

## "GHOSTING" OF ELECTRO-HYDRAULIC LONGWALL SHIELD ADVANCE SYSTEMS

Gerald D. Dransite, Electrical Engineer,  
Department of Labor, Mine Safety and Health Administration,  
Technical Support, Approval and Certification Center,  
Division of Electrical Safety

Abstract - As a result of reports of malfunctioning electro-hydraulic longwall shield advance systems resulting in unplanned movement ("ghosting"), one resulting in a non-fatal accident, investigations were conducted at longwall installations utilizing these systems. These investigations identified the instances of malfunctions producing unplanned movement of electro-hydraulic shield advance systems, the cause of the unplanned movement and the corrective actions taken.

Of the 20 installations that had experienced unplanned movements, 30% were due to maintenance problems or sticking solenoid valves, 10% due to operator error or poor training, 40% due to past start up problems that had been resolved, and 20% due to software programming problems or erratic movements due to moisture entry into the control units. Existing problems at the time of the investigations were corrected through improved sealing of the control units and improved software with error diagnostic and self-checking features.

Recommendations were made for training of system operators as to correct operating procedures, and increased awareness of abnormal operational sequences, alarm displays, moisture entry into control units, and timely maintenance of system hardware. A new investigation was initiated to determine the adequacy of present requirements and to consider additional requirements in the approval and acceptance process of future systems of this type to minimize the possibility of unintended shield movement.

### Introduction

This paper summarizes the results of Mine Safety and Health Administration (MSHA) Coal Mine Safety and Health (CMS&H) investigations conducted during the period of February through March of 1991 at longwall installations utilizing electro-hydraulic shield advance systems. The

purpose of the investigations was to identify instances of malfunctions producing unplanned movement of electro-hydraulic shield advance systems, commonly known as "ghosting." Goals included documenting the cause of the unplanned movements, the corrective actions taken and a determination of the adequacy of such actions.

The investigations were conducted in response to a report of a malfunction of an electro-hydraulic longwall shield advance system which resulted in a non-fatal accident. A malfunctioning shield control unit initiated unplanned movement of an adjacent shield causing it to advance, thereby pinning the victim between the base of the shield and a section of face conveyor spill tray, which was lying between the shield and face conveyor. The cause of the malfunction was found to be due to moisture collecting inside the shield control unit enclosure which caused false signals to be sent to the shield control circuitry,

Although shield advance systems using micro-processor control technology are generally designed with error checking software and the shield control unit (SCU) enclosures sealed to prevent the entry of water, the goals of the investigation included determining the adequacy of these measures.

### Investigation Findings

A total of 57 longwall mine installations were inspected. The results from the district investigations for mines that had experienced unplanned shield movements are summarized in Table 1, "Investigative Summary Report, 'Ghosting' of Electro-Hydraulic Longwall Shield Advance Systems." This summary lists the type of unplanned movements, the number of incidents, the approximate time frame the incidents occurred, the causes, and corrective actions taken at each mine visited,

TABLE I  
 INVESTIGATIVE SUMMARY REPORT  
 "GHOSTING" OF ELECTRO-HYDRAULIC LONGWALL SHIELD ADVANCE SYSTEMS

Mine No,	Man . Code	Number of Incidents	Cause of Unplanned Movement	Type of Unplanned Movement	Time Frame of Incidents	Action Taken
1	Q	>1	v	R	0	Valves replaced
2	Q	>1	v	R	0	Valves replaced
3	C	>1	T	R	N	Additional training
4	J	2	U	R	0	Followed Recoin. maintenance
5	J	>1	M	E	0	Installed dry bags in SCU
6	C	>1	u	R	0	Manual control mode used
7	C	1	v	R	N	Valves replaced
8	C	>1	M	E	0	SCU boards waterproofed
9	Q	1	M	E	0	SCU sealing method changed
10	Q	1	M	E	0	SCU sealing method changed
11	T	>1	T	R	0	Reprogrammed & retraining
12	c	>1	v	R	0	Valves replaced
13	A	>1	v	R	N	Valves replaced
14	c	2	v	R	N	Valves replaced
15	c	>1	s	R	N	Software changed
16	C	>1	P	R	0	PC Board repaired
17	c	1	u	R	0	SCU replaced
18	c	2	s	R	N	Software changed
19	J	1	M	E	N	SCU sealed, installed shield
20	J	>1	M	E	N	SCU sealing improved, software changed

