IMPACT OF MAINTAINABILITY DESIGN ON INJURY RATES AND MAINTENANCE COSTS FOR UNDERGROUND MINING EQUIPMENT

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ABSTRACT

In the U.S. underground coal mining industry, maintenance of the mining equipment accounts for over 30% of the lost-time injuries. In addition, the steadily increasing cost of maintaining this equipment has focused attention on the need to find ways to contain or reduce these expenses. To obtain a better understanding of why maintenance injuries occur, the U.S. Bureau of Mines has conducted a research project to analyze the design of underground mining equipment with respect to ease of maintenance and maintainer safety. The objective was to identify design factors contributing to these high injury rates and maintenance costs. The work included a review of relevant maintainability design literature, analysis of maintenance-related accident data, field reviews of equipment design in underground operating environments, and interviews with mine maintenance personnel and equipment manufacturers. Based on the findings, a set of maintainability design recommendations have been prepared and published. The documents include basic maintainability engineering information for equipment designers, as well as a **buyers' guide** to assist purchasers of mining machinery in evaluating the maintainability of equipment.

INTRODUCTION

In the 1950's underground coal mining equipment consisted of relatively simple but rugged machines powered by electric motors and hydraulics. These machines were used to cut, dig, load, and transport coal from the mine face to the surface. The machines were maintained by mine maintenance personnel armed with a basic knowledge of hydraulics, electricity, and mechanical design. These maintainers were expected to repair all of the equipment at the minesite using only simple hand tools.

Over the years, the basic mining machine has been transformed into powerful, complex mining systems. To boost productivity, the horsepower and size of the original machines have been increased. To enhance unit productivity, machines were designed to perform multiple functions. To increase throughput, continuous miners, longwall and shortwall systems, and continuous haulage were introduced. To reduce injuries, numerous safety features have been added to the machines. To protect the miners' health, environmental control systems have been tacked on.

With few exceptions, however, little improvement in the basic design of equipment for maintainability has been made. In many cases, equipment maintainability has been sharply decreased. Many of the above design changes were achieved by simply modifying existing machine designs. On certain mining machines, sharp reductions in maintainability and, consequently, maintainer safety were experienced as a result of added-on safety and environmental systems designed only with the machine operator in mind.

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Even with all of the above changes, the maintainer is still expected to service and repair these ever more complex machines. This must be accomplished in an operational setting providing little in the way of new maintenance tools, procedures, automatic test equipment, or other technology-based maintenance aids and in an environment that usually lacks proper lighting and clearances. All in all, there has been little concern directed at the well being of the maintainer. It is no wonder that equipment maintenance has traditionally accounted for one-third of all lost-time injuries in underground mines. This injury rate persists in spite of concerted efforts on the part of mine management to minimize accidents, U.S. Mine Safety and Health Administration (MSHA) efforts to enforce health and safety rules, and USBM efforts to conduct safety research.

In addition to the safety of the maintainer, another area of concern has been the escalating cost of mining equipment maintenance. Underground equipment maintenance typically accounts for 25% to 35% of the total mine operating costs. These costs have continued to rise over the years despite efforts to contain them. Mine operators have attempted to gain control of these steadily increasing costs through (1) optimization of scheduled maintenance operations, (2) reductions in maintenance staff, (3) reduction and better control of spare parts inventories, (4) contracting for maintenance support, and (5) deferring nonessential maintenance.

Unfortunately, little attention has been focused on the design of the mining machine itself with respect to maintenance costs. The cost of maintaining a machine is, after all, a direct function of—

1. Maintenance frequency and failure interval for the machine and major components.
2. Time and labor required to complete unscheduled maintenance actions.
3. Time and labor required to complete routine maintenance tasks.

