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By J. L. Kohler and J. Sottile

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	s	second
ft	foot	V	volt
ft/min	foot per minute		

A GENERAL DESIGN AND IMPLEMENTATION PROCEDURE FOR SENSOR-BASED ELECTRICAL DIAGNOSTIC SYSTEMS FOR MINING MACHINERY

By J. L. Kohler[1] and J. Sottile[2]

ABSTRACT

Component failures in the electrical control circuits of mining machines account for a large percentage of the total downtime of the machine. Once a failure has occurred it is always a tedious and usually a time-consuming task to locate the failed component. Moreover, the pressure to quickly locate the cause of a delay can lead to compromises in safety. Thus an onboard diagnostic system, essential for an automated machine, would be a very useful addition to existing machines.

This report details U.S. Bureau of Mines development of a generic procedure for synthesizing diagnostic systems for electrical-control-circuit failures in mining machinery. A continuous mining machine is used as the testbed to illustrate the application of the developed methodology.

Substantive differences among mining machine control circuits made it impossible to achieve a generic diagnostic system, but a generic approach for the synthesis of the diagnostic system was possible. As the research progressed, it became apparent that an algorithmic approach was better than an expert-system-based implementation. A prototype system was constructed and used to evaluate the diagnostic system. Prototype implementation issues are also examined.

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INTRODUCTION

The U.S. Bureau of Mines, through its Advanced Mining Systems research program, seeks to improve the safety of the underground workplace. The use of sophisticated control technology would allow miners to be located safely away from the face area. To accomplish this remote operation, mining machines will become increasingly complex. Improved diagnostic maintenance will be needed to keep these productive, complex machines in operation. In support of that goal, the Bureau is examining improved electrical system diagnostics.

Mining machines are generally operated under severe conditions that often stress the machines' electrical, hydraulic, and mechanical components to the limit of their designed capabilities. At the same time, preventive maintenance practices frequently are less than ideal. Moreover, these machines contain numerous components fashioned into increasingly complex subsystems, and accordingly, breakdowns of these machines on a regular basis are likely. Normally a breakdown also idles a working section, and because of this, there is significant pressure to diagnose the cause of the problem and to effect a repair as quickly as is possible.

Fault diagnosis, in an ideal sense and regardless of the domain, consists of a logical and disciplined approach based on established procedures, knowledge of the involved equipment, and personal experience. Fundamental steps involved in this process usually consist of several or all of the following steps:

- Symptom analysis.
- Equipment inspection.
- Fault-stage location.
- Circuit checks.
- Replacement or repair.
- Performance tests.

Symptom analysis involves the collection and evaluation of all pertinent information about the fault. Once preliminary conclusions are drawn from the symptom analysis, close inspection of the suspected equipment is performed for any obvious signs of failure. Fault-stage location involves the process of systematically checking inputs and outputs within the system until the faulty stage is found. The circuit-checks stage is similar to fault-stage location, except that the specific component or components are located. Once located, repairs are initiated, and performance tests are carried out on the repaired circuit.[3]

Despite the time-tested advantages of following these rigorous diagnostic steps, maintenance personnel often attempt to abbreviate the diagnostic process. These short cuts lead to varying degrees of success in the diagnosis of the problem. Sometimes, the experience of the repair person will allow a correct diagnosis at the symptom analysis stage, while in other cases, the failure to follow a more rigorous procedure results in wasted time as the repair person, blinded or fooled by previous experiences, pursues one erroneous hypothesis after another. As the frustration level mounts, there is a tendency to work less safely, and in extreme cases, safety devices may be defeated in an effort to get the equipment back on-line.

Clearly, diagnostic procedures will have to be improved if faster and more accurate diagnoses are to be made without compromising safety. These improvements may be as direct as increased training for maintenance personnel at the plant, or the increased use of technology such as annunciators to improve the maintainability of the equipment. Many mines, for example, have added annunciator bulbs to the control circuit of their belt starters; the logical reason for a belt stoppage is then easily determined by observing which bulbs are lit, rather than by making and interpreting a series of electrical measurements. Of course, this process has been automated in modern mine-monitoring systems, but regardless of the mode of implementation, diagnostic time is reduced through the use of these annunciators.

The diagnosis of many problems cannot be accomplished by simply adding annunciators to the circuit, for different reasons. In some cases the result would be an incomprehensible bundle of wires and bulbs, while in others more sophisticated procedures are required. The widespread use of knowledge-based expert systems (KBES) in the 1980's was, in large part, fueled by the desire for improved diagnostic systems. The diagnosis of an ailment—in the human body, in an automobile engine, or in a control circuit—is often a very artful process driven by both the knowledge and intuition of the diagnostician. Some people can make accurate diagnoses quickly, while others require more time. Accordingly, there has been much interest in capturing the knowledge of human experts and making it more widely available as an expert system.

One such system was developed to aid in the diagnosis of hydraulic system failures in a Joy 16CM continuous miner.[4, 5] Another, known as SCAR (*S*huttle *Car*), is a KBES for the diagnosis of failures in the electrical circuit of a Joy 21SC shuttle car. SCAR's inference engine is

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[3] George Godwin Ltd. (London). Systematic Fault Analysis. 1982, pp. 13-49.

[4] Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

[5] Mitchell, J. Diagnostic Expert System Techniques for Improving Hydraulic Maintenance of a Continuous Mining Machine. Min. Eng., v. 43, No. 4, April 1991, pp. 419-423.

goal driven. The user of the system supplies the necessary inputs, such as voltage measurements or continuity checks, based on system-generated prompts. Model-based techniques, i.e., knowledge and behavior of the circuitry, were used to establish the knowledge base.

SCAR is a comprehensive and powerful diagnostic tool, and it demonstrates the efficacy of such systems in mining-electrical applications. The system does have some notable limitations, which were cited by the developers of the software.[6]

1. The system does not support the use of certainty factors or unknown responses to questions. This is not a limitation in the application, because the requested information can be unambiguously established. However, it is not always easy to get the requested information, and moreover, that information may not add significantly to the certainty of the diagnosis.
2. No generalized systematic procedure for creating and organizing the knowledge base was made. Instead, potential faults were considered in the sequential order that the components occurred in the circuit, and it was assumed that all faults were equally likely to occur.
3. The program requires the user to refer to a hard copy of the schematic because of graphic limitations with the specific software used in this development.

Another expert-system program for diagnosing control-circuit-component failures has been developed for a Joy 16CM continuous miner.[7] The development of this KBES was based on the following criteria.

1. The expert system should lead the user through a logical diagnostic procedure by emulating a qualified expert troubleshooter.
2. The expert system should indicate physical locations of components and test points that the user is required to access.
3. Pertinent sections of the control system should be displayed as necessary.
4. Access to a data base of part numbers, quantity and location of spares, and interchangeability of components should be readily available.

This system is also goal driven. As with SCAR, it generates appropriate requests for user inputs, such as measurements and observations. This system has been successfully utilized by novice mechanics to diagnose complex electrical problems both quickly and accurately.

These systems have the demonstrated advantage of providing expert-level diagnoses, and their potential benefits as training tools should not be overlooked. Nonetheless, they have a serious limitation: They require the user to make a series of electrical measurements during the consultation. This in itself is time consuming, and it exposes the electrician to certain electrical hazards. Thus, the next logical step would be to develop a sensor-based diagnostic system that could make diagnoses without any user input.

RESEARCH OBJECTIVE

The objective of this research was to develop a sensor-based diagnostic system for generic application to mining machinery, using a KBES implementation. The efficacy of the system was to be evaluated by constructing a prototype and installing it on an actual mining machine. A Joy 14CM continuous mining machine was to be used for the prototype development.

It became apparent in the earliest stages of the project that it might be impossible to develop one diagnostic system that would work on many different mining machines, such as all continuous miners. The control circuits of many different models and manufacturers were studied, and it was found that significant differences can exist even among machines with the same model number. These differences are due to customer-specified options, technological improvements, and even date of manufacture. Certain portions of the circuit, particularly the traction-related components, tend to vary more than others.

Concurrently, however, it became apparent that if the development of a generic piece of hardware was not possible, a generic approach to the development of the hardware might be, and if so, the approach could be demonstrated through the development of a prototype for the Joy 14CM continuous miner. Such an approach was developed; it and its application are the subject of this report.

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[6] Novak, T., J. R. Meigs, and R. L. Sanford. Development of an Expert System for Diagnosing Component-Level Failures in a Shuttle Car. IEEE Trans. Ind. Appl., v. IA-24, No. 4, 1989, pp. 691-698.

[7] Berzonsky, B. E. A Knowledge-Based Electrical Diagnostic System for Mining Machine Maintenance. IEEE Trans. Ind. Appl., v. IA-26, No. 2, 1990, pp. 342-346.

SYSTEM SYNTHESIS

A general procedure for the synthesis of a machine diagnostic system is presented. This procedure is then illustrated through its application to the development of a diagnostic system for the control circuit of a Joy 14CM continuous mining machine. Before introducing the general procedure, however, relevant background on the formulation of the problem domain will be presented.

Initially, the problem domain, i.e., diagnosing mining-machine control-circuit failures, was formulated as an expert-system application. The success of the previously described systems for the diagnosis of electrical-circuit failures on mining machines established their ability to provide expert-level diagnoses. Their main weakness, as noted earlier, was the need for manual measurements to be made within the control circuit. However, this deficiency could be overcome by developing a sensor-based system, and one of the challenges of this work seemed to be interfacing a knowledge-based diagnostic system with onboard sensors. As this work progressed, it became apparent that the result of such an approach would be quite unwieldy and probably unworkable.

Using the number of sensors required to support the KBES would have been impractical, as their presence would have reduced both the reliability and the maintainability of the machine. Accordingly, it was necessary to establish criteria for reducing the number of sensors. After some deliberation, two criteria were established: First, a limited number of failure modes would be diagnosed rather than all possible modes; and second, only the minimal set of sensed values needed to uniquely define a failure mode would be used. Practically, this had the effect of requiring that the system developers function like an expert system, while the final system, reflecting the developers' expertise, would be algorithmic in nature. Additional considerations related to the method of implementation, e.g., algorithmic versus nonalgorithmic or KBES, are presented later in this report. However, as will be seen in the next section, defining the two criteria constitutes a major part of the general procedure.

GENERAL PROCEDURE

First, the purpose of the diagnostic system must be clearly articulated. Should the system include both the power circuit and the control circuit, or only one of these? Will the diagnostic system have the capability to detect all possible failures, or only those that are known to occur? Practical constraints suggest that the diagnostic system should be limited to failures that have a higher probability of occurring and are difficult to diagnose, as opposed to those that are theoretically possible or easy to diagnose. The most critical constraint is the increasing number of sensors required to diagnose each additional failure. Other constraints include sampling requirements and reliability of the diagnostic system with increasing size and complexity.

The second step, based on the foregoing, is to determine the failure types or modes that should be included in the system's diagnostic capabilities. The only way to accomplish this is to obtain failure data from mines and machine manufacturers. These data, i.e., the component failures, form a starting point for the desired capability of the diagnostic system. Selection of failure types for inclusion should be based on both frequency of occurrence and difficulty of diagnosis. For example, headlight failures frequently occur, but they can be diagnosed quickly and easily. As such, their inclusion in the diagnostic system would be frivolous.

