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Automation of the Longwall Mining System

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16. Abstract

The longwall automation study presented in this document is the first phase of a study to evaluate mining automation opportunities. A similar analysis on the room and pillar system will be conducted in the second phase of the automation effort. The mining automation evaluation is part of an overall effort to identify and develop innovative underground coal extraction systems.

In conclusion, it is recommended that the shearer operation be automated first because it provided a large number of other sensor inputs required for face alignment (i.e., shields and conveyor). Automation of the shield and conveyor pan-line advance is suggested as the step since both the shearer and face alignment operations contributed the greatest time delays to the overall system downtime. Therefore, automation of these areas first would allow a more rapid payback on the R&D investment. It is finally suggested to complete the total automation effort with installation of management information and fault isolation systems.

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ABSTRACT

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The objective of the study was to identify cost-effective, safe, and technologically sound applications of automation technology to underground coal mining. The longwall analysis commenced with a general search for government and industry experience of mining automation technology. A brief industry survey was conducted to identify longwall operational, safety, and design problems. The prime automation candidates resulting from the industry experience and survey were: (1) the shearer operation, (2) shield and conveyor pan-line advance, (3) a management information system to allow improved mine logistics support, and (4) component fault isolation and diagnostics to reduce untimely maintenance delays. A system network analysis indicated that a 40 % improvement in productivity was feasible if system delays associated with all of the above four areas were removed. A technology assessment and conceptual system design of each of the four automation candidate areas showed that state-of-the-art digital computer, servomechanism, and actuator technologies could be applied to automate the longwall system. The subsequent health and safety evaluation of the automation candidates projected: (1) a major improvement in reducing exposure to respirable coal dust by removing the face crew to a remote location, and (2) a possible overall reduction in disabling injuries of 23%. The final cost benefit analysis of all of the automation areas indicated a total net national benefit (profit) of roughly $200 million to the longwall mining industry if all automation candidates were installed. This cost benefit represented an approximate order of magnitude payback on the research and development (R&D) investment.

In conclusion, it is recommended that the shearer operation be automated first because it provided a large number of other sensor inputs required for face alignment (i.e., shields and conveyor). Automation of the shield and conveyor pan-line advance is suggested as the step since both the shearer and face alignment operations contributed the greatest time delays to the overall system downtime. Therefore, automation of these areas first would allow a more rapid payback on the R&D investment. It is finally suggested to complete the total automation effort with installation of management information and fault isolation systems.

FOREWORD

The JPL Advanced Coal Extraction Systems Project is part of a program to develop advanced mineral extraction systems. Automation of underground coal mining equipment is one research task under the Advanced Coal Extraction Project. This document, the first of two reports resulting from the coal automation task, provides the results of a longwall automation evaluation. The second report will present the results of a room and pillar continuous mining automation evaluation. The research was sponsored by the Division of Coal Mining, United States Department of Energy, through an interagency agreement, NASA Contract 7-918, with the National Aeronautics and Space Administration (DOE Contract No. DE-AI01-76ET12548; Task RE 152, Amendment 90). Ralph Avellanet, Deputy Director of the Divison of Coal Mining, is the project officer.

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SECTION I

INTRODUCTION AND SUMMARY

A. OBJECTIVES

The Jet Propulsion Laboratory (JPL), sponsored by the U.S. Department of Energy (DOE), Division of Coal Mining, was asked to identify and develop cost-effective and technologically sound applications of automation technology to underground coal mining. Ultimately, plans are to be developed that provide a step-by-step approach for automating longwall and room and pillar continous mining systems that are practical and useful to the mining industry. This report evaluates and ranks several automated functions and provides an estimate of benefits and costs of technology development.

To meet the objectives, the study used: (1) the longwall mining guidance and control system work conducted by the NASA Marshall Space Flight Center (MSFC) for DOE; (2) existing automation work done by the mining industry on longwall, continuous miner, roof bolter, and shuttle car systems; (3) the system modeling and evaluation tools developed by JPL under the Advanced Coal Extraction Systems Project; (4) automation technology advances developed at JPL; and (5) an assessment of useful automation and remote control technology advances available in other industries. This document, the first of two external reports, identifies the most likely automation areas for a longwall mining system.

The following sections discuss the major assumptions which form the foundation of the study, the constraints under which the study was performed, and a summary of the results of the analysis. Finally, a brief statement of the general structure of the document is provided to assist the reader.

B. ASSUMPTIONS AND CONSTRAINTS

Although several different approaches were used to establish the best opportunities for automating the longwall system, the final ranking of the automation areas and measure of benefit to industry was based on an economic analysis. The cost benefits were calculated in 1982 dollars. It was assumed that all supporting reference material for the cost benefit calculations obtained from the Department of Energy, other government agencies, and industry was reasonably accurate. In addition, it was assumed that once the automation candidates were selected, a successful R&D effort would follow so that eventually all the automation opportunities would be incorporated by industry. This was a necessary assumption in order to: (1) realize the total cost and cost benefit for automating the complete system, and (2) retain continuity of the analysis and not attempt to second-guess each mine operator's equipment configuration preferences.

In addition, several ground rules evolved from sponsor requests and time and budget considerations. First, the DOE Division of Coal Mining requested that the longwall study utilize the production projections provided by the Energy Information Agency in 1981. Second, the sponsor indicated a desire to limit the market impact analysis to the U.S. coal industry. Third, although the user requirements revealed a need for automation concepts which encompassed state-of-the-art developments as well as evolving technology, the sponsor requested that the study only consider candidates which utilize existing technology and could be incorporated in the near term (i.e., 1984-1986 time frame).

The user requirements developed to identify the desired automation areas depended partly on a survey which included equipment manufacturers and designers, mine managers, equipment operators, and maintenance personnel. Although it would have been desirable to have interviewed more individuals in each group, project funding and milestone commitments constrained the scope of this survey. Although the number of individuals interviewed was limited, the consistency of the answers increased our confidence in the results.

The final major constraint revolved around the longwall network analysis developed as a tool to assess potential automation impacts on productivity. Again, project funding level and milestone commitments prevented the development of a longwall probabilistic PERT network similar in sophistication to the current KETRON Room and Pillar Critical Path Model. Because of the lack of an equivalent longwall critical path model, a deterministic network was developed using KETRON longwall industrial engineering data. The resulting network provided adequate detail to establish the critical path and assess the impacts each automation candidate would have on productivity.

C. SUMMARY OF PREVIOUS WORK ON LONGWALL AUTOMATION

The potential for automating longwall mining components has been widely examined from both a micro and macro system viewpoint. For example, at a micro level research has been conducted toward the development of proper motion and spatial sensors for guiding and controlling the longwall shearer. At the macro level, several studies have been completed which examine the feasibility and productivity benefits of automating the longwall mining system. This section provides a brief review of some of the well-known technical developments and studies at both the micro and macro system levels.

Mining industry experience has indicated several areas where automation could enhance longwall machine operating efficiency. One major area of concern has been the problem of controlling the amount of coal remaining on the roof after the shearer has made a cut. Of equal concern is the opposite problem of cutting rock along with the coal. The Bendix and A.D. Little studies of longwall system operation suggested that these areas were major contributors to low face production (1, 2). Industry has responded to these problems through several developments. One technological development that has appeared promising is the natural radiation background sensor. This system allows the coal thickness above the shearer to be measured (and maintained as the shearer cuts) using the natural background radiation of the above strata (3, 4). Other similar applications of technology include the use of acoustics and the "sensitized pick" for seam thickness measurement and coal/rock interface detection (5, 6). The whole thrust of the above technologies has been to provide more accurate information about seam characteristics to the shearer operator so that he can cut the maximum amount of coal with each pass. One important aspect of plotting and controlling the path of the shearer as it traverses the face is locating its position as the seam undulates. Lasers are presently being employed to allow the last cut to be duplicated based on locating the shearer position relative to seam dips (7, 8).

Industry experience has also indicated that face alignment problems have contributed to many conveyor and panline failures. One example of the mining industry's response to this problem is the yaw measurement sensor developed by the Benton Corporation. This sensor measures angular deviations in the panline and transmits information about the straightness of the face to the operator. As an adjunct to all of the above research, the NASA Marshall Space Flight Center Longwall Program tested the performance of several shearer and conveyor sensors, and then examined design problems associated with retrofitting the shearer and conveyor with the most promising sensors.

In the area of longwall shield operation it appears that low coal conditions inhibit the support operators from keeping pace with the shearer. The remote shield operation system designed by Eickhoff is another good example of applications of automation to the longwall system (9). A microprocessor system, which stores sensor inputs on the position of the shearer loader, transmits pulses to the shield control device to serially activate each set of shields as the shearer passes (9). Up to 200 support units are controlled by one microprocessor.

The above discussion on automation research at the micro (component) level is not intended to cover all the developments in sensor, guidance, and control technology. For the purpose of this study, it sufficed to simply understand state-of-the-art component automation well enough in order to establish conceptual designs for various automation options. Using tested technology in the conceptual designs confirmed the feasibility of incorporating various automation options and also allowed the research, development, and capital investments to be approximated.

At the macro (system) level, several studies have been done on the potential impact of longwall automation on productivity. Two major system studies were performed by Skelly and Loy and COMINEC (10, 11). The results of the Skelly and Loy study suggested that a 60% increase in productivity was feasible if both the shearer and face advance systems were automated. The productivity increase stemmed from: (1) a projected improvement in the shearer traverse speed (caused by not having the shearer and conveyor speed paced by operator mobility); (2) a reduction in face personnel, therefore allowing the productivity per man to increase; and (3) alleviation of trim cuts caused by poor face alignment (10). The Skelly and Loy study also suggested an environmental and equipment monitoring system be employed since there would be no face personnel present to monitor methane emission and equipment failures (10).

The COMINEC study similarly projected a 60% improvement in productivity (11). As with the Skelly and Loy study, the COMINEC analysis suggested major increases in productivity through shearer and shield automation. The COMINEC analysis also indicated that shearer efficiency could be increased by incorporating a coal-rock interface detecting system (11). The COMINEC study examined other sources of operational problems revolving around operators and mine management. The resulting recommendations included: (1) an educational program on equipment operation, and (2) development of a computer simulation to optimize system design and predict productivity improvements (11).

It is interesting to note that the results provided in this document, although derived independently, are essentially the same as both the Skelly and Loy and COMINEC studies. The major differences between the results provided in this document and the other studies stem from the depth of the cost benefit and safety analyses. For example, this document considers: (1) time of market penetration, (2) long-term national coal demands, and (3) expected longwall growth as key inputs to the cost-benefit calculations. Similarly, the safety analysis draws on detailed historial injury and worker activity data to project the safety impacts. Overall, it appears that the results provided in this document serve to enhance and extend the findings of previous longwall automation studies.

D. SUMMARY OF EVALUATION APPROACHES AND RESULTS OF ANALYSIS

1. Summary of Evaluation Approaches

Several steps were required to identify potential areas for automation, establish the appropriate sensor, guidance, and control technology, and determine productivity impacts and cost benefits, namely:

(1) Identification of automation opportunities.

(2) Network analysis.

(3) Automation technology assessment.

(4) Cost-benefit projections.

The following discussion summarizes the approach used in each step of the analysis.

a. Identification of Automation Opportunities. The state-of-the-art assessment consisted of developing functional descriptions for each major component in the longwall system, followed by conducting an industry survey of equipment manufacturers and designers, mine managers, and miners. The functional description provided information on mining operations, the present degree of system mechanization, and operations potentially amenable to automation. The survey confirmed the system operational and functional descriptions, and provided valuable information on problem areas where automation could enhance productivity or improve miner health and safety. These findings formed the basis for determining the automation opportunities. The other considerations were: (1) the previous experience obtained from the NASA Marshall Space Flight Center longwall sensor program and automation experience; (2) consideration of potential costs, increases in system complexity, and decreases in reliability; and (3) health and safety impacts based on the major historical longwall hazards.

b. Network Analysis. A detailed longwall operational network was assembled based on the functional analysis, industry inputs, and additional industrial engineering data obtained from the KETRON longwall study. The industrial engineering data were crucial to understanding system delays which detracted from production time, but had potential to be streamlined with automation. Once the automation opportunities (developed from the considerations summarized above) were reflected in the form of appropriate delays in the network, an estimate of potential increase in productivity was obtained. This estimate became a pivotal variable in the cost-benefit assessment.

c. Automation Technology Assessment. The technologies required to implement each automation opportunity were identified. This effort included an investigation of appropriate sensor technology, development of mathematical models for each affected system component to establish the location and data feedback for each sensor, and conceptual design of guidance and control systems. The technology assessment included preliminary cost estimates and schedules for developing the various automation candidates. Mitigation of potential health and safety hazards was also part of the technology assessment. This was done by considering how each area automated would reduce worker exposure to hazards (e.g., through removing the worker from a proven hazardous area or by providing more protection). A projection of the expected reduction in serious injuries was then made and converted into potential cost savings.

d. Cost-Benefit Projections. Costs and benefits were established for each automation opportunity by comparing the projected productivity improvements against capital and operating costs. Other variables derived from health and safety impacts, market potential, and market penetration rates were also factored into the final cost benefit calculation. The automation opportunities were then prioritized to allow formulation of a development plan.

2. Results of Analysis

The automation candidates were derived by integrating the findings of the NASA Marshall Space Flight Center longwall sensor development program, the user needs as identified by the industry survey, considerations of excessive costs or system complexity, and potential health and safety improvements. The following resulting automation opportunities are summarized as follows:

(1) Shearer automation (cutting, face aligment, coal-rock interface detection, last cut memory, shearer arm articulation, and tramming).

(2) Shield advance (remote operation or semi-automated).

(3) Conveyor and pan-line advance.

(4) Computer monitoring (information management for sources of system delays).

(5) Preventive maintenance system (fault isolation and failure diagnostics).

(6) Face sensing ahead of the shearer (to detect hard rock partings).

(7) Remote seam mapping (as related to mine planning and development).

(8) Semi-automated movement of equipment components to a new panel.

As stated earlier in Section I.B, one of the study guidelines was that the longwall automation study consider only those opportunities which could be incorporated in the near term using state-of-the-art technology. The technology assessment of both existing and evolving automation indicated that only the first five of the above areas would fit the near term category. These five areas (shearer automation, shield advance, conveyor/pan-line advance, computor monitoring, and preventive maintenance) became the focus of the automation study.

Once the sensor, guidance, and control technologies were identified and conceptualized for each automation area, approximate development costs for implementation in commercial longwall systems were estimated. The costs and benefits were then calculated using the net dollar worth of improved productivity, minus the capital and operating costs. Miner health and safety, the other major areas impacted by automation, were also quantified where possible. Table 1-1 provides a summary of the quantitative and qualitative benefits in the areas of productivity, health, and safety.

Table 1-1 shows that the smart (remotely operated) shearer and shield/conveyor opportunities are the most promising of the five automation options. This is because the largest system delays are associated with the shearer, shields, and conveyor, and these components have the largest impact on safety and productivity. The above results do not imply that the remaining automation options should not be pursued. Once the appropriate sensors and data retrieval systems are built into the shearer, shields, and conveyor components, the benefits associated with the management information and fault isolation options will also be realized. In conclusion, the recommended development program for longwall automation has three thrusts:

(1) Pursue the development of sensors, data retrieval, guidance and control technology for the smart (remotely operated) shearer, since the shearer is a pivotal component which controls the position of the shields and conveyor.

(2) Develop the additional sensors (e.g., shield-to-shield alignment), guidance, and control technology required to automate the shields and conveyor pan-line advance.

(3) Utilize the sensor feedback information from the face components and add the desired additional sensors and feedback linkups for the computer monitoring and fault isolation options.

E. STRUCTURE OF DOCUMENT

Section II provides an introduction to contemporary longwall system components and operation through a detailed discussion of system architecture, interaction of components during operation, and other support activities.

Table 1-1. A Summary of Total Longwall Automation Benefits (1989-2000)

Opportunity	Productivity ($1,000,000)	Safety ($1,000,000)	Safety (Injury Reductions)	Health[a]
Smart (remotely-operated Shearer	158	7.7	385	+
Automated Shearer	48	2.3	114	+
Shields and Conveyor	124	8.3	416	+
Computer Monitoring	28	0	0	0
Fault Isolation	0	0	0	0
Combined Automation (all of the above)	199	13.7	683	+
Smart Shearer/Shields/ Conveyor	193	15.1	753	+
Smart Shearer/Shields/ Conveyor/Computer Monitoring	226	15.1	753	+

[a]A plus (+) indicates an improvement in health conditions by reducing worker exposure to dust.

This information forms the basis for understanding the key areas where automation could enhance system operation. Section III develops the automation opportunities based on NASA Marshall Space Flight Center longwall experience, industry survey, cost and complexity considerations, and health and safety impacts. Once the basic system components, operations, and automation areas are identified, the productivity, technology assessment, health and safety, and cost benefit aspects of the study are developed. In preparation for presentation of the final study results, Section IV briefly introduces the evaluation tools used in each aspect of the study to allow the ultimate ranking of automation opportunities. Section V then provides the detailed results of: (1) the network and productivity analysis, (2) the automation technology assessment, (3) health and safety evaluations, and (4) the cost benefit analysis. Section VI presents a recommended plan for implementing the automation opportunities, based on the results presented in Section V, and also provides concluding comments on the overall study with a detailed summary of the results. Supporting data for the analysis are provided in the Appendix.

SECTION II

DESCRIPTION OF THE CONTEMPORARY LONGWALL SYSTEM

A. OVERVIEW

The longwall coal mining method is a combined system of excavation, roof support, and bulk material handling across a wide coal seam face (12). Although the method can be adapted to seams sloped as much as 45 deg or more, the usual application in the United States is in flat or nearly flat coal seams. Given a good match between mining conditions and selection of mining equipment, the longwall can produce as much as 1,000 tons per operating hour. The long-wall section crew is ordinarily composed of 10 or 11 miners.

Longwall mining requires the development of a rectangular panel in the coal seam, with the narrow side as the excavation face. Face dimension varies from 400 to 800 ft. The longer side of the panel, running between sub-main or main entries, ranges from 2,500 to 4,000 ft in length (12). Preparation of the panel requires end entries for starting and ending the extraction, and multiple side entries to accomodate worker access, ventilation, coal removal, and supplies. Panel entry patterns and supporting pillars vary according to the mining conditions encountered (13). In America, the panel is usually mined in a retreat mode. Retreat mining allows the roof to cave behind the protected face line of the longwall. The roof is supported mechanically with hydraulic self-advancing support structures (shields) immediately behind the coal excavation line. The successful and orderly collapse of the immediate roof strata behind the roof supports is critical to the safe and efficient operation of the longwall. An array of mining system hardware, sub-systems and equipment components is available from both European and American firms. The two well-developed longwall excavating systems presently in use are the plow and the shearer. The plow is basically a line of blades which are dragged bi-directionally across the face. The shearer is a cutting drum which is moved across the face, cutting a web 28-30 in. deep. The cutting drums can be mounted at each end of a chassis, and can either be rigidly set in a vertical position or have ranging capabilities that elevate and depress the drum. Control of the horizontal speed of the shearer and the cutting height of the drums is the responsibility of the shearer operator.

The extracted coal is dropped onto a continuous floor-mounted chain conveyor haulage system. The conveyor structure also serves to support and guide the excavator, and provide an anchor point for the roof support units.

In this discussion the shearer (rather than the plow) will be used as the excavating component because it presently represents the most widely used longwall extraction device in America (12). The shearer described below consists of a double drum type with ranging arms and will travel across the face unidirectionally (since this configuration offers the most favorable way of controlling dust at the face). The shearer, its companion conveyor, the line of roof supports that protect the face area, and the crew constitute a system which, when complemented with support systems, allows the longwall system to operate. Inefficiency, poor productivity, injuries, dust problems, and equipment breakdowns sometimes result from the cramped quarters and poor visibility. The following sections examine each of the system components in detail and provide the foundation for the automation considerations developed later in the document.

B. SHEARER OPERATION

The dual-drum shearer is designed to do two things as it traverses the longwall face: to cut coal from the seam in a 30-in. deep vertical slice from a selected upper limit to a lower limit near the bottom of the coal seam, and to load the cut coal onto the chain conveyor (12). The shearer is operated by converting electrical power from a transformer to a gear or hydraulic motor drive. The dual-drum shearer is capable of varying travel and drum cutting speeds.

The dual-drum shearer can cut coal in seams as thick as 18 ft. Ranging arms, which elevate and depress the drums, enable the shearer to change drum cutting postures, thereby allowing bi-directional movement. The drum leading in the direction of shearer travel usually cuts to the upper limit while the trailing drum cuts to the lower limit. These limits are determined and adjusted by two operators, who accompany the shearer as it moves along the face. Each operator also controls the position of the drum cowling, which helps direct broken coal toward the face conveyor. In bi-directional practice, the cowls are repositioned when the cutting direction is reversed. The following discussion demonstrates shearer operation as it is commonly practiced in the United States.

The operating pattern of the double-drum, shearer, and loader calls for a cut across the entire face. Although the depth of cut is limited by drum dimension, a shallower cut depth can be achieved by changing the position of the face conveyor structure that supports the shearer. Detailed attention is given to face alignment normal to the entries on either side of the panel as well as linearity, because severe stress is placed on the shearer and conveyor components if the face is not straight (12, 13). In addition, production is adversely affected if clean-up (alignment) cuts are necessary. The operators position the drums, cowls, and water sprays, prior to starting a face pass. The major operator concerns are:

(1) The shearer travel rate as judged by the power draw, volume of coal leaving the face, and coal lump size.

(2) Roof and floor cut limits and adjustments.

(3) Condition of the freshly exposed roof.

(4) The dust condition.

The shearer generally cuts and loads at 10-12 ft/min. The full face pass ends when the leading drum breaks into the far entry (tailgate). At that point, the operator backs off the shearer, lowers the leading drum, and cuts the short bench segment of coal that the trailing drum could not cut. The shearer then retreats (flits) toward the starting gate until it arrives at a point some 50-100 ft from the starting entry (headgate). The trailing drum is raised to the upper position and the shearer cuts the top coal into the headgate entry to prepare for another pass. Meanwhile, the entire conveyor pan-line is moved in position against the freshly established face in preparation for another pass. These periodic shearer stops at the headgate or tailgate offer the best opportunity for maintenance or inspection.

C. ROOF SUPPORT OPERATION

Roof support (shield) operation is a parallel activity of the longwall system (14). While the shearer and the chain conveyor components provide for the removal of the coal from the face, the roof supports allow the system to retreat or advance. The supports shield the operating personnel and equipment from roof falls.

The roof supports are hydraulically lowered, advanced, and raised against the exposed roof by a support operator to allow the freshly exposed roof to be supported as closely as possible to the working face. The shield move is initiated after the shield canopy is lowered hydraulically. A hydraulic ram fixed to the support base pulls the shield forward across the floor. When the new face alignment is achieved, the operator raises the canopy by activating the cylinders carefully to avoid disturbing the roof. This series of steps can be initiated as soon as the shearer has passed the shield (14).

The conveyor positioning maneuver is done by thrusting the pan components forward in conjunction with shield advance after the shearer has passed.