A review of current mining equipment design suggests that considerable improvements in safety, as well as substantial cost savings, could be achieved with relatively simple design improvements. For example, by relocating difficult to access, but frequently replaced hydraulic valves and hoses on certain roof bolters, this 1-h plus removal and replacement (R/R) task is reduced to a 5-min operation. Improved component accessibility and increased ease of R/R tasks reduces the maintainer's risk of injury. Numerous other maintenance improvements could be realized with minor design changes on new or existing equipment. As part of its program to enhance the safety of mine workers, the U.S. Bureau of Mines (USBM) completed a project entitled "Assessment of the Maintainability Design of Underground Mobile Mining Equipment," which was performed by VRC Corp. The final report was published in 1988 (*1*).[3] Other papers published by the USBM based on this work are listed in the references (*2-6*).

DESIGN-INDUCED MAINTAINABILITY PROBLEMS

The USBM analyzed underground coal mining equipment with respect to design for maintenance and maintenance personnel safety. A maintainability design review and human factors analysis of equipment was completed at nine operational coal mines. Mining machines in large and small mines operating in high- and low-seam coal were surveyed. Conventional, continuous, and longwall operations were included. Shuttle cars, scoops, roof bolters, continuous miners, longwall equipment, undercut machines, face drills, utility vehicles, and personnel carriers were reviewed. The survey identified the following design limitations that directly impacted maintenance time, cost, and personnel safety.

1. Accessibility problems: Inability of maintenance personnel to access failed or suspected components to inspect or remove and replace them. Accessibility problems resulted from—
   a. Inadequate access opening size.
   b. Poor layout of components in a compartment, necessitating R/R of nonaffected parts to access the failed units.
   c. Inability to access mounting bolts or connectors or to use required tools.
   d. Installing components in inaccessible interior cavities and running cables inside the frame or chassis where they cannot be reached.
   e. Locating fasteners and mechanical interfaces where they physically cannot be reached unless the machine is partially or completely disassembled.
2. Inadequate component-handling capability and component-machine interface design.
3. Inadequate design for routine maintenance: Inability to quickly remove and replace leaking hydraulic hoses and water lines, to remove and replace failed hydraulic valves,

[3]Italic numbers in parentheses refer to items in the list of references at the end of this paper.

to perform routine lubrication and to perform visual and physical inspections.

4. Inadequate fault isolation capability:

a. Difficulty determining the precise cause and location of a failure.

b. Accessing components to perform visual inspections and to perform checks.

c. Limited or no designed-in fault diagnostic capabilities.

d. Lack of effective failure indices.

5. Increased maintenance burden resulting from poor design and placement of components, subjecting them to impact damage.

6. Poor design with respect to resources available: Need for maintenance personnel to "jerry-rig" tools, to handle 45-kg (100-lb) to 450-kg (1,000-lb) components, and to substitute brute human strength to overcome poor component interface design or lack of requisite tools.

7. Equipment complexity resulting from poor layout: Crowding of components into compartments without regard to the need to maintain or replace individual items, overlaying hoses and power cables, and making R/R needlessly difficult.

8. Design conveniences: Multiplying the number of valves, connectors, and other high-frequency replacement components as a design convenience.

EQUIPMENT DESIGN AND MAINTENANCE SAFETY

A summary of maintenance-related accident statistics in the underground coal mining industry in 1981 is presented in table 1. A majority of the maintenance injuries involve strains-sprains, low back injuries, and crushing injuries. These injuries typically occur during R/R of components weighing from 16 kg (35 lb) to over 450 kg (1,000 lb) (*7*).

In many instances, two or more workers with crowbars, 4 by 4's, or other makeshift tools must manually remove the component from the mining machine or lift it into place so that it can be secured. In most cases, no provisions have been made during component-machine interface design to provide for mechanical assist in the R/R process (*7*). A review of mining equipment design suggests that, in many cases, this designed-in assistance could be readily achieved. For example, adding guide pins to hold components while they are being bolted or unbolted. If incorporated, the guide pins would minimize personnel exposure to the types of injuries identified in table 1. They would also expedite the R/R process itself.

One of the objectives of maintainability engineering is to minimize the need to manually handle components. With proper design and engineering, all components should be provided with mechanical means to interface them with the machine itself. With optimized maintenance design, it is reasonable to assume a substantial reduction in maintenance-related accidents.