Next, it is necessary to gain an understanding of the normal and abnormal functions of the targeted components in the circuit, as well as their interaction with other components in the circuit. Such an understanding is necessary before sensor types and locations can be determined; the development of the diagnostic logic also requires an accurate and detailed knowledge of component functions.

After component operation and interaction are understood, a method for detecting the failed component should be developed. Essentially, this consists of two steps: determining specific measurements, e.g., temperature, resistance, voltage, and so on, that are symptomatic of a failure, and then defining a set of logical relations that must exist so that the specific failure can be uniquely defined. It is at this stage of the process that it becomes necessary to consider the benefit and feasibility of including each failure type in the diagnostic system.

In some instances, the state of many components will have to be monitored to define a specific component failure. This will increase the complexity of the diagnostic system and, to the extent that this will increase the number of sensors and interconnecting wires on the machine, may be of questionable value. Nonetheless, further study may reveal the value of including that failure, as illustrated in the following example. Assume that for a machine to tram, the following conditions must be met:

- The traction switch must operate;
- A safety switch must operate;
- A fuse must complete the circuit; and
- An interlock must operate.

If any one of these conditions is not met, the machine will not tram. And, of the four components involved, the first two are known to fail quite frequently, while the third and fourth are fairly reliable (note that a blown fuse is treated as a component failure for diagnostic purposes). Furthermore, traction failures are quite common and difficult to diagnose. Thus, it would be advantageous to monitor all four of the components, even though two of them are reliable.

The previous example illustrates two important points relevant to the general case. First, it is sometimes necessary to monitor components that rarely fail when they are part of a sequence of component actions necessary for the correct operation of some other component. Second, if a fairly reliable component, such as a fuse, can be easily monitored, and if diagnosing the failure is time consuming, then serious consideration should be given to monitoring it. In the case of the fuse, it is easy to diagnose the failure, but considerable time can be wasted in removing the covers of explosion-proof enclosures to access fuses, and therein lies the motivation for monitoring certain of them.

A few cases may be encountered in which expensive or otherwise constrained sensors are required. Sometimes an appropriate sensor is simply unavailable. Both of these situations require another evaluation of the importance of including a particular failure type in the system, and in the end, it will probably be determined that it is not worth the effort to include that one. Occasionally, a component modification, e.g., replacing a four-pole switch with one of five poles, would alleviate a sensing problem or facilitate sensing a specific component, and accordingly, it may be worthwhile to pursue such a course of action. However, a modification by anyone other than the manufacturer is strongly discouraged.

The final stage of the general procedure is to address miscellaneous implementation issues. These include the physical location of sensors and the routing of wires on the machine. Obviously, if it is impossible to locate a sensor in a certain control case, it will be necessary to alter the diagnostic logic or to make some other arrangement. Another issue that must be addressed is the possibility that the circuit on a given machine is slightly different than the one illustrated on the prints used to develop the system. Such discrepancies may alter the logic, the interpretation of sensor values, or may be inconsequential, but they should be checked.

The description of this general procedure has provided an overview of an approach toward the development of an onboard diagnostic system. The remainder of this report illustrates application of the system to the development of a prototype system for a continuous mining machine.

CONTROL-CIRCUIT FAILURES

Prototype

The prototype diagnostic system was developed for a Bureau-owned Joy 14CM09-10DX continuous miner. This machine, shown in figure 1, is typical of commonly used equipment in U.S. coal mines, and the control circuit represents one of the more advanced circuits in mining equipment.

The electrical circuit of the Joy 14CM continuous miner is composed of two distinct parts: (1) the control circuit and (2) the power circuit. The control circuit operates at 120 V ac and is isolated from the power circuit; consequently, all control-circuit measurements must be referred to the common return wire. The cutter, conveyor, pump, and dust collector all operate on the machine's three-phase voltage. The traction circuit is composed of an ac-dc drive that includes one independent three-phase full-wave rectifier for each of two traction motors.

Features included in the machine's electrical circuit are current regulation and cutter-motor feedback. Current regulation is used during motor startup and plug reversals to provide smooth operation and to minimize drive train shock loads. The cutter-motor feedback system varies the sump speed depending on the cutter-motor load; as the load increases, the speed decreases.

The (solid state) components of the drive circuit on the machine are identical to those on the 12CM continuous miner and the 10SC22 and 21SC shuttle cars. The traction circuits are updated frequently, with the result that differences are based more on date of manufacture than on machine type or customer preference. Minesite modifications to these circuits cannot be overlooked either, and must be considered.

The operation of the 14CM continuous miner is divided into five circuits:

1. Control circuit.
2. Pump circuit.
3. Conveyor circuit.
4. Cutter circuit (with or without the dust collector).
5. Traction circuit.

The operation of each of these circuits follows a distinct hierarchy to avoid unsafe conditions. This is achieved by requiring that the control switch be activated first. This determines if the machine will be controlled manually or remotely. Once the control switch is on, the pump must be energized before any of the remaining circuits. This gives an audible signal to nearby personnel that the machine has been activated. Consequently, the conveyor, cutter, and tram circuits must be off before the pump will start.

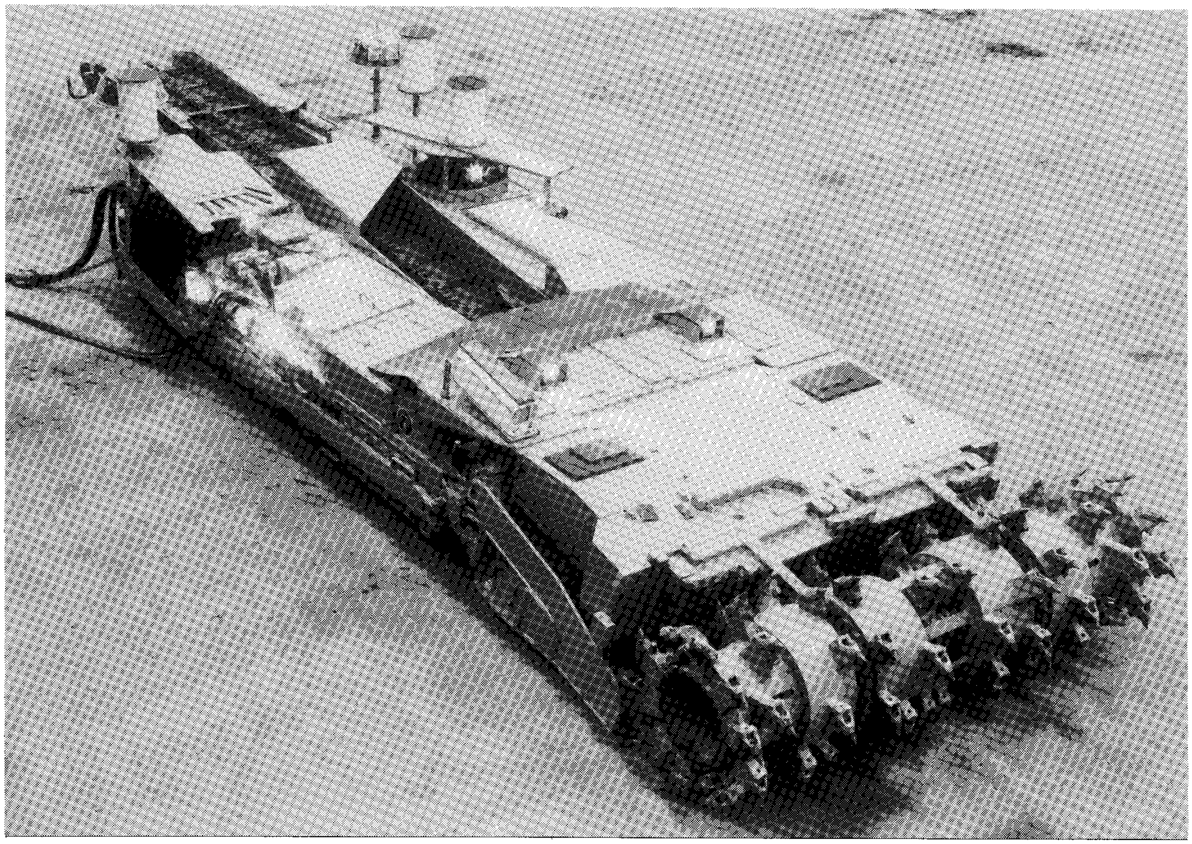

Figure 1.—Continuous miner used as testbed.

The initial step in machine operation is to place the control switch to the REMOTE or MANUAL position. This supplies control power to the emergency stop and pump switches. The pump switch may then be rotated to the START position, energizing the pump motor and giving an audible signal that the machine has been activated. The cutter and the traction circuits must be off in order to energize the pump. If these conditions are met, the pump will be energized and the pump switch can be placed in the RUN position. Any of the three remaining circuits (conveyor, cutter, or traction) may now be energized based on the operator's need.

The conveyor switch has three active positions: START, RUN, and REVERSE (RUN implies forward direction). In order to run the conveyor in the forward direction, it is necessary to first place the conveyor switch to the START position. In the START position, the conveyor forward (cF) coil is energized, which closes the cF contacts completing the conveyor forward circuit for the RUN position. To operate the conveyor in the reverse direction, the conveyor switch must be held in the REVERSE position.

For safety purposes, the cutter motors can only be started by simultaneously moving the pump and the cutter switches to the START position. In this position, the instantaneous overload, a unitized overload device, reduces cutter-motor starting current by providing sequenced starting of the motors. Once the cutters are running, this unit provides overload protection by monitoring the cutter-motor current and deenergizing the motors if the instantaneous current level is exceeded for a specified time. This instantaneous value, known as the instantaneous overload, is determined by the manufacturer and is not adjustable.

The traction circuit is activated by operating the left and right hand tram levers while simultaneously depressing the foot switch. Current Joy miners have three speeds in forward and reverse. Forward speed is limited to second if the cutters are running. Additional speed reduction is possible with the maximum sump speed adjustment and cutter feedback adjustment.

If remote control operation is desired, all of the previously mentioned control operations are valid from the remote control station. The requirements for remote operation are that the control switch on the machine be placed in the REMOTE position, and that each of the other control switches be placed in the OFF position. In this mode of operation, signals from the remote control station are transmitted to the machine, where the demultiplexer, which is wired into the control circuit at the appropriate points, controls machine action. One notable difference of remote operation is that the machine has only first and third speeds (low and high speeds). However, as with manual operation, cutter-motor feedback limits speed while the cutters are running. (Note that remote control stations for other continuous miners may have three speeds available.)

This brief review of the fundamental operation of the 14CM continuous miner applies equally to a 12CM miner and other variations of the 14CM miner. If more detailed information is required, the manufacturer's manual, entitled "Joy 14CM Dual 6 SCR (now System II Dual 6 SCR) Electrical Circuits and Components," should be consulted.

Component Failure Rates

Failure rates for control-circuit components were collected from mining companies and mine-machinery manufacturers to determine the types of failures that are occurring in everyday use. A preliminary list was obtained through telephone conversations and personal interviews at various mine sites. Then companies were invited to submit written documentation of failure types and frequency of control-circuit failures in 14CM mining machines. Finally, this information was used to establish priorities for including various types of failure within the diagnostic capability of the prototype system. Obviously, the more frequent a failure, the more important it is to have the capability to diagnose it.

The information provided by each company varied. Some companies provided failure type and frequency information for each machine in each of their mines, while others provided average data for all machines in each of their mines. In total, data were obtained for approximately 80 machines operating in mines in Pennsylvania, West Virginia, and Ohio.