The rate of shield and conveyor repositionings is determined by the rate of shearer cutting and loading. This rate varies with seam height, efficiency of the operation, and operator judgment. Shield movement time ordinarily ranges from 8 to 10 s, and permits a support operator to maintain pace with the shearer. In low coal (less than 48 in.), the face line may be worked by two shield operators to reduce some of the physical stress of following the shearer. Controls for each shield, or for a group of shields, are mounted on the adjacent unit on the supply air side, so that when the shield move is started, the operator is placed in a safe area where there is less dust.

The support operator's console includes a hydraulic supply system pressure gauge, a valve block having independent adjustable pressure relief valves for each cylinder, main support activity valves, a face conveyor ram valve and a valve for any canopy extension control. If mining conditions require, the mine operator may incorporate optional capabilities and controls to establish enhanced side shielding, face shielding, and horizontal steering assistance.

Supports may be also placed at both ends of the pan-line in the gate entries to protect power components such as the conveyor drive, the gear reduction units, the head and tail pulley assemblies, and the chain tensioning device. Often these additional supports are fitted with hydraulically activated canopy extensions to provide greater protection at the critical face-gate junctions. In some conditions, roof supports may be deployed fully across the entries to protect against roof or rib collapses caused by stress buildup in the overburden.

D. FACE CONVEYOR OPERATION

The chain conveyor is the unifying element in the longwall system. It guides the shearer and removes the sheared coal (12). It is positioned in its working place by the roof support shields, and in turn provides anchorage for moving the shields. The shearer operator often relies on the conveyor's position to obtain a reading on face alignment. Also, the productivity of the operation is gauged by how much coal the conveyor is carrying.

The chain conveyor unit is composed of a core component which is a wide H-section pan, usually open on the bottom, and a septum which supports the coal-carrying upper flight and guides the flight bars of the haulage chain. The conveyor run is formed by joining all the individual pan units, each approximately 5 ft long, so that each corresponds with the width of a roof support shield. The pans are closely joined with couplings and pins that maintain alignment while allowing a few degrees of horizontal and vertical movement between pans.

In operation, the pans remain in their "cutting pass" position until the shearer returns to the headgate. As soon as the shearer flits back toward the headgate, the pan-line is snaked to its new position near the face, ready for the next shearer cut cycle.

E. OTHER COMPONENTS

Several lesser subsystems complement the principal components of the longwall mining system. The following sections describe these necessary subsystems (12). The group excludes basic services such as electrical supply and distribution, ventilation, transportation, water supply, and communications which are common to all underground mining systems.

1. Hydraulic Supply Sub-system

A constant supply of oil-water emulsion is provided to the mechanized roof-support group by a skid-mounted power pack, usually placed in the headgate. The pack serves as reservoir, emulsion controller, filter station, and pump station for the closed loop that serves and interconnects the roof shields. The hydraulic supply sub-system is a fail-safe design in that the supports will remain locked in place if a supply pump or hydraulic line fails.

2. Stage Loader

The stage loader is a short, heavy-duty chain conveyor positioned perpendicular to the face at the headgate end of the face conveyor. The stage loader accepts coal off the face conveyor and redirects the coal down the adjacent entry toward an outby dumping point. The stage loader width and travel rate are often greater than the face conveyor so that it can contain coal surges from the face. The unit moves in step as the longwall shearer and face conveyor are positioned.

Because the stage loader is designed to contain coal surges, it offers a convenient location for a coal breaker. The breaker provision is widely accepted as the necessary means to size coal ahead of conveyor loading to prevent belt damage. The lump breaker is positioned on the stage loader astride the coal flow. Large lumps of coal are mechanically broken as they approach on the loader pan.

3. Temporary Roof Support

The head and tail gate areas are generally zones of maximum roof stress, and require placement of supplementary roof support to maintain roof integrity and geometry. Temporary roof support is typically accomplished via the use of hydraulic props, sometimes supplemented by timber cribs. Cribs are normally constructed by stacking timbers in a vertical box configuration between the floor and ceiling. The hydraulic prop is a metal column which is used as supplementary and temporary roof support. It is manually placed and activated by a hand-pump. A range of sizes and load-bearing capacities (commonly 10-40 tons) is available.

The preceding description was used in constructing a baseline operating scenario for longwall systems in the United States. This baseline scenario was employed in the identification of potential automation areas, development of an operational network to assess productivity impacts of automation, development of automation technical concepts, and cost-benefit projections. Each of these areas is discussed in greater detail in the following sections.

SECTION III

IDENTIFICATION OF AUTOMATION OPPORTUNITIES

A. OVERVIEW

The preceding section provided descriptions of the complete longwall system, the operating cycle of each of the major components, and potential system problems, and established a basis for structuring the approach to identify and develop automation options. The first step was to examine existing efforts to automate longwall systems, particularly the NASA Marshall Space Flight Center (MSFC) longwall study, and utilize this research experience to identify non-problem and problem areas. The second step was to survey the mining industry to confirm initial estimates of problem areas and obtain additional information on operation and maintenance problems that could possibly be solved by automation. Potential longwall cost impacts and system complexity were the next considerations for establishing automation opportunities. In the third and last step, potential automation opportunities for reducing worker exposure to hazards associated with longwall systems were identified. The results of these efforts are presented below.

B. RESULTS OF THE MARSHALL SPACE FLIGHT CENTER LONGWALL DESIGN EFFORT

1. Identification of Non-Problem Areas

Review of the MSFC longwall study suggested three main areas where automation was not particularly advantageous. First, operators apparently do not have a problem with roll. This stems primarily from the relatively slow rate of advance, thus allowing sufficient time to compensate, and the fact that some existing equipment already has hydraulic actuators built into longwall systems to level the machine. In addition, a slight amount of roll does not cause major machine stress or any reduction in shearer cutting efficiency. Second, the MSFC study pointed out that slight machine pitch does not particularly cause any operating problems. It is recognized, however, that major vertical undulations in the pan line do put stress on the conveyor. The third non-problem area involved identification of the coal-rock interface. If the operator is cutting up to the rock interface, the generation of sparks provides immediate identification of the interface. This area does become a problem if the operator wishes to leave coal on both the top and bottom.

2. Identification of Problem Areas

The MSFC study identified some major guidance and control problems with existing longwall systems. As stated above, under certain conditions, machine pitch and coal-rock interface location can be serious problems. In addition, the MSFC study suggested that machine yaw and cut following can lead to serious control problems, and can result in excessive stress on the pan-line and face conveyor. Not maintaining a straight line between the headgate and tailgate was recognized as contributing to roof control problems at the interface between the face and entries, and to interference between shields during shield advance. Cut following problems usually occur while cutting in thick seams where it is necessary to leave a certain amount of coal on both the roof and floor. These problems also occur when the operator attempts to cut around a parting in the coal. Improperly following each previous cut results in inefficient cutting, shield advance problems, and excessive stress on both the shearer and conveyor systems as the system gets out of alignment with each successive cut.

C. RESULTS OF THE INDUSTRY SURVEY

The survey sample was structured to obtain inputs from equipment and system designers, mine managers, equipment operators, and maintenance personnel. The equipment and system design organizations contacted were Joy Manufacturing, U.S. Steel Research, and Lee Engineering. The longwall mines contacted were Carbon Fuel #34, W. Va., Utah Power & Light (Deer Creek), and Utah Power & Light (Wilberg). These equipment and design companies were selected because they were either presently involved in longwall automation research, or had considerable knowledge of longwall mining and recent developments in automation. The longwall mines were selected based on personal contacts with individuals at the mine management level.

The survey questions were designed to identify major machinery design problems, guidance and handling problems, tasks or activities that are too demanding and therefore lead to operator or maintenance errors, and limitations of automation incorporation due to practicality (i.e., cost or system complexity) or non-acceptance by the worker. One overall result of the survey that lent weight to the acceptance of automation was a general consensus that there is a greater desire (sometimes due to corporate policy) to have more electronics and less hydraulics for system actuation. Apparently, industry experience suggests that electrical systems have greater reliability and lend themselves more readily to modular design and, subsequently, easier maintenance.

The number of organizations surveyed was small because of project funding constraints and the limited time available for project completion. However, the answers provided by the various participants were highly consistent. The following survey results are presented in a form similar to the questionnaire. A summary is provided at the end of this section to allow a comparison of the responses from the various individuals.

1. Results of the Equipment and System Designer Survey

a. Identification of Non-Problem Areas. Results of the equipment and system designer survey suggested that coal-rock interface detection was not a problem where operators remove coal up to the rock, because the cutter picks strike the rock and display easily visible sparks to the operator. This is consistent with the MSFC study results. The manufacturers indicated that they did not feel shield-to-shield alignment was a problem because it is generally easy to see when the shield pads are not parallel. Overall, the equipment manufacturers discouraged total system automation. The reasons for this were twofold: (1) total automation would considerably increase system complexity, and consequently, system cost; and (2) the increased system complexity most probably would cause additional maintenance downtime.

b. Identification of Problem Areas. There were several areas where the equipment manufacturers felt automation could assist existing longwall operations. The first areas identified were dust and methane control. The manufacturers were particularly aware of the problem present longwalls have with meeting the 2 mg/m^3 dust regulation. Removal of the operator and helper from the immediate face would allow compliance with the intent of the dust regulation, and concurrently decrease exposure to possible methane ignition. Other areas highlighted were equipment guidance and moving equipment from one panel to the next. Improper guidance and lack of appropriate support equipment for moving components result in considerable loss of production time. Associated with equipment guidance are horizontal and vertical alignment. These functions are presently performed visually, and reasonably well, by experienced operators. However, undulations in the seam aggravate these guidance problems. The manufacturers also indicated that a mine diagnostics and fault isolation system would greatly assist in reducing high maintenance downtimes. Two other relatively long-range areas considered as reasonable automation opportunities were remote roof quality sensing and remote seam mapping. These areas were suggested as important time savers for planning ground control schemes and mine development. A key equipment design concern apparent in the interviews was the need to include worker inputs on design problems so as to provide design changes that are useful and acceptable to the worker.

2. Results of the Mine Management Survey

a. Identification of Non-Problem Areas. The mine management interviews suggested two primary areas where operators do not experience major problems. The first area is machine roll. Apparently, the low machine advance rate, coupled with the availability of the hydraulically operated leveling device, reduces this problem considerably. Again, this is consistent with the MSFC findings. The second area is visibility. Although visibility of both the face and machine orientation is a problem associated with the dusty environment, it was felt that an experienced operator could compensate through having a good feel for the machine.

b. Identification of Problem Areas. Mine management identified several areas where automation, or remote control, could assist longwall operations. The first apparent area is dust control. As with the equipment manufacturers, mine management acknowledged the present problems associated with meeting the 2 mg dust standard. Another major problem area is the time involved in moving equipment from one panel to the next. The management suggested the design of smaller, more modular machinery. In the area of ground control, mine management recognized that the extremely variable nature of this task makes it difficult to automate. However, this is a major safety and time problem. They suggested some type of remotely operated self-advancing roof support for the entries interfacing with the longwall face (this suggestion also applied to room and pillar operations). Coal-rock interface detection was recognized as a major problem for machine guidance in thick seams. Management generally agreed that some type of fault isolation and diagnostics system would greatly enhance operation by allowing better scheduling of machine maintenance. Another recommendation addressed the problem of conveyor overload and damage due to oversized lumps of coal falling off the face. Management suggested a need to control the lump size through some type of automatic crusher. The mine management universally agreed that there was a great need for better remote seam mapping technology which would assist in mine planning and equipment selection. The last area addressed by management was miner acceptance of new technology. All of the managers cautioned against total system automation. The reasons for this were:

(1) Miners must perceive a need for a new system before they will effectively utilize it. This may take time.

(2) Trying to integrate a new, very complex system into the mine may exceed the present maintenance familiarity and knowledge of the miner.

(3) Results of the Operator and Maintenance Survey

a. Identification of Non-Problem Areas. The machine operators identified only one area as not being a major problem of the coal-rock interface. Apparently, operator experience with visually seeing sparks and feeling machine vibration are sufficient when removing coal up to the rock interface. In thicker seams, where coal is left on both the top and bottom, interface identification was recognized as a problem.

b. Identification of Problem Areas. In the area of machine control and guidance, the overall driving factor was productivity. Consequently, most of the problem areas addressed by the operators were generated from impacts on tons of coal produced in one shift. The operators generally felt that differences in operator experience and manner of operating the machine caused problems on a shift-to-shift basis. For example, one operator may not maintain face alignment, causing the next operator to have to make a clean-up cut. The net effect of this is a loss in shift production. Therefore, a means of standardizing machine operation seemed important. All operators indicated that dust generation was a major problem from the standpoint of health, and because it obstructed visibility of the face (causing guidance problems). The operators also stated that not maintaining face alignment could cause considerable stress on the conveyor system, resulting in machine downtime, and that system guidance and alignment was a problem when poor (soft) bottom conditions were encountered. Overall, the operators suggested that some assistance in shearer and shield alignment would help improve productivity and reduce stress on machine components, particularly the shearer and conveyor. Another problem area that surfaced was the need to have better knowledge of hard partings ahead of the shearer. This problem was cited as a large contributor to shearer damage and subsequent downtime. The operators also indicated that some type of feedback on machine failures (overheating, cutter pick overstress, etc.) would be useful to allow better control of cutting rates or alignment problems before the machine actually broke down, which would help reduce downtime. In the area of machine design, the operators suggested greater modularity and size reduction as a means of allowing easier machine movement and maintenance (again related to increasing productive time).

The inputs from the maintenance personnel revolved largely around reducing machine failures and subsequent downtime. As with the operators, suggestions were made to incorporate diagnostics and fault isolation, greater modularity, and reduced size for easier component handling and maintenance. All of the above suggestions were considered useful to the worker for improving productivity. Overall, the survey suggested that:

(1) Design improvements in the areas cited were acceptable to the operator and maintenance people.

(2) Although workers were interested in providing their experience to the designer, they did not feel a need to become involved in the redesign process.

In summary, it appeared that there was reasonable agreement between all or most of the parties concerning the following problem-solving suggestions:

(1) Remove the workers from dust and methane hazards in the environment.

(2) Maintain face alignment to increase productivity and reduce stress on machine components.

(3) Install diagnostics and fault isolation to allow better scheduling of maintenance.

(4) Provide a means to move equipment easily from one panel to the next (either through size and weight reduction, or self-contained motorized units).

(5) Provide for coal-rock interface detection in thick coal seams.

(6) Provide for remote seam mapping to allow better mine planning and equipment selection (such as locating rock intrusions in the coal seam or discontinuities in the overburden which could cause poor roof conditions).

D. SYSTEM COMPLEXITY, POTENTIAL COSTS, AND PRACTICALITY

Determining potential longwall automation opportunities was also examined from the standpoint of potential costs and impacts on system complexity. Both of these parameters operate hand in hand. For example, modeling results (Section V) indicate that total automation of the shield operation would require the development of a rather complicated 5-axis robot. The projected cost increase per shield (using known costs for existing robotic technology) is at least $30K. For roughly 100-120 shields (for a 600-ft face) the longwall cost increase in 1981 dollars would be $3 to $3.6 million. This does not consider the additional increases associated with other automation opportunities. This cost represents approximately a 30% increase in the cost of present longwalls.

Another area to consider is the labor efficiency of automation from the standpoint of classical man-machine tradeoffs (15). There are three basic man-machine systems:

(1) Uncompensated (man does all the information integration).

(2) Aided control (man and machine integrate information).

(3) Quickened control (total machine integration of information) (15).

Whether or not a system should be totally automated is determined by a measure of the input signal and output response of the system, resultant error, and impact of the error on the system. For example, the preceding survey indicates that total human integration of information on longwall operation is inadequate in that the resultant error in system alignment results in production inefficiency and possible machine system failure due to overstress. Therefore, these data suggest that an operator aided, or totally automated, system may be desirable. The degree of additional automation should be examined by first considering the advantages of total automation. Generally, quickened control systems are employed where:

(1) The task demands are greater than the operator can cope with.

(2) The task must be performed in an unacceptable environment for the operator.

(3) The resultant system error has catastrophic consequences.

(4) The allowable error is much less than the operator can insure.

(5) The operator is not required to be present.

For example, automatic pilot systems on high performance jet aircraft are a necessity to compensate for the relatively slow human response as compared to the demand for control of high speed aircraft. The potential error in not automating this system is catastrophic; both the pilot and the aircraft would be lost. This is not the case with guidance control on longwall systems. First, the longwall system operates and advances at a relatively slow rate. Second, an examination of the longwall operation and activity network indicates that workers must be present simply because many non-routine tasks are required (i.e., adjusting the conveyor, additional ground control, cleanup under the shearer, etc.). Classical human engineering principles suggest that if the human being must be present, then it is more efficient and cost effective to use the human's integrative abilities rather than the machine's, given that the potential impacts of a human error are not significant. In longwall operation, the only impact of a human error is loss in production time. Therefore, in view of the potential cost, the fact that none of the longwall activities and potential errors are of a critical nature (i.e., life and system endangering), and workers must be present, it appears that the best approach is to develop an aided control system. This approach is also consistent with the survey results, which indicate that workers desire aids to help them perform their tasks more efficiently, not aids that replace the worker completely.

E. POTENTIAL HEALTH AND SAFETY IMPACTS

The final aspect of determining automation opportunities concerned health and safety considerations. In the area of dust, longwalls presently do not conform with the 2 mg standard. Automation, or remote control, of the shearer and shields would remove both the operator and helper from the dust plume at the face. In the area of safety, the four major accident classes in order of severity, are: (1) handling material, (2) machinery, (3) roof/face/ rib falls, and (4) slips and falls. The bulk of the serious handling material injuries are associated with non-routine activities such as cleanup, handling supplies, and machine maintenance. Consequently, the more routine tasks which could be automated (such as operating the shearer, moving the conveyor, and advancing longwall shields), removing the worker from the hazards, would only marginally effect the total number of serious injuries. The major improvements in serious injury reduction through automation occur in the last three accident classes. The major causes of serious injuries in the machinery accident class are: (1) operators struck or caught while operating the longwall, and (2) operators struck or caught while advancing longwall shields. These two hazards cause 75% of the total disabling injuries. These same two hazards, along with being struck or caught while moving the conveyor, compose 24% of the roof/face fall disabling injuries, and 32% of the slip and fall disabling injuries. Overall, automation of the shearer, shield, and conveyor operations could reduce the average yearly longwall injuries by approximately 24%.

F. SUMMARY OF LONGWALL AUTOMATION OPPORTUNITIES

The final list of potential automation opportunities resulted from integration of all of the above findings. Identification of the major problem areas from the MSFC study, the industry survey, understanding that workers must be present for numerous other tasks, and the health and safety evaluation, led to the formulation of the following list of automation candidates:

(1) Shearer automation (cutting, face alignment, coal-rock interface detection, last cut memory, shearer arm articulation, and tramming).

(2) Shield advance (either remote operation or semi-automated).

(3) Conveyor and pan-line advance.

(4) Computer monitoring (information management for sources of system delays).

(5) Preventive maintenance system (fault isolation and failure diagnostics).

(6) Face sensing ahead of the shearer (to detect hard rock partings).

(7) Remote seam mapping (as related to mine planning and development).

(8) Semi-automated movement of equipment components to a new panel. (e.g., self-propelled towing units for shields).

One of the project constraints was that the longwall automation study consider only those opportunities amenable to near-term incorporation (the 1984-1985 time frame) using state-of-the-art technology. The technology assessment of state-of-the-art automation suggested that only the first five opportunities listed above would be available for the desired time frame of incorporation. The last three areas shown will require much more development effort.

SECTION IV

EVALUATIVE TOOLS FOR RANKING AUTOMATION OPPORTUNITIES

A. OVERVIEW

Sections II and III provided a longwall baseline design and operating description, and the background for selection of the automation options. The next step in the analysis was to establish a means of translating the desired options for longwall automation into measurable parameters which could be used to rank the various opportunities. Several tools were developed to accomplish this.

One important measure of improvement is productivity. It is hoped automation could streamline the longwall operation by deleting operator delays and hazardous tasks, thus, providing more production time at the coal face. The tool employed to measure productivity impacts was a network which described each activity and delay in the longwall system as time elements. Time savings realized by automation were then added to available production time and converted to coal tonnage. Another important aspect of production was the cost of incorporating automation. If the costs of automating a longwall system far outweigh production benefits, it would not be beneficial to change the existing design.

However, before the costs of developing and incorporating automation could be determined, the technology had to be identified. Appropriate automation technology was identified by examining robotic technology in other industries with similar applications. These applications were then redesigned to meet the harsher mining environment before being translated into development costs. The use of similar industrial applications as a tool for identifiying and costing the required longwall automation technology was a straightforward means of establishing cost tradeoffs.

The use of sophisticated automation technology in a harsh environment such as a coal mine does not serve a useful purpose unless the worker realizes a need for job assistance. Production and technology development should focus on areas where workers perceive a need for some type of job assistance. As discussed in Section III, the survey provided a means to isolate those key areas where the worker would view automation as a way to improve task performance and safety, and therefore accept it.

An important aspect of worker acceptance was whether the introduction of automation technology into the underground mining environment would improve health and safety. The assessment tools applied toward the health and safety areas were methodologies previously developed and tested under the DOE Advanced Coal Extraction Systems Project. These assessment schemes evaluate the change in hazard exposure between the new design and a similar existing design.

As indicated earlier, cost is an important measure of the potential benefit of automating the longwall system. The major economic tool employed in measuring cost benefits was the difference between productivity improvement (converted to 1982 dollars) and the total projected capital, operating, and development costs. In the economic impact study the development costs were deleted since they consumed only a small fraction of the total costs.

Each of the above analytical tools is explained in greater detail in the following discussion. The elements of the analytical approach are outlined in this section to provide a foundation for understanding the detailed analysis presented in Section V.

B. NETWORK ANALYSIS

In order to identify areas where automation might aid productivity, a network describing the key tasks in longwall operation was developed. The first large-scale application of networks to production problems was the PERT diagram (16, 17). PERT diagrams are useful tools for separating a large, complicated process into activities and delays in order to understand the major variables necessary to complete a project or process. The activities and delays are structured in a sequence similar to Figure 4-1.

Figure 4-1 illustrates how various events (i.e., activities and delays) are sequenced in the network. Events that occur in a straight line (events 1 and 2 above) are in series with each other because event number 1 must occur before event 2 can commence and end (17). However, event 3 can start and end while events 1 and 2 are proceeding. Therefore, event 3 is placed in parallel with the first two events (17). In a similar manner, the complete process is diagrammed from beginning to end, with the legs in the network representing the various times for task start, duration, and end.

