system performance.

Examples of some of the popular standards and protocols used at Inco in underground systems are as follows:

- RS232, RS422, RS485, ModBus are all part of a family of serial communications standards that define the connections and protocols associated with the transmission of data along a serial path.
- Bus protocols are similarly standardized as families, such as Fieldbus, ProfiBus, DeviceNet, CANbus etc.

- LAN protocols such as Ethernet (IEEE 802.3), broadband systems (IEEE 802.7), wireless Ethernet (IEEE 802.11)

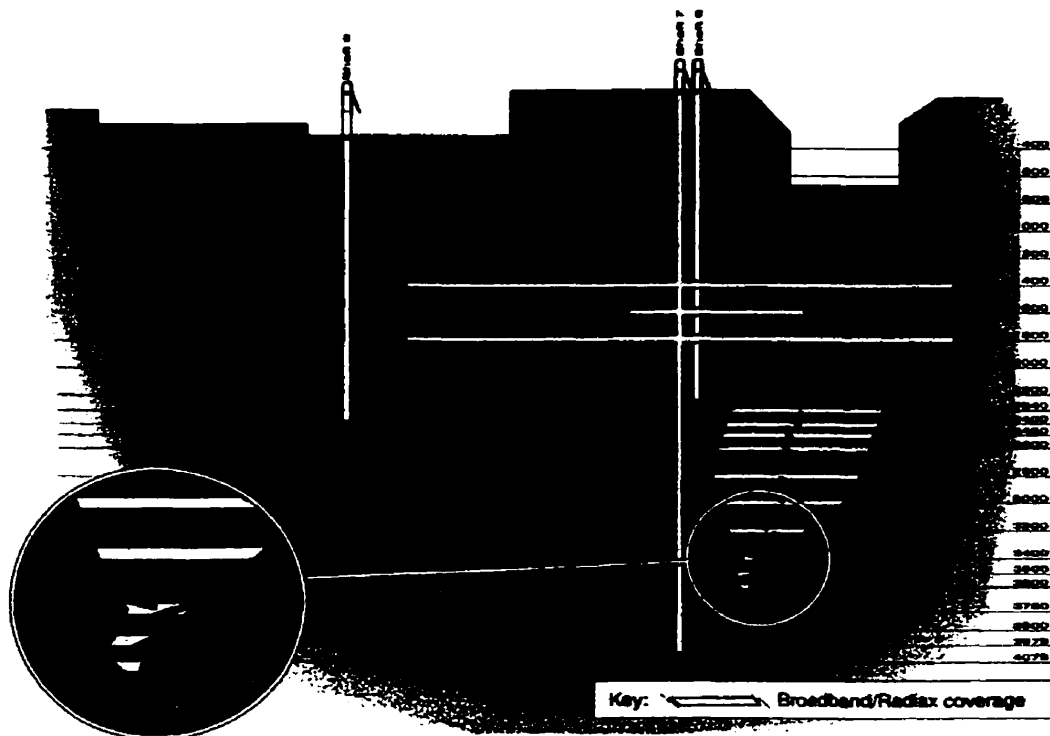
The DAT based architecture made use of standards-based equipment to provide mine-wide communications.

4.3 Communications based accessories: Stobie Mine Examples

The communications network installed at Stobie also encompasses a mine-wide radio communications infrastructure. The eight DATs installed cover the bulk of the current mining drifts with handheld voice radio coverage. More than 20% of these covered areas are currently available for machine operation and full video coverage. This coverage has been designed to guarantee all of the automation related communication needs for the mining zones in which the surface operated LHDs are deployed. It is also within these zones that the LHDs are able to be re-positioned with minimal attention to infrastructure changes, an important mining systems design issue.

Figure 28 (below) shows how the bulk of the current mining zones have communications available for automation purposes. The greatest radio coverage concentration was in the lower areas of the mine where the VRM mining method could take advantage of remote LHD operation. The other area with high concentration of communications was the SLC mining zone where the Data Solo drills were operating. Since Stobie mine is a very old mine, not all of the drifts were covered for communications purposes. Rather, the initial selections made by the mine were based on automation activities. The subsequent installations were based on more traditional radio communications to underground workers.

With this communications infrastructure in place it became a simple matter to implement automation wherever the communications support was available. Also, because of the number of sites and applications at the mine, sufficient volume of product was required to allow the sponsorship of several products specifically aimed at the mining industry, as the next couple of sections will outline.



Stobie Mine cross section showing broadband system and location of automated haulage project.

Figure 28: Stobie mine communications infrastructure⁴⁰

4.3.1 New techniques- AMS RoboSwitch

Implementation of underground automation requires the use of devices that are able to increase the speed and the distribution of the end effectors. Traditional techniques to control fans have been tried at many sites. These have included hard-wired connections, power line carrier control, as well as radio control techniques over the communications radio system. At Stobie, the vast majority of the fans are within view of the broadband cable. The power savings associated with controlling the smaller fans underground justified a capital project to install RoboSwitches at 50 auxiliary fan sites. This control scheme was designed to reduce ventilation at shift changes and off-times, and projected a payback within one year from the system installation. As a result of this product becoming commercially available, Stobie has been able to accelerate other aspects of their automation program. Based on this device costing under \$1,000, automation applications are able to conveniently actuate gates, lights, confirm safety guards are in place, and perform many other types of extended control. The only

communications requirement is a connection to the broadband system near the device to be controlled. With the majority of the main drifts covered, even the smallest of installations is now accessible for automation purposes, without geographical impediments.

4.3.2 New techniques- AMS ModBus Plus broadband modem

The majority of Sudbury Inco mines have standardized on Modicon as their vendor of choice for PLCs. The benefits of this decision are primarily associated with the savings on training electrical personnel and ease of PLC to PLC communications. At the time that the automation efforts were initiated, communications surrounding these controllers was usually done with either dedicated coaxial cables or much slower ModBus⁴² communications (9600 baud typically). As the use of these controllers became more widespread, replacing controllers of various vintages and manufacture, it became obvious that broadband interconnection would be desirable. This use of the utility would be preferable to the additional installation and maintenance costs associated with dedicated connection schemes. As a result of the expressed need, AMS developed the ModBus Plus⁴² (over) Broadband Modem. This allows users to set up PLC networks using the existing broadband, instead of separate infrastructure installation.

Both of the above are examples of the spawning of new products based on the needs of the underground workplace. Also, these are products that would not otherwise be developed for surface consumers where the implementation does not include the same physical barriers as in the underground mine.

4.3.3 Potential Stobie mine productivity benefits

The mine, according to the standard stringent capital rules, funded the installation of the communication system and automation equipment. These rules required that the future savings be quantified and results measurable prior to the initiation of the project. The benefits that would be accepted were constrained to analyses based on labour and equipment savings.

In addition to the accepted there were several other anticipated benefits. Some of these were economic and included the acceleration of the automated mining cycle based on the longer work shifts for the automated machines. Other benefits were as a result of the safety increases both for the

machines as well as the operators. The ability to reduce the number of underground staff-hours immediately translates positively to benefit the mines safety record. Based on the more predictable and repeatable machine cycle, a projected savings based on reduced rework and reduced damage to the machines was also anticipated.

4.3.3.1 Benefits- drill related⁴¹

An example of related savings is in the drilling required for the sub-level caving areas at Stobie mine. In terms of drilling, the future of Stobie was tied to being able to drill long production up-holes accurately. The requirement meant drilling at least 500 feet per man-shift with a deviation of less than 2%, with lengths that would allow the change to 100-foot sub-level spacing. If these targets were met, then Stobie would benefit in several ways. A significant savings would be from the reduction of development required. The original mining method at the start of the automation effort used sub-levels with a 70-foot spacing. The use of the teleoperated Data Solo 1000-sixty drills resulted in an increase in this spacing to 100 feet. The projected yearly savings from this reduction on development was anticipated to be in the order of \$1 million.

The second savings that Stobie would see as a result of the sub-level spacing change is a reduction of the number of setups and holes drilled. The drills, once set into a heading, require air, water and electrical hook-ups. Once set up, the difficulty of increasing the number of feet of hole length is minimal. The setup and the movement of these units between job sites far exceeds the modest time increase in time spent drilling in any particular stoping area. The change resulted in a 35% reduction in number of setups as well as number of holes, while providing the same total or overall footage of production hole.

Another significant, and hard to quantify saving, is the impact on the mining process of inaccurately drilled blast holes. Extra costs result from improperly fragmented ore. In the case of holes that wander too close to each other, the result is an over-fragmentation of the ore. This is wasteful of the explosives used in the process. On the other hand, when the holes deviate away from each other the result is poor fragmentation producing oversize. Secondary blasting of the oversize, in or adjacent to the stope, is required to reduce the fragment size to that suitable for the ore handling circuit, at a large cost penalty, prior to removing the ore. In the worst case, there is also a possibility that the oversize

may cause the caving process to stall or fail, probably compromising the ore recovery from that area. The introduction of automation increases the reliability and quality of the underground mining process. Based on these automation and mining changes, it was anticipated that there would be significant savings, encouraging the funding of these projects under the usual capital rules requiring logical business case analysis of the paybacks anticipated. These were not considered as research projects but as part of the active plans of the mine. The savings, based on reduced manpower requirements, were used successfully as justification for the capital required to automate the equipment.

4.3.3.2 Benefits- tramming related

Another goal was to evaluate increasing the utilization of LHD fleets. For example, the Stobie sub-level cave division fleet consisted of twelve Wagner ST8-B LHDs used for the extraction of the ore. Each of these machines was used in a manner typical of the at-face operator, usually 4-5 hours per shift. The goal was to provide the necessary changes to allow the machines to be used for almost the entire shift. This could be made possible by the operation from surface of teleoperated machines. ("Hot changes" are desirable to allow one operator to takeover from another. These are more easily done on surface than underground.) At Stobie, the mining zones are usually quite remote from the shaft. As a result, the travel and waiting time associated with getting to the work site are significant. Analysis of these delays projected very significant time savings if the mine could offer the operator access to the machine controls from the surface. This would allow the machine and operator utilization to increase, as a result of recovering up 2 to 3 hours per shift that would have been otherwise spent in transit. This was the primary reason that Stobie mine decided to implement the remote operation of part of their LHD fleet.

4.3.3.3 Benefits- power related

Stobie was the first mine to address the power savings associated with turning off unnecessary fans during shift changes and on weekends, using the installed broadband system. A large percentage of the fans at Stobie could be turned off, and the power saved, if there were a simple means of control. Based on the installation of 50 RoboSwitches, the mine could expect to realize enough power savings to allow the project to be sponsored by standard capital rules.