TABLE CODES

CAUSE	TYPE OF UNPLANNED MOVEMENT
M-Moisture entry into support control unit	R-Repeatable uncontrolled movement initiated by a valid system command
P-Shorted terminal on printed circuit board	E-Erratic uncontrolled movement not initiated by a valid system command
S-System software and programming	
T-Deficient operator training and improper operation	TIME FRAME OF INCIDENT
V-Sticking and defective solenoid valves	N-Recent within the past year
U-Unknown	0-Older than one year

The actual mines and manufacturers of the shield advance systems experiencing the movements are not identified by name but by an arbitrary code number to identify the mine and an arbitrary code letter to identify the manufacturer.

Of the total installations inspected, 37 (65%) had no reported uncontrolled or unplanned movement incidents.

Table 11 shows the distribution of all shield advance systems inspected and the distribution of systems having malfunctions by manufacturer code letter. All six manufacturers of shield advance systems were represented in the investigations with three manufacturers, Codes C, J, and Q, making up the majority (86%) of the equipment inspected. These same three manufacturers also made up 90% of the systems inspected experiencing malfunctions. Manufacturer C had a larger percentage of system malfunctions than their percentage of total number of systems inspected. Manufacturer Q had a smaller percentage of system malfunctions than their percentage of total number of

systems inspected. Manufacturer J's percentage of systems with malfunctions correlated fairly closely with their percentage of total systems inspected.

It is interesting to note, in the column for percentage of a manufacturer's systems experiencing malfunctions, that percentages ranged from 20.0 to 52.6, excluding Manufacturer B. Manufacturer B only had one system inspected which provides insufficient data for meaningful comparisons. No manufacturer experienced a 100% malfunction rate indicative of a major design deficiency. Also, no manufacturer experienced a 0% malfunction rate indicating a superior design. Any conclusions drawn as to the superiority of one manufacturer over another based on this data has to consider the limited database and the fact that some of the causes of the unplanned movements were due to causes beyond the manufacturer's control, such as deficient operator training, improper operation, and timely maintenance of sticking solenoid valves.

TABLE I I  
Shield Advance System Malfunctions Versus Manufacturer

MAN. CODE	TOTAL NO. OF SYSTEMS INSPECTED	PERCENTAGE OF SYSTEMS INSPECTED	TOTAL NO. OF SYSTEMS WITH MALFUNCTIONS	PERCENTAGE OF SYSTEMS WITH MALFUNCTIONS	PERCENTAGE OF A MANUFACTURER'S SYSTEMS EXPERIENCING MALFUNCTIONS
A	2	3.5	1	5	50.0
B	1	1.7	0	0	0.0
c	19	33.3	10	50	52.6
J	12	21.1	4	20	33.3
Q	18	31.6	4	20	22.2
T	5	8.8	1	5	20.0

The number of incidents of unplanned movement at each mine are indicated in Table I. When the exact number is not known, but more than one was indicated during the investigations, the entry ">1" is used. It is important to note that for every mine, even when multiple incidents were reported, there was only one cause for the incidents and only one corrective action taken to cure the malfunction. This indicates that multiple incidents of unplanned movement were not due to multiple occurrences of a design deficiency, but to a failure of maintenance personnel to determine the correct cause in a timely fashion. This allows analysis of the data on the basis of one cause for unplanned movements for each mine installation rather than on the basis of total number of incidents which would result in an erroneous cause distribution.

The distribution of the causes of the malfunctions considering all incidents regardless of age is shown in Table III. This table shows that the two most prevalent causes for the malfunctions were sticking and defective solenoid valves, and moisture entry into support control units.