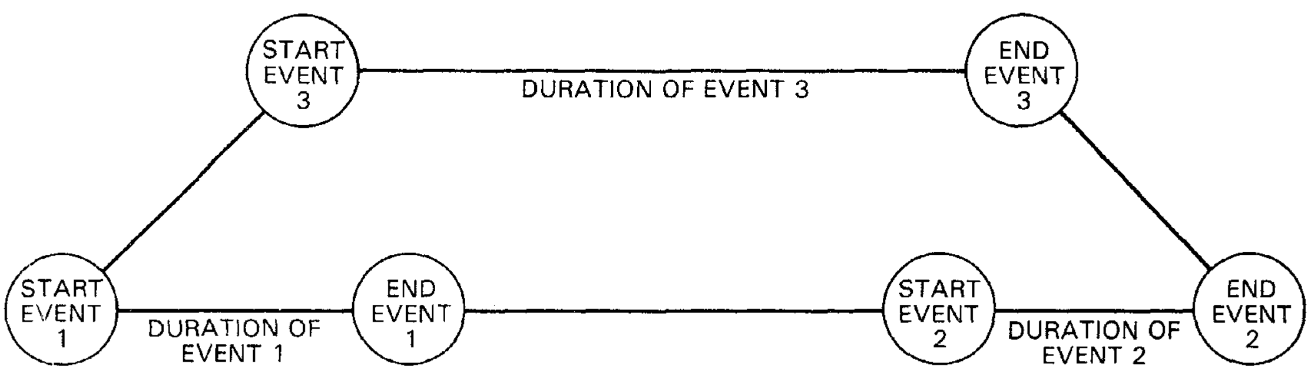


Figure 4-1. Example Network

The complete application of the PERT method also requires that best, worst, and desired event completion times be used. Multiplying the probability of an event being completed (based on historical experience) by the three completion time estimates results in the expected value for finishing a given task (16, 17). When all the expected values (the best estimates of task completion) have been placed in the network, the minimum time to complete the whole process can be determined. This is called the critical path and is an important baseline to establish in order to examine ways of streamlining the process (17).

Probabilistic simulation calculations are extremely important for networks that have several parallel activities. These calculations help prevent errors in determining the critical path. However, networks that are basically a series structure greatly simplify the process of identifying the critical path. In these cases a deterministic approach is acceptable. Given that the process is basically a series of events, the mean values of the activities and delays become a good representation of the critical path. The longwall process examined in this study, being basically a series type operation, was therefore amenable to using a deterministic type network.

As stated earlier, it is very useful to determine the critical path before a process can be examined. The critical path for the longwall process represented the main tool for evaluating the productivity impacts of the automation opportunities. This was accomplished by first determining which delays and activities on the critical path were affected by automation. Each automation option was converted into a time savings, where applicable. These savings were then added to the available face production time. The estimates of the production time improvements were later reviewed by a group of experts from the mining industry to ensure that these projections were reasonable. The automation options were ultimately ranked by examining which one, or combination, gave the best improvement in productivity. The results of the longwall critical path analysis, productivity projections, and expert review are explained in greater detail in Section V.

C. AUTOMATION FEASIBILITY AND DEVELOPMENT COST INDICATORS

The evaluation tool for determining the feasibility of applying automation to underground mining was based on finding the required technologies in other industries. The evaluation of the automation options included an assessment of: (1) the required sequence and time for technology development, and (2) the respective development costs for similar equipment of comparable complexity.

Generic automation technologies already exist in varying degrees in industry. A brief description of these technologies was provided in Section I.C and is continued in the following discussion. The first area, digital electronics, is one major component of automated systems. Digital electronic computers appeared first in the scientific world, followed by the business world. It took the invention of the large-scale integrated circuit before digital electronic computers invaded the timekeeping world (i.e., digital watches). Roughly 10 yr after the microprocessor was introduced to industrial applications, a longwall shearer was developed with a microprocessor installed (18). Since then, the British Coal Board has developed a mine monitoring and control system called MINOS (Mine Operating System) with over 10 units delivered to mines. The fact that U.S. mines have started to introduce similar systems underground is a solid indication that digital electronics are evolving toward a practical application in the mining industry.

Servomechanisms and actuators are also key components of automated systems. An input signal (such as a digital electronic signal) causes an action (via an actuator). The observation (feedback sensor output) of the action is compared to the input. If the desired action is not achieved, additional action (done through a comparator) is taken until the feedback matches the input command. The comparator subtracts feedback sensor output from the input. When the result is zero, the system is in the desired state and the process stops. An automobile speed control system is a simple example of a modern electro-mechanical servo system. A typical servomechanism is shown in Figure 4-2.

Over the years the summing network, or zero seeking comparator, has evolved from hydraulic or mechanical components through analog electrical components to digital electronic computer components. With evolution has come a reduction in cost and size, and an increase in performance and speed of operation. Taken one step further, several digital electronic servos, incorporated in an assembly which processes several incoming signals for the purpose of performing a distinct set of functions, form a fully automated device. The servos which actuate the system may be electrical, pneumatic, or hydraulic units.

The above discussion attempts to show that the basic automation technology components have existed for some time. The key to automating longwall systems lies in transferring the proper combinations of present digital electronics, servos, and comparators to the appropriate shearer, shield, and conveyor machine functions. This transfer is provided with supporting designs, later in the document.

Once each automation area has been conceptualized using applicable state-of-the-art technology for the selected machine functions (based on the previously developed automation areas), the development costs can be reliably estimated. However, since some applications may require extensions of existing technology such as a more rugged circuit design suitable for the mining environment, coal industry experience was incorporated to provide a more realistic indication of development time and cost.

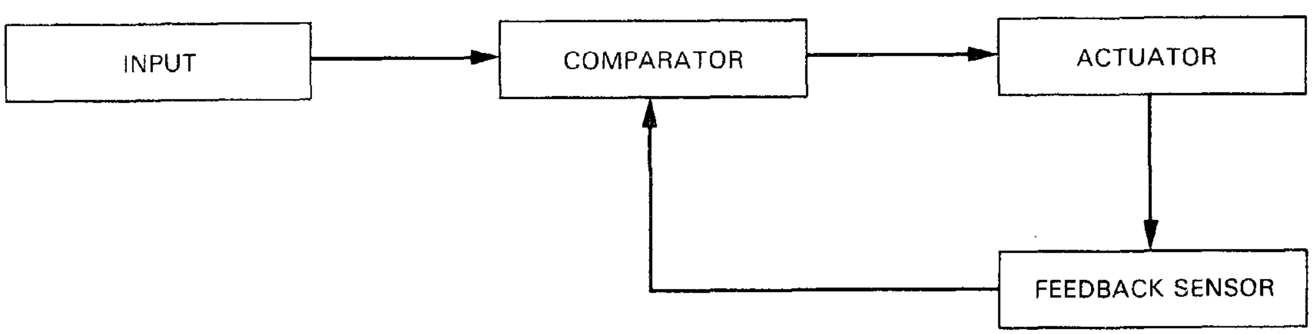


Figure 4-2 Servomechanism Data Flow Diagram

D. MINER ACCEPTANCE

As stated in Section III, the survey was designed to sample opinions from equipment designers and manufacturers, mine managers, and miners. The key opinions concerning worker acceptance of new technology were obtained from the interviews with mine management, equipment operators, and maintenance personnel. The survey, if structured properly, is a useful tool for determining user needs and preferences. The basic approach taken in developing the survey was to make site visits and personally question the managers and workers. Each interview was structured to identify major machinery design problems, equipment guidance problems, and tasks or activities that were excessively demanding. Major machinery design problems were important to isolate because of their relation to potential operational errors and maintenance problems. Understanding these problems lent credibility to the need for an operator-assist system or failure diagnostics. Equipment and guidance problems and excessively demanding tasks were important for identifying other operator or maintenance-assist opportunities. The interview was not intended to alienate workers from the introduction of automation into the mining environment. It was understood at the onset of the survey that miners are very sensitive to any technology that might infringe on their jobs (19). Therefore, the approach taken was to develop automation as an additional tool rather than as a job threat. One final aspect of the survey was to determine the degree to which miners should be involved in the design process. This last aspect was included so that the design would jointly benefit from the worker's experience and provide the worker a means of participating in the design process. Through the survey approach outlined above the important automation acceptance criteria were identified.

E. HEALTH AND SAFETY INDICATORS

The evaluation tools for assessing the health and safety impacts of automation were developed separately under the JPL Advanced Coal Extraction Systems Project (20, 21). Potential health improvements are evaluated using a qualitative methodology. This approach was selected because any stage of development prior to the prototype test does not provide information on actual dust concentrations or toxic material emissions. However, by understanding the comparative levels of exposure to health hazards of a proposed design and a similar conventional system (considering worker activities which interface with hazards and design improvements such as additional protection), the methodology provides a relative means of rating the effectiveness of various health design features (20).

The safety methodology is both qualitative and quantitative. The qualitative portion serves the same purpose as the above health hazard evaluation scheme. However, using the historical injury data base for the comparable conventional system, the design analysis can be carried one step further into a quantitative stage. The quantitative injury projection takes the changes in hazard exposure time during task performance, changes in the number of workers exposed, and improvements in protection and adjusts the historical injuries accordingly (21). Once the injury projection is completed, the relative contribution of each new design feature to the overall reduction in injuries provides the means of ranking the automation opportunities. This procedure is developed in greater detail in the next section.

F. COST-BENEFIT INDICATORS

A number of factors contribute to the costs and potential benefits of the automation opportunities. These factors are summarized in terms of the present value of net national benefits of the new automation technologies. The present value of the benefits was determined by discounting at a 7% (real) rate and summing the difference between benefits and costs (to American mine operators) over the time period 1985 to 2000 for each option. This approach also provided the means of ranking the various automation options. The elements used to evaluate cost-benefits of automation were as follows:

(1) Influence on productivity.

(2) Changes in capital and operating costs.

(3) Size of potential market (1985-2000).

(4) Time of availability and rate of penetration into the potential market.

(5) Health and safety impacts and costs.

The time of availability and penetration of automation into the potential longwall market was based on several factors. These factors included the following:

(1) Time required for R&D and prototype development.

(2) MSHA approval time.

(3) Acceptability to mine personnel and mine owners (e.g., automation must produce a high rate of return on equity in excess of 25% after taxes, and will not increase health and safety hazards in the mine).

(4) Historical penetration rates of longwall technology in the U.S.

Other cost factors which were not addressed in this study were: (1) national security, as it is affected by domestic energy availability, (2) international trade, as it might be affected by increased export of coal and coal mining equipment, and (3) possible spinoff benefits from the proposed R&D.

This section introduced the various methods of design and assessment in the areas of productivity, technology development, miner acceptance, health and safety, and cost benefits. Section V will show how these analytical tools were applied specifically to integrating and evaluating the automation options as part of the baseline longwall design.

SECTION V

RESULTS OF THE LONGWALL AUTOMATION STUDY

A. OVERVIEW

The previous section briefly characterized the various tools used to evaluate the impacts of automation on the longwall system. This section presents the results of applying these tools to various automation options. In the productivity area the deterministic network was employed, along with the automation options developed in Section III, to determine potential improvements in productivity. These improvements were later converted to present-value dollars for the cost-benefit analysis. The necessary hardware and software for each automation option were identified through the technology assessment analysis. As stated earlier, state-of-the-art digital electronics and servomechanisms were used where possible. The development and production costs followed once the off-the-shelf components had been identified. These cost data were later employed to establish a baseline for understanding the relative payback on the research and development investment. The technology assessment also included evaluation of health and safety impacts. Reductions in serious longwall injuries were translated into cost savings for the cost-benefit analysis. Last, the cost-benefit evaluation took the above data inputs (with the exception of the development costs; these costs were considered separately) and provided the net national benefits. Where possible, conservatism was exercised in the calculations to prevent overly optimistic projections. For example, market penetration rates of automated longwall equipment were assumed to be no greater than historical longwall growth, despite an extremely favorable payback time.

B. RESULTS OF NETWORK ANALYSIS

The longwall network analysis was divided into four basic steps. The first step was the development of a longwall and operational network. The automation options and respective estimates of time savings were inserted into the network where it was felt a given delay could be affected. As these delay reductions only represented estimates, the next step involved meeting with experts in the mining industry and revising the projections based on actual experience. In some cases the estimates proved to be optimistic, while in other cases the estimates were rather conservative. Based on the input from the experts, the final projected time savings (and productivity impacts) were determined. Each of the above steps is explained in the following discussion.

1. Longwall Operational Network

The longwall operational network was based on the general operating scenario provided in Section II, a set of operating projections prepared earlier under the DOE Advanced Coal Extraction Systems Project, and on-site observations. As stated above, the series nature of the longwall process allowed a deterministic approach to be used in designing the network. Additionally, control of dust and face ignitions (small explosions of methane gas at the face) constrained the cutting cycle to a single pass from the headgate to tailgate. It is understood that ideal environmental conditions (very little dust and no methane) in conjunction with a seam height below 48 in. does permit some longwalls to cut in both directions. However, this is not normal practice. Using 480 min as the baseline shift definition, Figure 5-1 illustrates the basic longwall operation. The key for the definition of each numbered activity and delay element shown in the network is provided in Table 5-1. It should be noted that the first seven activities listed in Table 5-1 do not have mean times listed because these activities are not part of the normal longwall operating cycle and are not affected by the automation options.

As illustrated in the network, event combinations 5 through 16 basically represent the shearer cutting cycle. The conveyor and shield movement, events 13-16 and 11-14 respectively, operate in parallel with the shearer. Similarly, the haulage operation (events 5-30), power and water delivery (event 5-25), and new panel development (event 35-36) also occur in parallel with shearer operation. The "critical path" for the system is denoted by the dark arrows in the network diagram. Delays associated with some of the parallel events can cause total system shutdown (e.g., power outage). When these delays occur they become part of the critical path and subtract from the available production time. These delays, where they could have major impact on production, were considered when examining the various automation options and their impacts on shortening the critical path.

After development of the longwall network, the next step was to integrate the various automation options into the network at the appropriate delay points. As indicated earlier, the primary automation candidates were:

(1) Shearer automation.

(2) Shield advance.

(3) Conveyor and pan-line advance.

(4) Computer monitoring (management information system).

(5) Fault isolation and failure diagnostics.

Qualitatively, it would appear that automation or remote control of the shearer would prevent the shearer from stalling due to heavy cuts, and allow continuous operation during periods of normal operator delay. In addition, operator errors in face alignment would also be reduced. Remotely controlling or automating the shield and conveyor advance, in conjunction with maintaining face alignment, would remove some of the delays associated with equipment breakdowns caused by poor alignment (e.g., chain broken/out of guide, pan hangups, flight jamming, and shield interference). Examination of the longwall operational network suggests that delays associated with shearer maintenance, face conveyor problems, and outby haulage are sufficiently large that a fault isolation and diagnostics system would allow better maintenance scheduling on the shields, pumps, section power/water, and electrical systems during these periods. A simple model was developed to merge the above qualitative assessment into the activities and delays on the critical path. A preliminary estimate of the increase in production time was calculated by subtracting the delay times associated with each of the above event descriptions from the critical path. The following equations and flow diagram (Figure 5-2) explain how the production increases were calculated.

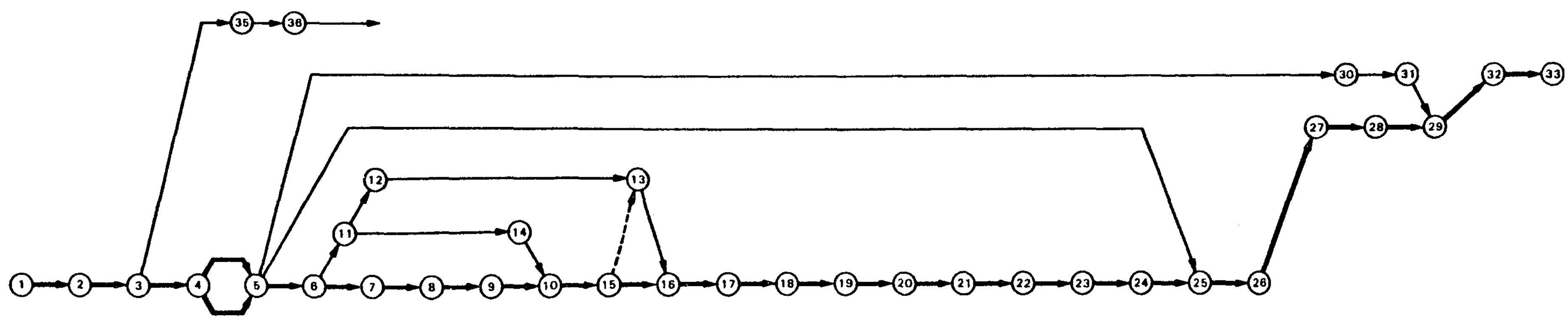


Figure 5-1. Longwall System Functional Network

Table 5-1. Longwall System Functional Network Key

Event Description Activity	Description	Mean Time Per Shift (Min)
1-2	Drive initial entries	
2-3	Establish initial crosscuts	
3-4	Haul equipment	
3-35	Drive other entries	
35-36	Develop new panels	
4-5	Install support systems Entry conveyor, stage loader, hydraulic pumps, water pumps, power center, cables, etc.	
4-5	Setup and checkout longwall Shields, face conveyor, shearer, position mechanical/hydraulic roof supports and lines, etc.	
5-6	Sump to 100 ft from headgate	8.4
6-7	Amortized headgate move Conveyor and shields-advanced	3.6
7-8	Face cut - 500 ft. @ 11 fpm	89
8-9	Amortized trim cut	22.5[a] 8.5[b]
9-10	Cut termination and turn around Stop shearer travel, range drums, reverse cowls, reverse shearer direction	4.2
10-15	Flit travel back toward headgate (500 ft @ 28 fpm), range drums	35
15-16	Return cut to headgate (100 ft @ 11 fpm)	18

[a]New section with inexperienced operators

[b]Experienced section

Table 5-1. (Cont'd.)

Event Description Activity	Description	Mean Time Per Shift (Min)
6-11	Shield delay Hydraulic lines, weld repair, stuck shields	9.5
11-12	Conveyor delay Chain broken, out of guide, pan damaged, flite damaged, jammed	31
12-13	Conveyor jammed, adjusted	2.0
13-16	Conveyor advance	1
11-14	Shield advance	Same as shearer
14-10	Shield advance lag (after shearer movement)	4.5
16-17	Stop shearer, check and/or replace picks	35
17-18	Prepare for next cut to tailgate Start and range drums, reverse cowls	3.8
18-19	Provide added ground control	18/36[a]
19-20	Shearer maintenance Gearbox, drive shaft, etc.	26/66[b]
20-21	Headgate overload	6.0
21-22	Cleanup under shearer	22
22-23	Operational problems (oversized coal)	6.0
23-24	Stage loader/crusher hangup Spillage, oversized lumps, etc.	5.0
24-25	Head/tailgate drive problems	11
5-25	Section power, water, face Ventilation operation	Same as shearer

[a]18 min for good roof; 36 min. for bad roof

[b]26 min for high coal; 66 min. for low coal

Table 5-1. (Cont'd.)

Event Description Activity	Description	Mean Time Per Shift (Min)
25-26	Section power and water shutdown	7.0
26-27	Electrical maintenance (overloads)	3.0
27-28	Pump failures	3.0
28-29	Rearrange supports at headgate and tailgate	3.0
5-30	Outby haulage delays Conveyor, railcar spotting, etc.	47
30-31	Outby haulage operation	Same as shearer
31-29	Electrical maintenance Power failures, cable defects, Warning/communication devices	8.0
32-33	Amortized retreat of support System (for 100 ft of cut; 40 cuts)	

Where,

t_i = The time delay element affected by the automation opportunity.

D_T = Total system delay time, where D_T ranges between 279-319 min/shift.

P_T = Total average production time, where P_T for one-way is 199 min/shift.

The initial projections for time savings (considering only one way cutting) are shown in Table 5-2.

This production time increase, when placed back into the cut cycle times, resulted in the shearer being able to perform one more 490-ft cut. This represents a 50% increase in production time.

2. Discussion of Projections with Industry

The above model represented a first attempt at a projection of the aggregate impact of automation opportunities on production time. It was also assumed that several large delays would not be removed from the critical path as a means of being conservative for the initial projection. The next step was to involve a group of equipment experts using both the present operating delays and projected improvements as an initial starting range through which, given the rationale for the projections, they could extrapolate a more

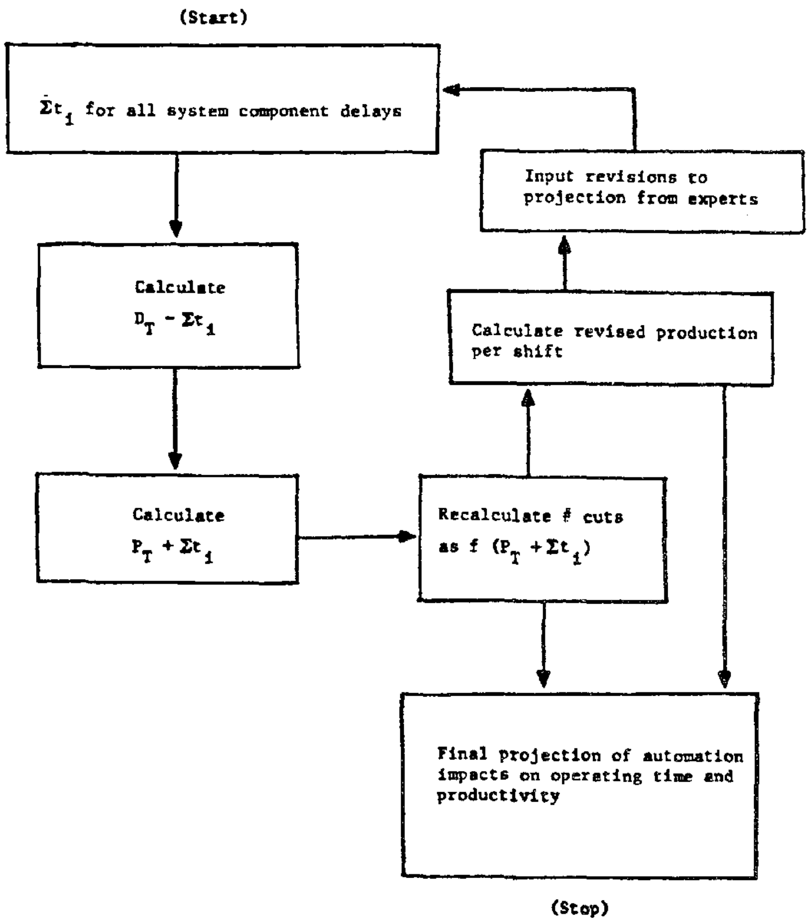


Figure 5-2. Flow Chart to Project Automation Impacts on Operating Time and Productivity

realistic answer based on their experience. This procedure allowed the initial projections to be refined. The basic process was as follows:

(1) Experts were familiarized with the automation effort, rationale for the opportunities, and list of automation opportunities.

(2) Technical backup and feasibility of incorporating opportunities were presented.

(3) Overall results of network analysis were presented; essentially, the production time increases, when placed back into the cut cycle times, resulted in the shearer being able to perform one more 490-ft cut travel in the case of a one-way cut. This represents a 50% increase in production time.

(4) Areas where automation opportunities apply were provided along with the rationale.

(5) Experts were provided data on the present operating time scenario, and the projected improvements based on automation, for:

(a) Shearer operation.
(b) Shield/conveyor advance.
(c) Fault isolation/diagnostics.