Table 1.—Maintenance-related injuries in underground coal mining industry in 1981 (*8*)

Code	Type of accident	Mine maintenance		Machine maintenance	
		Number of injuries	% of total	Number of injuries	% of total
1	Stationary object	185	5.6	272	8.9
2	Moving object	2	Neg.	6	Neg.
3	Concussions	0	0	1	Neg.
4	Falling object	611	18.4	511	16.8
5	Flying object	62	1.9	62	2.0
6	Rolling object	62	1.9	18	Neg.
8	Struck by, NEC	231	6.9	265	8.7
17	Fall, walkway	8	Neg.	7	Neg.
18	Fall on object	3	Neg.	5	Neg.
21	Caught, moving-stationary	169	5.1	190	6.3
22	Caught, moving objects.	6	Neg.	9	Neg.
23	Caught, collapse	2	Neg.	0	0
24	Caught, NEC	261	7.9	292	9.6
25	Rub, abrade	3	Neg.	1	Neg.
26	Bodily reaction, NEC	2	Neg.	2	Neg.
27	Overexert, lifting	1,132	34.1	793	26.1
28	Overexert, push-pull	78	2.3	147	4.8
29	Overexert, welding	112	3.4	13	Neg.
30	Overexert, NEC	360	10.8	373	12.3
33	Contact hot object	3	Neg.	26	Neg.
36	Inhale noxious fumes	1	Neg.	8	Neg.
38	Absorb noxious fluid	26	Neg.	25	Neg.
39	Flash burns, electrical	0	0	2	Neg.
42	NEC	1	Neg.	2	Neg.
43	Insufficient data	2	Neg.	6	Neg.
Total		3,322	NAp	3,036	NAp

NEC Not elsewhere classified. Neg. Negligible NAp Not applicable.

HUMAN ERROR AND DESIGN FOR MAINTENANCE

So-called human error is a problem that must be addressed in design as well as during operation and maintenance of complex equipment (*9-13*). Errors may occur in operating mining machines, performing maintenance tasks, or in making management decisions. Fortunately, most human errors result in limited negative consequences (e.g.; lost time and production waste). In many cases, the error ends up costing the party involved time or money. Unfortunately, in a smaller percentage of cases, people are injured or killed and equipment destroyed.

Dramatic evidence of the impact of a maintenance error was the 1979 American Airlines DC10 crash that killed 272 people. This crash was directly attributed to maintenance error. The probability of recurrence of this type of error was reduced substantially by means of a simple component design change.

OPERATIONALLY INDUCED ERRORS

What does human error have to do with mining equipment maintainability? In an interesting review of the subject, researchers report that a significant percentage of all operational equipment failures are human error induced (*11-12*). In fact, human error accounted for—

1. Fifty to seventy percent of all electronics failures.
2. Sixty to seventy percent of all aircraft and missile failures.
3. Twenty to thirty percent of all mechanical failures.

Many of these are operator induced errors resulting in machine damage or prolonged down time. Maintenance requirements could be reduced by designing out these types of errors. Other errors are made by maintenance personnel while performing maintenance tasks (*13*).

MAINTENANCE-INDUCED ERROR RATES

The above study also reports that 20% to 25% of all failures are directly traceable to maintenance errors. A separate study found 25% of all maintenance problems to be human error induced during maintenance operations (*11*). Another study reports human error rates for specific types of maintenance tasks. These data, summarized in table 2, were derived from an earlier study (*13*). The values are indicative of the error rates found in many industrial and military settings.

Another maintenance study reports that the average human reliability in adjusting or aligning tasks is 0.0987 (*13*). This value suggests that out of every 1,000 attempts to adjust a component, you can expect 13 errors. Many of these errors could be eliminated through improved design of the component-machine interface. Although not directly applicable to underground mining operations, the above error rates are suggestive of the types, frequencies, and sources of human errors in maintenance. It is reasonable to assume that similar error-rate patterns could be expected in mine maintenance operations.