These data are believed to be representative of failures occurring in general on 14CM machines, as well as all continuous mining machines, although the sample size may not be large enough to compute certain reliability measures such as mean time between failure and so forth. Nonetheless, the purpose was not to establish reliability measures, but rather to identify the most common failures, which the survey did quite clearly. A summary of the compiled information is given in table 1.

Table 1.—Control-circuit failures for continuous miner

Component	Failures per machine per year	Circuits primarily affected by component failure
Firing package	1- 6	Traction.
Foot switch	1-12	Do.
5-A traction-circuit fuse	2	Do.
2-A firing-package fuse	1- 2	Do.
Cutter-motor (A,B) interlocks	1	Cutter.
Left reverse (eREV) interlock	1	Traction.
Left forward (eFOR) interlock	1	Do.
Right reverse (fREV) interlock	1	Do.
Right forward (fFOR) interlock	1	Do.
Pump (D) interlock	1	Pump.
Instantaneous overload	1	Cutter.
Conveyor forward (cF) interlock	1	Conveyor.
Control switches	2- 6	All.
Connections between switches	1- 2	All.
Demultiplexer[1]	< 1	All.
Control transformer	< 1	All.
Emergency stop switch	6	Not applicable.

[1] Remote control.

The first column lists the specific entity that fails. In some cases this is a simple component like a fuse or a switch, while in others it is a complex subsystem such as the firing package. However, these entities represent the level at which a replacement would be made. Thus, using the examples here, a fuse failure would result in the replacement of a fuse, and a firing-package failure would result in the replacement of the entire module, since it is not possible to replace individual circuit boards or components within the module. The second column shows the average number of failures that occurred per machine per year in the data collected for this project. In some cases two numbers are shown because there was a wide spread in the data provided, and in these cases the numbers represent the average of the minimum and maximum values for each mine. Finally, the third column identifies the particular circuit that is affected by a failure of that component.

This table shows that components in the traction circuit account for the majority of failures on continuous miners, and because these component failures are among the more difficult ones to diagnose, their inclusion in a diagnostic system should be given high priority. Accordingly, these components were emphasized in the prototype diagnostic system developed as a part of this project.

IDENTIFICATION OF SENSING POINTS

In general, determining sensor type and location and developing the diagnostic algorithm is an iterative procedure based on many possible tradeoffs in complexity and performance. Processing limitations and space constraints must also be considered, as well as possible applications to other pieces of equipment. With this in mind, additional guidelines for determining sensor type and location are listed below.

1. The sensors should be reliable and inexpensive, and they must not reduce machine availability.
2. The sensors must fit within existing control boxes.
3. The sensors should not hinder repairs or replacements.
4. The sensors must not create safety hazards.
5. Sensor wiring must not interfere with, or be mistaken for, existing control wire.
6. The sensors must not alter the behavior of the control circuit.

The selection of specific sensor types is based on the parameters that must be measured. If, for example, the value of current flow at a point in the circuit can be used to evaluate the integrity of a component, then a current sensor must be placed at that location. Or, if the temperature at a particular point is useful in detecting a specific failure, then a temperature sensor must be selected and located at that point. In the case of control-circuit diagnostics, the state of the circuit can be defined if voltages are known at key points throughout the circuit. More complicated measurements could be made, including hydraulic pressures, linear position, conveyor speed, and so on, but these would not significantly improve the ability to diagnose a problem. Moreover, it is not necessary to distinguish between various magnitudes of voltage. Based on the characteristics of electromechanical control circuits of the type used in mining machinery, it is sufficient to differentiate only between a voltage being "present" or "absent."

Given that the required measurand is the presence or absence of a control voltage, the sensor is simply a wire connected to the point where the voltage is to be sensed. This wire is then routed to a logic box, where the voltage is reduced to a level that is compatible with the electronic logic unit that will evaluate the signals. In each case, the measured states, essentially "on" or "off," are evaluated in a series of logic equations, which will be discussed later in this report.

Once the types of failures that are to be detected have been determined, it is a reasonably straightforward process to identify the requisite sensing points. The process can be summarized as follows. First, the location of the critical component is determined, and then the voltage levels at the component, which define its state, are determined. For example, suppose the state of a component is defined by the voltage level on either side: If one side is high and the other low, the component is fine. Thus, a sensing point would be placed on either side of the component. In most cases, however, other components connected in series with the subject component may need to be monitored as well. If the component is in series with an interlock, and the interlock is open, then the voltage levels across only the component will not be sufficient to determine if it has failed. Sensing points must be added across the interlock, and the corresponding voltages at these points must be considered when assessing the integrity of the component. Any parallel paths that interact with the component must also be considered, and appropriate sensing points must be added. An appropriate point is one where the voltage level must be known before a component's integrity can be ascertained. While not a difficult process, this aspect of the general procedure can be very tedious and time consuming.

As a further illustration of the process, consider the circuit shown in figure 2. Potential sensor locations are illustrated for a switch supplying an electronic device that controls the directional outputs of a traction circuit. The switch is designed to supply (exclusively) a forward, reverse, or no signal to the directional controller. In this example, switch terminals 2 and 3 establish the expected input to the controller, terminals 4 and 5 measure the signal that the controller receives, and terminals 6 and 7

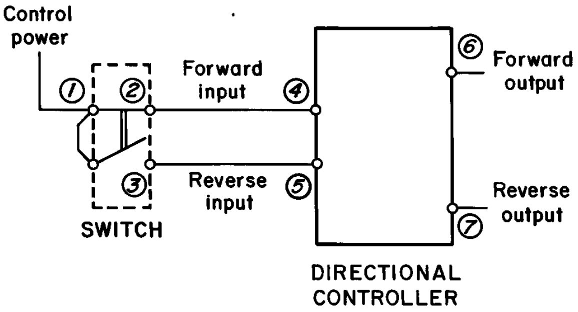

Figure 2.—Simplified diagram of switch and directional controller. Circled numbers correspond to sensor points.

are the controller outputs. Terminals 2 and 3 establish the intended function to be performed by the circuit, while terminals 4 to 7 can be used to determine the condition of the controller within the circuit.

Monitoring terminals 2 and 3, in this example, appears to be redundant for diagnosing the directional controller, but both of these points can be used to establish the continuity of the circuit between the switch and controller. In an actual machine, a similar path may be composed of 50 ft of control wiring and several interlocks. In that case, verifying continuity could be a great time-saving action. Despite the simplicity of this example, it illustrates how the electrical location of sensors is determined.

The foregoing discussion has focused on a procedure for identifying the electrical points that must be monitored in the control circuit. The physical location of these points can be quite different than their location on an electrical print. Accordingly, the next step is to locate the points on the machine and to verify the feasibility of connecting a sensor at that physical point. All of the control circuitry, other than interconnecting cables, is located inside of control cases on the testbed machine. These are the master control station and the right-hand and left-hand control cases; their location on the machine is shown in figure 3.

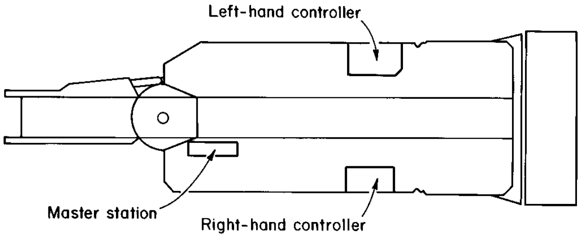

Figure 3.—Plan view of testbed machine.

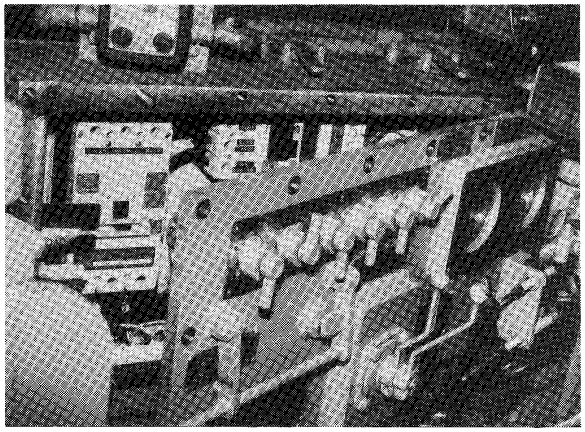

Figure 4.—Master control station.

The master control station, which is located in the operator's platform, is shown in figure 4. Space constraints prevent full opening of its access panel without first removing the hydraulic control levers and other devices within the cab area. The left-hand control case is shown in figure 5. It should be noted that removing the access panel to this case requires the removal of 22 bolts. Figure 6 shows the right-hand control case with the access panel removed and one of its swingout panels exposed.

The locations of the sensing points are illustrated in figures 7 to 9. These locations have also been tabulated, and they are shown in tables 2 and 3. As will be discussed later, because it may be desirable to implement this system in two phases, the sensor locations have been separated by the implementation phase. Phase 1 sensor locations are given in table 2, and phase 2 sensors are listed in table 3; a summary of these points by physical location on the machine is given in table 4.

Table 2.—Phase 1 sensors and locations

(Maximum expected peak-to-peak voltage, 340 V)

Sensor	*Location*
1	Supply side of 2-A firing-package fuse.
2	Load side of 2-A firing-package fuse.
5	Left forward input to firing package.
6	Left reverse output to eREV coil.
7	Left forward output to eFOR coil.
8	Right reverse output to fREV coil.
9	Right forward output to fFOR coil.
10	Left 2d speed input to firing package.
11	Left 3d speed input to firing package.
12	Right 2d speed input to firing package.
13	Right 3d speed input to firing package.
14	Right forward input to firing package.
15	Left reverse input to firing package.
20	Cutter switch terminal 2.
39	Left reverse output on firing package.
40	Left forward output on firing package.
41	Right forward output on firing package.
42	Right reverse input on firing package.
43	Right reverse output on firing package.
44	Left-hand traction switch terminal 7.
45	Left-hand traction switch terminal 8.
46	Right-hand traction switch terminal 7.
47	Right-hand traction switch terminal 8.
52	Supply side of 5-A traction circuit fuse.
53	Left-hand traction switch terminal 5.
54	Right-hand traction switch terminal 5.
55	Left-hand traction switch terminal 3.
56	Right-hand traction switch terminal 3.
57	Line 2 connection on 5CB (common return).

Table 3.—Phase 2 sensors and locations

(Maximum expected peak-to-peak voltage, 340 V)

Sensor	*Location*
18	Pump switch terminal 5.
19	Pump switch terminal 6.
21	Cutter switch terminal 4.
27	Conveyor switch terminal 2.
32	Pump switch terminal 3.
33	Pump switch terminal 4.
34	Cutter switch terminal 3.
35	Cutter switch terminal 7.
36	Cutter switch terminal 11.
37	Cutter switch terminal 12.
49	Pump switch terminal 10.
51	Control switch terminal 4.
58	Demultiplexer terminal 21.
59	Demultiplexer terminal 20.
60	Demultiplexer terminal 19.
61	Demultiplexer terminal 18.
62	Demultiplexer terminal 17.
63	Demultiplexer terminal 16.
64	Demultiplexer terminal 15.
65	Demultiplexer terminal 14.
66	Demultiplexer terminal 4.
67	Demultiplexer terminal 3.
68	Demultiplexer terminal 2.
70	Demultiplexer terminal 5.
71	Demultiplexer terminal 27.
72	Demultiplexer terminal 9.
73	Demultiplexer terminal 10.