Table 5-2. Initial Projection of Production Time Savings

Automation Component/Activity		Time Savings (min/shift)
Shearer -		
Headgate overload		6
Operator delays		2-10 (avg 6)
Lunch		60
	Subtotal	72
Shield/conveyor advance -		
Conveyor jammed/adjusted		2
Chain broken/out of guide		6
Pan hangups (nominal)		10
Conveyor flight jamming		2
Shields stuck/interference		5
	Subtotal	25
Fault isolation/diagnostics -		
Electrical maintenance		11
Pump failures		3
Section power and water shutdown		7
	Subtotal	21
	Total	118 min/shift

The experts were provided both the present and projected time impacts as a baseline from which they could make their own projections. The review process commenced with asking each expert if he believed the actual effects of automation would be closer to the projected or present operating scenario based on his own experience and the design analysis. The range between the two operating times was then cut in half, and the experts were asked to refine their estimates. This process continued until the experts could not refine answers any further. The final answer is typically provided as a range and the reasons for each answer were also recorded in order to establish a sound foundation for the revised projection.

The experts chosen were from Foster-Miller (FM), Joy Manufacturing (J), and Skelly and Loy (SL). All of the participants had a good working knowledge of existing automation practices and longwall machinery operations. It is important to note that although the experts varied in their perceptions of the magnitude of the automation impacts on production time, the types of responses, in terms of losses or improvements, were consistent. The final production time improvement estimates were displayed as a range, encompassing all of the answers. Each group of experts was interviewed separately and not informed of the results of the other interviews. This approach ensured that each participant was not biased by the other responses. Table 5-3 summarizes the results of the interviews.

3. Impact of Reduced Operating Delays on Available Production Time

The potential time savings resulting from incorporation of automation opportunities can be determined by subtracting the final projected delays from the average delays presently experienced by longwall systems. The only deviation from this is consideration of the trim cut delay. In the original network the cut sequence did not include a trim cut because no experience was available. As a result, the calculated 199 min of cut time per shift (for one way cut) represented the total production time available considering the other known delays. Incorporating the trim cut delays essentially reduced the available production time down to a range of roughly 170-190 min/shift, which is well within the range of present longwall operations. By removing the amortized trim cut delay through automated face alignment, the production time is returned to the expected operating scenario shown in the network. Any additional time savings due to automation are then simply added on to the available production time.

a. Shearer Improvements. Table 5-3 shows that although the original projection for the preliminary scenario conservatively indicated no improvement in shearer maintenance time, the experts disagreed. The two main reasons given for a reduced delay time were: (1) automating the shearer would control machine stress better, thus reducing maintenance (e.g., cutter pick wear); and (2) installing fault isolation sensors on major components would save time spent isolating an unknown failure and gaining access to the component. The experts all agreed that controlling the load on the shearer would greatly reduce the headgate stall problem. It was interesting to note that all the experts similarly felt that automating the face alignment task would alleviate the problem of having to take trim cuts.

In the area of operator delays, the original network suggested an operator delay of 2-10 min/shift and a lunch delay of 60 min/shift. This would result in a total operator delay of 62-70 min/shift. All the experts indicated that delineation of the total delay by "operator" and "lunch" was not accurate in that workers' lunch breaks are staggered such that machine operation is continuous. The experts did comment that staggered lunch breaks usually result in a reduced face crew. The net impact of this reduction is a slower operating speed so that the available face crew can perform the tasks of the absent workers. Considering the loss in production time due to the slower operating speed and other operator delays, the experts adjusted the original baseline from 62-70 min/shift down to 20-40 min/shift.

Table 5-3. Expert Adjustment of Projected Automation Impacts on Production Delays

Automation Opportunity and Affected Activity	Initial Projected Delay (min/shift)	Adjustment by Experts (min/shift)	Reason
1. <u>Shearer Automation</u> Shearer maintenance	High coal-26 Low coal-66	20-25 50-63	FM/SL - Controlling the shearer load through automation should reduce maintenance slightly. J - Fault isolating major components should save access time
Cleanup under the shearer	22	Same	FM/J/SL - this activity will not bc affected by automation
Headgate overload resulting in shearer stall	0	0-1.5	FM/J/SL - generally agree that controlling the load on the shearer will prevent overload; some delay might still be experienced due to roof conditions
Need for trim cuts to realign face (one-way cut):			
o Inexperienced operator, or opening a new longwall section	No historical data available for projection	[a]One trim cut every 1.5 shifts, or a delay of 15-30 min	FM/J/SL - This is an average trim cut requirement based on experience; auto face alignment would solve problem
o Experienced operator	No historical data available for projection	One trim cut every 4 shifts, or a delay of 6-11 min	FM/J/SL - alignment is limited by face visibility; auto face alignment would solve problem

[a]Experience indicates that for every trim cut, approximately 0.5-1 cut per shift is lost in the process of squaring up the face, adjusting ground control, and positioning the head or tailgate sections.

Table 5-3. (Cont'd.)

Automation Opportunity and Affected Activity	Initial Projected Delay (min/shift)	Adjustment by Experts (min/shift)	Reason
Operator delays	0	0	FM/J/SL - Concur that total shearer automation would remove operator delays (remote control will still require at least one operator to be present)
2. <u>Shield/conveyor advance</u>			
Conveyor chain broken or out of guide	0	0-1	FM/SL - There still may be a slight delay due to chain stretch. J - Agree with projection; poor alignment is the major contributor to conveyor chain problems
Conveyor pan failure/ hangups	10	10	FM/SL/J - Agree with projection; poor alignment puts stress on the conveyor pan connecting pins; it is understood that other kinds of pan failures, such as gob falling on the conveyor, will not be affected by automation
Conveyor flight damaged or jammed	3	3	FM/J/SL - Agree with projection; this failure is often related to stress induced by not coordinating headgate, shield, and panline moves so that stress on the conveyor flight is minimized - other failures such as gob damage will not be affected

Table 5-3. (Cont'd.)

Automation Opportunity and Affected Activity	Initial Projected Delay (min/shift)	Adjustment by Experts (min/shift)	Reason
Conveyor is jammed or requires adjustment	0	1	FM/J/SL - Although this delay is sometimes caused by alignment, other factors such as bad floor conditions may prevent this delay from being eliminated
Shields stuck or require maintenance	5	5	FM/J/SL - Agree with a medium improvement in delay time since shield interference and guidance would be aided by automation; bad floor conditions and maintenance would not be helped by automation
Head/tail drive failures requiring maintenance (such as gear drives, fluid couplings, seals)	11	8.5-11	FM/J/ - Improving alignment will reduce some of the stress experienced on components (such as fluid couplings); fault isolation will help identify major component failures and save some access time SL - Automation will have no effect
Rearrange support at the head/tail	3	Same	FM/J/SL - Agree that automation will not affect this delay
Cleanup and breaking oversized lumps	11	Same	FM/J/SL - Agree that automation will have no effect on this delay

Table 5-3 (Cont'd.)

Automation Opportunity and Affected Activity	Initial Projected Delay (min/shift)	Adjustment by Experts (min/shift)	Reason
3. Fault isolation/ diagnostics			
Electrical maintenance (cable failures, power overload) pump failures section power/water	0	15-19	J/SL - Electrical failures are difficult to diagnose in sufficient time to schedule maintenance (accept for cable failures); also, manpower would most likely be at face during face breakdowns, so impact would be marginal. FM-Only a marginal impact would be felt since the maintenance manpower would most likely be concentrated at the face
Outby haulage delays (conveyor breakdown, rail car delays)	Less than 47	24-42	FM/J/SL - The conveyor system is too large to monitor, but some improvements would be realized through better rail car scheduling, loading, and moving materials in and out of the mine more efficiently

All three groups of experts agreed that by completely automating the shearer and shield activities, operator delays would largely be removed. However, time savings could also be realized if remote control were employed, since one operator could still operate the shearer and have time to monitor and control other events (e.g., one operator could activate the shearer sequence and remotely control the shields).

Assuming that the full cut time of 199 min is available (by removing the amortized trim cut delays), the total range of time savings related to other shearer delays is as follows:

(1) Low coal: 27.5-62 min/shift, 44.8 min/shift average.

(2) High coal: 25.5-52 min/shift, 38.8 min/shift average.

b. Shield - Conveyor Improvements. The experts generally agreed that most of the conveyor stress and shield interference problems were associated with face alignment. Although the experts felt that normal conveyor chain slack due to chain link stretch would still require adjustment and therefore cause some delay, other major problems such as the chain coming out of the guide would be largely mitigated. Similarly, although pan/conveyor jamming and damage due to poor roof or floor conditions or falling gob would still exist, the experts indicated that automated face alignment would largely reduce stress on the panline connecting pins, reduce panline jamming, and reduce stress on the head and taildrive components. In the area of shield interference, the experts agreed that automated movement and alignment would assist greatly in maintaining shield spacing and a level advance. The total shield delay could not be removed because of uncontrollable variables such as bad roof and floor conditions.

The projected time savings for all of the above areas is 22-25.5 min/shift.

c. Improvements in Component Failure Identification and Logistics Support. The experts provided useful comments on the application of sensor technology to system monitoring and failure diagnostics. All the experts indicated that sensor applications are limited primarily by cost. For example, it is possible to monitor a total conveyor system in terms of motor performance, bearing wear, belt tension, belt stress, roller wear, etc.; however, the overall size of the conveyor system requires a large number of sensors and a complicated data retrieval and processing system. This system would be costly and would introduce a greater number of failure possibilities. At the onset, the experts made it clear that only major system components (such as the main drive shaft bearing, circuit breakers, and pressure line junctions) and key associated failure modes can realistically be identified. Examples of key failure modes might be bearing wear, midpoint conveyor belt tension, motor temperature, change in resistance in a cable segment, critical pressure loss in a group of shields, or main water line blockage.

The two major delays in the network that could potentially be reduced by fault isolation or a management information system were: (1) electrical maintenance, pump/water, and power delays, and (2) outby haulage delays such as conveyor breakdown or rail car problems. In line with the comments outlined above, the experts generally felt that a diagnostics system, although useful, would only marginally reduce outby maintenance delays. The reasons for this were threefold. First, except for cable failures, electrical failures are difficult to fault isolate or monitor before they actually occur. Even though one could save some troubleshooting time by knowing where the failure occurred, the delay would not be removed from the critical path due to the extremely rapid progression of the failure. Second, a system such as the outby conveyor is extremely difficult to monitor. Third, even if workers were informed of impending failures that could be repaired during shearer delays, the available maintenance crew would probably be at the face repairing the shearer. One definite advantage of a monitoring system, as pointed out by the experts, would be in moving rail cars to and from the face area. Mine management would be able to schedule rail cars, control rail car loading and spotting, and schedule delivery of support material much more efficiently. Other areas pointed out as being favorably affected by a failure diagnostics system are: (1) reduction in troubleshooting and access time for major shearer components, and (2) reduction in troubleshooting time for major headgate and tailgate components.

In total, the final projected time savings associated with utilizing fault isolation and management information systems was 7-29 min/shift.

4. Summary of Projected Automation Impacts on Operating Time and Productivity

In summary, the total projected reduction in delays is simply the sum of all the above time savings. Assuming one way cutting as the baseline system, this total is respectively 56.5-116.5 min/shift for low coal, and 54.5-106.5 min/shift for high coal. The largest segment of the time savings associated with both low and high coal operations stems from removing operator delays. The next largest impact on production time is derived from alleviating the need for trim cuts.

Thus, for a one way cut,

t_i = 56.5-116.5 (86.5 avg) min/shift for low coal

t_i = 54.5-106.5 (80.5 avg) min/shift for high coal

Calculating $P_t + t_i$ results in

255.5-315.5 min/shift for low coal, and

253.5-305.5 min/shift for high coal.

These available production times (when placed back in the cut cycle times) result in the shearer being able to perform an extra three-fourths of a 490-ft cut. This represents an approximate 40% increase in production time.

C. AUTOMATION TECHNOLOGY ASSESSMENT

As illustrated in Sections III and IV, the operator and support personnel are necessary components of the longwall system. For example, the human operator of the longwall shearer functions as a comparator in a servo system. His vision and other senses provide the control signal, and his actuation of the control allows the ranging arm to operate. In analyzing the results of machine operation, the operator receives inputs on shearer pitch, roll, and heave along with geological inputs on coal seam dip. These inputs, plus other variables, such as roof quality, require constant attention and place a heavy load on the operator. Easing of this load should allow operators to handle the remaining tasks more safely and efficiently.

Development of any new application includes a breadboard phase, a prototype phase, a preproduction phase, and a production phase. The breadboard phase is essential for quickly designing, assembling, and testing digital electronic systems required for automation. The breadboard phase also facilitates the development of a reliable prototype design. The use of digital computers in conjunction with multiple servo systems (manually assisted robotics) is sufficiently mature to develop sensor mountings with data feedback on a production shearer during the breadboard stage. The sensors and controls that are incorporated into a production machine must not degrade machine performance, and must be able to be actuated or cut out by a single switch. The choice of the digital electronic computer approach allows an easy way of servo performance modification by software changes during the breadboard stage. The software development is not as mature as hardware development. Thus, the system software will continue to be refined during in-mine testing of the breadboard designs and prototype. As each subsystem is tested, it can be combined with other subsystems and retested. It is for this reason that a breadboard phase is extremely useful. In this manner, a totally integrated system can be developed. An approach to accomplish this goal is presented in the following discussion.

1. Identification and Detailed Description of Opportunities

One type of automation technology for the longwall will be electronic digital computers. The opportunity to apply this technology can be subdivided into several hardware/software programs, and an experimental configuration can be designed. This experimental set-up consists of sensors located on the shearer, the headgate, the shields, and elsewhere as needed. Each sensor sends its data to a general purpose computer away from the coal face. The computer makes the calculations, prints summary charts with a plotter, and sends commands back to actuators on the mining equipment. The mining equipment will have a manual/auto switch so that the operator can select modes. During the course of the test period, different forms of automation can be tried and compared. The general purpose computer will make the calculations necessary for the selected type of feedback and transmit these signals to the mining equipment. In addition, the computer can format the data tor management information plots. The general purpose computer will initially be used as a development tool for each of the concepts presented, and represents a fixed cost in the development of any of the following concepts. It is envisioned that computer monitoring/control and auto fault isolation data handling and display will always be done at an above ground location. Thus, a general purpose computer installed for software development will also find use in general mining operations. In addition to the above computer (which will process incoming sensor signals) and associated communications, sensor and actuator development packages are required. The development packages are described below; block diagrams are employed to illustrate the complete conceptual design for each automated component.

a. Smart Shearer Ranging Arm Articulation Package. The following sensors are required for ranging arm articulation on the shearer:

(1) "Distance-along-the-face" sensor.

(2) Ranging arm to shearer body angle sensor.

(3) Shearer tilt angle sensor.

(4) Shearer roll angle sensor.

(5) Left armored face conveyor section tilt angle sensor.

(6) Right armored face conveyor section tilt angle sensor.

Figure 5-3 illustrates how the various sensors would be used to operate the shearer ranging arm.

b. Smart Shearer Cowl Articulation Package. In addition to "distance-along-the-face" sensors shown above, the following sensors are also required for cowl articulation.

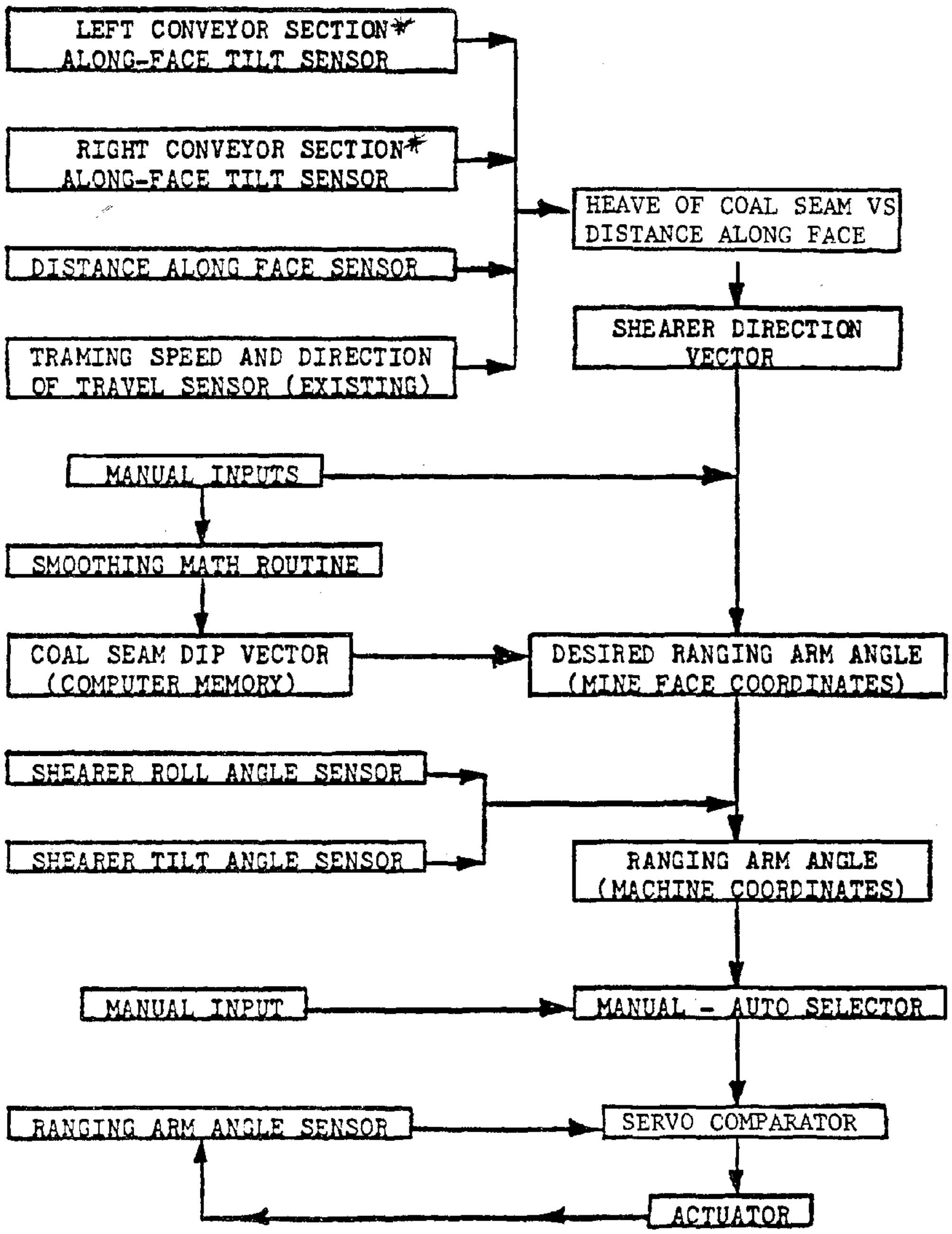
(1) Left cowl to shearer body angle sensor.

(2) Right cowl to shearer body angle sensor.

Figure 5-4 below illustrates how the additional sensor feedbacks would be used to operate the shearer cowls.

c. Smart Shearer Face Alignment Package. "Along-the-face" sensors similar to the ones shown in Figure 5-3 may also be employed to maintain face alignment. In addition to making face tilt and roll measurements, the desired movement must be computed and then communicated to the individual shields. Figure 5-5 demonstrates this iterative process.

d. Face Conveyor Alignment Computation Package. Using the "distancealong-the-face" sensors and the face alignment sensors described above, a software package can provide the communication with the smart shearer via the computer, and calculate the desired movement of the ram on each shield in order to adjust for face conveyor misalignment. This information would be trans- mitted to separate microprocessors located on each shield. The shield micro- processors would then signal the respective actuators (i.e., the ram servo mechanisms) to control each shield. Figure 5-6 illustrates this control loop.



*The left and right conveyor sections are those immediately left and right of the shearer cowl.

Figure 5-3. Shearer Ranging Arm Articulation Flow Diagram

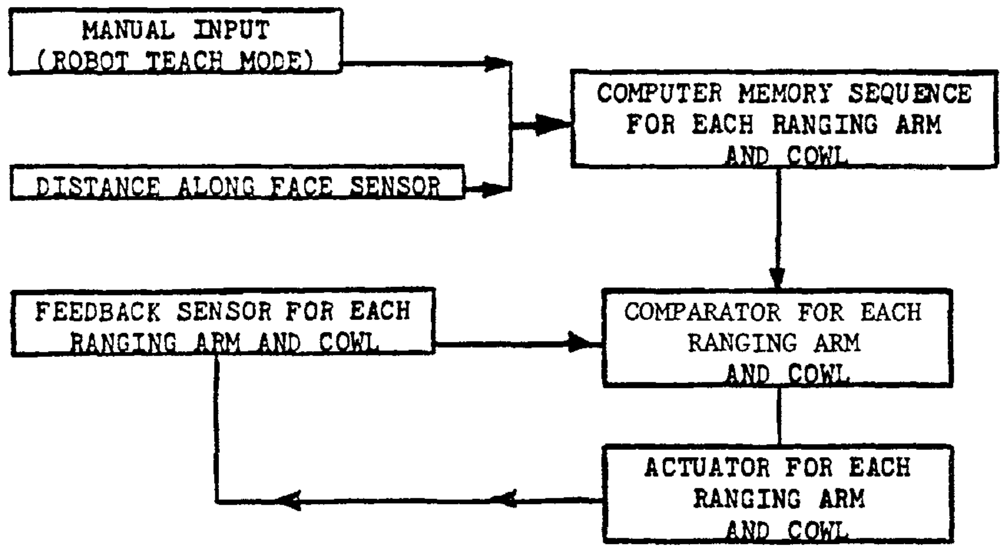


Figure 5-4. Shearer Cowl Articulation Package Flow Diagram

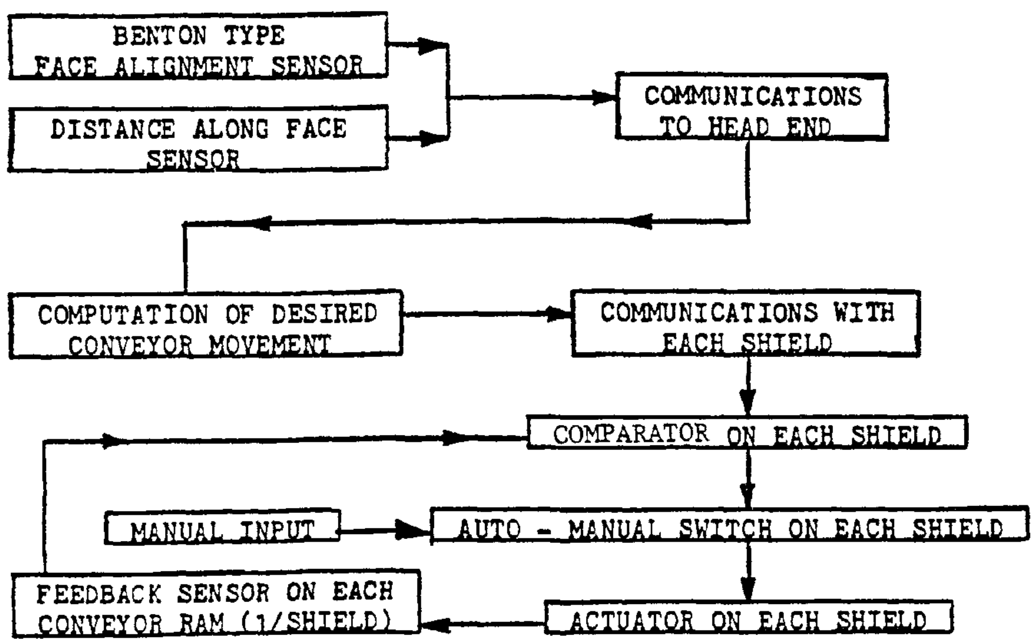


Figure 5-5. Shearer Face Alignment Flow Diagram

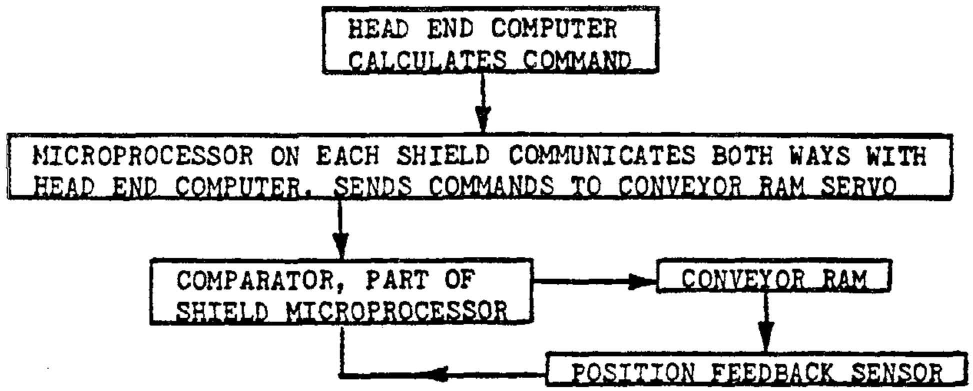


Figure 5-6. Face Conveyor Alignment Flow Diagram

It is expected that the task of calculating the shield advance sequence will also be done as part of the control loop described above. The shield advance command is communicated to the microprocessors controlling pan-line advance. Each shield will be modified to include a movement warning light, an obstacle/emergency stop control, an unacceptable tilt sensor, and a roof pressure sensor. The hydraulic controls must be modified to accept electric control. The microprocessor controlled shield advance program will turn on the warning light, and, while moving, continuously check that there are no obstacles and that the tilt is within acceptable limits. The microprocessor-controlled shield will go through the following movements: lower, move, forward, raise, set pressure. If the movement is not within acceptable limits, all movement stops and the warning light will change to flashing to indicate that human help is needed. The block diagram is shown in Figure 5-7.