Table 2.—Representative maintenance task error rates (*13*)

Action	Object	Error description	Error rate[1]
Observe ..	Chart	Improper switch action	1,128
Read	Gage	Incorrectly read	5,000
Read	Instruction	Procedural error	64,500
Connect ..	Hose	Improperly connected	4,700
Torque ...	Fluid lines	Incorrectly torqued	104
Tighten ..	Nuts, bolts	Not tightened	4,800
Install	Nuts, bolts	Not installed	600
Install	O rings ...	Improperly installed ...	66,700
Solder ...	Connection	Improper solder joint ..	6,460
Assemble	Connector	Bent pins	1,500
Assemble	Connector	Missing part	1,000
Close	Valve	Not closed properly ...	1,800
Adjust ...	Linkage ...	Improperly adjusted ...	16,700
Install	Orifice	Incorrect size installed	5,000
Machine ..	Valve	Wrong size drill and tap	2,083

[1]Per million operations.

ERRORS IN UNDERGROUND MINING EQUIPMENT MAINTENANCE

Representative underground mining maintenance errors have been identified, with the major types summarized in table 3. It was also possible to identify a number of factors contributing to maintenance-related human error. These include—

1. Confined workspaces: Crowded equipment bays.
2. Inability to make visual inspections.
3. Inaccessible components:
   a. Lube points that could not be reached.
   b. Adjustment points that are hard to access.
   c. Major components that could not be reached.
4. Poor layout of components in a compartment.
5. Inappropriate placement of components on machine.
6. Poor or no provision for hose and cable management.
7. Lack of troubleshooting guides and tools.
8. Lack of positive component installation guide pins and other installation controls.
9. Insufficient task inspection and check-out time.
10. Cumbersome or inadequate manuals.
11. Excessive weight of components being manually handled.

Table 3.—Typical mining equipment maintenance errors

Frequency	Type of error
I	Install incorrect component.
S	Omitting a component.
	Parts installed backwards.
	Failure to properly torque.
	Failure to align, check, or calibrate.
	Use of incorrect fluids, lubricants, or greases.
O	Reassemble error.
	Failure to seal or close.
	Error resulting from failure to complete task due to shift change.
	Failure to detect while inspecting.
	Failure to lubricate.
	Failure to act on indicators of problems due to workload, priorities, or time constraints.
	Failure to follow prescribed instructions.

I Infrequent (less than once per year).
S Somewhat frequently (2 to 5 times per year).
O Often (over 5 times per year).

Listed below are several engineering design improvements that reduce maintenance errors:

1. Improved component-machine interface:
   a. Design interface so that the component can only be installed correctly (e.g.; irregular bolt pattern).
   b. Provide mounting pins and other devices to support a component while it is being bolted or unbolted.
2. Improved fault isolation design:
   a. Designate test points and procedures.
   b. Provide built-in test capability.
   c. Clearly indicate direction of fault.
3. Improved indicators, warning devices, and readouts to minimize human decisionmaking.
4. Use of operational interlocks so that subsystems cannot be activated if they are incorrectly assembled-installed.
5. Use of positive decision guides to minimize human guesswork:
   a. Arrows to indicate direction of flow.
   b. Correct type of fluids or lubricants.
   c. Correct hydraulic pressures.
6. Design to facilitate detection of errors:
   a. Locate connections on front of component to facilitate visual inspections.
   b. Lay equipment out in a logical flow sequence.

If maintainer-induced errors could be reduced by 50%, overall equipment availability would be increased by more than 10%. These reductions can be achieved through improved design.

MAINTENANCE SAFETY COSTS

Maintenance operations account for a significant percentage of all coal mining accidents and injuries. MSHA accident statistics for 1984 suggest that maintenance-related injuries account for 33% of all lost-time accidents (*14*). These accidents impact mine operating costs in the form of decreased productivity, increased benefits costs, and increased insurance rates.