Table 4.—Number of sensing points in controller boxes

Controller	Phase 1	Phase 2	Total
Right hand	1	15	16
Left hand	18	0	18
Master station	10	12	22
Total	29	27	56

NOTE.—Phases refer to development phases of the prototype.

RELATIONSHIPS BETWEEN SENSOR DATA AND FAILURES

A group of components was selected from table 1 for diagnosis. The selections were made based on considerations mentioned in the general procedure; the main considerations are listed below:

1. Most of the components are associated with the traction circuit, where failures are difficult to diagnose;
2. Sensing requirements are reasonable;
3. Sensors are reliable;
4. These components account for a large number of control-circuit failures; and
5. No machine modifications are necessary.

Table 5 lists the components that were selected. A brief description of the components is given in the next section.

Table 5.—Control-circuit components to be diagnosed

Component	*Phase*
Firing package	1
5-A traction-circuit fuse[1]	1
2-A firing-package fuse[1]	1
Left reverse (eREV) interlock (2)[1]	1
Left forward (eFOR) interlock (2)[1]	1
Right reverse (fREV) interlock (2)[1]	1
Right forward (fFOR) interlock (2)[1]	1
Remote tram (RT) interlock or fuse[1]	2
High-speed remote (HSR) interlock or fuse[1]	2
Open connections	2

[1] Diagnosis of these components also includes the possibility of an open connection.

Component Descriptions

Firing Package

The drive unit for each traction motor consists of a silicon controlled rectifier (SCR) bridge in the power circuit and the firing package in the control circuit. The firing package is a solid-state, self-contained circuit that (1) controls tram speed by sending gate signals to each SCR in the bridge, and (2) controls tram direction through outputs to directional contactors in the power circuit. Inputs to the firing package are listed below:

- Control power.
- Direction:
  - Left (forward, reverse).
  - Right (forward, reverse).
- Speed:
  - Left (first, second, third).
  - Right (first, second, third).
- Cutter-motor-current feedback.

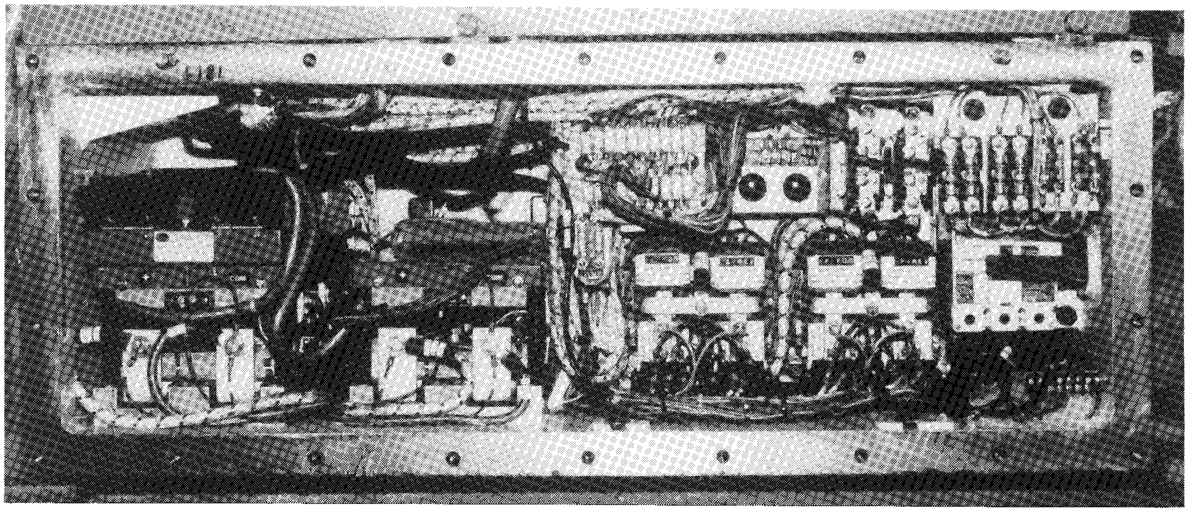

Figure 5.—Left-hand control box.

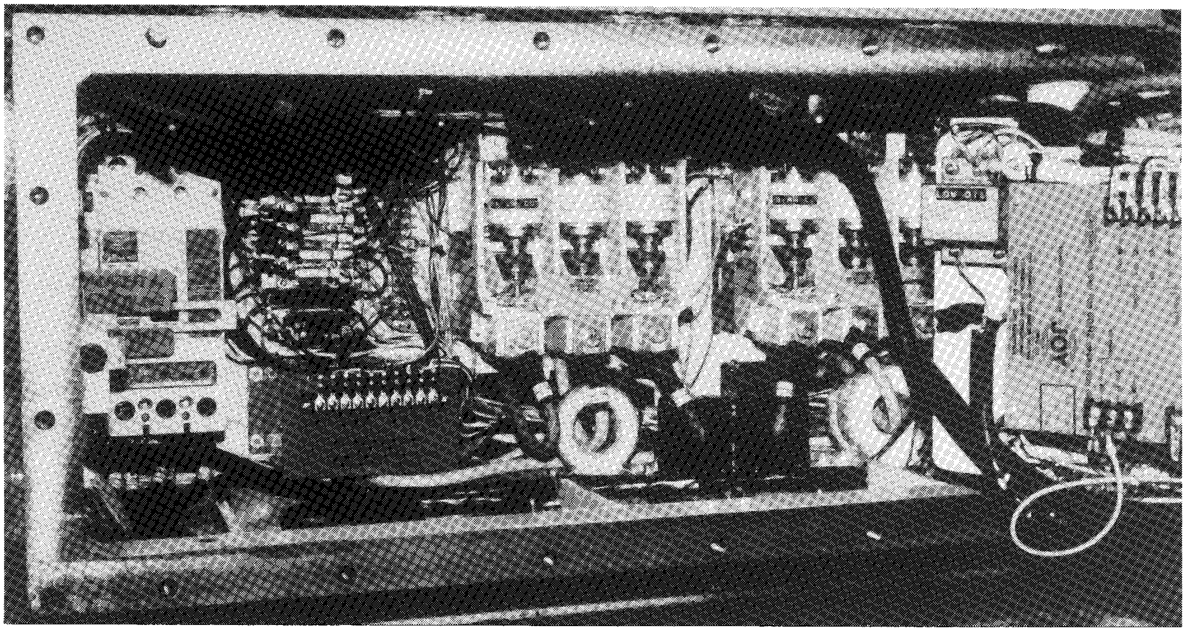

Figure 6.—Right-hand control box.

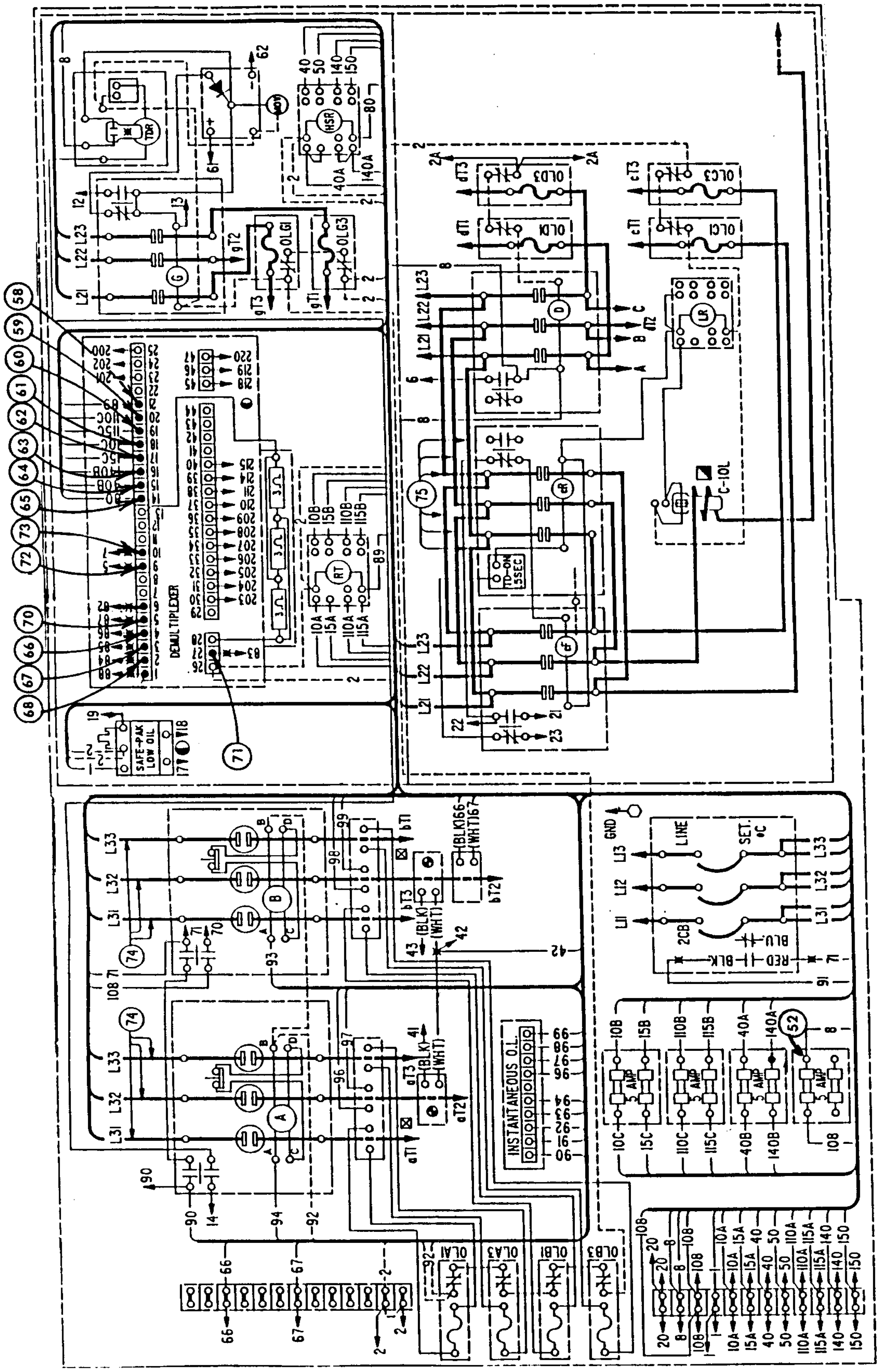

Figure 7.--Sensor locations (circled numbers) in right-hand controller.