4.4 Synopsis of issues surrounding underground communications

The implementation of mine-wide communications systems in the underground work place allowed the mine the ability to take advantage of automation and safety techniques routinely available to the surface community. There are, however, many other unique attributes to the underground hardrock mines that need to be considered as these communications schemes get implemented. Some of the more significant issues surrounding underground communications are summarized in table 8.

Issue	Questions and comments
Coverage area:	Cover the whole mine, or just areas of automation? Is there sufficient capacity to meet the long-term goals of the automation zone?
Installation	Is it possible to locate the center of the communications cell in the center of the automation zone to reduce the cable and coverage lengths? Has the best cable routing been established to minimize losses? Can the electronics be installed in suitable areas to be secure from damage? Will the media installation suit long-term life? Should bore holes, even at higher cost be used to safeguard the cable Does the path take into account the long-term mining plans of the zone (will the access stay accessible)? Is the media suited to the environment?
RF energy:	Does the equipment generate RF energy? Are the systems installed susceptible to RF energy, and what are the impacts of extraneous energy in the environment?
System standards:	What standards will be met in the implementation process? Will the sub-system components interconnect easily and exchange data in a uniform format (bus types, data formats etc.)? Is there a need to meet international or non-mining communications standards (for example NTSC and PAL video standards)? Are the installations and components installed and tested to meet or exceed recognized performance? Does the documentation suit the service technician/technologist's needs and skills level?
Diagnostics:	Does the installation have the ability to diagnose faults or assist with the faultfinding process? Where the equipment is remote, does the system support diagnostics from surface, or by the experts at the manufacturer's factory?
Cost:	Automation communications is costly, have all users and applications shared the installed cost?

Table 8: Implementation: Issues regarding underground communication systems

5.0 MACHINE ISSUES

5.1 Communications latency

A simple definition of latency in this discussion is that it is the amount of time, after information is made available by a sender, before the information is usable by the receiver/user. The latency of the communications link is very important to the security of the system. Once the choice of media has been made, the method of encoding the data onto the media is next determined. In the case of wire-per-circuit control, the message is not delayed except for the time that the signal takes to get from one end of the cable to the other. In all cases except for parallel wire communications, the techniques are fundamentally serial in nature. In serial communications the data is usually spooled into modems, and then discharged along the path after the appropriate protocol encoding. The protocol defines how the information is contained in the data stream. The delay is based on the speed of the encoder and the basic travel velocities. With care, the latency is low if the modems are of suitable design and matched to the application. Simple serial, with low encoding delays, and wire-per-circuit connections are the most obvious candidates for real-time control situations.

In the case of spread-spectrum communications, a spread-spectrum message is chopped-up into a defined packet size and then the resultant data stream is transmitted a multiplicity of times. In this case, the signal has been buffered by the modem and the apparent transmission speed is limited by the time to transmit the multiple messages, as well as the time required to reassemble the detected message. The benefit of these techniques is the ability to compensate for an imperfect transmission medium. In the event that some of the sub-messages are garbled, other sub-messages fill-in with the missing data. The drawback of this is that the configuration of the protocol used needs to be carefully tuned to the application to get maximum throughput.

The potential worst case is where communications is on a non-prioritized Local Area Network (LAN). In this case the data may be successfully encoded and made available to the LAN in a timely fashion. However, traffic volume over the LAN affects the timing of message entry (and potentially exit) to the recipient. In the event that the LAN is busy, messages may be delayed until traffic level is reduced. In this case, the protocol should be setup so that the time-sensitive users are serviced in spite of other

traffic. This priority-based access to LAN communications reduces conflicts and allows effective control of equipment to be available.

5.2 Real-time video and perception issues

One of the machine control difficulties that has to be accommodated is human sensitivity to the real-time nature of control signals. In the case of surface teleoperation, it is usually possible to view the process under control and to have the option of using direct line-of-sight radio or simple wired transmission paths. Underground the opposite is typical: it is seldom possible to watch the process and the capability for radio control and straightforward wiring is limited by the intervening ground. Underground, the appropriate infrastructure must be installed to move the information between locations. These communications paths must not introduce so much delay as to be detrimental to the process. One of the significant reasons is the distress that delays cause the operator. If these delays are lengthy, the result is the operator feeling the machine has "sloppy controls" and is unable to finely control the system.

In addition to the problems of limited view and choosing communications paths, care must be taken with the choice of the protocol used along the paths. Digital techniques for video transmission often buffer the signals, as a part of the digitization process. This may be acceptable for applications such as home video playback using standards like MPEG and MPEG-2. In this case the absolute timeliness of the video is not critical. (The system, unlike underground communications systems, has few rate constraints, and overall the video is available at an even rate, whether the media availability is in fact bursting at a very high rate.) However, it is not as acceptable in situations where the video is used as part of a machine control system. Delays in the transmission system that inevitably occur, can cause the video displayed to be delayed. The operator needs to have full time, full motion video to provide the accurate feedback required. Delays in the operator's video images are very stressful and can cause serious operator discomfort.

Another challenge to overcome in underground automation is the effect of signal degradation on the resultant video. In the case of fixed (wired) video, the signals are received at the interface devices without time variant deficiencies. This makes the task for video processing equipment relatively simple and the modems have little adjustment to make. This is not necessarily the case when the signals

have been captured from a radio path. Standard transmission deficiencies related to noise, signal reductions, phase and ghosting problems often interact with the signals in such a way that the modem gets confused and has great difficulties in interpreting the correct way to handle the signals. A "confused modem" can often make inaccurate decisions. The closer the incoming signals can be represented without adjustment the better.

Perhaps the best analogy is the operation of the current generation of television and VCR. In these devices the lack of signal is noted and the television/VCR blanks out the communications, no signal results in no picture. In the event that the signals are radio transmitted, it is guaranteed that there will be situations whereby the signal momentarily reduces. Now imagine the disturbance experienced by an operator of an LHD receiving a "dramatic blue screen" during tramming. When driving a car in a rainstorm, the driver is confident that the view will recover after the sweep of the windshield wiper. Similarly, it must be guaranteed that the degradation of signals momentarily is not offensively passed to the operator. The same is applicable to other electronic "remedies", such as last image retention, partial screen redraw and delayed screen image interleaving. These all can be very aggravating to an operator if inappropriately applied.

5.3 Communication protocols

The communications methods and protocols for surface automation have been developed to create a robust and secure transport of the data required by the process. A whole PLC (Programmable Logic Controller) industry developed to address and satisfy the needs of factory automation. Several manufacturers created protocols and communications techniques to suit their PLC products. These techniques discover, and in some cases recover from, errors. Usually several techniques are used that, in combination, provide the communications path security sufficient to operate the plant processes in a safe manner.

In attempting to move automation techniques underground, it is necessary to choose and implement protocols that will be used to guarantee the control links. Most of the decisions remain the same for both underground and surface automation, except for communications issues. As previously noted, several issues impact the choice of technique underground, and the overall decision process must

accommodate these issues. These issues are further complicated by the use of radio-linked systems where the path is variable with location.

One protocol that is widely used is the Modbus protocol, developed by Modicon.⁴² This protocol uses several coding and message schemes to create a data frame that can be verified to be correct using the error checking built into the protocol. In addition to the basic error checking, the Modbus protocol is unusual in the inclusion of a time sensitivity in the protocol. In this case, if the message is not received in a continuous packet, the full packet is discarded. In the event that there is insufficient space between the packet end and the next packet, it is also noted and the packets are discarded. This timing data, suitable to the use of direct-wired serial links, can often be difficult to handle in a packetized or radio-link environment.

In addition to concerns regarding the integrity of the data transmission path, there are also concerns about the way that the protocol handles deficient communications paths. On the surface there are many protocols that assist with the transmission of data as files, without much regard for absolute timing. In the case of the computer industry, it is very common to have delays between the transmitter of information and the recipient. In the case of a file being transferred, it is often reasonable to queue the message until the whole file is present, or until there are a few cycles of computer time to manage the communications process. Usually this is transparent to the user. Contrast such a casual file transfer scenario to the control of a machine at distance. Assuming that the feedback (video and audio cues) from the machine under control is received in a timely fashion, then the operator assumes that control commands will be transmitted/received without delay. The addition of any control path delay makes fine control increasingly difficult. In mining, the machines are frequently slow to respond and the operator will not usually notice small delays, rather they will appear as additional sluggishness. However, any increases reduce the operator's control capability.

A severe problem occurs if a digital technique used to pass control information does not track the message latency, or even worse, queues the messages. The hazard this creates is the possibility that the machine, when finally connected to the transmitted messages, may perform the actions well outside of the desired time frame. One example would be an operator that sent a movement command, noted the lack of motion and then tried several other commands, before shutting down the process. In a queued system, it might be possible that the messages were stalled from delivery. This

means that when the reason for the messages being stalled is removed then the machine could make several jerks prior to acting on the stop command. This poses a definite hazard.

Another pitfall that must be avoided is the issues that surround the safe control and monitoring of multiple mobile machines in the same relative area. This is an issue that relates to the use and re-use of the radio spectrum in various areas underground. It is anticipated that equipment automation will increase with time. Since each machine requires connections to the operator, there will be an increase in the amount of radio traffic. This will require that the spectrum use be managed and organized to assure that the various systems co-exist safely. The evaluation should include such issues as how the radio signals of one system affect those of another system. Issues, such as unintentional desensitization of radio receivers by carriers from other equipment are important. As well, the random interaction of the various signals creates a variable noise pattern that may affect the stable operation of radio-controlled systems. All of these issues are significant to the safe operation of radio controlled underground equipment.

Overall, the issues of underground communications and protocol choice are not trivial and inappropriate selections will be a barrier to safe and efficient operation. Interconnection difficulties remain during the choice of equipment and protocols, since in most cases the protocols are proprietary to the manufacturer. While standardization on a particular vendor's equipment increases the chance that a cell of automation will operate, there are no established techniques that will guarantee interconnectivity between products from various equipment suppliers. This issue is probably the most significant to the increase of integration of automation systems underground.

5.4 Equipment enclosures

The underground mining environment consists of air heavily saturated with corrosive moisture and abrasive, often conductive, rock and ore particles. Typical mines have multiple drifts originating at the central shaft, at various depths below the surface. These drifts frequently extend thousands of feet out from the shaft. Over these underground drifts the environmental conditions vary dramatically. Depending on location, the range of conditions can vary from freezing to too hot for an operator's presence, dry and dusty to perpetually "raining", clear air to silty and dust laden. Because of these

harsh environmental conditions, equipment used in the mines is exposed to a variety of severe and extreme operating ranges, a very difficult set of environmental design problems to satisfy.