Many injury accidents can be directly traced to equipment design in this and other studies (*6*). Inadequate accessibility, lack of means to lift and maneuver heavy components, inability to visually observe the maintenance task being performed, inadequate maintenance safeguards, and other design-induced problems account for a significant percentage of maintenance accidents. Improved accessibility, enhanced component-machine interface, and simplified maintenance procedures could have a positive impact on these statistics. Improved maintenance safety will reduce maintenance as well as overall operating costs.

COST OF MINING EQUIPMENT MAINTENANCE

Reliable maintenance cost data are not currently available across the underground coal mining industry, although several industry estimates are available. These estimates, however, vary substantially from source to source.

Informal data gathered over the past several years reveal that equipment maintenance costs range from 20% to over 35% of total mine operating costs. Actual values varied based on the size and type of mine, mining technology employed, management attitude toward maintenance, and other factors.

FACTORS CONTRIBUTING TO MAINTENANCE COSTS

The current review of mine maintenance operations suggested that the following factors contribute to equipment maintenance costs:

1. Management attitude towards maintenance: Attitudes range from "when it breaks—fix it" to strong top management support for professionally planned and implemented preventive maintenance (PM) programs geared to reducing unscheduled equipment down time and to controlling maintenance costs.
2. Skill of maintenance management personnel: The skills required to organize and manage an effective mine maintenance program differ from the skills required to perform "hands on" maintenance of mining equipment. Poor maintenance management contributes to increased costs.
3. Maintenance training and experience: Poor maintenance skills on the part of maintainers resulting from inadequate training; lack of job performance aids, manuals and guides; and complexity of maintenance tasks.
4. Maintenance environment: It is an entirely different task to maintain a continuous miner in a 91-cm (36-in) coal seam than it is to maintain one in a well-equipped standing height underground repair shop.
5. Age of equipment: Older equipment tends to be smaller and inherently simpler in design. As a result, older machines are somewhat simpler to maintain. Newer equipment tends to be larger, more complex, and overlaid with numerous "add-on" systems and components, making accessibility and the basic maintenance process more difficult.
6. Maintenance errors: Reliable data are not available, but most maintenance personnel interviewed informally concede that maintenance errors contribute substantially to overall maintenance costs. Removing and replacing nonfailed items, troubleshooting one system too long, not replacing suspected components during a previous maintenance opportunity, failing to install or repair a component correctly, failing to test a component prior to reassembly, and related errors account for an estimated 10% to 25% of all maintenance time.
7. Design of equipment itself: Certain makes and models of mining equipment are designed to facilitate maintenance and repair, while the basic design of other models hinder maintenance actions.
8. Regulatory compliance: Safety and environmental control devices required for regulatory compliance add to the complexity and increase maintenance costs.

COST OF DESIGN FOR MAINTAINABILITY

The value or worth of any machine resides in its ability to generate a return on investment. If a machine has an initial cost of "Y" dollars, it must produce "Y plus" dollars of coal to have a positive worth or value. On this assumption, it is possible to illustrate the cost savings derived from improved design for maintainability using simple economic models.

There are many economic models that can be used to compute the worth of equipment. For this discussion, a simplified model will suffice. Figure 1 presents an overview of this model. (Readers interested in a more comprehensive treatment are referred to references 8, 15, 16, and 17.) The following model suggests that the worth (W) of a piece of mining equipment can be defined as—

$$W = I + C + M - P,$$

where I = initial purchase price of machine,

C = cost per hour to operate machine,

M = maintenance costs per hour of operation,

and P = production value per hour of operation.

The initial purchase price of the piece of equipment is fixed or "inelastic." It is set at the time of purchase. The price is simply amortized per hour over the useful life of the machine. Of course, the more hours of production it sees, the lower the amortized cost per hour.

The cost per hour to operate the machine is relatively fixed or "inelastic" and composed of the following cost elements:

1. Labor costs for the machine operator(s), support personnel, and immediate production supervision.
2. General overhead costs, which include insurance, utilities, royalties, brokerage, and related costs.
3. Cost of mining supplies and materials.
4. Other management and administrative costs.