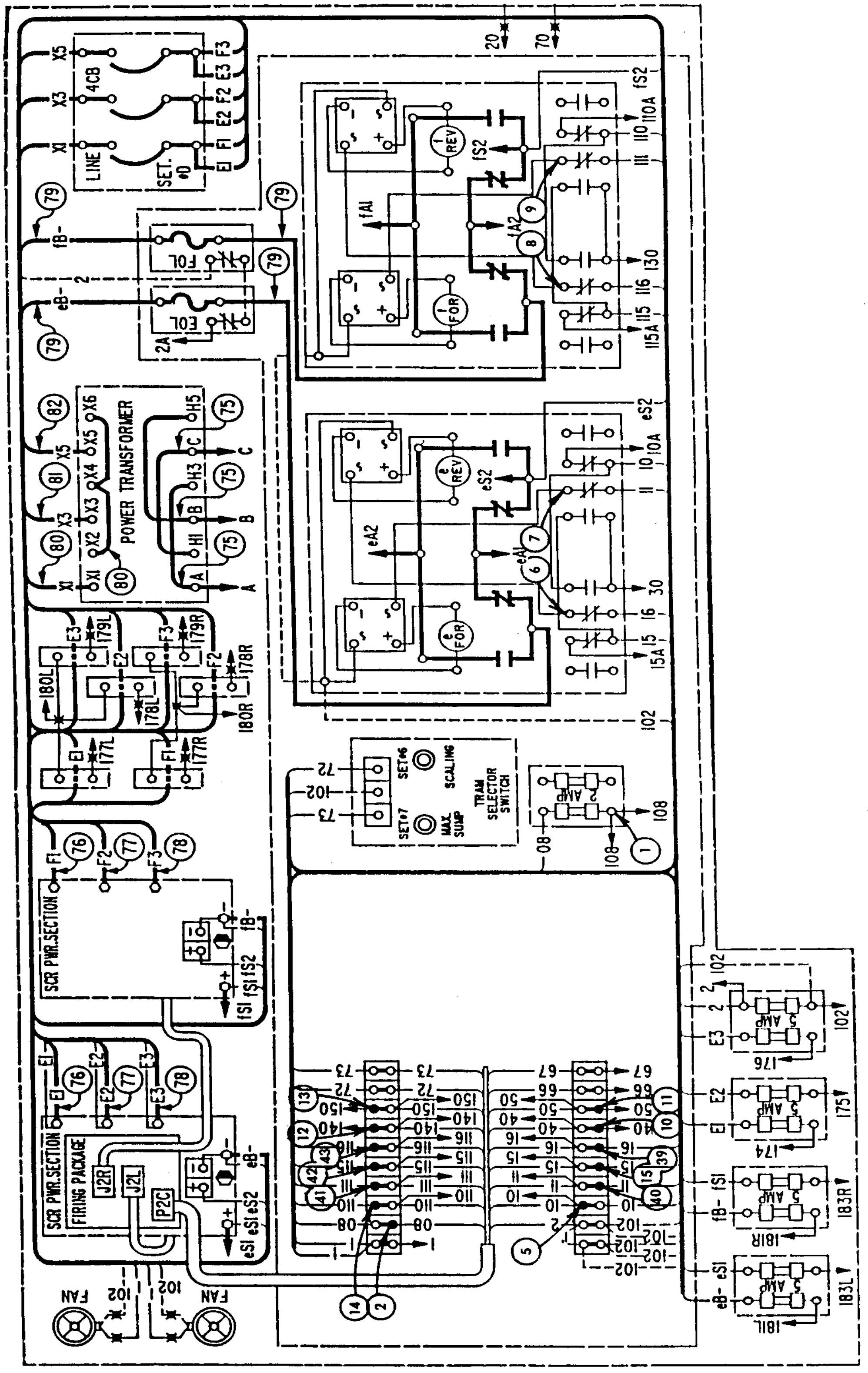

Figure 8.—Sensor locations (circled numbers) in left-hand controller.

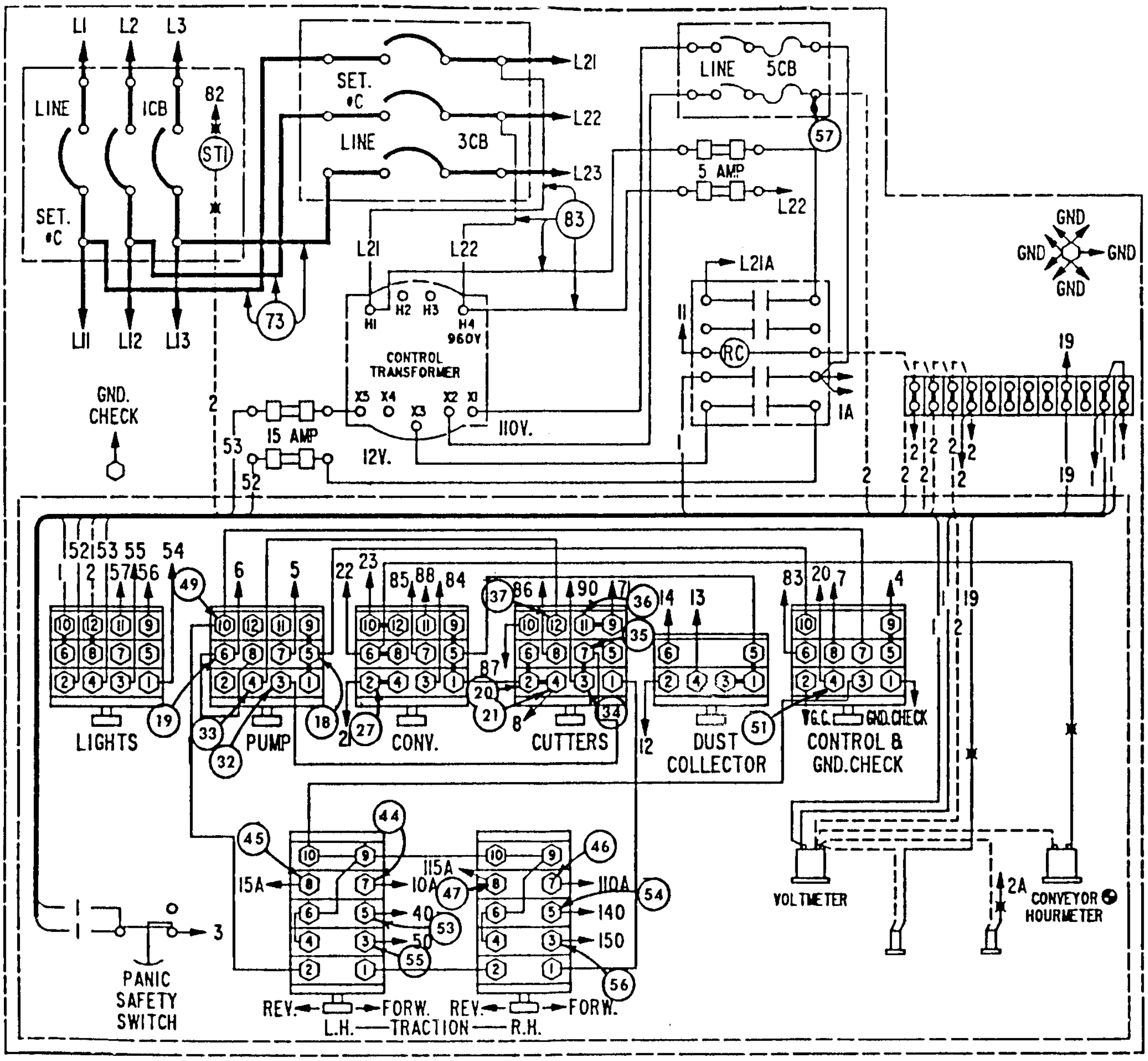

Figure 9.—Sensor locations (circled numbers) in master station.

From these inputs, the firing package sends the proper outputs to control the direction and speed of each traction motor. To prevent machine overloads, a maximum sump speed adjustment limits the tram speed when the cutter motors are running. Additional speed reduction is obtained through the cutter-motor-current feedback input, in which motor speed is reduced as the load on the cutter motors increases. The amount of speed reduction can be varied by selector switches in each of these two circuits.

Fuses

It has been mentioned that certain fuses are being monitored in the control circuit in spite of the fact that a blown fuse does not strictly represent a failed component. The reason for including these fuses is to add additional diagnostic capabilities to the traction circuit of the miner and to reduce diagnostic time for traction-circuit failures. The two fuses selected are in the traction circuit: The first one is a 5-A fuse that supplies the entire traction circuit, and the second one is a 2-A fuse that protects the firing package. Other fuses that are in series with components diagnosed in the control circuit are implicitly included in the diagnostics as well.

Directional Interlocks

There are eight directional interlocks on the prototype machine that serve to control the directional signal that the firing package receives and sends. Four are located on the input side of the firing package and four are located on the output side. These interlocks help to prevent the firing package from sending (or receiving) a forward and reverse signal simultaneously to the same traction motor. Figure 10 illustrates how this is accomplished, and a brief explanation is provided here. A left forward input to the firing package energizes the eFOR coil; this coil operates two sets of normally closed eFOR contacts. One set is in series with the left reverse input to the firing package and the other is in series with the eREV output of the firing package. This prevents the firing package from receiving or sending a left reverse signal while there is a left forward signal. An analogous situation also exists for a reverse signal; however, the left and right traction circuits are designed to operate independently of one other.

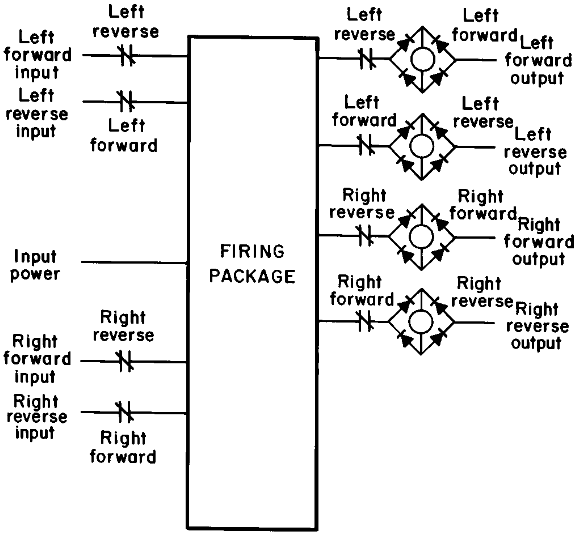

Figure 10.—Directional interlocks in traction circuit.

Demultiplexer

The demultiplexer is not being diagnosed; however, many of its outputs are monitored to establish the operational function that is intended for the machine. The applicable outputs from the demultiplexer are listed below:

Start pump
Start cutter
Right forward
Left forward
Right forward or right reverse
(for high-speed operation)
Fast (tram)
Start conveyor
Run conveyor reverse
Run pump
Safety switch
Right reverse
Left reverse
Left forward or left reverse
(for high-speed operation)
Run cutters
Run conveyor forward

In addition, control power to the demultiplexer is monitored.

Remote Tram Interlocks

The remote tram interlocks act (collectively) as a safety switch in the traction circuit for remote operation of the continuous miner. As such, their function is similar to that of the foot switch during manual operation. The remote tram interlocks open and close the circuit between the demultiplexer and the firing package. When a traction switch (either left or right) on the remote control station is activated, the remote tram interlocks close the circuit between the demultiplexer and the firing package so that the directional signals from the demultiplexer can be received by the firing package.

High-Speed Remote Interlocks

During manual operation of the continuous miner, tram speed is determined by the position of the traction levers. Each point on the traction lever corresponds to a specified tram speed. The first point is first speed (16 ft/min), the second point is second speed (35 ft/min), and the third point is third speed (68 ft/min). During remote operation of the machine, only two speeds are available, slow (first) and fast (third). In addition, these speeds are not determined by the position of the traction switch. Instead, they are determined by a separate speed selector switch on the remote control station. When the operator selects high speed on the selector switch, the high-speed remote interlocks close, and any forward or reverse signal becomes a third speed input to the firing package.

Open Connections

Depending on the location of the monitoring points, it is impossible to distinguish between a failed component and a broken connection. Therefore, some failures are best diagnosed as failed component OR an open connection (to the component). By doing this, the remote chance of a broken connection is not overlooked.