Creating drifts through the Canadian Shield geology is expensive. Therefore drift openings are minimized and the dimensions of mining equipment are maximized to utilize the available space. To simplify acceptance, any additional automation equipment must be able to fit into the current vehicle outline without impeding the vehicle's performance in any manner. In addition, the automation enclosures for equipment used at fixed locations along the drifts must also be small and robust enough to be installed without major changes.

The LHD vehicles used in the extraction of ore operate in a harsh environment that exacerbates the situation. Typical vehicle operating temperatures exceed 50°C, and vehicles operating with diesel engines exhaust hot caustic fumes. Any enclosure used to house the electronics must be sealed against these fumes in addition to the other environmental hazards. As well, most onboard electronics will also need cooling paths, usually by cooling fins on the outside of the enclosure. With the enclosure on the vehicle, these fins must be properly designed and efficiently located (due to the space restrictions).

The normal operation of LHD vehicles results in additional stresses in the form of vibration and shock to on-board equipment. Vehicles are driven into "muck", where the ore is scooped into the front buckets. The result of such action is large g-forces with both shock and vibration components. The enclosure and internal electronics of the automated equipment must be able to withstand the operating mechanical forces.

With environmental conditions that are so difficult and stressful, the mechanical isolation and environmental isolation features of the packaging are of utmost importance in keeping the electronics functioning. In addition to the environmental challenges, the ease of repair is also an issue that needs to be addressed. The cells of automation are typically located long distances from the service garages. Being able to identify the failures and problems with underground gear can be difficult. It is therefore important that field diagnostics and tools be available, either via the communications link or with portable tools. Additionally, if the enclosures are of the appropriate size, the concept of module change-out rather than internal access becomes possible.

Table 9 identifies some of the features that require careful consideration as electronic equipment is considered for installation onboard mobile equipment.

Issue	Solution
Location	Avoid heat sources, disturbance to local and remote operator's views
Mounts	Well anchored to structure, but able to be dismounted with relative ease assists with service changes
Power sources	Most electronics requires a moderately stable power source. The power grid on the machine should be specifically oriented to supply a low impedance, stable source of power.
Dust, fog	In many mines the dust is conductive and the humidity is acidic. Reduction of these hazards will assist with the equipment longevity.
Maintainability	It can be assumed that the electronics will need service or adjustment in the field. With this in mind the ability to conveniently remove the electronics packages would be logical.
Shock and vibration	It is preferable to reduce the effect of shock and vibration by choosing locations that are as mechanically isolated as possible from the bucket and engine sources.
Functionality confirmation	Wherever possible design the system so that it is easy to confirm correct operation of subsystems, such as appropriately designated LEDs etc.
Connectors	Ensure that the connectors are keyed or otherwise protected from cross connecting. In the event that there are several connectors with like purpose, similar keying might assist with the identification of failed equipment.
Failsafe	Require that the electronics fail in as safe a manner as possible (i.e. outputs passive, communications still active). Perhaps monitor some of the critical outputs to assure correct and stable equipment operation (identifies "stuck" relays etc.).
Operating range	Require that all of the equipment will operate over the full range of temperature, supply voltage and mechanical abuse that can be expected for the system.

Table 9: Issues and solutions regarding electronics on-board mobile equipment

5.5 Sensors, actuators and fusion

The sensors and actuators are the extensions of the operator's abilities on the machine. Whereas the operator on-board the machine has the full use of all senses including heat, smell and subtleties of vibration and sound, the remote operator is at a disadvantage. Most of the sensations that the operator on-board would have indicate status and describe the function of the vehicle based on experience and history. In most cases these sensations disclose secondary effects and not the actual problems. The correct choice of sensors can provide two vital paths to machine safety: they provide

data to the operator for interpretation (sounds and vision) and to the machine control systems in terms of the specifics of temperatures, pressures and other vitals. The direct connection of sensors to the monitor function allows the machine to independently analyze and adjust features of the systems to maintain the operation within safe limits.

5.5.1 Sensor systems

Sensors of various categories currently exist on the LHD machine as part of the standard manufacturers' offering, and others will be required for automation to be successful. These comprise subsystems used for operator feedback, machine vitals and automation issues. Often there is a crossover between these systems, however, careful choices can reduce the impact and confusion that could occur.

5.5.1.1 Machine sensors

The primary systems that need to be monitored are those issues that affect the machine health and the correct operating parameters of the machine. Examples of these are the standard on-board dash instruments that indicate critical operating pressures and temperatures. These sensors are basic to the machine and reflect the minimum parameters that an on-board operator needs to observe, and in conjunction with sight, smell and vibration will allow the alert operator to identify problems with the machine.

5.5.1.2 Remote operation sensors

As the operation of the machine becomes remote, using tele-operation or remote control, the number of sensors that need to be integrated into the system increases. The basic dashboard data is not sufficient to guarantee machine and process security. Additional sensors need to be incorporated to replace those senses of the operator that were previously used. While the simplest of these sensors is audio feedback from the machine, other transducers and display technologies that allow the remote operator or monitoring system to monitor engine effort, machine health and security become valuable. Emphasis on expanded use of intelligence onboard the machines to observe and trend such attributes,

as well as future use of acoustical and vibration signatures, will have increasing importance to assist with the predicting of problems and impending failure.

The importance of suitable sensors is increased when the amount of time and effort that the machine is used is increased as a result of the automation of the process. Since the format and frequency of service intervals described by the manufacturer usually suit the manual operation of their product, it is possible that the extended operation of the remotely operated machine may exceed some portion of their specification (for example heat buildup that exceeds limits based on the lack of cool down periods). Lacking the information from suitable sensors, the system may appear unreliable due to typical conditions being exceeded, consequently creating abnormal operating conditions for the automation system.

5.5.1.3 Automation sensors

The last classes of sensors are those that are installed to allow the automation processes to take place. One set are the sensors that provide the feedback required to allow the machine and associated equipment to intelligently perform the required actions to complete the tasks for which the system was designed, while not under the direct and constant control and observation by the operator. These sensors are distinct from the basic machine sensors. Examples include guidance systems, positioning systems, loading and dumping assists.

A second set are those sensors that safeguard the function performed by the machinery and control system in the application. Examples of these are watchdog timers that sense the failure of the control processors, guidance and “electronic bumpers” that stop collisions, and other system safeguards. Future extensions of these sensors may also allow the detection of people or equipment in the zone of automation and either avoid or halt the process if detected. It is this set of sensors that will require the most attention to reduce the risk and increase the safety of personnel in a mixed man/automation zone.

5.5.2 Actuators

The standard controls onboard an LHD are those necessary to allow the operator to operate all machine functions. These local controls are usually proportional hydraulic and are located on several

surfaces around the cab area. The local controls accommodate their use by a local operator. When the machine is remote-controlled, the number of functions, the number of control circuits and feedback issues become significant. Issues such as response speed to an operator's command, delay to the operator of the machine response, and variability of the communications paths become the limiting factors surrounding the ability to correctly and safely control the remote machine. In cases where the operator is controlling a machine with significant delays in the communications chain, it becomes more critical that local sensors and automation intelligence are in place to monitor and safeguard the machine against damage.

5.5.3 Tele-operation techniques

As the desire for longer distances for teleoperation increases, then the number and style of actuators also increases. Original radio interfaces were digital in nature, acceptable since the operator was at a near distance from the machine and had a reasonable view of the machine. Processes such as the radio remote operation of a machine in a VRM stope by an operator on the level, at a distance from the machine, did not require any more sophisticated techniques since the observation ability was so impeded, and therefore fine control made difficult. For early installations, the most rudimentary controls were often suitable.

As distances became greater, sensor and actuator complexity increased, to allow the operator closer control of the machine. Also, better views of the process became available using video and audio feedback. The application of careful modifications to the lighting for the tele-operator's camera view allowed a significant reduction of operator stress, particularly in the muck pile. Appropriately implemented, the lighting changes allowed an increase in depth perception as well as assisting with relative position assessments.

Other techniques, including additional remote control features such as the implementation of gear changing, production monitoring and loading assists, were also installed to assist the operator. As these automation assists evolved, the sophistication of the operator's controls was also updated to enable better machine control and take advantage of the better views and tools available.

Additional machine control and communications issues became significant during the extended teleoperation of the LHDs. These issues were related to the various states that the machines had the

ability to enter, and the communications required to keep the machine competently controlled. The definitions and the applicable communications issues are summarized in table 10.

Mode	Communications requirements
Manual operation	<ul style="list-style-type: none"> • No requirement for surface communications
Local teleoperation (line of sight)	<ul style="list-style-type: none"> • Requires constant control communications with local operator • Machine is dependent on communications for movements
Remote teleoperation	<ul style="list-style-type: none"> • Requires constant control communications with remote operator • Machine is dependent on communications for movements
Automated operation (during guidance etc.)	<ul style="list-style-type: none"> • Requires partial communications, sufficient to convey the acceptance of the continuance of the task • Machine is able to travel, initiated by communications, and requires a continuous set of permission communications
Sleep mode	<ul style="list-style-type: none"> • Waiting for communications to be received to change from state of dormancy. • No communications until state changes to active

Table 10: Comparison of communications requirements for automated machine modes

5.5.4 Guidance techniques

With the LHD, the use of guidance eliminates some of the repetitive activities for the operator. The earliest automation attempts were focused on the tramming task, leaving the operator doing the loading and dumping operations. There have been several guidance techniques that have been explored over the past decade of LHD automation. A brief review of some of these techniques and their significant attributes is provided in table 11.

Description	Features	Drawbacks	Popularity
Buried wire systems	Does not involve any vision and therefore is relatively dust / fog immune.	Hard to install and modify.	Attempted at LKAB as one of the first guidance attempts
Reflective tape	No power required for the fixed portion of the light path.	Sensitive to dust and fog (double length light path). Also sensitive to the optical path angles between tape and transmitter and receiver.	Used frequently for truck haulage applications, promoted by Mintronics and Noranda ⁴³ .
Light rope	Uses a simple vision system as a basis for following the light rope. Easy to follow an active source, light path length is half of a reflective system.	Power is required for the light rope. Some sensitivity to heavy dust and fog environments.	The primary method used at Inco and promoted by Automated Mining Systems.
Painted stripes	Simple and low cost installation	Similar sensitivity as reflective tape systems.	Recent attempts at Noranda and LKAB ⁴⁴ .
Wall following	No infrastructure required. Able to learn and change paths based on maps internally generated.	Requires significant computational capability on the machine. Does not have any specific guide attribute so path cannot be absolutely forecast (i.e. light rope etc. must be present to have LHD follow a path)	Research initiatives in many countries.
Inertial Navigation Systems	No infrastructure required. Able to learn and change paths based on maps internally generated and retained.	Same as above for wall following with the added complexity of the high cost of the sensor system.	Research initiatives in many countries.