The cost to maintain consists of the following cost elements, some of which are fixed and some of which are relatively "elastic":

1. Labor costs for maintenance personnel.
2. Cost of spares, replacement parts, and supplies.
3. Loss of production during maintenance.
4. Cost per hour of idled machine operators.
5. Other maintenance-related costs.

The costs of replacement parts and maintenance supplies are also relatively inelastic. Certain savings can be realized with careful buying. The cost of labor and other overhead items, on the other hand, are a function of the duration of repair time for unscheduled corrective maintenance (CM) actions.

More importantly, a reduction in repair time for downed equipment contributes positively to the overall worth equation by increasing the time available for production. Thus, decreased time to repair not only reduces direct maintenance costs, but also increases the production per hour, thereby offsetting other costs. If we look at the maintenance process again, we observe many points at which time can be saved through improved design for maintenance (fig. 2). Several of these points include—

1. Prediction of pending failures to facilitate PM scheduling.
2. Decreased fault isolation time.
3. Reduced component access time.
4. Decreased inspection and diagnosis time.
5. Diminished component R/R time.
6. Reduced test and alignment time.

A review of underground maintenance task completion times at two large mining operations revealed that the time required to change hydraulic hoses on continuous miners and shuttle cars ranged from 15 min to over 3 h. The estimated average time for a failed hydraulic hose R/R was over 35 min. Examination of these machines revealed that the time differences were directly linked to accessibility of the hose connectors. In several cases, two or more nonfailed components had to be removed to access a failed hose connection.

By relocating several components or rerouting hoses, maintenance personnel could directly access over 90% of all hydraulic line connections on the surveyed machines. This would have reduced the average hydraulic line R/R time to well under 15 min per replacement.

If a maintainability design standard for new or rebuilt machines specified that all hydraulic hoses had to be removed or replaced in less than 15 min, the average repair time for this task could be reduced 50%. Similar performance criteria could be developed for other maintenance tasks. The result would be significant reductions in all maintenance task completion times.

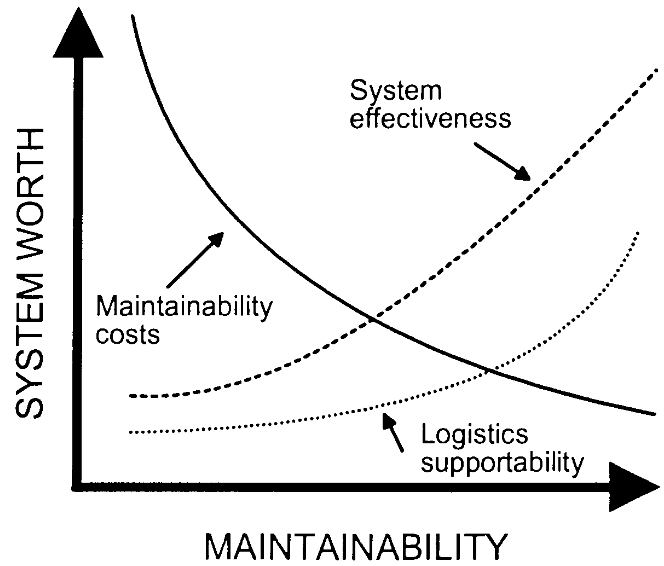

Figure 1.—System worth versus maintainability (*13*).

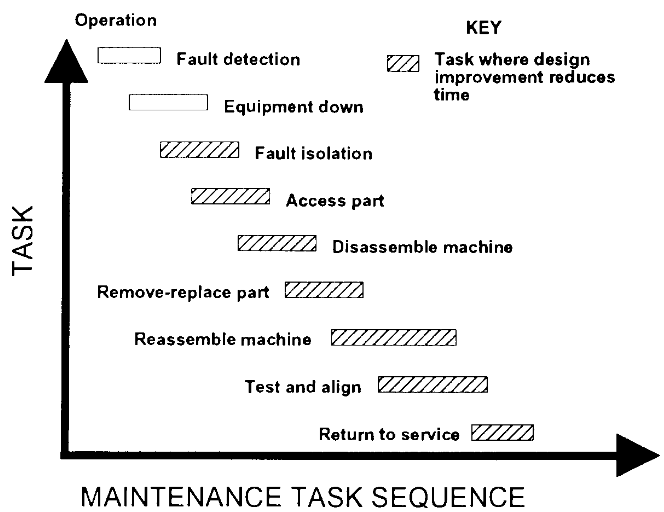

Figure 2.—Sample maintenance task sequence.