In other cases, the sensor locations for the determination of failed components may allow for additional diagnostics not originally planned. In most cases, these will consist of open connections. If some of these broken connections can be included with little additional effort, they should be. Although they are relatively rare, open connections are known to occur predominantly after components are replaced, indicating that certain connections either may not have been made during the repair process or were poorly made.

Failure Modes

As described in the general procedure, failure modes must be considered when diagnosing component failures. In many cases, the inclusion of multiple modes of failures increases the complexity of the diagnostic system considerably. If each mode of failure is to be detectable, then the sensing, data acquisition, and algorithmic requirements may become prohibitive. In some cases, this problem can be alleviated by choosing to detect the common modes of failure, or to monitor parameters that are indicative of many modes of failure. This type of problem is most common on sealed electronic devices that actually contain many components, such as a firing package.

Failures of the firing package could not be simulated; therefore, firing-package failures are diagnosed from the presence or absence of directional outputs. If the inputs to the firing package are correct but the proper outputs are absent, the firing package is considered to be failed. This procedure should not misdiagnose any failures; however, other failures may exist in the firing package that will go undetected.

Diagnostic Logic

Logic equations using ON-OFF control-voltage signals were developed for the diagnostic algorithm. The logic symbols used are as follows: $\cap$ denotes logical AND, $\cup$ denotes logical OR, ~ denotes logical NOT, → denotes THEN, and M denotes failure mode. One equation exists for each mode of failure diagnosed. At the present time, 19 modes of failure in the traction circuit are diagnosed using 28 of the sensing points (plus one for the reference) for the phase 1 diagnostics; they are listed in table 6. This table includes the problem that the operator would experience, the failure mode, the sensing-point condition (high or low), and the logic to diagnose the failure. Phase 2 diagnostic information is listed in table 7 for the additional 21 modes of failure that have been developed. An example is given below to illustrate the logic.

The form and function of the logic equations that are used to diagnose failures can be illustrated with the simplified traction-control circuit shown in figure 11. The main purpose of this circuit, which is similar to one on the testbed machine, is to output a signal that will cause the mining machine to tram either forward or reverse. One function of the control circuit is to ensure that the tram controller does not simultaneously attempt to move the machine both forward and reverse. Such an undesirable event is prevented by interlocking both the input and the output of the tram controller.

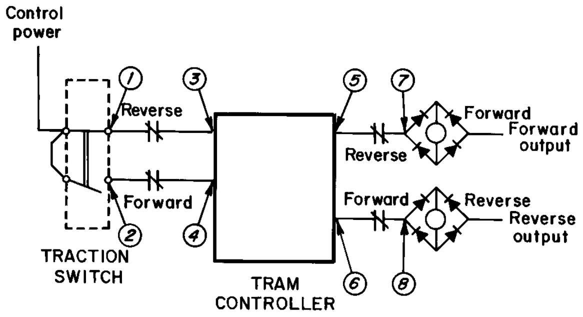

Figure 11.—Simplified diagram of traction-control circuit. Circled numbers correspond to sensor points.

Table 6.—Diagnostic information for phase 1 failures

Problem	Failure	Mode	Sensor condition[1]		Diagnostic logic[2]
			High	Low	
No tram[3]	Foot switch	1	1, 2, (20), 52	51	P1 ∩ P2 ∩ P52 ∩ ~P51 → M1.
Do.	2-A firing-package fuse	2	1, (20), (52)	2	P1 ∩ ~P2 → M2.
Do.	5-A traction circuit fuse	3	(20), 52	1, (2), (51)	P52 ∩ ~P1 → M3.
Do.	Broken connection: Cutter switch and 5-A fuse.	32	20	(1), (2), 52	P20 ∩ ~P52 → M32.
No left forward tram[4]	Firing package	6	(1, 44, 51), 2, 5	15, 40, (45)	P2 ∩ P5 ∩ ~P15 ∩ ~P40 → M6.
No left reverse tram[4]	do.	7	(1, 45, 51), 2, 15	5, 39, (44)	P2 ∩ P15 ∩ ~P5 ∩ ~P39 → M7.
No right forward tram[4]	do.	8	(1, 46, 51), 2, 14	41, 42, (47)	P2 ∩ P14 ∩ ~P41 ∩ ~P42 → M8.
No right reverse tram[4]	do.	9	(1, 47, 51), 2, 42	14, 43, (46)	P2 ∩ P42 ∩ ~P14 ∩ ~P43 → M9.
No left forward tram	eREV NC interlock Line 10A-10 failed open (or open connection).	10	2, 44, (1, 51)	5, 6, 15, 39, (45)	P2 ∩ P44 ∩ ~P5 ∩ ~P6 ∩ ~P15 ∩ ~P39 → M10.
No left reverse tram	eFOR NC interlock Line 15A-15 failed open (or open connection).	11	2, 45, (1, 51)	5, 7, 15, 40, (44)	P2 ∩ P45 ∩ ~P5 ∩ ~P15 ∩ ~P7 ∩ ~P40 → M11.
No right forward tram	fREV NC interlock Line 110A-110 failed open (or open connection).	12	2, 46, (1, 51)	8, 14, 42, 43, (47)	P2 ∩ P46 ∩ ~P8 ∩ ~P14 ∩ ~P42 ∩ ~P43 → M12.
No right reverse tram	fFOR NC interlock Line 115A-115 failed open (or open connection).	13	2, 47, (1, 51)	9, 14, 41, 42, (46)	P2 ∩ P47 ∩ ~P9 ∩ ~P14 ∩ ~P41 ∩ ~P42 → M13.
No left 2d speed	Broken connection: Left tram switch to left 2d speed input.	27	(1), 2, 53	10	P2 ∩ P53 ∩ ~P10 → M27.
No left 3d speed	Broken connection: Left tram switch to left 3d speed input.	30	(1), 2, 10, 53, 55	11	P2 ∩ P10 ∩ P53 ∩ P55 ∩ ~P11 → M30.
No right 2d speed	Broken connection: Right tram switch to right 2d speed input.	28	(1), 2, 54	12	P2 ∩ P54 ∩ ~P12 → M28.
No right 3d speed	Broken connection: Right tram switch to right 3d speed input.	29	(1), 2, 12, 54, 56	13	P2 ∩ P12 ∩ P54 ∩ P56 ∩ ~P13 → M29.
No tram[5]	Tripped EOL or FOL overload	31			
No left forward tram	eREV interlock Line 11 failed open.	36	(1, 44, 51), 2, 5, 40	6, 7, 15, 39	P2 ∩ P5 ∩ P40 ∩ ~P6 ∩ ~P7 ∩ ~P15 ∩ ~P39 → M36.
No left reverse tram	eFOR interlock Line 16 failed open.	37	(1, 45, 51), 2, 15, 39	5, 6, 7, 40	P2 ∩ P15 ∩ P39 ∩ ~P5 ∩ ~P6 ∩ ~P7 ∩ ~P40 → M37.
No right forward tram	fREV interlock Line 111 failed open.	38	(1, 46, 51), 2, 14, 41	8, 9, 42, 43	P2 ∩ P14 ∩ P41 ∩ ~P8 ∩ ~P9 ∩ ~P42 ∩ ~P43 → M38.
No right reverse tram	fFOR interlock Line 116 failed open.	39	(1, 47, 51), 2, 42, 43	8, 9, 14, 41	P2 ∩ P42 ∩ P43 ∩ ~P8 ∩ ~P9 ∩ ~P14 ∩ ~P41 → M39.

EOL	Left overload relay.
FOL	Right overload relay.
NC	Normally closed.

[1] Parentheses indicate redundant points.

[2] Logic symbols are as follows: ∩ denotes logical AND, U denotes logical OR, ~ denotes logical NOT, and → denotes THEN.

[3] Diagnostic system must recognize that the foot switch is engaged.

[4] Must check effects of cutter-motor feedback, feedback adjustment, and maximum sump speed adjustment.

[5] Not diagnosed because control power is present in circuit, but current is limited to values less than the amount needed to close pump interlock.

Table 7.—Diagnostic information for phase 2 failures

Problem	Failure	Mode	Sensor condition		Diagnostic logic[1]
			High	Low	
No left forward remote tram	RT interlock open, fuse in line 10C-10B, open connection 10-C-10A.	40	2, 71, 72, 58, 61, 64	44, 5, 45, 15, 39, 40,	P2 ∩ P71 ∩ P72 ∩ P58 ∩ P61 ∩ P64 ∩ ~P44 ∩ ~P5 ∩ ~P45 ∩ ~P15 ∩ ~P39 ∩ ~P40 → M40.
No left reverse remote tram	RT interlock open, fuse in line 15C-15B, open connection 15C-15A.	41	2, 71, 72, 58, 62, 64	44, 5, 45, 15, 39, 40	P2 ∩ P71 ∩ P72 ∩ P58 ∩ P62 ∩ P64 ∩ ~P44 ∩ ~P5 ∩ ~P45 ∩ ~P15 ∩ ~P39 ∩ ~P40 → M41.
No right forward remote tram.	RT interlock open, fuse in line 110C-110B, open connection 110C-110A.	42	2, 71, 72, 58, 59, 63	46, 14, 47, 42, 41, 43	P2 ∩ P71 ∩ P72 ∩ P58 ∩ P59 ∩ P63 ∩ ~P46 ∩ ~P14 ∩ ~P47 ∩ ~P42 ∩ ~P41 ∩ ~P43 → M42.
No right reverse remote tram.	RT interlock open, fuse line 115C-115B, open connection 115C-115A.	43	2, 71, 72, 58, 60, 63	46, 14, 47, 42, 41, 43	P2 ∩ P71 ∩ P72 ∩ P58 ∩ P60 ∩ P63 ∩ ~P46 ∩ ~P14 ∩ ~P47 ∩ ~P42 ∩ ~P41 ∩ ~P43 → M43.
Unknown	RT interlock closed line 10B-10A	44	2, 18, 19, 44, 5, 51, 61	58, 71, 72	P2 ∩ P18 ∩ P19 ∩ P44 ∩ P5 ∩ P51 ∩ P61 ∩ ~P58 ∩ ~P71 ∩ ~P72 → M44.
Do.........................	RT interlock closed line 15B-15A	45	2, 18, 19, 45, 15, 51, 62	58, 71, 72	P2 ∩ P18 ∩ P19 ∩ P45 ∩ P15 ∩ P51 ∩ P62 ∩ ~P58 ∩ ~P71 ∩ ~P72 → M45.
Do.........................	RT interlock closed line 110B-110A.	46	2, 18, 19, 46, 14, 51, 59	58, 71, 72	P2 ∩ P18 ∩ P19 ∩ P46 ∩ P14 ∩ P51 ∩ P59 ∩ ~P58 ∩ ~P71 ∩ ~P72 → M46.
Do.........................	RT interlock closed line 115B-115A.	47	2, 18, 19, 47, 42, 51, 60	58, 71, 72	P2 ∩ P18 ∩ P19 ∩ P47 ∩ P42 ∩ P51 ∩ P60 ∩ ~P58 ∩ ~P71 ∩ ~P72 → M47.
No left forward fast remote tram.	HSR interlock open, fuse in line 40B-40A, open connection line 80.	48	2, 71, 72, 58, 61, 64, 65. 40	53, 55, 10, 11, 15	P2 ∩ P71 ∩ P72 ∩ P58 ∩ P61 ∩ P64 ∩ P65 ∩ P40 ∩ ~P53 ∩ ~P55 ∩ ~P10 ∩ ~P11 ∩ ~P15 → M48.
No left reverse fast remote tram.	HSR interlock open, fuse in line 40B-40A, open connection line 80.	49	2, 71, 72, 58, 62, 64, 65, 39	53, 55, 10, 11, 5	P2 ∩ P71 ∩ P72 ∩ P58 ∩ P62 ∩ P64 ∩ P65 ∩ P39 ∩ ~P53 ∩ ~P55 ∩ ~P10 ∩ ~P11 ∩ ~P5 → M49.
No right forward fast remote tram.	HSR interlock open, fuse in line 140B-140A, open connection line 80.	50	2, 71, 72, 58, 41, 59, 63, 65	54, 56, 12, 13, 42	P2 ∩ P71 ∩ P72 ∩ P58 ∩ P59 ∩ P63 ∩ P65 ∩ P41 ∩ ~P54 ∩ ~P56 ∩ ~P12 ∩ ~P13 ∩ ~P42 → M50.
No right reverse fast remote tram.	HSR interlock open, fuse in line 140B-140A, open connection line 80.	51	2, 71, 72, 58, 60, 63, 65, 43	54, 56, 12, 13, 14	P2 ∩ P71 ∩ P72 ∩ P58 ∩ P60 ∩ P63 ∩ P65 ∩ P43 ∩ ~P54 ∩ ~P56 ∩ ~P12 ∩ ~P13 ∩ ~P14 → M51.
Pump will not start in remote.	Open connection line 7 (demux term 10 to control term 8 to pump term 10).	52	71, 72, 73	18, 49	P71 ∩ P72 ∩ P73 ∩ ~P18 ∩ ~P49 → M52.
Pump will not start in remote.	Open connection pump term 10 to cutter term 1, or failed cutter or traction switches.	53	71, 72, 73, 49	18, 20	P71 ∩ P72 ∩ P73 ∩ P49 ∩ ~P18 ∩ ~P20 → M53.
Cutters will not start in remote.	Open connection demux term 5 to cutter term 10 (line 87) or failed cutter switch.	54	71, 72, 73, 70, 66, 34	18, 36	P71 ∩ P72 ∩ P73 ∩ P70 ∩ P66 ∩ P34 ∩ ~P18 ∩ ~P36 → M54.