Table 11: An analysis of the common guidance systems.

5.5.5 Autonomous guidance techniques

The differentiation between guidance techniques and autonomous guidance is in the amount of operator intervention required, as well as the method and ability to interface to an outside system. In the discussion of guidance, the methods and the style of the control is not in question. In a trivial

sense, the rails of a train system are a guidance method. In an autonomous rail system it might be anticipated that the automation extends to all aspects of the process. This would include the safety of the engine, the assurance that the cars are all still connected and rolling adequately, through to the ability to report position and perhaps trigger load and dump sequences.

In the case of LHDs, systems are gradually being extended to encompass greater portions of the full tram process. Various attempts have been made to assist the operator with the loading of the bucket, most notably by Noranda and Elphinstone, as well as several smaller design facilities. These techniques are a great supplement to the tramming task, but still require the operator to be "in the loop" to monitor the process and orient the attack on the ore pile. One current research project is focused on the detection of the best attack strategy for a LHD and autonomously guiding the loader to the correct angle and position to efficiently load the bucket. At present, since the operator is needed to load the bucket, the dumping portion of the process has not been a target for automation. Once reliable loading is available, it is anticipated that there will be significant industry pressure to increase the ore pass openings appropriately to allow unattended LHDs to dump easily. These tasks, along with a guidance system for the tram and a control system that supervises the system against all hazards, make up a system that could be considered fully automated. At that point, the interface would be to request a quantity of material from a particular stope, to be conveyed to a given ore-pass: a completely autonomous system.

In considering the autonomous operation of an LHD underground, several observations and questions are significant in guiding the development and design of the process. A few of these questions are offered:

- What variables are significant to the process and the equipment? How frequently should the data be transferred, and where and how will a communications or hardware failure impact the operation of the full system? Is too much data being collected and the ensuing communications volume creating difficulties?
- Are there systems in place to interpret the data collected and are those systems able to report the summarized data to the next level up in the communications pyramid?
- Is the machinery, process and methodology failsafe?
- Who needs the data and what will the transport mechanism and media be?

- Should the machine be constrained to keep within a safe operating envelope (does the machine “know better” than the remote operator)?
- Will the process stay operating longer if we place limits on the parameters of operation to avoid inadvertent operator damage?
- Has the whole process been evaluated, or is there a fundamental obstacle that needs to be addressed to enable the complete process automation?
- Remote controls introduce unusual technical features such as the means to “lock-out” equipment or provide “emergency stop” capability. How do the safety experts and automation experts accept remote control and automation (non-wired) safety devices?
- How does the process guarantee the unique addressing for each machine and controller so that no unexpected control channels get created⁴⁵?
- How much “time of continued operation under loss of communications” is allowed, what is the appropriate response and is there a distinction between automated and remote operation in the severity of the interpretation of the failure?

5.6 Equipment standards

The preceding questions in section 5.5.5 all focus on the careful examination of the process and the evaluation of the correct operation and the impacts of deficiencies in the system. The significance of these questions is further impacted by the ability of the system to make available the requisite data and have the capability to transfer that data to the correct recipient. Frequently, there are impediments to the process of this transfer created by the proprietary protocols, formats or transfer techniques. The manufacturer is often the coordinator, not necessarily the author of all of the systems onboard. This may represent a fundamental difficulty in terms of the openness of the data available from the machine, and often may represent a future support problem if the manufacturer is incapable or not interested in the ongoing support of that aspect of the system. Often the software and electronics is viewed as “bells and whistles” and therefore continued support and evolution may not be as available as the future stream of spare parts and consumables. These problems typically depend on the technology capability and growth focus of the manufacturer and whether the industry continues to accept “part solutions” that may not necessarily be amenable to all automation efforts.

5.7 Vehicle electrics and electronics

5.7.1 Vehicle wiring schemes

The early LHDs were very simple and robust in their wiring techniques. Since initial machines did not require significant electronics or accessories, the rudimentary electrics were well suited to their application. Based on a wire-per-service, the repair and diagnostics was simple and easily accomplished. This simplicity also extended to the manufacture of the machines during the initial periods, as long as the machines were simple and few components were involved.

As the level of electrics and electronics onboard the vehicle increased, their simplicity and serviceability diminished. The wiring harness of current machines is complex and repairs are often difficult because of the myriad of wires and connections involved. When added to the extremely abusive environment within which the LHD operates, the requirement to simplify the wiring schemes is logical. Recent machines also employ intelligent sub-systems, such as DDEC engines and production monitoring systems. These additions further complicate the wiring of the LHD and assist with the pressure towards re-organization of the wiring schemes to take advantage of serial based interconnection schemes. These techniques would reduce the wiring to a common serial bus to carry the commands and common power supplying energy to the devices. This will simplify the wiring and diagnostics, at the modest expense of the addition of intelligent input and output modules.

5.7.2 Communications on-board the vehicle

With the approaching era of serial bus controlled modules on the machine will come the ability to accelerate the integration of the remotely controlled LHDs with their operating parameters in a straightforward and logical manner. In the case of a single serial data stream that addresses the machine as well as the engine and onboard production systems, the future machine will have all of the techniques necessary to simplify the transfer of machine, production and control parameters directly to the operator's control panel. This will allow the remote diagnosis of all onboard systems as well as the information to logically safeguard and control the LHD.

5.7.3 Standards

The preceding sections address the benefits of the use of serial communications onboard the machines. Implicit in the benefits was the assumption that the communications schemes were compatible. The choice of format and protocol is usually made at the manufacturer's level. With the significant savings available with common schemes, it is anticipated that a common standard will emerge. Until such time as the standard is defined, the integration of onboard electronics will be hampered as protocol conversions and wiring bus bridges are required to transfer data. In addition to the increased complexity, the maintenance and service costs will remain sub-optimal as long as there are multiple standards involved.

6.0 WORKPLACE ISSUES

6.1 Changes to the workplace

6.1.1 Automation assists for the operator

The techniques utilized at present in underground mobile machinery automation have focused on the reduction of the operator's responsibility for repetitive and boring tasks. In the haulage function, the operator is relieved from the tedious tramming tasks and left to handle the more challenging loading and dumping tasks. In the case of drills, the surface operator is relieved from the repetitive tasks associated with drilling and pulling the rods, and is left with the more challenging tasks of repositioning the drill and collaring the hole. The reduction of the repetitive tasks allows the operator to be responsible for more than one machine at a time. This use of technology leverages the operator's skills, creating a better work cycle for the operator, with greater reliability and quality. Taking advantage of the automation and control of these machines from the surface required the communications between the operators and the machines to be of high bandwidth and in real time.

At present the assistance that is supplied to the operator of remote LHDs is based primarily on the use of a "light rope" based guidance system. In this system a plastic rope containing incandescent light bulbs on an approximately two and a half centimeter spacing is positioned in the drift above the path the LHD is to follow. The LHD vision sensors use this visual cue.

Onboard the LHD, a camera at the front and another at the rear are focused above the machine viewing sections of the light-rope at positions that are representative of the extremities of the machine, front and rear. These cameras are connected to an on-vehicle vision system that reports the machine position to the onboard automation equipment. The result, when the command to move is given, is that the LHD can determine its location within the drift and thereby is able to self-position and tram on its own. This is a modest technique in terms of technology and has proven to be quite robust over the years. The problems have been primarily associated with damage to the sensors and the fragility of the "off the shelf" vision processor used onboard the vehicle. While this system will be replaced or supplemented with better sensor systems resulting from current and future research efforts, this simple

system has allowed the early insights into the gains and difficulties associated with the implementation of LHD automation.

6.1.2 Work place readiness

Historically, workplace requirements have been related to the needs of the physical aspects of the planned mining process. The usual needs are for air, water, electricity, wastewater and sometimes task lighting. The shift over the past decades has lead to a greater emphasis on personnel communications and most recently communications to machines. Recent changes in the mining method have increased the complexity of the specifications for the mining zones. Now when the mine opens an area it is with the potential that new techniques of mining might be used. Previously, the development attributes varied from shaft, main access, ramp, through final mining zone access crosscuts. Each of these areas defined a requisite level of ground support, utilities and had a forecast life expectation. In the cases of areas ear-marked for automation, several new requirements emerge and must be satisfied prior to declaring the workplace ready for automation.

Of key concern are drift dimensions, after the implementation of the necessary ground control efforts. Often the mine creates drifts with dimensions based on the needs of manually operated machines, impeding the use of automated versions of those machines. One example is the smaller drift area provided for manual Solos as compared to the larger automated Solo 1000-sixty blast-hole drills, which tends to prohibit the use of the larger machines. Furthermore, in the case of drills, the use of alternative ground support techniques such as Shotcrete, rather than bolted screen, is desirable to avoid drilling into installed steel.

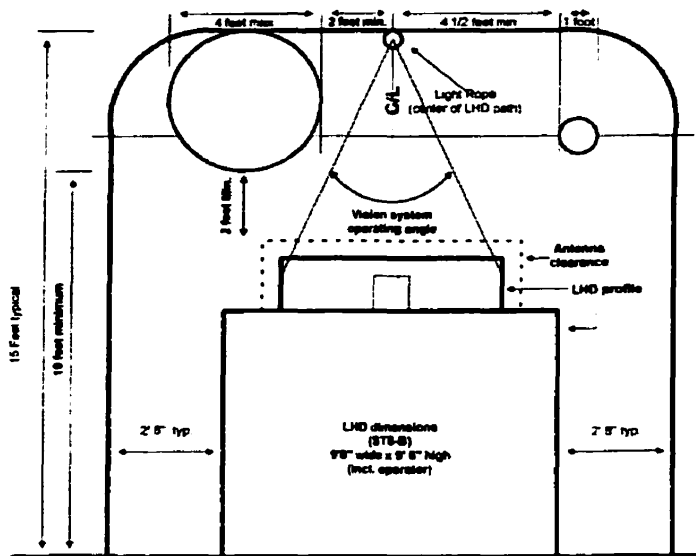


Figure 29: Pictorial of drift layout example for LHD automation

Another example is the design foresight required that would allow future installation of the automation features that are not immediately necessary for manual operation. Currently primary infrastructure installations include air, electricity and water required for the machines driving the drifts. Subsequently, the ventilation tube that is needed for the development crew is installed, again on an ad-hoc basis, by the miners. Communications, if present at all, usually reflect the needs of the instant.

This typically means that significant rework is required to rearrange the previously installed services to allow for the use of back-mounted light rope and other automation techniques.