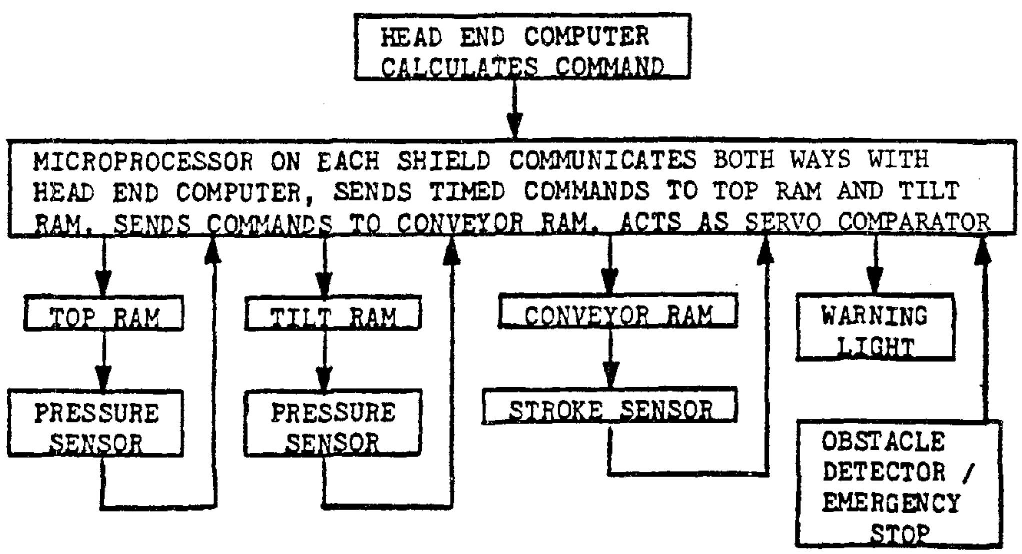


Figure 5-7. Shield Advance Control Flow Diagram

e. Computer Monitoring/Control System Software Package. As indicated in the network analysis outby problems could cause reduced shearer capability. One example might be the failure of the outby conveyor to remove the coal received from the face conveyor. Computer monitoring/control would allow a means of slowing down or otherwise modifying the operation of one piece of equipment so that another piece of equipment can operate within design limits and not delay the whole operation by failing. The simple block diagram is shown in Figure 5-8.

f. Auto Fault Isolation Software Package. The longwall system can be subdivided into subsystems, such as the electrical distribution system, the water system, the hydraulic support system, and the methane monitoring system. Each major system can be broken into measureable variables such as power at the headgate and power at the shearer. By monitoring the key variables via sensors, faults in the system can be isolated. Knowing the general failure characteristics of each component via the fault sensors allows timely dispatching of repair parts and maintenance personnel. The block diagram is shown in Figure 5-9.

2. Discussion Of Technology Integration Into Existing Longwall Systems

In assessing any proposed new technology, technical feasibility at an acceptable cost is paramount. In making this cost/benefit tradeoff, mine safety, ruggedness, and reliability are the main goals of the equipment designer. The technology outlined in the previous section is servo mechanism and digital electronics technology. Servo mechanism technology is already well established for a variety of products, and rugged methods of implementation are available. Electronics of comparable complexity have been built for oil well drilling instrumentation, manufacturing robotics, and military applications. The technology thrust is to adapt existing computer knowledge to the specialized longwall application.

In ranging arm articulation control, the designer will be concerned with routing wires safely in a protected enclosure. One present longwall shearer design already contains a microprocessor with the ranging arm actuators electrically controlled. All that needs to be installed on the shearer to convert the ranging arms into servo mechanisms are feedback sensors. This system represents an example of the reasonable feasibility of automating longwall components. The physical location of the feedback sensors, however, present a bigger problem than the problem of selecting the appropriate sensors. The sensor physical location problem may require extensive modification of existing shearer structures. However, once modified, the provisions for these sensors would be insignificant compared to the overall cost of the shearer. The same problem would be experienced by the face alignment measurement sensors in relation to modifying the shields and face conveyor. In summary, the sensor and servo mechanisms technology is available, along with an identification of the necessary system modifications. However, the system modifications could be costly.

In the following sections costs are grouped as smart shearer costs, shield costs, and information/fault isolation costs. This grouping also reflects the sequence of the development effort. The benefits of work on the shield are impossible to achieve unless the smart shearer is completed first.

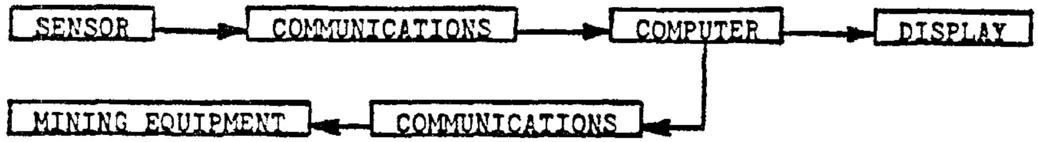


Figure 5-8. Monitoring/Control Flow Diagram

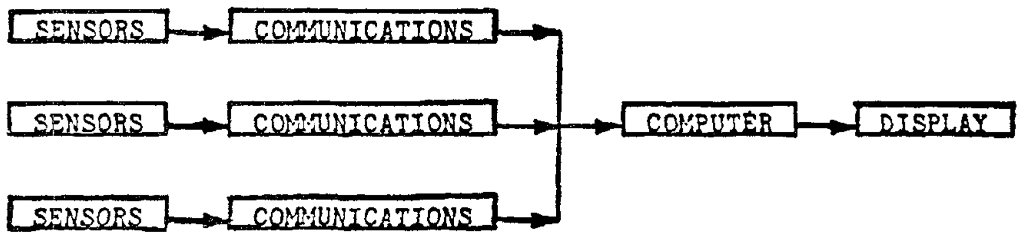


Figure 5-9. Auto Fault Isolation Flow Diagram

Similarly, meaningful information/control display relies upon information coming from the shearer. Therefore, the shearer automation option was considered the most important candidate, followed by the shield and conveyor options. The management information and fault isolation candidates could be accomplished very easily once the above options have been installed.

3. Estimation of Cost and Time to Develop Technology

a. Development Time. The method used in estimating cost and time was to draw on industry experience for developing similar hardware. Where applicable, direct experience from mining equipment manufacturers was also used (18). For example, automation instrumentation for oil well drilling involving a microprocessor and sensors costs approximately $300,000 and took 12 mo of development effort before a prototype unit was field tested. In the robotic field, specialized single-function hardware can be designed and constructed in approximately the same time frame.

The development schedule appears to be tied to resource availability. A one-year development schedule seems to be nominal for a complex project involving state-of-the-art technology. Hardware work on several automation opportunities would most likely proceed in parallel, thus allowing the most complex piece of hardware to drive the development schedule. There is some software interaction between the opportunities (i.e., the shearer and conveyor sensor information). Based on industry experience, it is estimated that sufficient software can be developed in the one year following completion of the hardware to provide for a meaningful test. Additional software can be developed as the test program progresses (such as integrating the management information sensor imputs into the computer).

After initial feasibility testing using breadboard equipment, the envisioned concept of development is a joint effort by a U. S. government agency, an American longwall equipment manufacturing company, and a U. S. longwall shearer customer. Since an industrial equipment manufacturer would be utilized, an additional 6-mo effort is needed in contract definition and award of a contract. Since it may be necessary to modify customer-owned equipment, additional time may be involved while waiting for a cooperative manufacturing agreement. It is essential that the proposed automation system components be integrated with a production longwall shearer in order to permit the concept to be tested using the most reliable and readily available components.

In summary, it appears that the minimum time for development will be 6 mo for contract definition, 12 mo hardware development after award of contract, and 12 mo software finalization after completion of hardware. This gives a total of roughly 2.5-3 yr minimum development time. In-mine testing would follow this development time.

b. Development and Production Cost Estimates. As stated in Section IV, the cost estimates were based on similar technology applications in other industries using components of equal complexity. The one refinement made in the case of the longwall system, as compared to the previous oil drilling example, was that the automated longwall system would be 3-4 times more complex owing to the extra degrees of freedom (i.e., roll, pitch, and yaw). Thus, it is conservatively expected that the longwall development costs would be proportionally higher. The development and production costs shown in Table 5-4 below reflect this conservatism. The detailed cost elements are shown in Appendix A.

Based on the above cost figures it appears that the total development phase costs are on the order of $4 million.

D. MINER ACCEPTANCE AND HEALTH AND SAFETY IMPACTS

Miner acceptance information was obtained from the survey described in Sections III and IV. This segment of the document concentrates on the results of the health and safety analysis of the various options, and relationships to the final cost-benefit projections.

1. Description of the Health and Safety Evaluations

The health and safety evaluations used in this report were developed in accordance with methods developed for the Advanced Coal Extraction Project (20, 21). The evaluations are performed at both a qualitative and quantitative level. The analysis revolves around: (1) an identification of hazardous system failures, (2) human interfaces with these system failures (which comprises the hazard analysis), and (3) both a qualitative and quantitative evaluation of design changes including a projected impact on injury reduction. The qualitative analysis helps the evaluator determine whether a new design offers sufficient merit over existing systems to warrant further development, and also directs the evaluator toward both strong and weak design areas that should be examined more closely. The

Table 5-4. Estimated Longwall Automation Development and Production Costs

Item	Development Cost	Production Cost
Common automation elements (Table A-1)	$ 860,000	$ 48,000
SHEARER ADD-ON COSTS		
Ranging arm articulation (Table A-2)	340,000	3,000
Cowl articulation (Table A-3)	160,000	3,000
Face alignment measurements (Table A-5)	320,000	21,000
Smart shearer cost (Including common elements)	$1,680,000	$ 75,000
SHIELD ADD-ON COSTS		
Face alignment control (Table A-6)	$1,100,000	$215,000
Shield advance automation (Table A-7)	500,000	35,000
Microprocessor-controlled shield add-on cost	$1,660,000	$250,000

Note: During the breadboard phase, the face alignment computation package is run on the above ground computer. During the preproduction phase, it is anticipated that this software package will be run on a dedicated microprocessor located near the headgate. The exact equipment configuration will be decided after completion of the shield development phase.

FAULT ISOLATION / MONITORING / CONTROL ADD-ON COSTS

Item	Development Cost	Production Cost
Fault isolation (Table A-9)	$ 360,000	$62,000
Monitoring/control (Table A-10)	128,000	3,000
Information/control add-on costs	$ 488,000	$65,000

important qualitative measures for safety improvements are: (1) reduced exposure time by improved equipment design and/or streamlined operations, and (2) more worker protection. The health evaluation of new designs ends at this stage because actual levels of exposure to elements like dust and toxic materials can only be determined when a prototype is developed and operated (20).

The quantitative injury projection converts the qualitative measures of exposure time and protection into a means of numerically measuring potential changes in historical injuries (21). Historical data suggest that as both exposure time and number of workers exposed increase, the actual number of injuries also increases. The model developed to project injuries assumes that as each variable increases or decreases, there is a proportional increase or decrease in injuries. Although the actual relationships are more complicated, tests of the model demonstrate reasonable accuracy (22). The field of data elements includes task times and descriptions, crew sizes, and protective devices for both the proposed design and a piece of contemporary equipment chosen for comparison. Also tabulated are historical injury experiences related to major hazards associated with the various conventional tasks. For each task and hazard, manhours and populations at risk are multiplied by the historical injury rates observed for similar equipment. Total system safety performance is then estimated by aggregating rates for various tasks and hazards (21). Expert judgment can also be incorporated as an additional weighting factor if desired. For the purpose of this initial examination of longwall automation opportunities, this factor will assume a value of unity. The injury projection equation is as follows:

$$n_i = N_i \; t_i/T_i \; f_i g_i$$

where,

- n_i = the projected injuries for a given task i and hazard in the new system (injuries/yr).
- N_i = the total number of injuries associated with a given task i and hazard of the contemporary system used as a comparison (injuries/yr).
- t_i/T_i = the measure of the fractional change in task exposure time between the new (t_i) and contemporary comparison (T_i) systems (dimensionless).
- f_i = the manpower ratio for a given task i and hazard of the new and contemporary comparison systems (dimensionless).
- g_i = the injury adjustment factor, which reflects the consensus of the group of experts pertaining to the safety integrity of the new system (expressed as a fractional change in injuries).

The "expert adjustment" variable related to protective measures is assigned qualitative values of large, medium, or small, relative to the projected affect on reducing injuries. Later, during the consultation with experts, this variable is given a numerical value. The expression for consideration of protective aspects of a new design is as follows:

$$b_j = B_j d_j$$

where,

- b_j = the injury projection considering the incorporation of new protective design measures for a given hazard and accident class j (injuries/yr).

b_j = the aggregate number of historical injuries to the body (or the initial exposure time injury projection) for a given hazard and accident class (injuries/yr)

d_j = the general consensus of the group of experts pertaining to the integrity of the new protective device (expressed as a fractional change in injuries).

Since the automation opportunities apply to the existing longwall designs, all the supporting task time, labor, and injury statistics used in the projection were extracted from present longwall operational data and Mining Safety and Health Administration (MSHA) injury history. Normally, the first stage of the safety evaluation requires that a detailed system failure analysis be conducted. This facilitates identification of the hazards through an understanding of how workers interact with potentially dangerous system failures (e.g., bursting pressure lines). This level of detail is often required because new designs may not resemble existing equipment sufficiently to use historical injury experience as a means of revealing the hazards. This is not the case with the proposed automation opportunities. Since the basic design of the longwall remains unchanged, the hazards will not change, allowing the historical hazard experience to be used. As a result, the system failure and human interaction evaluation was not required for this analysis. The historical hazard and injury data base is shown in Table 5-5. Four years of injury data (1976-1980)* were averaged to obtain the yearly expected injury levels. Task time and general labor involvement data required to assess hazard exposure were also tabulated. These data were developed from the network flow analysis.

2. Qualitative Health and Safety Evaluation

After identification of near-term automation opportunities and evaluation of supporting data for the injury projection, the next step was to examine each opportunity and relate it to hazard areas where a potential improvement could be realized. Table 5-6 summarizes the relationships between the automation opportunities and the hazards that could potentially be reduced.

The qualitative health and safety analysis can be performed using the above table. The health hazards associated with dust inhalation would be greatly reduced by removing the need for the operator and helper to be near the shearer while it is cutting coal. Similarly, by removing the operator and helper from the vicinity of the shearer, the noise hazard is somewhat reduced. This would only be a marginal reduction since many other kinds of machinery contribute to the noise hazard. Fatigue and psychological stress caused by working in a cramped working space (such as operating a longwall in low coal) would be favorably affected by automation or remote control in that the operator and helper would not have to traverse the face with the shearer. Table 5-7 summarizes the effects of automation on the major recognized health hazards.

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*Data obtained from MSHA, "Injuries by Worker Activity," Report CM341L2, 1979-1980.

Table 5-5. Average Yearly Longwall Disabling Injuries (DI) by Task/Hazard and Accident Class

Accident Class \ Major Tasks and Hazards	Struck doing cleanup	Electrical maintenance	Struck hand loading coal	Struck handling coal or rock	Struck handling supplies	Struck or caught doing mach.maint.inspec.	Struck or caught operating longwall	Struck or caught operating or moving conveyor	Struck or caught positioning/removing props or jacks	Struck or caught advancing longwall shields
Roof/face/rib falls	4	0	2	1	6	6	5	0	1 Fatality 15DI	6
Haulage	2	0	2	1	5	5	0	3	0	1
Machinery	1	0	0	0	3	9	33	2	3	20
Handling Material	5	2	11	10	141	38	3	10	15	10
Explosion/Fire	0	0	0	0	0	0	0	0	0	0
Electrical	0	10	0	0	1	3	0	0	0	0
Slip/fall	2	0	1	0	14	8	2	5	0	5
Handtools	0	0	0	0	0	0	0	0	0	1
Pressure release	0	0	0	0	0	2	0	0	0	1

Table 5-6. Hazards Potentially Affected by Automation Incorporation

Activity/Hazard Affected	Automation Opportunity
<u>Health</u>	
Operator/helper exposed to dust, noise, and cramped workspace while operating the shearer and advancing shields	Automation of the shearer, shield advance, and conveyor advance, and total environmental monitoring
<u>Safety</u>	
Struck or caught while operating the longwall	Fully automated or remotely controlled shearer
Struck or caught while operating the conveyor	Fully automated or remotely controlled conveyor advance
Struck or caught while advancing longwall shields	Fully automated or remotely controlled shield advance
Explosion/ignition occurs while operating shearer or or advancing shields	Remotely controlled shearer, shield and conveyor operation
Shocked while performing electrical maintenance	Fault isolation/diagnostics system for component failure recognition
Struck by high pressure hydraulic fluid release while advancing longwall shields	Fully automated or remotely controlled shield advance

Table 5-7. Results of the Longwall Automation Health Analysis

Health Hazards	Improvement Positive	 Neutral	 Negative
Dust	X		
Toxic Compounds		X	
Temperature/Humidity		X	
Noise	X		
Vibration		X	
Poor Lighting		X	
Psychological Stress caused by cramped workspace	X		

The results of the qualitative safety evaluation suggested that automation or remote control could provide both an exposure time reduction and an increase in worker protection. The exposure time reductions largely affect the hazards associated with the activities of operating the shearer (and being struck or caught), operating or moving the longwall (and being stuck or caught), and advancing longwall shields (and being struck or caught). The fault isolation and diagnostics system would provide protection for the worker while he is performing electrical maintenance or moving the shields. By knowing where an electrical failure is located (such as a shorted cable), or a pressure line failure on a shield, the worker would be notified of the hazard in time to avoid injury.

3. Quantitative Injury Projection

The injury projection is the last stage of the safety evaluation and utilizes the qualitative findings provided above, along with the task time and historical injury data. The exposure time calculation for the use of remote control or full automation is unimportant since the worker would be totally removed for certain activities. Therefore, the exposure time drops to zero. The following list of activities, when automated, will reduce hazard exposure time to zero.

Accident Class	Automated Activity
Roof/face/rib falls	Operating the shearer. Advancing longwall shields.
Haulage	Operating or moving the conveyor. Advancing longwall shields.
Machinery	Operating the shearer. Operating or moving the conveyor. Advancing longwall shields.
Handling Material	Operating the shearer. Operating or moving the conveyor. Advancing longwall shields.
Explosion/Fire	Operating the shearer. Operating or moving the conveyor. Advancing longwall shields.
Slips and Fall	Operating the shearer. Operating or moving the conveyor. Advancing longwall shields.
Hydraulic Pressure Release	Advancing longwall shields.

The two major areas where automation would provide protection are electrical and machine maintenance. The accident classes affected are respectively electrical, and hydraulic pressure release. The actual expected decrease in injuries is determined by consulting experts in the field of machine design and safety. Two experts were chosen from the Bureau of Mines and MSHA (23, 24).

The final injury projection, considering both exposure time reductions and improvements in protection, are shown in Table 5-8.

Although the exposure time reductions are straightforward, the protection aspects are not. The reasons given by the two experts for the expected reduction in electrical and pressure release injuries are presented below.

Table 5-8. Longwall Disabling Injury Projection Considering Automation Opportunities

Accident Class	Average Yearly Historical Injuries	Average Yearly Projected Injuries
Roof/face/rib falls	46	35
Haulage	19	15
Machinery	71	16
Handling Material	245	222
Explosion/fire	0	0
Electrical	14	11-13 (avg 12)
Slips/fall	37	25
Handtools	1	1
Pressure release	3	2
Total	436	328

a. Bureau of Mines

Electrical. Based on the information provided, it appears that some minor improvement would be experienced by knowing where cable failures have occurred. However, the total electrical system will be too large to completely monitor. Consequently, workers are still unaware of the potentially hidden failure that could cause injury. Also, many electrical maintenance injuries are associated with poor practices, such as not shutting off main power before performing maintenance. Even with fault isolation, this error could still occur unless an auto shutoff system was included. Given this rationale, perhaps a 10-15% reduction is feasible. A much larger reduction (50%) could be realized with an automatic power disconnect included with the diagnostics system.