See notes at end of table.

Table 7.—Diagnostic information for phase 2 failures—Continued

Problem	Failure	Mode	Sensor condition		Diagnostic logic[1]
			High	Low	
Cutters start but will not run in remote.	Open connection demux term 4 to cutter term 8 (line 86) or failed cutter switch.	55	71, 72, 73, 70, 66, 36	18, 34, 35	P71 ∩ P72 ∩ P73 ∩ P70 ∩ P66 ∩ P36 ∩ ~P18 ∩ ~P34 ∩ ~P35 → M55.
Conveyor will not start (forward) in remote.	Open connection demux term 3 to conveyor term 7, or failed conveyor switch.	56	71, 72, 67, 68, 19, 20	18, 27	P71 ∩ P72 ∩ P67 ∩ P68 ∩ P19 ∩ P20 ∩ ~P18 ∩ ~P27 → M56.
Unknown, possible jump from 1st to 3d speed.	HSR failed closed line 40A-40 ...	60	NA	NA	P2 ∩ P18 ∩ P64 ∩ (P44 U P45) ∩ (P53 U (P53 ∩ P55)) ∩ ~P71 ∩ ~P72 ∩ ~P58 → M60.
Do.	HSR failed closed line 140A-140	61	NA	NA	P2 ∩ P18 ∩ P63 ∩ (P46 U P47) ∩ (P54 U (P54 ∩ P56)) ∩ ~P71 ∩ ~P72 ∩ ~P58 → M61.
Cutters will not start	Open connection cutter term 7 to pump term 3.	65	18, 19, 21, 34, 20, 35, 49	32, 33, 36, 37	P18 ∩ P19 ∩ P21 ∩ P34 ∩ P20 ∩ P35 ∩ P49 ∩ ~P32 ∩ ~P33 ∩ ~P36 ∩ ~P37 → M65.
Do.	Open connection pump term 4 to cutter term 12.	66	18, 19, 21, 34, 20, 35, 49, 32, 33	36, 37	P18 ∩ P19 ∩ P21 ∩ P34 ∩ P20 ∩ P35 ∩ P49 ∩ P32 ∩ P33 ∩ ~P36 ∩ ~P37 → M66.

demux	Demultiplexer.
HSR	High-speed remote.
NA	Not available.
RT	Remote tram.
term	Terminal.

[1] Logic symbols are as follows: ∩ denotes logical AND, U denotes logical OR, ~ denotes logical NOT, and → denotes THEN.

This interlocking is achieved by using auxiliary contacts on power contactors. For example, suppose that the bridge output in figure 11, which is labeled "Forward output," will energize the coil of a contactor that will then allow current to flow to the tram motors. Also assume that this contactor has one or more auxiliary contacts. Two of these are normally closed and are labeled as "forward" in the figure. Thus, when the coil of the contactor is energized, the power contacts will close and current will flow to the motors, and at the same time, the normally closed auxiliary contacts will open. As can be seen in the figure, when these contacts open, it is impossible for a "reverse" output signal to occur, thereby achieving a control-circuit objective. Given this explanation of the circuit, an example of the diagnostic logic can now be shown.

The circled numbers correspond to sensor points. Consider a failure of the interlock, located between sensor points 5 and 7, that causes the "reverse" contact to remain open. For this failure mode, control voltage will exist at points 1, 3, and 5, and will not exist at points 7, 2, 4, 6, and 8. As such a logic equation can be written in terms of the sensed voltages, as follows:

$$P1 \cap P3 \cap P5 \cap \sim P2 \cap \sim P4 \cap \sim P6 \cap \sim P7 \cap \sim P8 \rightarrow M1,$$

where Pi = control voltage present at sensor point i,

$\cap$ = and,

$\cup$ = or,

$\sim$ = not,

$\rightarrow$ = then, and

Mj = failure mode j.

There are, of course, several other failure modes that could be diagnosed, but this should serve to illustrate how the equations operate on the sensed data.

In this example, there first appears to be a great deal of redundancy; however, the additional monitoring points can be used to diagnose other components in this circuit. For example, the tram controller could fail in many different modes such that monitoring points 3 through 6 are used to establish that the controller is performing its intended function before any further diagnostics are performed. Monitoring points 1 and 2 establish the prerequisite conditions necessary to determine the intended function of the circuit. In addition, they can be used to detect certain types of failures in the traction switch (shorts).

In many cases, redundancy can be used for developing additional confidence if the monitoring points are necessary for detecting other types of failures as well. In table 6, the redundant points are enclosed in parentheses in the "sensor condition" column; however, these points were not incorporated into the diagnostic logic of the prototype.

During the development of the diagnostic system, failures were simulated where possible, and the appropriate measurements were taken to compare with the expected values. Although the values compared well in most cases, there were a few in which an expected value of 0 V was closer to 50 or 60 V. Sometimes this is due to indicator lamps that have been placed in the circuit to aid troubleshooting; other times the cause is more elusive. Consequently, it is important to have an a priori knowledge of this, so that the "absence" of a voltage can be correctly defined. In the prototype system a value less than 80 V was considered to be the same as 0 V.

SYSTEM IMPLEMENTATION

A diagnostic system was synthesized and a logical basis for diagnosing failures, given certain sensory input, was established. The evolution of this basis from mathematical procedures to a functional system is described.

SYSTEM STRUCTURE

A variety of implementation methods are commonly used to realize diagnostic systems, including hard-wired logic (HWL) and computer-based systems. The latter are further divided into algorithmic and nonalgorithmic classes, depending on the type of software used by the system. Each of these classes of implementation has its advantages and criteria for appropriate application, although there is often considerable overlap in these. HWL is favored if the logical relationships between the system input and output can be economically modeled with circuit elements, such as logic gates. If very high throughput rates are required in the diagnostic system, HWL systems are favored. Programmable controllers and other computer-based systems can mimic an HWL system, but with a loss of speed, and usually at a greater cost. These disadvantages are offset, however, by the relative ease with which a working system can be realized. Moreover, changes to the logic are relatively simple to make with a computer-based system. Thus, if only a few systems are to be constructed, the computer-based system is almost always favored, as was the case here.

There are many application areas or domains in which it is not possible to establish mathematical relationships, using Boolean logic or otherwise, between the system inputs and the system outputs. In other cases, the required inputs to the decision-making process may not be easily quantified or may be heuristic in nature. Sometimes one or more of the inputs may be unknown. In still other cases the certainty of the data elements may vary and these variations may alter the certainty of decisions made by the system. The presence of one or more of the aforementioned conditions tends to suggest that a nonalgorithmic approach, typically a KBES, may be more appropriate for the application.

An algorithmic implementation was selected for this prototype for the following reasons:

1. The input information required to diagnose a control-circuit failure is obtainable from sensors; these sensors are inexpensive and reliable, and they can be located on the machine without compromising the machine's reliability or maintainability. It is unnecessary to speculate about input values.
2. Various combinations of input values definitively indicate the presence or absence of a specific failure with a 100% certainty. There are no circumstances under which the inputs would indicate the possibility that a component has failed with less than 100% certainty.
3. Simple mathematical relations between the sensor inputs and the various failures can be established.

Thus, the decision to select an algorithmic approach was independent of the number of failures to be diagnosed or the number of inputs required to make the diagnosis. The facts that direct logical relationships between inputs and failures could be defined and that the inputs could be measured with certainty were central to the decision to select an algorithmic solution to the diagnostic problem.

Existing expert-system shells can evaluate Boolean expressions quite easily, and accordingly, such a shell could be selected for this implementation, if there were some other mitigating factor. For example, the shells generally support extensive graphics and permit effortless interfacing with other software. Had any of these capabilities been required, an expert-system shell would have been a viable option. However, in the absence of any such factors, the shell requires significantly more computer resources, with the attendant cost. Thus, after considerable study, an algorithmic structure was selected as the more appropriate approach.

Although an HWL implementation would have been possible, a microprocessor-based system was specified for the following reasons:

1. The time required to process the logic equations is very small; thus the speed of the diagnostic system, i.e., the throughput rate, would be satisfactory without the use of HWL.
2. The development time for a hard-wired system would have been unacceptably long for the constraints of this project.
3. The cost savings that can be realized with an HWL implementation would be offset by the development cost. However, if several copies of the diagnostic system were to be fabricated, it would be practical to utilize HWL.
4. The test program objectives of the project would be served best if it were possible to alter the logic used in the diagnostic system. Additional information required for specification of the microprocessor-based system is given in the appendix.

INFORMATION MANAGEMENT ISSUES

The research summarized to this point has focused on the types of failures that are to be detected and the means of sensing and diagnosing them. After a diagnosis is made, the information must be communicated to someone in a useful form. The "who" and "what" aspects of this are crucial information issues, and the resolution of these will directly impact the utility of the developed system. Certainly there are many different people to whom this information might be conveyed, and similarly, a variety of formats for communicating the information can be imagined. The reality of cost and time constraints, however, require better defined goals.

A good starting point is to define why the system exists; in this case it is to diagnose control-circuit failures. Normally, when the machine malfunctions or "breaks down," an electrician or mechanic is summoned to investigate the problem. Time is required to remove control case covers and to perform troubleshooting activities. After the problem has been diagnosed, parts are obtained, and the required corrective actions are performed. It is apparent that significant time savings could be achieved, resulting in less downtime, if the failure could be automatically diagnosed.