Remote mining will need to be founded on intelligent integrated information systems, linking orebody models and mine planning systems to real time machine monitoring for production decision making. Scheduling and designing work places to account for production targets as well as machine automation systems will be critical.

6.2 Mine automation planning techniques

With all automation systems, the system depends on a reliable level of knowledge to provide the structured environment within which an automated machine and system is capable of operating. This knowledge is a result of the careful planning and setup of the environment, so as to minimize the variables and create identifying features with which the machine can become familiar. Examples of these features include the effort to supply power, guidance assists and cues, and communications. As well, the sensors required for the mining process, including grade and production data needed for the mine database, and other automation supporting tasks will need to be available. These are issues that require a significant level of advance planning and effort. Since the machines and systems require a

"known" environment to be able to function competently, these preconditioned work areas require careful setup in advance of use.

The difficulty with the setup of "machine automation" areas in the mine is that several will likely need to be available at the same time, to accommodate the realities of the mining process. The underground mining process is seldom suitably defined as to eliminate all issues of sequence and element failure. Occurrences in other areas of the mine, common access points and distributed difficulties with mining methods all impact on the installation and use of automation. Frequently, a change or deviation from plan in one area will inadvertently affect another area. This may require installation of further infrastructure, additional support; there may be breakdowns in the other areas of the mine that impede that access to the mining area. With these interrelationships mine planners can seldom be confident that alternate sites will not be required. The ability to be able to move the automated equipment into a new area, in a timely manner, because of a deficiency in the previous zone, is a requirement that should be anticipated for the near future. As automation becomes more capable, it is assumed that these alternate preparations will become less onerous. However, having a multiplicity of fully prepared work places available on schedule to exploit the potential of the automated region will likely be a requirement of the implementation of LHD automation for some time into the future.

6.2.1 Zone of operation identification

The mine that includes LHD automation as part of its haulage process also needs to have modifications to several attributes of the mining areas to enable effective control and automation; it is no longer a case of automating a static positioned machine. Rather, a region exists within which the trackless vehicles will be operating without on-vehicle operator. The extent of the zone includes all draw-points, drifts, crosscuts and passes or dumps. This is a change from static machines in that the automation takes place in a zone or area rather than a static position. The automation environment is therefore spread over a much larger area than previously.

Some of the criteria and the design solutions for the zone of automation that need to be characterized and modified are summarized in table 12.

Issues	Solutions
Ventilation	Depends on machine needs, not on-board operator for quantity, allows a net reduction of the air delivered to the area.
	Need to be able to add supplementary air in the event that service at the face is required (on an as-needed basis).
	Still requires that the effect of discharged air contamination is considered in areas further along the ventilation path.
Ore passes, drawpoints	Include the ore-pass within the zone if possible so as to contain the automation and create process independence from other mining processes
Manual Intervention	Attempt to arrange manual intervention locations in areas that are external to the automation area: reduce operators in automation areas
Access	Arrange to have the area interlocked with barriers and gates to reduce miscellaneous personnel hazards
	Establish alternate means for external mining travel to be able to exclude entry or crossing of the zone of automation
Automation services	Keep garages, refuge stations, fuel bays, explosives, materials storage out of the zone of automation
	Arrange for power for electrically operated ancillary automation equipment
Muck sizing	If possible keep muck sizing restrictions to other points in the process (avoid mantles), reduces manual process interventions
Back height	Where possible maximize back height at dump points where tele-operator's view may be restricted
Cross cuts & roadways	Wherever possible attempt gradual and smooth intersections, smooth and even roadways to increase the speed of the automated vehicle
Communications equipment	Provide relatively clean power to the equipment locations where the communications equipment is installed.
	Provide suitable niche to allow the communications equipment to be mounted in a hazard-free area away from mobile equipment
	Provide access to mine-wide communications infrastructure.
Safe state	Where is a safe location for automated machines when other personnel are present?

Table 12: Design issues and solutions for operating zones of automated systems

6.3 Fail-safe process review

The most significant issue that mobile machine automation highlights is the need to be able to keep other personnel from being in the path or proximity of the machine under automatic control.^{46, 47} This requirement to keep personnel safe must be guaranteed under all circumstances

As table 12 indicates, there are several other criteria that should be met when considering the installation of zones of automation within a mine. Most of the solutions indicated are straightforward in implementation; however, there are many times that the mining zone cannot be completely modified. For this reason, the automation process must be able to be modified and techniques developed and documented to accommodate the presence of personnel in the area. To be able to safely accomplish this task requires the completion of extensive analysis and solution implementation prior to placing the automated machines into production. This is called fail-safe analysis and is used to discover, define and anticipate problems prior to implementation; in this case the issues relating to safety for the personnel interacting with the automated system.

The fail-safe process is a formal process wherein each of the potential error conditions is analyzed and the desirable responses discussed. The most significant issues are those that affect the safety of personnel, but the process also extends to the machinery and environment. In practice, the technique involves members from all of the stakeholders of the process meeting and discussing the possible failures. Failures in the system as well as the machine need to be identified. It is important that the failure of a portion of the system does not cause the system to fail in a manner that is a safety hazard to personnel in the area or other areas of the mine. Examples of identified potential failures include such possibilities as communications failures, machine failures, and automation and control system failures.

Once identified, each potential failure is analyzed to identify cause, effect and hazard created. Frequently, perfect results are not possible and a less than optimum resolution is achieved. The usual method, since the system works by implementation of process safeguards, is through a process such as procedural steps for the personnel in the area.

6.4 Installation techniques requiring change

Installations of haulage automation have attributes that guide the design and implementation process. Some of these installation techniques can be altered to comply with the mining method and scheduling of the mining area. Most of the hazards that are involved are based on the effect on people, machines or the system as a whole. Some of the questions that assist with the logical installation of automation are summarized in table 13.

Personnel	Will the zone be free of casual interference from personnel?
	Are there communications facilities available to allow personnel entry?
	What interlocks are necessary to maintain personnel safety?
	Who takes priority: personnel or automation?
Equipment	What happens if communication is lost; does the system stop smoothly?
	What happens if fire breaks out on the machine; does it self-extinguish?
System	Is an interlock required with the ore-pass system to indicate over-fill/under-fill?
	Are the water sprays, traffic signals, warning systems interlocked?
	Is the mining area amenable to being automated?
	What is the defined safe-state of machine when personnel are present?

Table 13: Pre-installation of automation cell check-list

The information in table 13 will assist with the discovery of challenges that might be encountered. As well, the list includes several points that need to be discussed during the fail-safe process meetings. These points will lead the installation process through methods of addressing safety and process viability.

After the viability of the method of automation in an area is established, the specifics of the changes required can be identified. While there are many alternatives and solutions available, some of the more significant issues are summarized in table 14.

Drift attributes	Confirm whether drift width is suitable for the required physical size of the equipment
Piping/electrical installation	Logical concentration of these services allow simple views of back-mounted guidance tracks and enhanced radio communications with installed cables
	Arrange for independent light rope and communications electrical sources to the zone of automation
Light guides	In general should be located at the highest, centered location to provide the best view to the machine-mounted sensors avoiding shadows etc (18 inches free area on either side?).
	Consistent height enhances the control characteristics of the system
	Remove all pieces of hanging "Cari-Strap" and chains to eliminate "noise to vision sensors"
	Reduce wherever possible cross-drift obstructions to reduce false vision paths
	Installation of power circuits to active light guides will be required and separately controlled
	Arrange for the mining process to guarantee that the light rope be on whenever blasting occurs to take advantage of the better shock immunity of a warm filament
	Reserve the light rope installation until the first mining blasts (most on-level concussion) have been taken
Personnel safety	Provide access controls and methods that will allow personnel to safely shut-down the system and gain access
Schedules	Attempt to arrange visits to the area to coincide with machine service periods

Table 14: Automation cell equipment installation checklist

6.5 System Overview

The automation of LHDs is similar to the automation of many surface and underground systems. Each attribute of the automation effort needs to be reviewed to establish its relevance and sensitivity to the whole process. Since a failure of any part of the system can disable all of the process, careful examination, along the line of the fail-safe process, is necessary to make sure that the system will continue to function irrespective of problems.

A few points of interest that assist with the evaluation of system in terms of overall response are outlined in table 15.

Issue	Solution
Simplicity:	Have the number of sensors and actuators been kept to a minimum?
Accuracy	Are all sensors self-calibrating (or simple to calibrate if manual)?
	Do all sensors indicate recalibration criteria and/or recalibrate automatically?
	Is there sufficient self-test ability to validate all sensor systems?
Standards	Do all systems adhere to convenient and common standards?
Operator's sensors	Has the control and video latency been reduced to the lowest level, and is it amenable to the process?
	How will critical sensors such as cameras be maintained and cleaned?
	Does the system perform reliably enough for the operator to feel comfortable with its stability?
	Is the operator supplied with comforts and tools suitable to the task?
Safety	What systems provide security against personnel or obstacles in the area?
Standards	Is the system approaching or building towards ISO 9000-style standards?

Table 15: Overall system automation installation checklist

7.0 CONTROL STATIONS AND CONSOLES

The operation of remote machinery requires many changes to the machines as well as an ability to communicate the required information between the operator and the remote equipment. As these changes are made, then the need to be able to manage the information and create an intuitive control environment becomes critical. The operator's ability to monitor necessary features and attributes of equipment decreased as soon as the operator was not in the immediate vicinity. The automation of equipment allows that distance to increase based on the addition of sensors and other machine features. The data emanating from the machine replaces the previous use of the operator's senses. Since the information is of various forms, the development of appropriate operator consoles and stations was extremely important.

7.1 Initial tests at Copper Cliff North Mine using extensions to broadband network



Figure 30: CCNM tests at surface

The first tests of teleoperation of a LHD took place at Copper Cliff North Mine (CCNM) in early 1989. These tests demonstrated the remote operation of a LHD using communications extensions of the communications from a Moog radio remote control to the machines located underground. These tests used the standard radio remote package, wire connected to the broadband system at surface, and rebroadcast on the

active level underground. An unwieldy array of electronic modules, cables and multiplicity of connections made the requirement for integration into a unified package a necessity. However, the success of these first tests demonstrated the feasibility, both from the communications, as well as the operator's perspective, of long distance remote control.

7.2 The White Chair



Figure 31: "White Chair" in use at CCNM 3000 level

After the first successful surface tests at CCNM surface, the next logical step was to create an integrated control station that would shelter and support all of the components necessary to safely operate an LHD in the mining environment. The first of the series of these interfaces was called the "White Chair".