Hydraulic Pressure Release. A fault warning for the shield operator would definitely provide more protection when advancing shields. However, no improvement would be experienced in the maintenance area because the complete hydraulic system would be too complex to monitor, and even if a hose or fitting failure was isolated, the worker must still interface with the hazards associated with residual pressure release or hose whipping during component replacement.

b. MSHA

Electrical. By knowing where (or in which component) an electrical failure has occurred, workers will exercise more caution when performing maintenance. However, poor maintenance practices (such as trying to save time and troubleshoot systems while the power is still on) are the major contributors to electrical injuries. Without an automatic power disconnect included in the diagnostics system, only a 20-25% reduction might be realized. With a fail-safe feature, probably a 50-75% reduction would be obtained.

Hydraulic Pressure Release. Fault isolation and warning could definitely protect the shield operator. However, no improvement would be experienced in the maintenance area since the worker must still interface with the pressure failure during repair.

In summary, the above health and safety evaluation suggests that several areas could be improved through automation. In the area of health, it appears that the greatest improvement would be realized through the reduction in exposure to dust. In the safety area, the largest injury reduction (in terms of the percent of the total injuries in a given accident class) would be experienced in the machinery accident class. This reduction would then be followed, in decreasing order, by pressure release, slip and fall, roof, face and rib falls, and haulage. In all of the health and safety areas listed above the related automation areas are shearer automation and automated or remotely controlled shield and conveyor advance. Both of these automation opportunities have approximately the same overall impact on injury reduction. The use of the fault isolation opportunity effects a reduction in the electrical and pressure release injuries. However, the net impact on overall injuries is considerably less than the other two automation areas.

4. Health and Safety Cost-Benefit Considerations

The last step in the health and safety analysis was to provide a means of incorporating the results into the final cost-benefit projection. This was done by establishing reasonable estimates for the cost of an injury, as well as the amount of lag time required for MSHA approval of new technology. The MSHA approval period was an important contributor to the market penetration rate of the automation options.

a. Cost of Serious Injuries. The cost-benefit indicators for the safety analysis are based on a "value of human life" concept. This concept is defined as the "willingness to pay" approach developed by a study conducted by Thaler and Rosen (25). The approach infers what people require as compensation for risk by analyzing acceptable wage rates for hazardous jobs. Although it is felt that these values still underestimate the true value, or willingness to pay, of the population at large, they are considered more realistic than the human capital approach. Since serious injuries are of greatest concern for proper design of equipment and developing meaningful cost-benefit indicators, the following values appear to be realistic:

Cost of fatality = $200,000 (in 1973 dollars)
Cost of disabling injury = $6,500 - $10,000 (in 1973 dollars)

b. Steps and Timeframes Required for MSHA Approval. The steps, and approximate timeframes, shown in Table 5-9 were established through discussions with representatives of the MSHA Technical Support, Approval and Certification Center in West Virginia (26). Due to the wide range of hydraulic, mechanical, and electrical equipment approved by MSHA, the timeframes for approval could vary considerably. The timeframes presented here, therefore, are representative of the approval process.

Based on the data shown in the following table, it appears that the total approval period ranges roughly from one to three years, depending largely on the complexity of the new system and the similarity of the experimental and production designs. Discussions with the MSHA representatives suggested that a longwall system, automated to the degree indicated in this study, would require probably three years to approve.

E. THE COSTS AND BENEFITS OF AUTOMATION

The automation opportunity descriptions and production costs were established in Sections III and IV. The opportunity descriptions were used to estimate the maximum possible benefits* (with emphasis on productivity) for representative mines in the United States.** Automation cost estimates (capital and operating) were used to derive net benefit, which is the difference between maximum possible benefits and estimated costs in one mine section for an average year. Other factors included in this study were: (1) the size of the underground coal industry and the potential market share of longwalls in that industry between the years 1985 and 2000, (2) the rate of penetration of new longwall technology into the potential longwall market, (3) the time delays associated with R&D, MSHA approval, and industry adoption,

*Maximum possible benefits means: the benefits for one year at one mine section using zero cost automation. This establishes an upper bound (or budget) for automation costs.

**Representative mines include low coal (48-in.-high seams) and high coal (72-in.-high seams) cases. In some instances, calculations are made for new mine sections and experienced mine sections.

Table 5-9. Steps and Average Timeframes for MSHA Approval

Steps Required for Design Approval	Approximate Timeframe for Completion (Months after receipt of design)
1. Manufacturer submits application for component certification to MSHA	On receipt
2. Application received and logged	On receipt
3. Drawings or design specs are requested by MSHA 4. Specs forwarded to appropriate MSHA test center for review 5. Design reviewed by MSHA	3-12 (depending on complexity of system)
6. MSHA notifies manufacturer of test dates for prototype	0.5-1
7. Design deficiencies are assembled and reported to manufacturer (resubmittal process would begin after completion of this step)	0.5-1.5
8. MSHA forwards certification letter to manufacturer	0.5
9. MSHA/Bureau of Mines select a mine for experimental testing 10. Experimental permit is issued to user (mine operator) 11. System/component is tested and approved/not approved	6-12 (depending on complexity of system)
12. Manufacturer submits application of production design & steps 2-11 are repeated	3-12 (depending on similarity of test design to production design)
Total Time Required	13.5-39

and (4) health and safety benefits. The steps in the methodology are shown in Figure 5-10. R&D costs are not addressed, but they are small relative to the potential net national benefits.

The longwall market is composed of the expected future expansion of longwall equipment usage plus the eventual replacement of existing units. Retrofit automation is not considered here. The time interval addressed is 1985 to 2000 because any period beyond this would have to consider advanced technology which would cause large uncertainty in the results. The approach taken was to use the most recent projections of underground coal mining made by DOE's EIA (27) and to develop a classic market penetration curve (28) that is consistent with historical data (29, 30), a current census of longwalls (31), and known constraints on longwall technology.

Penetration into the potential market, another major consideration, will not be instantaneous. Three steps must occur in order to obtain any market penetration: (1) successful R&D; (2) MSHA safety approval; and (3) initial mine experience. Normal market growth can then occur if the new technology provides a satisfactory return on equity investment and is relatively safe. The technologies that meet these criteria are expected to penetrate the longwall market at the same rate as similar historically successful coal mine innovations.

National benefits, the last calculation in the methodology, are the product of net mine benefits times the penetration into the potential market over the time period 1985 to 2000. These results are discounted with a 7% real discount rate to 1982 dollars and summed to yield a net national benefit which can be used to compare to the R&D budget available for this program. The following analysis provides the detailed background and results for each of the above evaluation elements.

1. Cost Methodology, Financial Requirements, and Potential Market

a. Cost Methodology. The cost estimation methodology selected was Improved Price Estimation Guidelines (IPEG). This is a complete cost methodology which estimates the annual revenue required after startup to meet all direct and indirect costs, including profit and taxes. The IPEG methodology was chosen because it included all the important variables. This includes costs of profits and income taxes, and all the other financial and operational overheads that exist in industry. The methodology must assign financial overheads to the actual capital investment, and operating overheads to actual operating costs. This is an essential feature whenever capital investment (e.g., automation) is used to increase productivity or reduce operating costs.

IPEG was originally developed for DOE's photovoltaics program in 1977 (32) and has been updated (33) and adapted for coal mine applications (see Appendix B). This adaptation required an analysis of the financial conditions of the coal industry.

b. Financial Requirements. A survey of financial literature (34) indicated that a 15% after-tax return on equity investment has been a normal rate of return for the majority of successful coal firms. A JPL study

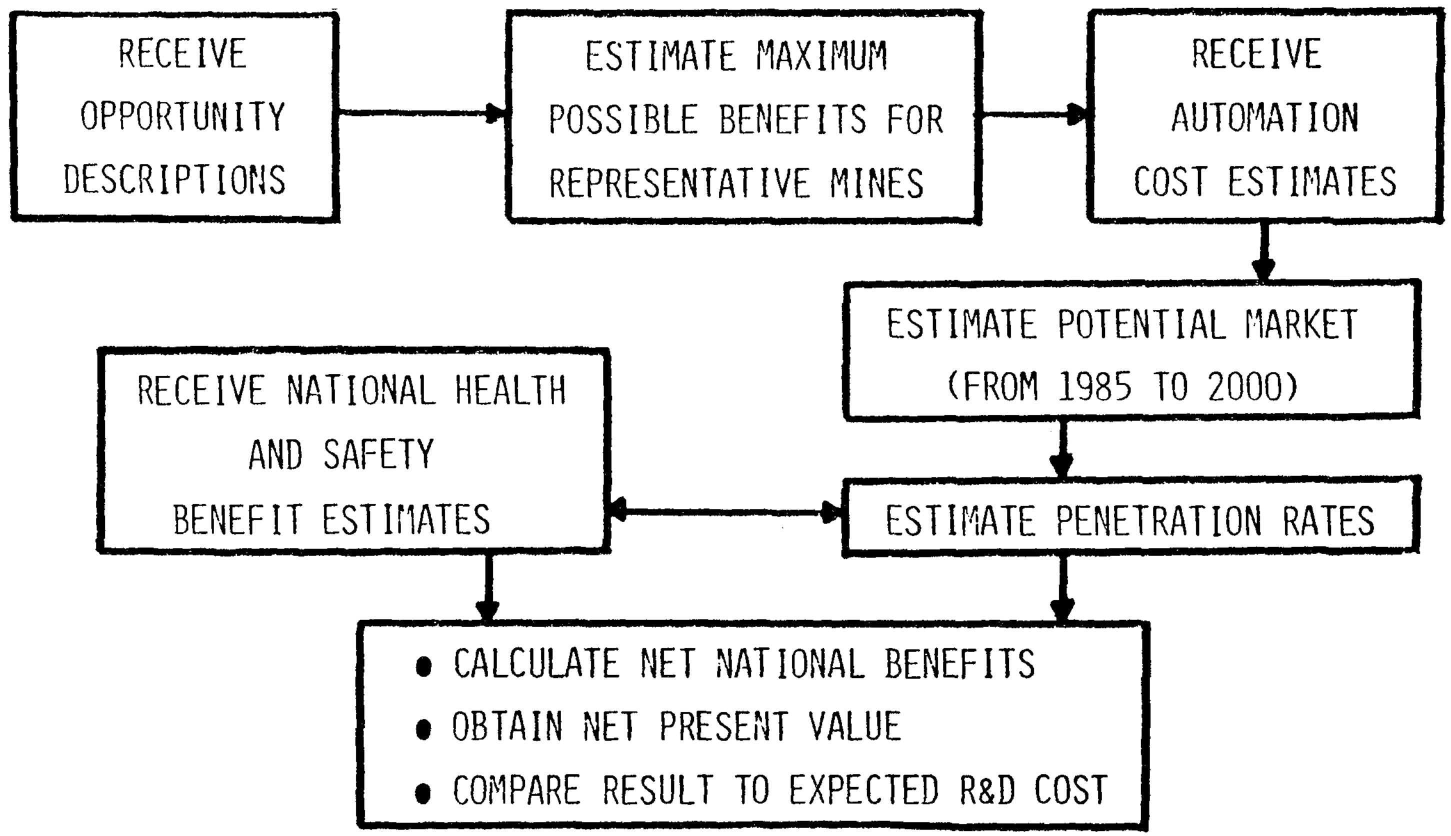

Figure 5-10. Steps in Cost-Benefit Analysis

(35) derived a method for obtaining the higher rate of return required for innovations, given a normal rate of return and the lifetime of the investment. That study was based on research conducted by Mansfield (36). Mansfield determined that a 25% rate of return on equity, after taxes, would be required to make an innovation such as automation attractive to the coal industry.

Therefore, two cost equations were developed for the projection; one with a normal rate of return (15%), and the second, with a higher rate of return (25%).

IPEG employs a fixed charge rate (FCR) for equipment which depends on equipment lifetime, a second fixed charge rate for land, long-life investments and facilities, an overhead rate for labor, and another overhead rate for materials and supplies. A constant charge per ton of coal is also included in order to account for union welfare costs. The expression for a 15% return on a nominal coal mine is:

$$\frac{FCR(15) \times EQPT + 1500 \times ACRE + 2.16 \times DLAB + 1.18 \times MATS}{QUAN} + 1.385$$

and the expression for a 25% return on a nominal coal mine is:

$$\frac{FCR(25) \times EQPT + 3200 \times ACRE + 2.33 \times DLAB + 1.23 \times MATS}{QUAN} + 1.385$$

where the FCR number is taken from Table 5-10, EQPT is the delivered and installed cost of equipment in 1982 dollars, ACRE is the area of the mine in acres, DLAB is the annual cost of wages for direct labor, maintenance personnel, and foremen, in 1982 dollars, MATS is the annual cost of material, supplies, and utilities in 1982 dollars, and QUAN is the tonnage of coal produced in a year.

The result of this calculation is the revenue required per ton of coal to meet expenses and make a return on investment. The financial and operational overheads include profit, income taxes and credits, amortization of investment, insurance, startup costs and revenues, working capital, indirect labor, fringe benefits, royalty payments, and other miscellaneous expenses.

Table 5-10. FCR For Equipment

	Equipment Lifetime							
	3	4	5	6	8	10	12	20
FCR(15)	0.58	0.49	0.43	0.40	0.36	0.33	0.32	0.29
FCR(25)	0.81	0.71	0.66	0.62	0.58	0.56	0.55	0.55

c. Potential Market. The potential market for longwall innovations consists of future expansion into new sections and replacement of worn out units. Historically, longwalls have been increasing their share of the underground coal mining industry since the 1960's at a rate which closely matches a classic "S"-shaped curve, sometimes referred to as a logistics curve. A general formulation of the logistics curve is the following:

$$\text{Market Share} = K_1 + \frac{K_2}{1 + e^{(A+BxT+CxTxT)}}$$

where T is time expressed in years, and $K_1 + K_2$ is the upper bound for market share. This equation is nonlinear with parameters K_1, K_2, A, B, and C which must fit historical data or reliable theory.

The approach taken for calibrating this curve for longwall market share was as follows:

(1) Establish an upper bound on market share based on the fact that 37% of today's underground production comes from mines which produce less than 200,000 tons annually and are too small to use longwalls (37). This statistic has not changed significantly since 1962 (30). Furthermore, even in longwall mines, some 20% of the coal is obtained by other means during mine development and initial tunnel construction. This sets an upper bound on longwalls of 50% of total underground coal.

(2) Using 1995 as the point at which T = 0, a form of nonlinear programming called a line search was used on each parameter to determine the values which best fit the historical data (38).

(3) The result of the previous step was used as a trial solution, and these results were compared to a projection made by Kuti (39), who used a substantially different method. The projections used in this report are somewhat more conservative than Kuti's. He predicted 12% longwall penetration by 1985, the logistics curve produces 11% for that year. Furthermore, the rate of expansion is consistent with data that received from industry (31, 40).

Both the longwall industry size, in terms of tons per year, and the annual potential markets are given in Table 5-11. The annual market is subdivided into expansion into new sections and replacement of old sections, and is further subdivided into low and high coal. This breakdown is shown in Table 5-12. The subdivision into low and high coal is based on the historical data on longwall seam heights provided in Reference 41. This distribution is shown in Figure 5-11. The number of sections comes from the estimates of tons per section, for low and high coal, directly resulting from the development in Section V.B of this report. These figures are summarized in Table 5-13. They are somewhat higher than historical averages in the U.S. due to expected improvements in future equipment and procedures (30).

Table 5-11. Underground, Longwall, and Potential Longwall Market Tonnage Projections (millions of short tons).

Year	Underground[a]	Longwall[b]	%	Annual Market[c]
1980	335	22	6.5	--
1981	350	25	7.2	--
1982	366	29	8.0	--
1983	382	34	8.9	--
1984	400	40	9.9	--
1985	418.0	46	11.0	7.3
1986	461	55	12.1	11.9
1987	509	68	13.3	14.9
1988	561	82	14.6	17.3
1989	619	99	15.9	20.0
1990	683.5	118	17.3	23.5
1991	728	137	18.8	22.5
1992	776	158	20.3	25.5
1993	826	180	21.8	28.4
1994	880	206	23.4	31.7
1995	937.6	234	25.0	38.3
1996	999	266	26.6	43.1
1997	1064	300	28.2	48.1
1998	1133	337	29.7	53.8
1999	1207	377	31.2	60.1
2000	1286	420	32.7	61.8

[a]Based on historical data reported by the United States Bureau of Labor Statistics and on projection by DOE's EIA (the low oil price scenario in Ref. 12). DOE projections were available for 1985, 1990, and 1995 (30).

[b]Derived from the total underground tonnage times the percentage of penetration. Penetration percentage was derived by fitting a general logistics curve on historical data, plus an estimate of maximum penetration by longwalls. See Appendix C.

[c]Includes expansion plus replacement of 10-yr old units. See Appendix C for the age distribution of most of today's units. Estimates for years prior to 1985 are not necessary for this study.

Table 5-12. Underground Longwall Annual Markets (Number of Sections)

Year	Replacement Low Coal	Replacement High Coal	Expansion Low Coal	Expansion High Coal
1985	1	2	7	9
1986	2	3	12	14
1987	3	4	14	17
1988	4	4	16	21
1989	4	4	19	25
1990	4	5	22	30
1991	4	6	21	27
1992	6	6	23	31
1993	7	7	26	34
1994	7	8	29	38
1995	10	14	31	43
1996	14	16	34	47
1997	15	20	38	51
1998	19	23	42	55
1999	21	28	45	60
2000	19	26	49	65

Table 5-13. Baseline Annual Section Production Rates (1,000 Tons/yr)

Type of Longwall Section	High Coal	Low Coal
New Sections (inexperienced operator)	472	262
Replacement (experienced operator)	500	281

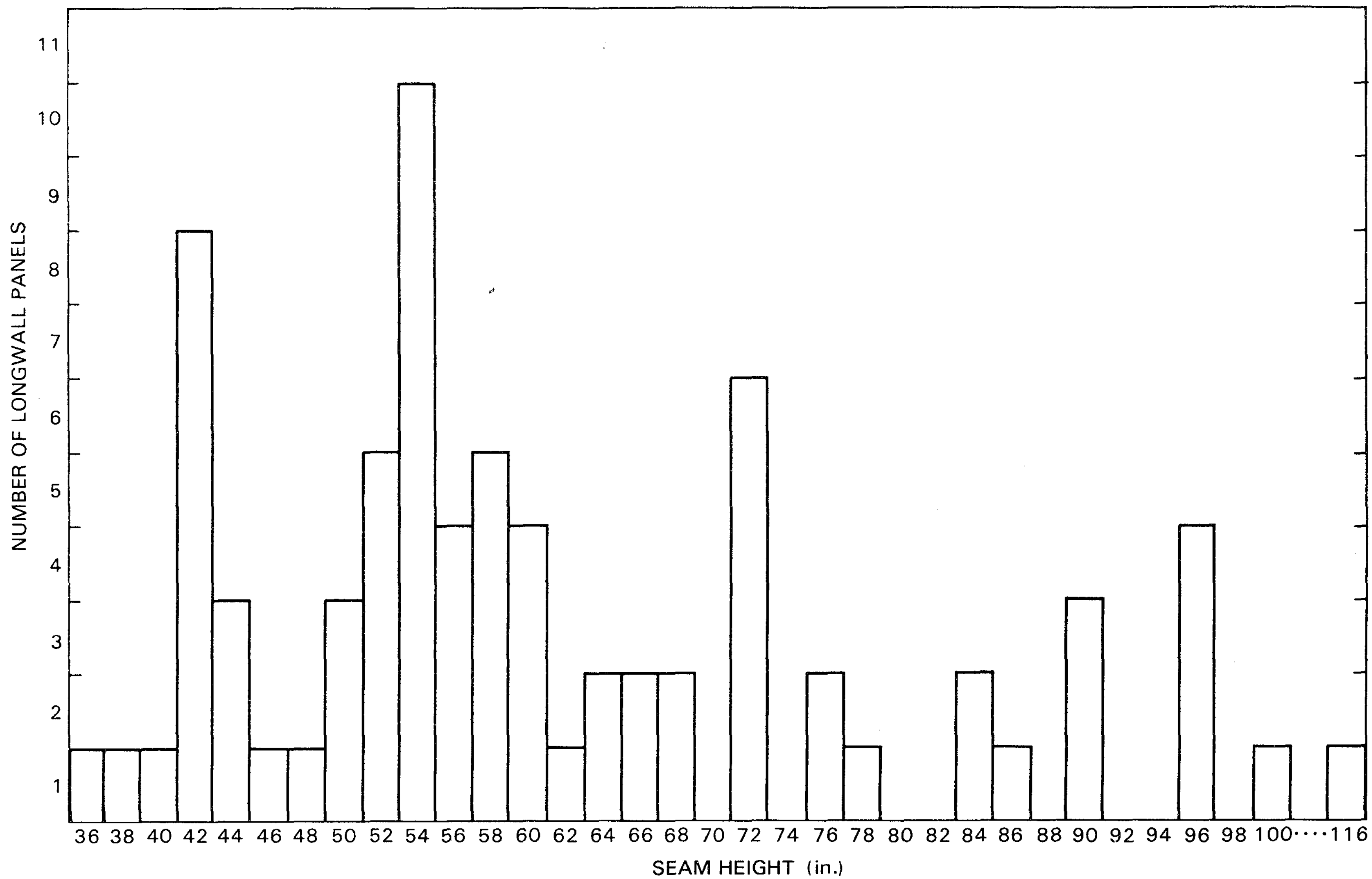

Figure 5-11. Seam Heights in USA Longwall Panels
(Source: Ref. 41)

2. Cost-Benefit Estimates for R&D Options

This section provides the estimated net national benefits of each R&D option using the methodology described above. In review, the following automation options were examined:

1A. The smart shearer

1B. The totally automated (no operator) shearer

2A. Conveyor/face alignment

2B. Dumb shield advance

3. Monitoring and control of environment and haulage systems

4. Fault isolation and diagnostics

These options have common elements so that costs and benefits of each of the six by itself will not add up to the correct cost and benefit for the group as a whole. Furthermore, options 1A and 1B are mutually exclusive. All other combinations are mutually compatible. Options 2A and 2B should go together. The maximum benefit comes from the combination of options 1A, 2, and 3. The combination of 1A, 2, 3, and 4 was also examined and is called the "combined automation" option. Each option is also explored separately.

a. Productivity Calculations. Table 5-13 provided baseline annual production levels for several kinds of longwall coal mines. As explained earlier, each automation option increases productivity per section by reducing some of the time spent on delays (see Section V.B). Table 5-14 summarizes the resulting annual productivity increase in terms of thousands of tons of coal per section per year. Table 5-15 gives the same information in terms of thousands of dollars of increased net revenue per year per section in new mine sections. Net revenue is the difference between total revenue, or $35/ton, and tonnage-related costs. Tonnage-related costs only include union welfare ($1.385), materials and supplies ($9.16), and power costs ($0.44), for a total of $11/ton (42). Net revenue is then $24/ton, in 1982 dollars. Table 5-15 strictly represents the maximum possible economic benefits from these opportunities. Table 5-16 contains the estimated automation production (capital) cost to a mine owner for each opportunity.

Table 5-17 gives the net benefits, including the automation costs, for each opportunity. Opportunities 1 through 3 all have positive net benefits. Opportunity 4, fault isolation and diagnostics, does not seem practical unless it can share some of its microprocessor and communications costs with the other automation opportunities. Table 5-17 is based on stand-alone automation except for the combined automation option. Table 5-18 shows the effect of deleting various opportunities from the combined automation option.