In order to uncover any trends in the distribution of causes of unplanned movements, a comparison is made between the cause distribution over the most recent year versus the entire operating period over which data was accumulated, (See Table IV). This is done because data

is not broken down or available for comparable time periods. Ely comparing the most recent year to the entire period, any change in the cause distribution representing a trend is diminished but, when present, may be considered more significant than indicated by the size of the numerical change.

Table IV shows the distribution for each cause category of malfunction for the two periods under consideration. The "unknown" category and the "shorted terminal on printed circuit board" category have been removed since the "unknown" category provides no useful data for comparison and the "shorted terminal" category was an isolated single manufacturing defect that doesn't represent a significant cause category.

Table IV shows sticking and defective solenoid valves to be a continuing problem with no change in cause distribution percentage. Deficient operator training and improper operation continues to be a problem with no change in percentage. System software and programming appears to be an increasing problem in the recent time period. In fact, the two instances of malfunction in this category occurred in the recent time period. It is suspected that the early incidents due to this cause were probably not properly identified and the cause was classified as unknown. In any case, system software is considered a continuing problem through the time period covered by the inspections.

TABLE III  
Distribution of Causes of Malfunctions-All Reported Incidents

CAUSE	PERCENTAGE OF TOTAL MALFUNCTIONS
Sticking and defective solenoid valves	30
Moisture entry into support control unit	30
Unknown	15
Deficient operator training and improper operation	10
System software and programming	10
Shorted terminal on printed circuit board	5

TABLE IV  
Comparison of Distribution of Causes  
Most Recent Year Versus Entire Period

CAUSE	PERCENTAGE OVER ENTIRE PERIOD	PERCENTAGE WITHIN MOST RECENT YEAR
Sticking and defective solenoid valves	37.5	37.5
Moisture entry into support control unit	37.5	25.0
Deficient operator training and improper operation	12.5	12.5
System software and programming	12.5	25.0

The remaining cause category, moisture entry into support control unit, is interesting in that even though still appearing to be a continuing problem with two occurrences in the more recent time period, it is the only cause category showing a downward trend. After studying the investigation reports and after discussions with the equipment manufacturers, it appears that moisture entry was a start-up type of problem related to introducing the computer control technology to the mining industry, and is a problem that has been addressed and brought under control.

Most manufacturers admit to early start-up problems involving moisture entry into the support control units. This did not always result in erratic "ghosting" type of behavior and many times resulted in the system simply not working.

Various steps evolved to cure the moisture entry problem. The printed circuit boards were sealed by protective coatings or encapsulated. The use of RTV silicone rubber and wax was sometimes added to the interior of the support control units. These steps were taken to prevent false signals from being generated on the printed circuit boards if moisture gained entry into the enclosure. Exterior

sealing methods were improved with the use of RTV and rubber gaskets between mating surfaces. The latest effort to ensure enclosure sealing includes the addition of a vacuum test port to the enclosure to test under a vacuum to ensure the sealing of the enclosure.

In addition, desiccants have been added to the interior of the enclosure to absorb any moisture that might accumulate due to condensation. Some manufacturers believe condensation occurs on the inner metal panels due to the use of cold water sprays to clean the exterior enclosures. Some manufacturers use a desiccant cartridge with an indicator to show when moisture is present in the enclosure. The color of the indicator changes from blue to white with moisture.

In order to present the cause of malfunction distribution in a manner that is more illustrative of the "ghosting" situation at the time of the investigations and the more recent past, Table V shows the cause distribution where the unknown, the shorted terminal categories and the old moisture entry incidents due to early system start-ups from Table III have been lumped into a new category called new installation start-up problems over one year old,

TABLE V  
Distribution of Causes of Malfunctions  
Formatted to Reflect Old System Start-up Problems

CAUSE	PERCENTAGE OF TOTAL MALFUNCTIONS
Sticking and defective solenoid valves	30
Moisture entry into support control unit	10
New installation start-up problems (over 1 year old)	40
Deficient operator training and improper operation	10
System software and programming	10

The use of the term "ghosting" to describe these unplanned movements is unfortunate in that it suggests that the movements are of an unknown, unpredictable, mysterious origin, and hints at computer control technology as being the root cause of the problem. After analyzing the investigation findings, however, the recent incidents of unplanned movements can be categorized into a small number of groups of mostly definable, ordinary sources producing predictable behavior (See Table V). Only 10% of the recent malfunctions produced the type of movement that was classified as erratic uncontrolled movement not initiated by a valid system command, and these were due to moisture entry.