Created initially to be available to accompany the miner underground to

assist with the commissioning of remote control systems, the focus of the chair was on ruggedness and environmentalization against the mine hazards. To this end, the chair was a standard Grammer underground operator's chair similar to those mounted on scoops and trucks. The electronics were packaged in a double enclosed casing under the base of the chair. In front of the operator the standard Moog radio remote package was used, with the controls extended to additional controls on the chair. In this manner, the operator was able to use foot pedals to actuate brake and throttle functions. The steering and bucket functions were moved to joysticks mounted in both armrests. On this first iteration, the steering commands were on/off in nature rather than the proportional control currently available.

The movement of the steering control to the armrests was a feature that allowed the steering movements of the joystick to be rationalized and made more logical. In the typical use of the radio remote package the miner is provided with a pair of joysticks, one of which is used for steering and direction functions. When on-board the LHD, the miner is provided with a stick for steering. The operator is seated sideways to the direction of travel of the machine, and moves the joystick backwards and forwards to cause the machine to steer. Left and right movements cause forward and reverse direction movement. These movements are mimicked on the radio remote packages. A steering joystick movement to the left is for forward movement, to the right is for reverse with steering

similar to the on-board controls. These movements were acceptable for portable remote packages but could be improved when finalized in operator consoles.

When the controls were moved to the armrests of operator consoles, a decision was made to make the movements of the steering and direction more intuitive to the operator's view provided by the on-board cameras. The adjustments that were made to make the operator more comfortable with the video presentation included the reversal of the steering control effect when tramming backwards. With this reversal, the operator would then be able to move the steering in the same manner with respect to the video, irrespective of direction. (It is interesting to note that the steering changes were easily embraced by the operator while teleoperating . However, when *the LHD came into direct view, the operator reverted to standard radio remote control movements familiar through years of conditioning.*)

7.3 The Blue Chairs

With the success of the white chair as an assist to the underground commissioning and operator training for teleoperated LHDs, the next logical step was the creation of a suitable station for use on surface. The criteria that would need to be satisfied included the ability to house all components of the operator's equipment, controls and monitors, in one console. The resultant system was the first to be duplicated (two were manufactured) for use both at the mine as well as in the conference hall.

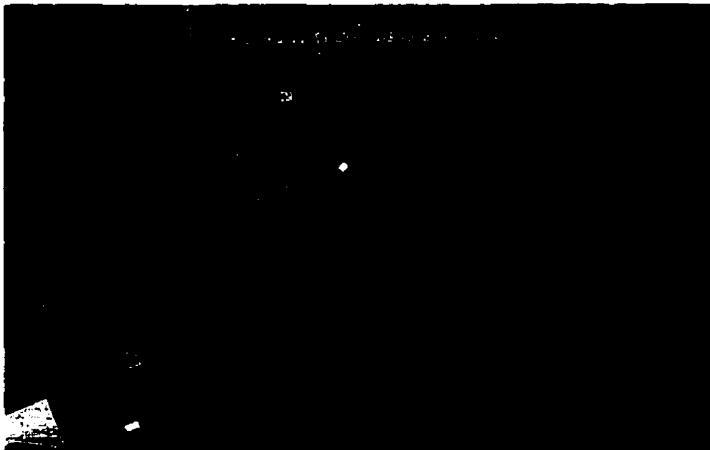


Figure 32: Operator in "Blue Chair" at Stobie mine (1997)

The most significant change from the White Chair was the attempt to define the area, position and size of the monitors available to the operator. This was also the first chair to include features such as drawers for the computer keyboard and mouse, as well as the day-to-day correspondence of the operator.

The first major installation for the Blue Chair was at Stobie mine. This chair, previously used for several public

demonstrations during 1994, was installed in the surface warm room area at the mine, and initially

used to control LHD #16 in the VRM areas underground. This was the first time that these teleoperated machines entered the formal production schedules. As the first LHD became reliable, then a second, LHD #15 was commissioned at the mine. This was the first time that multiple LHDs, under a single operator, became responsible for production in an operating mine.

This console, known as the Blue Chair, was essentially substantially a dressed-up version, incorporating all of the features of the White Chair, integrated into a clone of the first integrated chair used at CCNM. In this applications, there were a few minor changes that made the system operable in the production environment. Some of these changes and their impact are reviewed in table 16.

Feature	Function	Benefit
Power assist to chair movement	Allowed the operator to easily adjust the angles, cushions and height of the chair	Encouraged the operator to adjust the chair to his comfort where previously the operators tended to "live with" someone else's settings
Exchange of underground operator chair for surface trucker's chair	Increased the number of adjustments available and adjustment convenience	Allowed the operator to customize the chair to their use.
Radio desk set at the chair	Allowed the operator direct access to the underground areas where the machines are being used.	Safety messages as well as quicker access to the other personnel made the process tighter and safer.
Quad video views	Provides views of machines not currently being controlled	Allowed the operator to feel more comfortable with the progress of the other machines under his control
Supplementary switch additions	Allowed access to features of machines as they became available	Used to initiate functions such as weighing, auto-loading etc.

Table 16: Summary of features available with the blue chair development

7.4 The CAST Chair

As the number of mines using teleoperated machines increased in Inco's Sudbury area, a desire for control consoles at each site became obvious. When CAST Resources became involved in the teleoperation of LHDs at Creighton Mine, starting in 1997, the original Blue chair was offered as a basis for the control chair at that mine.

Several changes were implemented in the CAST approach, however the most notable was the addition of a touch panel as an input device for the operator. This panel allowed the expansion of the control capability beyond the small number of switches on the previous console and joysticks. As a result of this change, the addition of new tasks and adjustment of the system became more available and intuitive.

A second change made was to create a dashboard that was as close to the underground unit as possible. This dashboard was composed of animated 'pictures' of the actual gauges that were to be found on the machine being controlled. This was a comforting feature to the operator who had underground LHD operating experience.

7.5 The Mining Operations Center (MOC)

Notwithstanding CAST's activities, the evolution of the operator's consoles was somewhat static for several years. This was mainly due to the focus on production and changes required to optimize issues affecting the production ability of the tele-operated and automated LHDs. Most of the remote operation of the underground LHDs occurred under the control of operators located at the surface at Stobie mine.

As the automation process became more stable, the decision was made to transfer the control chairs and support equipment for both the Data Solo 1000-Sixty drills and the remote controlled LHDs to an off site location. The location was in an office-style building at a distance of 15 km. from Stobie mine. The intent of this change was to evaluate the issues surrounding the centralized control of mobile machines.

The communication systems required to enable the transplanting of the control consoles were modest in terms of the technology required but interesting logistically to arrange. For the first time, all of the various links that had evolved over time, required extension to the new location. A summary of the links required included:

One RS232 data link per machine controlled

- At least one video channel complete with audio per operator
- One radio channel desk-set per operator to allow operator interaction with underground personnel
- Unique phone lines for each operator, the numbers of which would be listed on all warning signs and barricades underground
- Common phone lines and Fax capability for transmission of mine data
- WAN links and associated computers to allow each operator to receive and file reports electronically

Most of the above communications links were as a result of the machine / operator requirements but it is interesting to note the other links required to soften the "off site" aspects of the MOC location. The requirements for these links are indicative of the discomfort and lack of in-place systems to make a remote control center geographically independent.

In addition to the remote control of the drills and LHDs, the MOC also included the surface diagnostics and maintenance capability for the SCADA and PLC networks at four mines. A technologist / diagnostician was able to remotely view and interrogate any networked system at the four mines and offer assistance in troubleshooting to underground electricians and technologists in the event of problems.

7.6 The Poetic Chair



Figure 33: The "Poetic Chair" installed at the Mining Operations Center

user, the chair provided a means to adjust light, heat and circulating air levels. Designed for the computer operator, this chair was chosen for integration into an LHD control console.

The product included a very versatile and adjustable chair that located and supported the operator in a stand-alone work environment. Within easy reach the operator had access to telephone, adjustable



Figure 34: View of the operator's controls in the Poetic Chair

In early 1999 a review of vendors of ergonomically designed work-stations highlighted a computer operator workstation made by Poetic Technologies of Montreal.⁴⁸ This workstation was designed to suit the needs and comfort of computer operators in an office environment. In addition to having integrated and ergonomically suitable locations and adjustments for the equipment of the

keyboard and mouse locations, as well as moveable table and footrest. With this module as a starting point, a new LHD operator station design was attempted, in time for a mid-year trade conference. The Poetic Chair introduced several other new features and was a positive step forward for the operators. However, the success was limited because of the mechanical fragility of the chair that limited the setup and positioning of various angles and operator supports. The poor mechanical

features of the prototype Poetic Chair did not detract from the appearance of the station as a whole. For the first time, all components of the surface LHD operator's world were integrated into a chair that

was psychologically "space-age" and "sexy". This approach made easier the challenge of moving the operator "mentally and physically" away from the mine environment into a more relaxed and professional looking office environment. The Poetic Chair was the catalyst that facilitated this transition.

7.7 The Black Chair

After the "glow of the new equipment" wore off from the Poetic Chair, attempts were made to upgrade and reduce the overall workstation fragility. Based on the unavailability of an updated and fully functional Poetic Chair, a "fast-track" modification was attempted to convert the Stobie Blue Chair into a better operator station using the knowledge gained. The Stobie Blue Chair was stripped of the large enclosure for electronics and foot controls. The remaining base was then narrowed to allow the chair to be passed through a normal doorway. A moveable and lockable table was added to support the touch panel and, potentially, future joysticks.

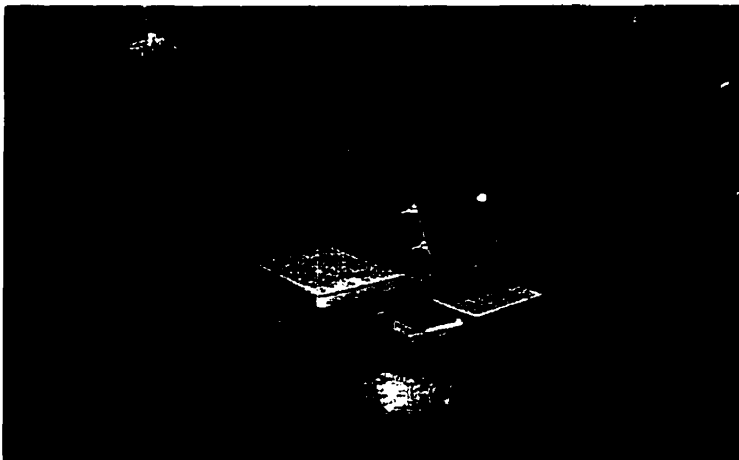


Figure 35: Operator at the controls of the "Black Chair"

In contrast to the Poetic Chair, the monitors were relocated on elevated supports at a greater distance from the operator, offering a more comfortable viewing distance. The size and distance to the monitors was altered to suit the operators at the time. Further tests were envisioned to establish the best size and distance for future installations. It was noted that there appears to be a desired distance to the TV monitor that suits

each operator. Whereas there is a continuum of size versus distance locations decreed by the ergonomists for the primary "cone" of view, the ability to view the whole screen at one time is desirable for mobile machine operators. This need, coupled with a preferred focal distance will require some further study.