Opportunity 1B, complete automation of the shearer, is not included in these combinations because of difficulties in estimating the cost and time required to successfully pursue this option. Complete automation presents

Table 5-14. Summary of Productivity Increases (1000 Tons Per Section Per Year)

	Opportunity Area	New Section Low	New Section High	Old Section Low	Old Section High
1A.	Smart Shearer	61	100	42	72
1B.	Automated Shearer	80	127	61	99
2.	Shields and Conveyor	59	89	40	61
3.	Monitoring and Control	19	28	19	28
4.	Fault Isolation	5	8	5	8
5.	Combined Automation	114	177	95	149

Table 5-15. Maximum Possible Benefits ($1000 of Revenue[a] Per Section Per Year)

	Opportunity Area	New Section Low	New Section High	Old Section Low	Old Section High
1A.	Smart Shearer[b]	1464	2400	1008	1728
1B.	Automated Shearer[b]	1920	3048	1464	2376
2.	Shields and Conveyor[b]	1416	2136	960	1464
3.	Monitoring and Control	456	672	456	672
4.	Fault Isolation	120	192	120	192
5.	Combined Automation	2736	4248	2280	3576

[a]Revenue is the average price of coal minus tonnage-related costs in 1982 dollars. Automation costs are not included in these figures.

[b]These options could lead to a reduction in section workers of 1-2 persons per shift for an additional savings of $134,000 to $268,000 in direct and indirect labor costs. This is not included in this table.

Table 5-16. Costs of Automation (Per Section)

Opportunity Area	Initial Capital Investment (1982 $)	Labor Per Shift	Annual Costs[a] (1982 $)
1A. Smart Shearer	300,000	b	174,000
1B. Automated Shearer	600,000	b	348,000
2. Shields and Conveyor	308,000	b	179,000
3. Monitoring and Control	158,000	0	92,000
4. Fault Isolation	207,000	1	254,000
5. Combined Automation	385,000	0[c]	223,000

[a]Based on a 3-yr service life for equipment, the IPEG coefficient used is 0.58.

[b]One to two persons could have been eliminated but this is not included here due to concerns about union requirements.

[c]In this case, the extra mechanic required for opportunity 4 can be exchanged for the available worker due to opportunity 1A and 2.

Table 5-17. Net Benefits Per Section
($1000 Per Year)

Opportunity Area	New Section Low	New Section High	Old Section Low	Old Section High
1A. Smart Shearer	1290	2226	834	1554
1B. Automated Shearer	1572	2700	1116	2028
2. Shields and Conveyor	1237	1957	781	1285
3. Monitoring and Control	364	580	364	580
4. Fault Isolation	-134	-62	-134	-62
5. Combined Automation	2513	4025	2057	3353

Table 5-18. Combinations of Automation Opportunities (Net Benefits Per Section Per Year in $1000)

Combinations	New Section Low	New Section High	Old Section Low	Old Section High
1A, 2, 3, & 4	2513	4025	2057	3353
1A, 2, & 3	2428	3868	1972	3196
1A, 2, & 4	2057	3359	1607	2687
1A & 2	1978	3202	1522	2530

substantial difficulties, in that it is possibly beyond today's state-of-the-art sensor technology and is not particularly desirable to the worker. The time required to conduct the necessary R&D is several years beyond what would be required for the smart shearer.

Time delays before market penetration are an important factor in calculating the present value of national benefits. Three periods of delay were identified: (1) an initial R&D period leading to a research prototype; (2) a MSHA approval period, and (3) time required by industry to get field experience with a production prototype. A schedule of delays is given in Table 5-19. This schedule could change after funding levels for R&D are decided upon, but the relative values should not change.

After these delays, the new technology can diffuse into the potential longwall markets described in Table 5-12. This study assumes that this diffusion will occur at the same rate as original penetration of longwalls into underground mines. Appendix C, Market Size Projections, describes the approach taken in greater detail. The diffusion of automated longwalls into the future longwall population is given in Table 5-20 for each of the six opportunities and combinations listed in Table 5-19. The monitoring and control opportunity (14) is most effective in mines which use rail transport, which will be used in some older mines and in the larger new mines (43). Unfortunately this is a small subset of the total potential market available to the other opportunities. Therefore, this would have the net effect of reducing the diffusion rate. Annual benefits and diffusion rates are then converted into annual net benefit terms in Table 5-21, and these are discounted at a 7% real rate for a present value result. The computations were simplified by the following procedure; for each opportunity,it was: (1) determined whether the mine operator would receive the return on

Table 5-19. Time Delays for Market Penetration (yr)

	Opportunity Area	R&D	MSHA	Industry	Total
1A.	Smart Shearer	3	2	2	7
1B.	Automated Shearer	9	2	3	14
2.	Shields and Conveyor	3	3	2	8
3.	Monitoring and Control	4	1	2	7
4.	Fault Isolation	4	1	2	7
5.	Combined Automation	4	3	2	9
6.	1A & 2	3	3	2	8

investment required to try the new technology (i.e., at least 25%) under different conditions, then (2) for those conditions for which the previous requirement was met an average net benefit per ton was calculated, and, finally (3) that result was multiplied times the fraction of the market given in Table 5-20.

b. Annual and Total Health and Safety Benefits. Impacts of automation on miner health and safety were in Section V.D of this report. Those impacts were expressed in terms of average yearly injuries. This section extends those estimates to annual and total impacts based on the penetration model developed for economic benefits.

Historical injuries in longwall operations over the time period 1976 to 1980 averaged 436 injuries/yr. Because longwall installations are increasing in number, this injury figure should also increase proportionately. Table 5-22 gives a projection of injuries in longwall coal mines, assuming that average injury rates per ton of production will not be reduced. Table 5-23 provides estimates of the total proportional injury reductions that could occur as a result of automation opportunities, based on the projections made in Section V.D.

In summary, opportunities 1A, 1B, and 2 offer good improvements in safety costs. Opportunity 3 does not lead to injury reduction, and opportunity 4, by itself, might reduce injuries slightly but fails to diffuse into the industry for economic reasons. Opportunities 6 and 7, similar to 5, have identical impacts on injury reductions.

Table 5-20. Diffusion of Automation Opportunities Into the Longwall Coal Mining Industry (%)

Year	Opportunity 1A	1B	2	3	4	5	6
1989	0	0	0	0	0	0	0
1990	2.0	0	0	1.0	0	0	0
1991	2.3	0	2.0	1.1	0	0	2.0
1992	2.6	0	2.3	1.3	0	2.0	2.3
1993	2.9	0	2.6	1.4	0	2.3	2.6
1994	3.2	0	2.9	1.6	0	2.6	2.9
1995	3.7	0	3.2	1.8	0	2.9	3.2
1996	4.1	0	3.7	2.0	0	3.2	3.7
1997	4.6	2.0	4.1	2.3	0	3.7	4.1
1998	5.2	2.3	4.6	2.6	0	4.1	4.6
1999	5.8	2.6	5.2	2.9	0	4.6	5.2
2000	6.5	2.9	5.8	3.2	0	5.2	5.8

The avoided injuries in Table 5-23 provide economic and noneconomic benefits. An economic measure of those benefits is $10,000 per injury in 1973 dollars (see Section V.D), or $20,000 in 1982 dollars. Noneconomic benefits include reductions in dust by removing the operators. As an overview, Table 5-24 summarizes both the benefits productivity and safety for each opportunity.

Table 5-21. Present Value of National Benefits
(Millions of 1982 Dollars)

	Opportunity							
Year	1A[a]	1B[a]	2[a]	3[b]	4[b]	5[c]	6[c]	7[c]
1989	0	0	0	0	0	0	0	0
1990	8	0	0	1.5	0	0	0	0
1991	11	0	9	1.9	0	0	14	16
1992	15	0	12	2.6	0	19	18	22
1993	19	0	15	3.2	0	25	24	28
1994	23	0	19	4	0	33	30	35
1995	31	0	24	5	0	41	38	44
1996	39	0	32	7	0	52	50	58
1997	49	25	40	9	0	67	62	73
1998	62	32	51	11	0	84	78	92
1999	78	41	64	14	0	105	99	116
2000	97	51	79	17	0	133	123	144
Net Present Value	158	48	124	28	0	199	193	226

[a]Stand-alone R&D options. Opportunity 1A is the smart shearer, 1B is a totally automated shearer, and 2 is an automated shield and conveyor system. All three include face alignment.

[b]Stand-alone R & D options. Opportunity 3 is mine monitoring and control, and 4 is fault isolation and diagnostics.

[c]Combined options. Opportunity 5 includes 1A, 2, 3, and 4. Opportunity 6 includes 1A and 2 only, and 7 includes 1A, 2, and 3.

Table 5-22. Annual Injuries in Longwall Coal Mines

Year	Injuries
1989	3100
1990	3700
1991	4300
1992	5000
1993	5700
1994	6500
1995	7400
1996	8400
1997	9500
1998	10700
1999	12000
2000	13300

Table 5-23. Annual and Total Safety Benefits from Longwall Automation (Injury Reductions)

Year	Opportunity 1A	1B	2	5	6 & 7
1989	0	0	0	0	0
1990	7	0	0	0	0
1991	10	0	11	0	19
1992	13	0	14	23	26
1993	17	0	18	31	33
1994	21	0	23	40	42
1995	27	0	29	50	53
1996	34	0	39	63	70
1997	44	19	48	82	87
1998	56	25	61	103	110
1999	70	31	77	129	140
2000	86	39	96	162	173
Totals	385	114	416	683	753

Table 5-24. Summary of Total Benefits[a]

Opportunity	Productivity ($1,000,000)	Safety ($1,000,000)	Safety (Injuries)[b]	Health[c]
1A	158	7.7	385	+
1B	48	2.3	114	+
2	124	8.3	416	+
3	28	0	0	0
4	0	0	0	0
5	199	13.7	683	+
6	193	15.1	753	+
7	226	15.1	753	+

[a]Based on inflation calculated from the GNP price deflator index, provided by the Department of Commerce.

[b]The total reduction in injuries for the years 1990 to 2000.

[c]A plus (+) indicates an improvement in health conditions by reducing worker exposure to dust.

SECTION VI

SUMMARY AND CONCLUSIONS

A. OVERVIEW

The previous section provided the quantitative cost-benefits associated with: (1) the difference between increase in production and projected capital and operating costs, and (2) the number (and cost) of the reduced disabling injuries. The qualitative health and improvements (primarily in reduced exposure to coal dust) were also indicated. In order to appreciate fully the implications of the various automation options, in terms of their respective effects on the longwall mining industry, it is important to examine the study findings in total. This section first summarizes the results of the productivity, technology assessment, health and safety, and cost benefit evaluations. Second, all the various options are ranked by the magnitude of their respective potential impacts in each of the evaluation areas. Finally, a technology development plan is suggested, based on the ranking of automation options.

B. SUMMARY OF RESULTS

The results of the productivity analysis suggested that removal of delays associated with shearer stalling, face alignment, and operation would greatly improve available shearer production time. Similarly, elimination of face alignment problems which overstress the face conveyor or cause shield interference would also enhance productivity. Some maintenance delays would also be favorably impacted by incorporating improved management information and fault isolation systems. Overall, almost a 40% improvement in production was projected for the case where all the automation options were incorporated.

The technology assessment area indicated that all of the various automation options could be developed using state-of-the-art technology in sensors, servomechanisms, comparators, digital electronics, and computers. This finding was based on the results of the conceptual designs presented in Section V.C. Consequently, development and production costs were not projected to be beyond a first order of magnitude, measured in millions of dollars invested.

The health and safety impact evaluations provided some interesting insights into longwall mining hazards. These results suggested that automation of the shearer, shield, and conveyor operations would allow approximately a 23% reduction in average yearly disabling injuries as well as reduced exposure to respirable coal dust.

Finally, the cost-benefit analysis examined the net economic benefit realized from each of the automation options as a function of benefits (increased productivity and safety) less costs (capital and operating). Overall, it was projected that incorporation of all the options would result in a net national benefit of roughly $200 million. The major controlling factor in the cost assessment was the influence increased production had on offsetting the costs.

C. IMPLICATIONS OF RESULTS

The above results have strong implications for the structure of an overall technology development plan. As a first step in developing the logic of such a plan, it is useful to rank the various options in order of relative impact.

1. Production Implications

Each of the automation options can be ranked by its respective impact on production by using the results of Table 5-14 (from the cost-benefit analysis). These values were calculated by taking the incremental time savings for each automation area calculated from the network analysis, and converting time into production. Each of the options is ranked in Table 6-1 as a function of operator experience and seam height.

It is obvious from the above ranking that shearer, shield, and conveyor automation make up the bulk of the overall productivity improvement; particularly, where an inexperienced operator (having to make more trim cuts) is working under ideal conditions (high coal). In other words, automation of the three major areas would allow the longwall system to operate as projected under ideal conditions, independent of any operator delays associated with skill. It should be noted that total shearer and shield automation were not considered practical due to the complexity of such a system. Additionally, it was indicated in Section III that workers would still be required to take care of non-routine tasks such as ground control. Therefore, it would be impractical to attempt to fully automate a system where workers are a necessary element to make the system operate properly.

Table 6-1. Ranking of Automation Options by Impact on Coal Production (1000 Tons Per Section Per Year)

Automation Option	Inexperienced Operator Low Seam	Inexperienced Operator High Seam	Experienced Operator Low Seam	Experienced Operator High Seam
Remotely Controlled Shearer	61	100	42	72
Remote Shield and Conveyor Advance	59	89	40	61
Management Information System (computer monitoring)	19	28	19	28
Fault Isolation	5	8	5	8
Combined Automation (all of the above)	114	177	95	149

Table 6-2 presents the net impacts of all the automation options on productivity in terms of percentage improvements over the original baseline figures.

Table 6-2. Percentage Improvement Over the Baseline Productivity

Operator Skill	High Coal	Low Coal
New sections (inexperienced)	38	44
Old sections (experienced)	30	34
Overall average	37	

2. Technology Implications

The technology choices are more difficult to rank. Table 5-10 in the previous section indicated that the largest portion of the development costs would be consumed by the shearer, shield, and conveyor options. Although these components are the largest cost contributors, their relative ranking in relation to the other automation options must consider other factors besides cost. These other factors include: (1) choice of options that achieve the best results for the money invested, and (2) choice of options that represent the best development sequence to achieve the most rapid payback on investment. When these factors are considered, it becomes obvious that automating the shearer, shields and conveyor achieve the best results in terms of seeing a rapid payback through increased production. Based on these conclusions, Table 6-3 gives the ranking of the options based on the impact on production.

It is important to recognize that the total cost cited in Table 6-3 makes no provision for amortization of expenditures. In fact, the total investment cost could be raised by two to four times higher (i.e., up to $20 million) to be conservative, and the total payback, based on the previously calculated $200 million net benefit, would still be an order of magnitude larger. Therefore, it is clear that the potential for improved production far outweighs the investment in R&D.

3. Health and Safety Implications

The ranking of the automation options as a function of health and safety impacts resulted in a slightly different order than the above rankings. The health impacts revolved largely around reduction in exposure to dust. The safety impacts resulted primarily from the fact that hazards

Table 6-3. Suggested Automation Technology Development Sequence Based on Impact on Investment Payback

Automation Option	Impact on Payback Large	Medium	Small	Total Investment (million $)
Common Elements (computer, sensor communication, software)	X			1.0
Remotely Controlled Shearer	X			2.0
Remote Shield and Conveyor Advance	X			2.0
Management Information System (computer monitoring)		X		0.1
Fault Isolation			X	0.4
	Approximate Total Cost			5.5

associated with being caught, being struck, or slipping and falling while advancing the shields and conveyor, comprised the largest fraction of serious longwall injuries. Table 6-4 provides the ranking of the automation options as a function of the potential reduction in average yearly disabling injuries and overall health improvements.

4. Cost Benefit Implications

The cost-benefit implications associated with each of the automation areas were clearly indicated in Section V.E. It, therefore, suffices to simply provide the ranking of the options based on the net benefits calculated for the productivity and safety area. This is provided in Table 6-5.

Table 6-5 indicates that, overall, the net benefit of incorporating all the automation options results in roughly a $200 million profit to longwall sections. Most of this profit comes from the improved production potential of automated longwall systems.

D. RECOMMENDATIONS

The findings presented in the preceding section have clear implications for the evolution of longwall automation. Clearly, the best plan of action should be to automate those areas where: (1) the most immediate and sizable

Table 6-4. Ranking of Automation Options Based on Health and Safety Impacts

Automation Option	Reduction in Average Yearly Injuries (%)	Reduction in Exposure to Dust: Large	Reduction in Exposure to Dust: Small
Remote Shield and Conveyor Advance	12	X	
Remotely Controlled Shearer	10	X	
Fault Isolation	1		X
Management Information System (computer monitoring)	0		X
Total Reduction in Disabling Injuries	23		

Table 6-5. Ranking of Automation Options Based on the Net Total Cost Benefits (Nationwide) for the Years 1989 to 2000

Automation Option	Productivity (million $)	Safety (million $)	Total (million $)
Remotely Controlled Shearer	158	7.7	165.7
Remote Shield and Conveyor Advance	124	8.3	132.3
Management Information System (computer monitoring)	28	0	28
Fault Isolation	0	0	0
Combined Automation (all of the above)	199	13.7	212.7

payback on R&D will be realized, (2) the most convenient and cost effective expansion of the system is feasible, and (3) the largest improvements in worker health and safety are realized. The one consistent element in all of the preceding rankings was the positive impact shearer, shield, and conveyor automation had on productivity, the technology development sequence, health and safety, and cost benefits. Therefore, the first step recommended is development of the smart (remotely operated) shearer. It is essential to incorporate the proposed shearer automation package (see Section V-C.) because it contains many of the spatial sensors which become integrated with the shield and conveyor automation package. As part of the shearer package, it is also suggested that a surface central computer system be developed to: (1) establish the appropriate sensor data processing links with the shearer, (2) allow the appropriate command, guidance, and control software to be designed, and (3) allow the sensor, guidance, and control subsystems on the shearer to be tested for accuracy, and calibrated. Once the surface computer and shearer package have been developed, it is recommended that the remaining sensors, guidance, and control elements be developed for remote shield and conveyor advance. Following the successful integration of the shearer, shield, and conveyor automation, the management information and fault isolation options should be developed. Although additional sensor and information retrieval subsystems may have to be installed, the data linkup, processing, and display system will already be in place via the surface computer system. This will jointly simplify the process of installing and testing other desired fault isolation sensors, and permit expansion of the total information system. This approach toward developing a management information and fault isolation system seems reasonable considering that a similar system has already been successfully implemented at the main Canelton Coal Company facility in West Virginia.

It is appropriate at this time to compare the major findings of this study with the results of the Skelly and Loy and COMINEC analyses. At the onset it should be stated that the automation options developed from the survey and network analysis were basically the same as those derived from the previous studies. One major difference between the respective analyses was the projected 40% versus 60% improvement in productivity. The original 60% figure was based on: (1) a projected decrease in face personnel, (2) more efficient shearer operation, and (3) an increase in shearer traverse speed (by not being limited by operator mobility). In keeping with the overall philosophy of conservatism throughout the document, it was decided that union restrictions concerning the number of workers required for various jobs could adversely affect the chances of realistically reducing the face crew size. Additionally, the study indicated that where one or two face personnel could be removed by automating the shearer and shield operations, one or two extra moving mechanics would be required to perform maintenance in support of the fault isolation system (see Table 5-16). Therefore, it was decided that the potential for reducing face personnel was not a viable assumption in the near term.

By comparison, all the studies were in agreement concerning the expected boost in production related to improved efficiency in shearer operation (which included maintaining face alignment). However, the results of this study diverged slightly from the two previous studies on the last element concerning increased shearer speed. It is clear that under certain circumstances (such as low coal), operator mobility can pace the cutting rate of the machine.

Similarly, many other variables such as soft floor, poor roof, or methane can prevent the machine from operating at maximum speed. Therefore, rather than assume that removal of the operator generally allowed a higher cutting rate, it was decided to keep the traverse rate of the shearer (regardless of automation) at the present average speed. Ultimately, this nominal value provided a rate which was not only representative of the industry in general, but it also allowed the study to retain its conservative (or worst case) approach. One last minor point of difference between the results of the respective studies stemmed from the management information and fault isolation options. Although not addressed in the COMINEC study, the Skelly and Loy analysis suggested that options would be required to monitor both the environment (for methane) and machinery failures since workers would not be present. The results of the network analysis in this study show that these options actually have an impact on reducing: (1) failure identification and access time, and (2) bottlenecks in outby haulage and supply delays. Consequently, it was discovered that these options could have an impact on increasing production time.

Overall, it seems that the analysis and results provided in this document not only confirm results of the previous studies, but provide a more substantial basis for the conclusions. For example, the safety analysis draws on a detailed historical injury data base (by worker activity) for the safety assessment. Similarly, the cost benefit analysis considered variables such as market penetration, future coal demands, and new longwall panels to accurately project the potential costs and profits of automation. In both of the above examples, well-constructed and tested methodologies were employed in the system assessment. Of key importance throughout the study was the necessity to not be too optimistic about the potential impacts of automation. This was achieved by using conservative values for the productivity, cost, and cost-benefit calculations where possible.

In conclusion, it seems that if the above automation development plan is adopted, several key areas would be addressed: (1) large productivity improvements could be realized, (2) cost benefits appear to far outweigh R&D investment costs, (3) worker health and safety could be greatly improved, and (4) the redesigned system would be responding to guidance, control and maintenance problems presently recognized as production inhibiting factors by operators, workers, and mine management.

SECTION VII

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APPENDIX A

DETAILED AUTOMATION DEVELOPMENT AND PRODUCTION COSTS

This appendix covers the cost of different approaches to longwall automation. The numbers provided are general order of magnitude costs. Each automation opportunity envisions the use of common equipment/subprograms that are shared by all five automation opportunities and the use of specialized add-on equipment/subprograms for each automation opportunity. Table A-1 list elements that are common to each automation opportunity.

Table A-1. Total Common Element Costs

Item	Development Cost	Production Cost
General purpose computer	$400,000	$20,000
In-mine communications	120,000	15,000
Display equipment, Printers, Plotters	120,000	10,000
Modifications to Shearer		
Communications	80,000	1,000
Distance along face sensor	20,000	1,000
System software architecture development	120,000	1,000
Total common element costs	$860,000	$48,000

Table A-2 is developed assuming that only the vertical profile of the shearer cut is placed in machine memory and utilized on the subsequent shearer cuts.

Table A-2. Add-on Ranging Arm Articulation Costs

Item	Development Cost	Production Cost
Shearer ranging arm modification	$100,000	$2,000
Ranging Arm Software	240,000	1,000
Add-on development costs	$340,000	$3,000

Table A-3 is developed for those cost elements associated with coal articulation only.