A large percentage, 40%, of the unplanned movements can be categorized as due to the initial start-up problems associated with introducing new technology to the mining industry and aren't representative of current field experience which is of most concern.

Only a few of the installations experienced current problems related to computer control technology, 10% due to system software and programming,

#### Summary of Comments on Malfunctions

Of the 20 installations that had uncontrolled or unplanned movements, 6 (30%) were due to sticking or defective solenoid valves. The undesired movements resulting from these failures were not of a random nature but resulted from deliberate system commands.

Of the 20 installations that had undesired movements, 2 (10%) were due to improper operation through incorrect operator procedure and poor training. The undesired movements resulting from these failures were not of a random nature but resulted from deliberate system commands,

Of the 20 installations that had undesired movements, 8 (40%) had problems in the past (over one year ago) that can be classified as start-up, debugging problems, and problems related to the application of this new technology to the mining industry. These problems were corrected and these systems have been operating satisfactorily with no recent undesired movement incidents and are not of present concern.

Of the 20 installations that had undesired movements, 2 (10%) were due to system software and programming problems. These installations produced undesired movements of a predictable nature related to a valid system command. These installations were considered a current problem at the time of the investigations,

Of the 20 installations that had undesired movements, 2 (10%) were due to moisture entry into the support control unit. These systems produced movements of a random nature that was unpredictable, and occurred without the input of a system command. These installations were considered a current problem at the time of the investigations.

Two of the installations experienced undesired movements due to programming and software problems which did not occur in a random manner and was accompanied by a system command, although the command was not intended or appropriate. On one installation, shields were observed lowering and advancing without any apparent manual or automatic command being given. This behavior problem was found to be due to a situation where a manually entered program function was not removed before a master control center automatic override function was initiated. On another installation uncontrolled forward movement of shields was observed. This system was designed so that a loss of hydraulic oil flow resulted in communication failure with the computer. If a shield had been programmed for move and the flow of hydraulic oil lost, upon restarting the system, the previously entered command would be executed and produce the undesired movement. These two installations were corrected through programming changes.

Random type movements are of the most concern and are the type of unplanned movement where the term "ghosting" is most applicable. Two installations produced random undesired movements with no system commands. One of the installations produced the unplanned movement that resulted in the non-fatal accident that initiated the investigation. A malfunctioning shield control unit initiated unplanned movement of an adjacent shield causing it to advance, thereby pinning the victim between the base of the shield and a section of face conveyor spill tray, which was lying between the shield and face conveyor. In the other installation, a malfunctioning shield control unit was observed operating its neighbor shield with no control commands given.

On both of these installations, the problem was caused by moisture entry into the control units producing spurious system commands through leakage paths on the keyboard circuitry which simulated valid system commands. The software lacked error diagnostic capabilities adequate to distinguish the spurious commands from valid system commands. Both of these installations used the same model shield control unit, manufactured by the same company. In the installation involving the accident, no obvious damage to the enclosure sealing was evident. The second installation had obvious damage to

the enclosure that affected its moisture resistance,

These shield control unit problems were corrected through improved sealing of the control units and improved software with error diagnostic and self-checking features added. These corrections were added to the two installations experiencing the problems and to all other longwall installations using the same model shield control units.