Initial response to these changes has met with mixed reviews. It is assumed that the changes will need to be validated with time and a variety of operators. Since the changes are primarily ergonomic in nature, there is an added complexity in that the current operators are from Inco's Permanently Partially Disabled work pool and therefore often have custom needs that are atypical of the balance of the workforce.

7.8 The Man-Machine Interface

The increased reliance on remote operation of LHDs requires an array of other support functions to enable full use of the system in production. Since the operator is not located at the same physical location as the equipment, the operator must therefore depend on others for assistance with many issues. As these automation cells proliferate, it is assumed that there will be a dramatic increase in the number and type of ancillary equipment and services required to guarantee equipment and personnel safety and productivity.

In all cases involving the automation of a process, there is also a desire for integration into a larger system. One of these issues is the passing of production information into the overall data network of the plant. Other needs include the overall assimilation of the automation into the tasks, procedures and processes of the plant. This process integration is only possible after the mine understands the unique needs and requirements of the automation cell and its extensions. In the cases described in this thesis, full integration has not been reached. This is primarily due to the mine, under stress of productivity pressures and global economic conditions, being unable to fully focus on the goal of integration. Instead of integrating the machines into a production process, a diverse group of systems, procedures and policies was implemented to address the causes and pitfalls of the imperfect alliance. This came about due to the mine's sense of immediacy, driven by the absolute necessity for full productivity at all times. In the event that alternate machines are unavailable, it is still frequent that these "remote-capable machines" will be transferred to onboard operator use with little consideration to the process and impacts that this can cause. This is a reminder that production is paramount, and the evolution and commissioning of products needs to be done off-line away from the producing mine. Changes are not made easily and the challenge is in finding customers who will understand and put up with a little strain (during the proving out period) for a future gain.

8.0 MINING PROCESS CHANGES

8.1 Safety and Changes Required

The automation of underground vehicles and systems has created special hazards and needs that relate to the environment. Most applications of mobile machines take place within the existing drift structure inside the mining area: the mobility and deviation is constrained by the drift envelope. This set of dimensions has evolved out of the needs of the on-board operator. The small size of the drifts typically presents few problems to the onboard operator since the hazards or difficulties are obvious. As the operator becomes more remote, then the ability to view the envelope of the machine is frequently impacted. As a result, one of the first automation efforts is usually the addition of assists to reduce the effort and challenges associated with wall impacts.



Figure 36: Operator in a potentially hazardous position in the event of a malfunction

Whereas these efforts of automation and guidance are meeting with great success, the hazard associated with reduced avenues of escape, and safety should the process or movement go awry is increasing. As well, the safety of all personnel in the area is immediately under question. The automation areas are defined as personnel free in most mines. However, there are still occasional requirements to approach automated equipment to provide

service and maintenance.

These are periods of extreme hazard since the only safety is from an automation system, and its continued reliable operation while personnel are present, until the changeover to local control has been made. For this reason it is recommended that the nearest approach point to any automated machine is the proposed location for the control that switches between local and teleoperation controls. As this switch is moved, then the risks to personnel in the area become reduced as the remote operator's controls are disabled and control is transferred to the local operator. Some manufacturers have proposed emergency stop (E-Stop) buttons for this purpose, however, it must be

investigated whether implications of an E-Stop are perhaps different, perhaps deleterious to the function of the automation system, rather than a separate control.

The physical location and isolation of the machines under remote control will increase as automation increases and systems become more unified. It is not hard to imagine automation increasing to the point that the timing and scheduling of machine operations becomes automated and therefore outside the immediate operator's control. As this system approach continues, potential hazards increase. The machine movements will then occur when the system judges it optimum and without warning to others around the mine. For this reason casual approaches to automated equipment should be procedurally avoided, and, wherever possible, physical lockouts and system shutdowns (not E-Stops) will need to be located where they are most convenient, to encourage their use by personnel approaching the area.

Other attitudes are widely entrenched in the mining community that often foster a feeling of immunity from harm. These attitudes are further entrenched by advertising and initiatives that do not review or may minimize the potential for failure and malfunction. Even the radio remote control industry appears to discount the likelihood and frequency of failure, a policy that ignores rather than examines failures. Advertising includes actions that demonstrate unsafe situations of radio control use. It could be concluded that such potential safety hazards are being viewed and incorporated into the subconscious culture in the mining community.

The preceding paragraphs have outlined a few of the hazards that have been viewed and some anticipation of a consequence of these failures. Table 17 outlines some of the more obvious challenges and issues that will need to be addressed as the industry embraces autonomous machines.

Issue	Comments and questions
Are we too complacent?	Are we permitting (allowing) operators to be too near an automated machine?
What tools do we have available?	Are we offering the best remote diagnostics tools we can? Can we increase the amount of troubleshooting that can be done in a place of guaranteed safety?
Is the planning process changing?	Are we optimizing the use and features of the automated machine? Have the layouts been altered to encourage the automation in areas that will not impact other personnel in either task or travel path?
Spares and replacement storage?	Zones of operation are frequently far from normal storage cribs, should there be a distributed replacement stores closer to the zone to reduce the effect on the repair time?
Hazards to service personnel?	As we encourage the use of automation in less desirable and potentially poorer ground-support zones, how will the breakdown repairs be effected? Are there remote control recovery techniques available?
Mining changes: are they evolving?	Are we leveraging off the abilities of the automation and remote operation to optimize cash flow and preserve resources? Are we planning better: ad hoc changes to automation processes are typically wide-ranging and intricately linked.
Machine safety?	Are we applying the same rules to the safety as to personnel? Are we going to continue to create openings that will suit miners when just machines will be present? Will that produce the savings that will assist with the decision to automate?
Right of way?	Who should have the right of way: person or machine? Have we reached the point that we can enforce man-less mining areas, or at least miner-less times?
Fail-safe?	Are we creating a zone and system that will fail in a logical and safe manner, no matter the causes and sequence of events? Are we keeping the size of areas of automation small enough to be able to reliably contain the hazards?

Table 17: Challenges and issues in the implementation of autonomous machines

8.2 Training

8.2.1 Support technician / technologist training

Most of the automation on LHDs installed in the mines to date has consisted of a group of “off the shelf components” assembled to accomplish a particular function or task. This technique allows the skilled technician to be able to troubleshoot and modify the system. While the flexibility is a necessity during the test and evaluation phase of the design of a system, the costs and added complexity can cause

problems. The eventual goal would be to resolve the equipment down to a single or small number of dedicated pieces of equipment that will reliably perform the function. The addition of this secondary development process allows the robustness of the product to be designed and implemented into the finished system. The result will make the service and maintenance of the product easier in the future, since the number and complexity of faults will reduce, based on the reduction of interconnections and components.

While the complexity of the electronics onboard the machine will decrease in the future, the number and skill level of the technicians and technologists required for the maintenance, setup, commissioning and failure resolution will be a topic requiring careful examination. The gains that automation produces in terms of labour and effort reductions will have to be accompanied and adjusted by the addition of skills and costs towards the maintenance and support of the system.

Added to the tasks of maintenance and service will be the additional requirements to assist with the installation and design of the automation cells. Mine planners, well suited to evaluating and adjusting the mine plans to suit the mining process, will need assistance to become skilled in the addition and integration of automation to the mining process. The evaluation of those plans in light of the equipment capabilities, communications installed and required, as well as the applicability to the mining information systems and the data required by the management and operations staff, will need to be accurately accomplished. These tasks, in addition to those previously described, will likely create a new job category, the mining automation specialist, a challenging technical position.

8.2.2 Operator training

Another issue that bears careful scrutiny is the experience and skill levels required for the operators of automated equipment. Previous paradigms have required apprenticeships and transfer of trained skills from generation to generation. The benefit of the addition of automation elements is the reduction of some of the training required. In fact, the time may be approaching when expert systems associated with equipment may be the most efficient method to evaluate, quantify and solve production, automation and operator deficiencies. This will quickly identify the change required to the operator's responses, to optimize the systems performance. As discussed previously, the paradigm of the "macho miner" and "cowboy miner" will need to be shifted to the "professional miner", a shift that

could be accelerated through the use of these impartial evaluation tools. The result will be a system that minimizes repetitive operator input and allows the operator to become more fully meshed into the automation process, where the human intervention is required.

Understanding the training needs, many companies and services have been formed to utilize virtual reality and expert systems to facilitate the training process. As early as 1996, Wormald Technology's virtual reality tools were being evaluated for use at North Parkes mine (Australia) in the evaluation of the performance and suitability of equipment and workers to mining tasks and methods.⁴⁹ It is anticipated that more tools will become available, such as those from surface automation activities; to augment the planning, training and expert systems required underground.

8.2.3 Planning assistance

In addition to the training process, Wormald's simulation tools also provided feedback to the evaluation of the proper fit of equipment into the drifts being designed for North Parkes mine. They enabled the mine planners to establish where the drift layouts were inappropriately tight and needed to be relieved, a process that would save many thousands of dollars when the mine installed the equipment, in terms of future modification and drift slashing. It is unfortunate that the use of virtual reality to assist the development and implementation of technology has not been as widely accepted for underground mining as into surface operations and plants. It is hoped that the confidence in these tools will increase so that more of this technology will be applied in the future in the underground arena, where the costs associated with errors in installation and implementation are so high. Mine planning errors, like in any process, are better and cheaper to modify and correct "while on paper" than after the drifts have been created underground.

8.3 The new generation of underground mechanic

The future mechanic will be supported and supplemented by previously described technical experts. With the increasing sophistication of the machines, the number of rough mechanical tasks will be reduced in the near future. The mechanic is likely to be involved in the repair and changing of many parts that will soon become pre-aligned and assembled subsystems. The ability to repair these parts

will diminish and component replacement will be more common in future; the specialized repair equipment and specialized personnel training requirements will become barriers.