Table A-3. Cowl Articulation Costs

Item	Development Cost	Production Cost
Shearer cowl modification	$ 40,000	$2,000
Cowl articulation software development	120,000	1,000
Add-on development costs	$160,000	$3,000

Table A-4 combines the ranging arm articulation function and the cowl articulation function into a combined task. The costs are as follows:

Table A-4. Combined Costs of Ranging Arm and Cowl Articulation

Item	Development Cost	Production Cost
Common costs (Table A-1)	$ 860,000	$48,000
Ranging arm articulation costs (Table A-2)	340,000	3,000
Cowl articulation costs (Table A-3)	160,000	3,000
Total combined costs	$1,360,000	$54,000

In Section III, the following automation opportunities constitute a single face alignment task:

(1) Smart shearer face alignment sensing package.

(2) Face conveyor alignment computation package.

(3) Face conveyor alignment hydraulic ram servo control package.

(4) Microprocessor controlled shield advance control package.

Each automation opportunity requires successful completion of the prior opportunities in order to function. Partial operation might be possible, such as microprocessor-controlled shield advance, however, such an operation is not believed to be cost effective by itself. Table A-5 lists the add-on items needed for the smart shearer face alignment sensing package. This package is located on the shearer and might be included in the total shearer development costs of Table A-4.

Table A-5. Add-on Face Alignment Measurement Costs

Item	Development Cost	Production Cost
Shearer face alignment sensor	$200,000	$20,000
Face conveyor alignment sensing software	120,000	1,000
Add-on development costs	$320,000	$21,000

After the alignment of the face is measured, these measurements must be converted into commands to individual conveyor rams. Initially this computation is done at the general purpose computer on the surface. In productions versions, the computions would be done by a dedicated computer at the headgate. The computations are used by the face conveyor alignment hydraulic ram servo control package. Table A-6 shows the cost for face alignment control. The work of Table A-5 must be completed before Table A-6 work can proceed.

Table A-6. Add-on Face Alignment Control Costs

Item	Development Cost	Production Cost
Modifications to Sheild		
Communications		
1st unit	$ 50,000	-----
100 units @ 1,000 each	400,000	$100,000
Conveyor alignment ram		
1st unit	50,000	-----
100 units @ 1,000 each	400,000	100,000
Face conveyor alignment computation software	80,000	10,000
Face conveyor ram servo control software	120,000	5,000
Add-on development costs	$1,100,000	$215,000

Face alignment control includes communication between the headgate and each shield, and a microprocessor at each shield. Shield advance utilizes the face alignment microprocessor on each shield to control the shield tilt ram and the top rams. This will result in automated shield advance. This capability is limited to good floor conditions, thus a tilt indicator and an obstacle detector are included to detect malfunctions and a warning light to warn personnel of pending movement and/or to summon personnel if operations are faulty. Table A-7 covers the add-on cost of microprocessor-controlled shield advance.

Table A-7. Add-on Shield Advance Automation Costs

Item	Development Cost	Production Cost
Control of Sheild top ram and tilt ram		
Electric solenoid valves		
100 units @ 500 each	$200,000	$10,000
Warning lights		
100 units @ 100 each	40,000	5,000
Emergency stop obstacle detectors		
100 units @ 500 each	200,000	10,000
Shield advance software development	120,000	10,000
Add-on development costs	$560,000	$35,000

The total add-on cost for face alignment and shield advance is shown in Table A-8.

Table A-8. Add-on Face Alignment/Shield Advance Costs

Item	Development Cost	Production Cost
Face alignment measurement (Table A-5)	$ 320,000	$ 21,000
Face alignment control (Table A-6)	1,100,000	215,000
Shield advance (Table A-7)	560,000	35,000
Add-on development costs	$1,980,000	$271,000

A stand-alone fault isolation system would have to duplicate much of the specialized equipment of the other tables and is not recommended. Rather, the recommendation is that fault isolation be accepted as a design philosophy during development of the other sytems. In this way the minimal additional hardware/software needed for fault isolation can be added while implementing other opportunities. The modifications to shearer and shield in Table A-9 reflect these minimal additional costs. In order to increase the usefulness of the fault isolation system, equipment not normally connected to the computer network would have to be instrumented. The following items in Table A-9 would be added-on to whatever system was developed.

Table A-9. Add-on Auto Fault Isolation Costs

Item	Development Cost	Production Cost
Modifications to Shearer	$ 20,000	$ 1,000
Modifications to Shield	20,000	1,000
Fault isolation		
(pumps, transformers, etc.)		
Modification 50 units @ 1,000 each	200,000	50,000
Fault isolation software development	120,000	30,000
Add-on development costs	$360,000	$62,000

A computer monitoring system would be a subset of sensors of the fault isolation system. If control was also included, additional sensors and controls would be needed. Assuming that one wished to vary the shearer speed as a function of the pan-line load, the items of Table A-10 would be add-on items. The addition of other types of control would cost about the same order of magnitude.

Table A-10. Add-on Monitoring/Control System Costs

Item	Development Cost	Production Cost
Shearer tram motor control	$ 4,000	$1,000
Headgate drive current detector	4,000	1,000
Control system software	120,000	1,000
Add-on development costs	$128,000	$3,000

APPENDIX B

DETAILED DESCRIPTION OF THE IPEG (IMPROVED PRICE ESTIMATION GUIDELINES) MODEL

IPEG stands for Improved Price Estimation Guidelines. It consists of a linear equation which provides overhead for equipment (EQPT), mine property (ACRE), direct labor (DLAB), and materials, supplies, and utilities (MATS). The coefficient for equipment overhead has different values for different equipment lifetimes. This equation can be used for an entire mine or for a portion of a mine.

Two IPEG equations are provided here, one for a 15% rate of return on equity (a typical average for most mines at this time), and one for a 25% rate of return on equity. The 15% rate, and many of the other financial parameters used to generate these equations, are consistent with the assumptions used in which describe a 1978 coal mine (44). A test case yielded a result within 6% of the result obtained in that report. IPEG produced a result of $18.7/ton and the more elaborate procedure gave a result of $17.6/ton when the same values for EQPT, ACRE, DLAB, and MATS were used.

The two equations below represent the 15% and 25% rates of return on equity, respectively, with a 10-year equipment life. The ACRE coefficient will be sensitive to land costs, site prep, and shaft development costs. The other coefficients will be reasonably accurate for most mines. A full list of financial parameters used to generate these equations is attached.

$$\frac{0.330 \times \text{EQPT} + 1497 \times \text{ACRE} + 2.16 \times \text{DLAB} + 1.18 \times \text{MATS}}{\text{QUAN}} \tag{1}$$

$$\frac{0.558 \times \text{EQPT} + 3208 \times \text{ACRE} + 2.33 \times \text{DLAB} + 1.23 \times \text{MATS}}{\text{QUAN}} \tag{2}$$

The financial and organizational overheads were derived from the values of parameters given in Table B-3.

The improved Price Estimation Guidelines (IPEG) were first derived in 1977 for photovoltaics (32). A computer program now exists to create new models based on the financial and operational data for any particular plant or industry (33). IPEG has now been extended to cover underground mining.

The intent of IPEG is to minimize the computational burden of engineering economic studies without compromising the validity of the analysis. This facilitates optimization and economic tradeoff studies. A second intent is to permit valid comparisons between the true costs of capital, labor, materials, and supplies. Each coefficient is a realistic representation of the overhead burden that should be attributed to its associated engineering parameter. This is a feature which is not always available from engineering economic models.

The input parameters are: equipment (EQPT), mine property size (ACRE), direct labor (DLAB), materials, supplies, and utilities (MATS), and the quantity of coal produced in a year (QUAN). These have specific definitions:

1. EQPT is the initial cost of equipment, including delivery and initial installation expenses, expressed in 1982 dollars.*

2. ACRE is the size of the mine property, expressed in acres. In most of the differential cost studies of the underground coal automation project, this term will cancel out. If not, then careful attention must be paid to calculating the appropriate coefficient.

3. DLAB is (for this model) the annual direct wages of direct labor, maintenance personnel, and foremen, expressed in 1982 dollars. Fringe benefits and indirect labor are included in the overhead coefficient.

4. MATS is the annual cost of materials, supplies, and utilities expressed in 1982 dollars.

Rebuilding equipment (e.g., continuous miners are rebuilt every two to three years at approximately 50% of their original cost) can either be capitalized (i.e., included as an equipment term) or expensed (i.e., included in the annual materials and supplies term). Expensing will lead to lower coal prices and, from an accounting viewpoint, is a more proper procedure. In either case, comparisons of alternative technology should be done on a consistent basis.

Financial and operational costs of doing business are included in the overhead computed by IPEG. This includes: profit, income taxes, amortization of investment, insurance, startup costs and revenues, working capital, indirect labor, fringe benefits, tax credits, royalty payments, and other miscellaneous expenses. The average annual revenue required to meet all direct and indirect expenses is divided by the average annual production quantity (QUAN). The annual revenue required is obtained by multiplying each of the engineering parameters by an appropriate coefficient. The coefficient for EQPT will change for different equipment lifetimes. In general, these coefficients will change if a major financial variable such as the rate of return on equity is modified. Table B-1 gives a set of coefficients based on a 15% after-tax rate of return on equity, which is a typical coal mine industry average. Table B-2 gives a set of coefficients based on a 25% after-tax rate of return on equity which would be an appropriate rate of return for relatively innovative, unproven investments. A complete list of input data is given in Table B-3.

*The results of this version of IPEG will be in 1982 dollars. If some other year's dollars are desired, then EQPT, DLAB, and MATS should be expressed in that year's dollars and the ACRE coefficient should be adjusted by the inflation rate.

Table B-1. IPEG Coal Mine Coefficients, 15% ROE

Equipment Lifetime	For: EQPT	ACRE	DLAB	MATS
1	1.535	1497	2.16	1.18
2	0.760			
3	0.578			
4	0.487			
5	0.433			
6	0.398			
7	0.373			
8	0.355			
9	0.341			
10	0.330			
12	0.315			
15	0.301			
20	0.289			

Table B-2. IPEG Coal Mine Coefficients, 25% ROE

Equipment Lifetime	For: EQPT	ACRE	DLAB	MATS
1	1.869	3208	2.33	1.23
2	1.014			
3	0.810			
4	0.711			
5	0.655			
6	0.619			
7	0.595			
8	0.578			
9	0.567			
10	0.558			
12	0.549			
15	0.548			
20	0.547			

Table B-3. IPEG4 Engineering, Financial, and Operational Inputs

Variable	Description	Default Value
EQPT	19,100,000 for test case (44)	--
ACRE	6,432 for test case (44)	--
DLAB	6,460,300 for test case (44)	--
MATS	6,324,600 for test case (44)	--
EL	Equipment lifetime, in years 10 for test case (44)	--
FL	Facility and mine lifetime, in years	20
BETA	Property tax rate, annual percent of capital investment	0
EITCR	Average equipment investment tax credit rate	0.10
TC	Construction lead time (site prep, surface buildings, shaft construction) in years	2
TS	Development and startup time, in years	1
L	Average fraction of steady-state production rate achieved during development (44)	0.77
N	Startup MATS usage fraction relative to normal annual cost (44)	0.47
TM	First year of full production (no influence on coefficients)	1990
NU	Insurance rate	0.01
RLAB	Indirect/Direct labor cost, includes 40% benefits, 25% indirect labor (plant visits) (44)	0.75
RUTIL	Indirect utilities cost/acre for ventilation, water pumping in $/acre/year (44)	28.6

Table B-3. (Cont'd.)

Variable	Description	Default Value
W	Working capital time lag, in years	0.20
TAU	Income tax rate	0.5
LAMBDA	Leverage, expressed as total capital/ equity capital (default is 100% equity financing)	1
	Interest rate on debt, bonds (not used here)	0.14
R	Rate of return on equity (44, 45, 46). A higher rate of return may be needed to introduce new technology into the industry.	0.15
P1	Price of land $/acre	2,500
P2	Price of buildings $/acre	187,500
D2	Building area/mine area	0.002
G	Inflation rate (not influential to coefficients)	0.09
XEC	Contingency during construction (fraction of EQPT)	0.15
XFC	Contingency during construction (fraction of facilities cost)	0.50
X	Miscellaneous expense fraction of revenue (-0.10 federal tax credit, + 0 .05 royalties, + 0.02 local taxes)	-0.03
XOPR	Miscellaneous expense fraction of operating costs (44)	0.15
CRT	Capital recovery time, in years	20

APPENDIX C

DETAILED ANALYSIS OF FUTURE LONGWALL MARKET PENETRATION

Historical data on longwall market share in the underground coal industry is summarized in Table C-1. In addition to this information, a histogram of longwall startups from 1965 to 1981 was developed and is included here as Figure C-1. This information is consistent with traditional market penetration curves ("S" shaped curves). This appendix describes the detailed procedure used to develop the particular longwall growth curve that was used in this study.

The "S" shaped curve that is used in market growth studies can be generated by a logistics function (28). A general formulation of the logistics curve is the following:

$$\text{Market Share} = K_1 + \frac{K_2}{1 + e^{(A + B \times T + C \times T \times T)}}$$

where: T is time expressed in years,

$K_1 + K_2$ is the upper bound on market share,

K_1, K_2, A, B, and C are parameters which

must be estimated from data or reliable theory.

The first step was to use a simple form of this equation by setting K_1 and C to zero and then seeing if the resulting formula provided a good fit to the data. This simplification seemed appropriate because there are only 13 historical data points available to estimate the model parameters.

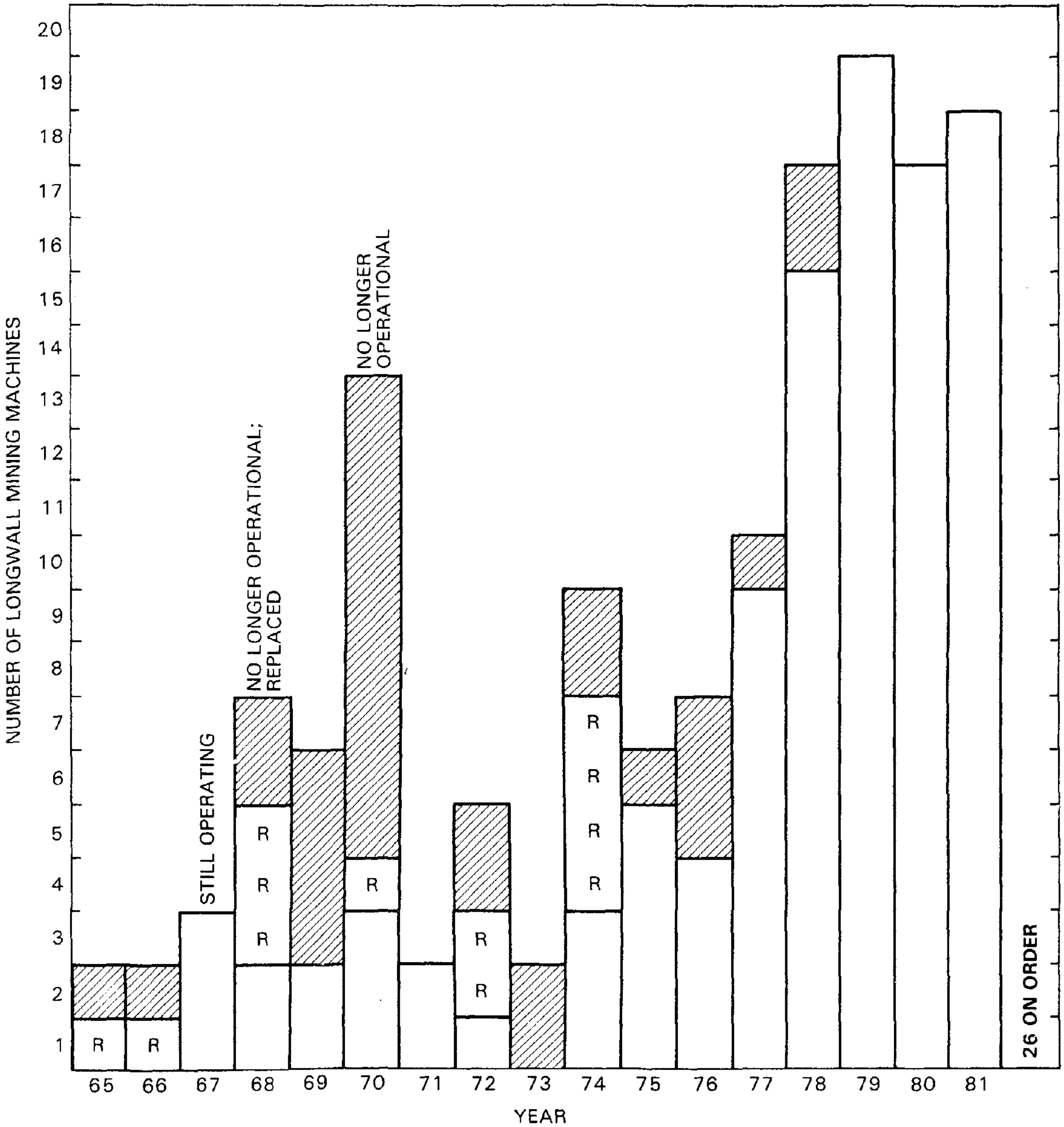
The second step required deriving a reliable estimate of an upper bound on longwall market share. Even if all coal mines eventually used longwalls, there would be tunnel boring for shaft and panel development which could produce roughly 20% of the coal that is extracted. However, many mines produce less than 200,000 tons/yr, which is too small for supporting a modern longwall section. In fact, 37% of the 1978 production came from mines of this size or smaller, and this percentage has not changed significantly since 1962 (30, 37). This sets an upper bound on longwall's underground market share at 50%, and establishes a value of 0.5 for K_2.

The next step required nonlinear programming techniques. Using 1995 as the point where T = 0, selecting a value for the market share at T = 0 determines the value of A (because K_2 = 0.5 and the other terms drop out).

Table C-1. Historical Longwall Market Share

Year	Market Share %	Market Share Tons (millions)
1967	0.9	3.2
1968	1.3	4.6
1969	1.8	6.3
1970	2.1	7.1
1971	2.4	6.6
1972	2.6	7.8
1973	3.2	9.4
1974	3.5	9.6
1975	3.1	9.1
1976	3.8	11.2
1977	5.0	13.3
1978	4.9	12.0
1979	NA	NA
1980	NA	NA
1981	7[a]	25[a]

[a]Estimated from the longwall census (31).



NOTE: There are 103 operating as of February 1982, 26 are on order, and 145 have been operated.

Figure C-1. Longwall Startups in the USA

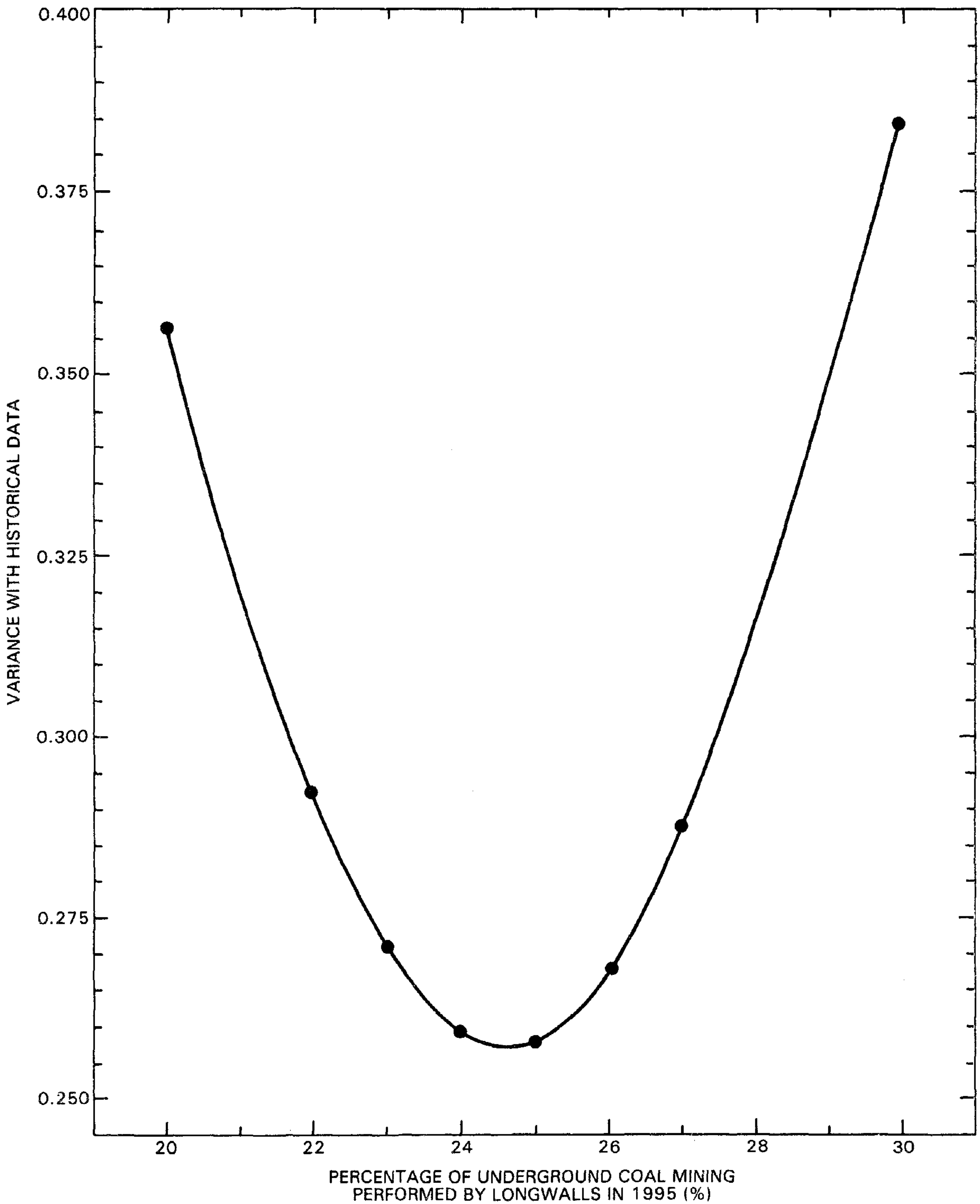


Figure C-2. Market Curve Fit Variance as a Function of Market Penetration by 1995

Therefore, the problem becomes one of choosing values of market share at T = 0 and values of B that minimize the variance between the historical data and the resulting logistics curve. Nonlinear line searches were conducted at a number of values of market share at T = 0 (38). A line search is a method of investigating a parameter of a nonlinear equation. An interactive computer program was used to perform this operation. Each line search found the best value for B (i.e., minimized the variance with historical data), given the assumed market share at T = 0. The resulting pairs of B and 1995 market share produce different market growth curves and different amounts of variance with historical data, which were plotted on Figure C-2. The combination that minimized the variance was B = -0.127, with a market share in 1995 of 25%. At these values, A= 0. The calibrated market share equation becomes:

$$\text{Market Share} = \frac{0.5}{1 + e^{(-0.127 \times T)}}$$

Where T = 0 in 1995.

VERIFICATION

The results of the market share curve were compared to projections by Kuti who used a different method in 1979. Kuti's projection for 1985 is 12%; this study's projection for that year is 11%. A less formal verification came from examination of data received from industry sources (31, 40). Current and planned longwall expansions seem to be consistent with the above projection at least to 1987.

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