Evidence from other civilian and military research efforts suggest that PM and CM task time reductions of from 40% up to 70% are achievable with planned maintainability design efforts (*15-16*).

PRODUCTIVITY

Productivity represents the other side of the maintainability issue. Productivity is a function of the machine producing coal. Hence, it is directly impacted by the speed and ease with which the mining machine can be repaired and returned to service. The more rapidly a machine can be returned to production, the more productive it will be.

Productivity is expressed in terms of the units (of coal) produced by a machine per unit of time. The greater the number of hours the machine is available to produce coal, the more productive it is going to be. For example, suppose that a continuous miner has a rated production capacity of 907 kg/h (100 st/h). Further, suppose that the same miner requires an average of—

1. One hour of PM per shift, and
2. One hour of CM per shift.

Assume that the mine operates the equipment during two production shifts per day for 300 d/yr. Hence—

$$(300 \text{ h PM} + 300 \text{ h CM}) \times 2 \text{ shifts} = 1{,}200 \text{ h/yr}.$$

If the CM and PM time could be reduced by 50%, this would result in the following increase in productivity:

$$(1{,}200 \text{ CM and PM h/y}) \times 0.5 = 600 \text{ h/yr savings}$$

$$600 \text{ h/yr} \times 90{,}000 \text{ kg/h (100 st/h)} = 54 \text{ million kg/yr}$$

$$(60{,}000 \text{ st/yr}) \text{ per machine increase.}$$

If the mine were operating eight miners, this 54 million kg/yr (60,000 st/yr) per machine increase would be the equivalent of adding another miner with no additional increase in cost.

$$54 \text{ million kg/yr } (60{,}000 \text{ st/yr}) \times 8 \text{ miners}$$

$$= 432 \text{ million kg (480,000 st) annual increase.}$$

Actual analysis of the design of three different continuous mining machines during this project suggested that productivity improvements exceeding the above example could be achieved with relatively simple redesign efforts.

CONCLUSIONS

The following conclusions were derived from this study of maintainability in the underground mining industry:

1. There is little evidence of the systematic application of maintainability design principles, concepts, or criteria to the design of operational underground coal mining equipment.
2. Similarly, there is little evidence of systematic application of human factors engineering principles, concepts, or criteria being applied to the design of this equipment with respect to maintenance.
3. Reduced task completion times and fewer maintenance problems were reported for the 10 most frequently performed maintenance tasks on older and smaller machines than for newer more complex equipment. This appears to be the result of simpler design on the older equipment.
4. Increased task complexity and completion times were generally reported for the newer, larger mining machines. This appears to be the result of increased design complexity, larger and heavier components to be handled, overlaying of safety and environmental control systems over the basic machine design, and inadequate accessibility to components.
5. For certain machines, heavy maintenance tasks could be performed on the surface or in high roof underground shops equipped with requisite lifting devices. The same maintenance tasks were extremely difficult, time consuming, and risky to perform at the mine face, where they often have to be completed.
6. With the exception of machines produced by 1 small mining equipment manufacturer, maintenance task completion times for the 10 most frequently performed maintenance tasks could be reduced from 10% to 30% or more with relatively simple design improvements.
7. Application of accepted human engineering design standards and criteria could substantially reduce maintenance risk. Over one-third of the reviewed maintenance lost-time injuries were traceable to equipment design deficiencies. Estimates of actual maintenance risk reduction resulting from redesign of the equipment could not be derived from the data.

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Improving Safety at Small Underground Mines

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