Many new techniques defined by the fail-safe process will be required to assure the safety of the mechanics underground. Since the locations of many of the systems will be onboard the LHD or in the operating zone of the LHD, the service personnel will have to enter regions usually barricaded against entry. To make matters worse, this entry will be during a period of system failure, when the reaction of the machine might be unknown or indeterminate. With these challenges in mind, the future service staff will have to understand in great detail the operation, interlocks and features of the automation cell so as to be able to effectively disable the machines on approach, and thereby minimize exposure to unsafe situations. This knowledge will also need to be accompanied by process steps and process safeguards to assist with the reduction of exposure to the minimum. In all cases, the automation system in failure mode will have to be assessed with the anticipation that the failure is in the worst possible location and severity. The approach will need to be conducted with logical, deliberate methodology to minimize risk to service personnel.

Many of the techniques will require departures from current policies and traditional practices. The changes will need to be managed in a constructive and realistic manner. Representatives from all of the stakeholders, including internal and regulatory safety representatives, mine workers and management, as well as the underground service personnel will need to work together to create standards and guidelines for the safe implementation of mining automation.

8.4 Management and union changes

Mines have historically been associated with strong worker's unions. Recent union communications demonstrates that these unions understand the changes to incorporate automation are inevitable. Within Inco, there is a large pool of Permanently Partially Disabled (PPD) Workers. These are employees who have been injured and are therefore unable to work underground for various reasons. Within this group, there are many miners previously qualified in LHD operation. The Stobie mine innovatively applied these workers to the task of tele-operating underground LHDs from surface. This provided the option of being able to offer a challenging career of surface mining to employees otherwise prohibited from underground work. The previous experience with the LHDs assisted the

automation process during its initial attempts. Their knowledge, and patience, supported the evaluation of several techniques during the refinement of the automation process. Their experience and energy lead to an upturn in productivity, unimpeded by some of the negativity demonstrated by bonus-driven production staff, threatened by perceptions surrounding future change. These PPD's were interested in the job and enthusiastic to confront the challenges of making the process work.

8.5 Impediments to the process of change

There are many cautions that need to be evaluated in anticipation of implementing underground automation. Some of these have been identified in previous sections; others are identified in the following table (18) that describes some of the overall automation sensitivities and issues around that automation implementation.

Issue	Comment
Profits or safety challenges	Profits are mandatory to justify the initial installation under capital rules, and requires an honest evaluation of all of the benefits.
Paradigm shifts	Operator responsibility and desire for automation observation needs to end after the machine is turned over to automation
Incentive systems	Many systems defeat the intent of automation since the assessment of the productivity is not tied to quality and representative costs
Machine / operator mapping	New skilled operators will not have the same manual operator's one-to-one mapping, rather the machines will likely be queue allocated.
Cross-machine training	Operators will need to operate many similar machines, the interface for each will need to be tailored to minimize differences
Management	Mining communities are seldom united in the embracing of technology; encouragement of technology and change will be required.
Optimization of the process	Integration of the automation with the information systems will dramatically increase benefits; enthusiasm must be supported until "the job is done"

Table 18: Impediments to the change of mining process

The mining community was one of the last to make significant change in the embracing of technology. Gradually the paradigm has shifted to encourage better planning and scheduling of processes and activities. As this shift occurred it became more evident that the benefits associated with the sharing and consolidation of data would provide gains in productivity and long-term profitability. Previous paradigms had much of the day-to-day planning based on tactical goals with little regard to strategic impacts. Using communications and automation will provide a better handle on the real issues in the future, as a better decision process evolves.

8.6 System limitations

The methods and equipment used in underground hardrock mining have not changed significantly over the last few years. It can be assumed that most of this "stall" in the process of change is based on the attempts to evaluate and "get comfortable" with the automation processes recently created. To be able to take the next step in evolution will require an industry-wide desire to create new machinery and equipment (and possibly implement those in the creation of new mining methods). Since this will require fundamental changes, creating machines that will integrate the automation into the machine at the manufacturer's plant, the manufacturers will be called upon to invest heavily. These costs will be difficult for suppliers to accept unless the mining community demonstrates commitment to the concepts of automation and forms alliances with its equipment suppliers to define and forecast automation equipment needs. As well, the users will need to create common standards and direction to focus suppliers into supplying a more uniform offering to the automation marketplace.

Another mine-related impediment is the long-range nature of the mining cycle. Typically mining plans and preliminary development are completed too far in the future to be able to integrate the newest techniques. This often impedes the implementation of new techniques and stifles the creation of new technology and methods based on issues and decisions previously made.

Other challenges in the mining industry relate to the fact that financial decisions are based on known methods to get a known (or anticipated) return. The commodity price unknowns caused by the variance implicit in a world-based mineral economy further complicate this. Conservatism and a tendency to approach the mining in a manner that will offer results with the fewest risks and unknowns (a dependency upon historical methods rather than newer options) is also a strong deterrent to implementing change.

9.0 DISCUSSIONS AND RECOMMENDED SOLUTIONS

9.1 Mining Systems

This document has traced the evolution of the underground hard rock mining methods and the LHD, including methods made possible as a result of the development of the LHD machine. Its refinement has allowed the mining community the benefit of an important and efficient tool, based on which mining methods have also changed. The results are machine and mining method combinations that have been optimized for each other. These combinations, and the LHD's agility and capabilities, have also diminished the impact of many single points of failure in the load, haulage and dump portions of the underground mining cycle. The use of the LHD is able to compensate for many impediments that previously would have halted production.

The increased capabilities of the LHD, especially the viable automation assists, will be useful tools in the future of autonomous haulage systems. The proliferation of the LHD and its increased capabilities, has increased the likelihood for greater use in future mine applications. The integration of these machines into the mining process, required to optimize the effectiveness of the tools, has not been clearly defined nor fully accomplished. Efforts to-date have been guided towards solving tactical problems, in part due to the mining community's approach of defining the machines rather than the process. The casual grouping of operator, machine, technology and mine does not create a system. Instead, without the necessary integration, the result is a stressed and complicated island of automation that sub-optimally contributes to the mining process. The effective integration into the mining community and processes has started, however the commitment of significant effort will be required to complete the task. The rewards, while not proven yet, will be worth the effort with increases in the safety of the mining personnel, economies of scale and better returns.

9.2 Recommended solutions

Based on the use of these automation and communications techniques, surface operators are successfully operating drills and LHDs from surface control stations. These machine operators have embraced the automation technology in a positive manner and appreciate the flexibility and convenience that the process offers. As outlined above, the balance of the effort required to take

advantage of all of the automation benefits will require significant effort. With the fundamentals of machine automation already accomplished, the next steps will tie the machines into automation cells, the automation cells into automation systems, and automation systems into automated processes. These changes will require effort that may not be well received by the mine operators, since the gains will not be immediately available. Unfortunately, the typical operator is primarily interested in the immediate bottom line and short-term goals. It is hoped that the support of the head-offices and mine consortia will be forthcoming and that the required systems, software and hardware, will be developed. These tasks have industry-wide applicability and will not assist individual operators; rather the effect will be to "level the playing field", increasing industry-wide the returns available from their ore bodies. As well as the mining benefits, the health and safety benefits associated with fewer and safer underground workers will contribute to the mining industry as a whole.

9.3 The Future

The Inco Sudbury automation program represents a situation where the results of research and development have been successfully applied in actual mine production environments. Based on the definition of the communications and the successful applications of automation, not only are the automation systems capabilities being advanced, but so too are the designs and performance of the new machines on the part of the equipment manufacturers.

With the majority of Inco's Sudbury mines equipped with communications networks, and extensions in place to a central control center (MOC), it is expected that significant changes will be possible in the near future. The number of cells of automation will increase as the various mines take advantage of the automation of parts of their processes. This will possibly take the shape of extended teleoperation and remote diagnostics from the MOC. With the increased quantity of machines involved, the development of sensors and actuators to allow the longer and more distant operation of the automation cells will be encouraged. Coupled with a forecast availability of alternate power sources with longer useful life becoming available, the time between visits and service opportunities will increase. This will guide and encourage changes to the machines and process accessories.

As local efforts become increasingly successful and simple to implement, it would be anticipated that further studies and tests will see application of these techniques into much longer distance automation

efforts. Locations such as Voisey's Bay mine and the Indonesian mines will be logical recipients of increased automation due to their relatively remote geographical locations. To be successful with these sites will require further refinements to the communications methods and automation techniques. The longest links tested for teleoperation have been to Toronto and Montreal. The delays and latencies in those links were within the capabilities of the operators. As distance increases the communications timing increases, especially significant in the case of satellite links that are significantly longer than landline links. It is expected that there will be a limit to the ability of the tele-operator to accommodate latency in the control loop due to communications delays.

The limit for operator acceptance of delay, when reached, will require the application of results from the automation and mining community research regarding unsupervised task deployment (for example, load a bucket and then wait for confirmation of permission to tram). This will require that the tasks of the automated system become logical entities or subcommands, available for initiation by the central control facility. Once a set of subcommands become reliable and available, the orchestration of the process will become a task list that is executed, in association with permissives from the safety systems at the mine-site.

Additional changes that will create the benefit in the future will come about based on the continuous re-evaluation of the "current state of the art". The use of new technologies allows core assumptions to be questioned and perhaps changed.

Examples of automation and personnel-free mining will produce a new suite of method/technology pairs that will take safety and productivity into the greater return and capability. The machines of the future will likely be supplied in an automation-ready format from the manufacturer. This will assist the introduction and integration of the machines into the mines by giving the mine operators the confidence that single-point responsibility offers.

10.0 CONCLUSIONS

The LHD has established itself as one of the significant workhorses of the underground community. Its evolution has been keyed and focused on specific tasks for which it has become well suited. The LHD was a critical component in the creation and refinement of several underground hardrock mining methods. These methods, made feasible by the LHD, were the triggers for further changes and increased abilities for the LHD. It has allowed the replacement of many smaller and more labour intensive machines, and joined with other automation initiatives to meet the goals of productivity and improved safety. The future expectation would be to increase the automation and integration of the LHD into the process of underground hardrock mining.

The results of Inco's Sudbury automation efforts program represent a situation where the results of research and development have been successfully applied in and benefited actual mine production environments. Based on the integration of communications to successful applications of automation, not only are the automation systems capabilities being advanced, but so too are the designs and performance of the mobile machines required from the equipment manufacturers.

By the early 1990s, these changes had created a modified LHD and mining methods. These changes were appropriate for the implementation of the automation techniques that are necessitated by safety and manpower challenges in the Canadian mining industry. Together these changes integrate into automated mining technology that will be part of the fundamental building blocks required to assure the viability of underground hardrock mining in Canada well into the next century.

The future will see mining areas where operators will enter such as the moon, undersea, and waste dumps. The challenges met by the automation of the LHD will be directly applicable to these tasks. With these tools, after the integration of the processes, we will have completed a segment of the Digital Mine²⁴ of the future.

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