Although enclosure sealing is the first line of defense to prevent unplanned movements due to moisture entry, system software and programming provides a second line of defense if the enclosure sealing becomes compromised. An example of the self-checking fault tolerant software implemented to help solve the above moisture entry problems was the addition of a keyboard diagnostic program that runs at system boot-up and continuously thereafter,

The diagnostic program conducts a self checking of the key controls on the keyboard of the shield control unit. The program verifies that the commands to operate a shield are received in a defined order and in a specific time frame. To perform a shield movement action requires the selection of a neighbor shield followed by a specific move command within the time parameter setting. If one of the keys programmed for a specific move command becomes activated at any time before or paralleling a shield selection, it will result in a key error. In addition, program changes have been implemented to check solenoid valve currents to discover short circuits in the valve driver circuitry and inhibit program execution until the short is corrected.

Other manufacturers use miss-match and cross checks on command signals and shut down the processor when errant data commands are received.

In recognition that hardware and software design features intended to prevent unplanned movements can ultimately fail, MSHA requires a hard wired emergency stop system, independent of system electronics and software, to allow system power down by operator activation of a panic switch in an emergency situation. The investigative reports provide no indication that the emergency stop system was ever activated in any of the unplanned movement incidents. Even in the case of the documented non-fatal accident "ghosting" incident, the shield movement was ultimately stopped by shutting off the hydraulic pumps. No reference was made to activating the emergency stop system. In another unplanned movement incident, a personal injury was reported, but this movement was later found to be due to improper operation and operator training. No indication was given that the emergency stop system was activated.

The emergency stop system can provide a final line of defense against personal injury due to unplanned movements, but it must be personally activated and that may not always be possible.

## Conclusions

The investigation identified the causes of reported incidents of unplanned movement of longwall shields, when adequate documentation was available. The causes were from definable sources which produced predictable behavior. The identified deficiencies were corrected by appropriate corrective action.

Although the percentage of unplanned movements that fit into the category or "ghosting" was low and all causes of unplanned movements were corrected by the conclusion of the investigation, the following recommendations are presented to ensure these systems continue to operate without undesired movements. The following actions should be carried out on a continuing basis:

1. Training should be given to mine personnel operating electro-hydraulic control systems to ensure proper operational procedures and sequences and to recognize improper system operation, alarms and displays.
2. Maintenance of system hardware, such as sticking solenoid valves, must be conducted in a timely fashion. This is also a common problem on control systems not utilizing computer control technology.
3. Mine personnel should be made aware that the entry of moisture or water into the control units can cause undesired movement of the shields. This is not unique to computer controlled circuits and can occur in any modern control circuit utilizing high impedance solid state devices. Control units should be inspected for damage that could compromise the sealing features designed into these units and allow moisture entry. They should also inspect for signs of moisture entry and, when observed, the units should be taken out of service in a timely fashion.

Some signs that indicate possible compromise of the enclosure sealing include mechanically distorted or bent support control unit housings, damaged gaskets or seals, damaged keypads, corrosion, desiccant indicators or evidence of internal moisture visible through windows or displays. The shield control units should not be disassembled for inspection because proper resealing is difficult to accomplish in the field.

4. Mine operating personnel should note and report to the manufacturer in a timely fashion any abnormal operational sequences of the system, alarm displays, or unintended shield movement which might be due to a software programming error. These software errors can occur even in

error detecting, fail-safe software, but usually occur only under an unusual combination of operational commands or sequence. These usually can be easily corrected by the manufacturer of the equipment.

5. Mine personnel should be instructed to activate the independent, hardwired emergency stop system, not the stop button on the shield control unit, whenever an unplanned shield movement is observed that might possibly produce personal injury to any mine personnel.

#### Recommendations For Further Work

The MSHA requirement for the independent, hard-wired emergency stop system provides a strong defense against personal injury caused by unplanned shield movements due to defective enclosure sealing and system software.

However, to insure the continued safety of mine personnel operating electro-hydraulic longwall shield control systems, the MSHA Approval and Certification Center has initiated a special study to determine if any additional requirements are needed in the approval and acceptance process of future systems of this type such as an evaluation of enclosure sealing and system software, to minimize the possibility of unintended movement of shields controlled by these systems.

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