Knowledge of the failure mode would allow the electrician to remove only the covers necessary to access the failed component and would eliminate the time spent attempting to diagnose the problem. Further, if a part is needed, the procurement could occur at the same time that the failed part is being accessed and removed. Based on the foregoing, it is clear that the diagnostic system must, at the very least, display the failed component, e.g., "eFOR interlock." Other information could be displayed such as the name of the control case enclosing the failed component. A schematic of the control circuit relevant to the failed component could even be displayed.

Although a variety of additional information could be displayed or otherwise made available, there would be no useful purpose served by doing so. Additionally, there would be a large cost in both system complexity and cost. Any electrician who would be authorized to make the repairs would know the location of the failed component and would rarely have a need to examine a schematic prior to executing the maintenance action. Thus, the objective of the onboard diagnostic system will be achieved if it simply displays the name of the failed component or an equivalent diagnostic code. The location of such a display is the next consideration.

The information could be displayed on a small light-emitting diode (LED) or liquid crystal display (LCD) screen in the operator's cab, and it could be telemetered to remote locations. While the information may serve some useful purpose in a remote location, such as for creation of a data base, it will be of most importance to people on the working section. Therefore, a display in the operator's cab of the machine is essential. Thus, when a failure occurs, the section mechanic will immediately know what has to be repaired; if the mechanic is unavailable, the section foreman can phone for assistance, and can also communicate the name of the failed component. The prototype uses an LCD display, mounted near the operator's cab, to display the code number of the failure. A more complete display, giving the actual name of the failure, might be desirable in a production-style system.

IMPLEMENTATION BY PHASES

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IMPLEMENTATION BY PHASES

An important aspect of the implementation is the determination of the component failures to be diagnosed. Although the surveys of component failures serve as guidelines for the likely components for inclusion, the developers must ultimately make the determination. As described before, the final selections are based on many conditions, e.g., frequency of failure, input requirements, circuit complexity, and circuit updates. In most cases, however, both hardware and economic constraints will dictate the number and type of failures that can be diagnosed by the system. It is simply impractical to monitor and diagnose every theoretically possible failure.

Similarly, it is often impractical to attempt developing the ultimate system in the first trial. A more effective and prudent approach is to establish multiple levels of development and implementation in which increased capabilities and sophistication are added. Such an approach is particularly desirable in the prototype stage since it allows for changes to evolve in an orderly fashion, rather than through major modifications and "fixes" to the "final product." Here, the work was divided into phases, thereby allowing for thorough testing and debugging of each stage while developing the next one.

Prototype development over multiple phases also offers opportunities to study certain aspects of interaction between the machine and the diagnostic system, and then to use this information to improve the subsequent system. In particular, there is some uncertainty over the characteristics of state changes that occur in the control circuit of the miner. If state changes occur (primarily in the traction circuit) while sampling is occurring, there is a chance of misdiagnosis or, at minimum, the collection of useless information. This is an aspect that should be investigated whenever the procedures outlined in this report are applied to a different mining machine. Very closely related to this issue is one of signal corruption; implementation in phases will allow for possible refinements in sampling procedures. The mineworthiness of hardware components can also be evaluated in the first phase of implementation, and modifications made in the second phase. Consequently, the experience gained with a phase 1 prototype will be invaluable in the development of a phase 2 unit that will have to diagnose a larger set of failures. Of course, it is possible to divide the implementation into additional phases, depending on the goals of the system developers.

Many of the failures previously listed in table 1 were selected for the phase 1 development, and are shown in table 5. All of the failures in this group are related to the traction circuit, and they were selected for two reasons: First, taken as a group, they account for the largest percentage of control-circuit failures on the continuous miners; and second, they are the most difficult to diagnose. Another desirable characteristic of this group is that they are applicable for all machine operating modes, i.e., remote and manual.

Generally, the phase 2 diagnostics detect failures of additional components that are required for remote operation of the machine. Although the number of additional failures that are detected is limited, the demultiplexer must be monitored to define its operational state. Accordingly, most of the phase 2 monitoring points are located on the demultiplexer output. Failures of fuses, interlocks, and connections between the demultiplexer and the rest of the control circuit are also diagnosed, although the logic does not distinguish them individually. The additional sensing requirements that this would impose is not justified by a corresponding time savings from such a specific diagnosis. Certain switch connections are also diagnosed.

TEST PROGRAM

The development and implementation of a diagnostic system requires testing at various stages of the work. First, it is necessary to make measurements on the machine to verify the proposed logic. Sometimes there are subtle but important differences between the schematic and the actual electrical implementation on the machine. These need to be detected and noted at this stage as well. Once the accuracy of the diagnostic logic has been verified, the microprocessor can be programmed and the sensors can be installed on the machine. Then it will be necessary to verify the integrity of the programming by testing it on the machine. Of course, testing in this sense means to simulate each failure on the machine and to check for a correct diagnostic response from the microprocessor. An incorrect response indicates an error in the programming or in the wiring of the sensors, assuming that the logic equations were previously verified. The final stage of testing would be to place the machine, with the installed diagnostic system, into the mine. Based on the outcome of this test it may be necessary to alter the diagnostic logic or some other aspect of the system. It is important to note that the addition of the diagnostic system to a mining machine will likely necessitate obtaining certain Mine Safety and Health Administration (MSHA) approvals, due to wiring or other hardware additions to the machine.

The test program for the development of the prototype system was more involved than suggested by the foregoing, because of the experimental nature of the work. Initially, a significant effort was made to study the electrical behavior and performance of the control circuit, to determine the feasibility of implementing a diagnostic system of the type described in this report. In addition to utilizing the testbed machine for this work, training panels were also obtained and utilized.

A prototype system was then constructed, and the sensors were installed on the machine. Next, the prototype system was tested and modifications were made as required. Finally, the system was documented, and an application was submitted to MSHA for an experimental permit to use the system in the mine. The experimental permit was not received prior to the testbed machine's departure to a West Virginia coal mine, where it is being used in the Bureau's computer-assisted mining project. Consequently, in-mine testing of this system has been delayed pending MSHA approval to mount the diagnostic unit on the machine. However, it will be installed on the testbed machine later this year when the machine is returned to the Bureau for additional modifications. Once the diagnostic system has been tested in the mine, it will be possible to determine its usefulness to mine personnel, in addition to its technical performance.

CONCLUSIONS

A general procedure for the development of onboard diagnostic systems for mining machines has been developed, although it was impossible to develop one diagnostic system for generic application to mining machines. The application of this procedure was illustrated through the actual development of a diagnostic system for a Joy 14CM09 continuous miner, the miner used in the Bureau's computer-assisted mining program.

Implementation issues were examined, and it was determined that an algorithmic approach would be more advantageous than an expert system one. Information issues related to the output of the diagnostic system and the use of this output by mine workers were also addressed.

The developed prototype system is capable of diagnosing approximately 40 different commonly occurring failures, and yet the system requires less than 60 measured voltage points throughout the control circuit. This translates into relatively few wiring additions to the machine's control circuit, and furthermore, these additions do nothing that would significantly change the machine's maintainability or reliability.

The logic unit is embodied in the prototype by a microprocessor. This was an expedient choice for the prototype, but for commercial units, the logic functions could be easily implemented with HWL. Such an implementation would have minimal cost and would be relatively trouble free.

The developed diagnostic system will be an important module on future computer-assisted mining machines, and it will be applicable for use on manually or remotely operated continuous miners. The system could be added to miners that are currently in service, and certainly it can be made an integral part of new continuous miners. The use of the system will result in an immediate improvement in the maintainability of the machine, and will result in a significant reduction in machine downtime. Moreover, personnel safety will be enhanced.

The generic procedure presented in this report can be used by mine personnel or machine manufacturers to achieve these advantages.

APPENDIX.—SYSTEM SPECIFICATIONS

This appendix provides a summary of the diagnostic system specifications developed for the Joy 14CM09-10DX continuous miner. These were used in the development of the hardware for the prototype system. Information on the synthesis and implementation aspects of the prototype was presented in the main body of this report.

SELECTED COMPONENTS FOR DIAGNOSTIC ACTION

Table A-1 lists the control-circuit components and modes of failure selected for the prototype system.

Table A-1.—Control-circuit components to be diagnosed in prototype

Component	*Failure mode*
Firing package	Many.[1]
5-A traction-circuit fuse	Open.
2-A firing-package fuse	Do.
Left reverse (eREV) interlock (2)	Do.
Left forward (eFOR) interlock (2)	Do.
Right reverse (fREV) interlock (2)	Do.
Right forward (fFOR) interlock (2)	Do.
Connections	Do.
Remote tram (RT) interlock	Open or closed.
High-speed remote (HSR) interlock	Do.

[1] Failure diagnosed by lack of proper directional outputs.

SENSORS AND SENSOR LOCATION

The "sensors" are voltage dividers for detecting the presence or absence of the control-voltage signals. Because the control circuit is ungrounded, the common return line is used as the reference. Table 4 in the main text lists the number of sensing points contained in each of the controller boxes. A description of each sensing point and the maximum expected peak-to-peak ac voltage signals are listed in tables 2 and 3 in the main text.

Each sensor should be connected under the existing screw head with a ring terminal at the appropriate sensing point. The wire should be fused with an in-line fuse holder that is located at a convenient point within the explosion-proof enclosure.

The most convenient location for the electrical diagnostic box is on top of the master station, if possible. For the prototype system, the computing requirements and the available sizes of explosion-proof boxes precluded using this location. Consequently, a small display box will be mounted on the master station; this unit will display a two-digit number that corresponds to the failure modes listed in tables 6 and 7 in the main text. The diagnostic computer will be mounted above the right-hand controller in an explosion-proof box.

INPUT REQUIREMENTS

The minimum input requirements for the microcomputer are listed here:

Number of sensors	55 + 1 for reference.
Maximum expected voltage	See tables 2 and 3, main text.
Reference point	Monitoring point No. 57.
Dc offsets	None at present time.

PROCESSING REQUIREMENTS

Input voltages are assigned a logic high (true) or low (false). In a perfect system, high would be defined as 120 V and low as 0 V root mean square (rms). Given voltage regulation problems on the machine, noise, etc., it is necessary to define high as any voltage over 100 V and low as any voltage under 80 V. Even this is problematic because of unintentional backfeeding of voltage in the control circuit. Accordingly, it may be necessary to change the definition of high and low on different channels after some operating experience with the prototype has been obtained; the software should allow such changes.

The method used to determine the magnitude of the sine wave also requires attention. A pure sine will be sensed at most points, allowing for a simple determination of the magnitude. Sensor points 6, 7, 8, 9, 40, 41, and 43, however, will yield harmonic-rich, i.e., distorted, sine waves, complicating the task of determining magnitude.

The state of the control circuit is defined by the presence or absence of voltages at specific points. Therefore, it is essential that these channels be sampled rapidly enough to minimize the possibility of sampling during a state change. There are several alternatives available for achieving this; each has advantages and disadvantages. The sampling scheme currently used is to collect three identical sets of samples consecutively before processing for a failure. The total sampling time is 0.5 s for the phase 1 logic.

At this time, 40 logic equations, corresponding to 40 modes of failure (not equivalent to component failures), have been defined. When these equations are evaluated, only one can be TRUE; the equation that is evaluated as