MINE VENTILATION EXPERT SYSTEM

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A growing trend in the area of artificial intelligence is the development of software that simulates the decision-making process of human experts. The purpose of this paper is to advance the use of available tools from the area of artificial intelligence, and in particular expert systems, into the field of mine ventilation management. The authors have developed an expert system (i.e., a smart manager) that controls the operation of a mine ventilation network. The expert system is rule based and hence can be (independently) enhanced in an incremental fashion. It serves as a smart interface between the monitoring and control components of a mine ventilation system.

INTRODUCTION

A rapidly growing trend in the field of artificial intelligence is the development of expert system software that simulates human experts in reaching conclusions or recommendations in situations requiring the application of relevant human knowledge. Successful expert system paradigms such as PROSPECTOR (Duda et al., 1979), MYCIN (Jackson, 1986), and R1 (McDermott, 1982), whose accuracy has been validated against a sample of human experts, systematically ascertain a collection of facts that establishes a valid deductive chain of inference culminating in a conclusion goal. Such goals may be quite diverse, for instance, identification of the likely presence of a particular ore deposit, as in PROSPECTOR; identification of a cause and most likely treatment for a given blood infection, as in MYCIN; or completion of a certain VAX computer hardware configuration, as with R1. In cases like these, the data used are (1) generally static (i.e., once data establish a fact, it remains true until the end of the consultation or session); (2) often user supplied (i.e., the user responds to prompts for data items); (3) usually concerned with one item at a time through-

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out the consultation (e.g., one surface formation, one patient, or one computer system order); that is, the data are seldom space varying; and (4) rarely required for a critical or immediate decision on the part of a user.

Recently, however, interest has been redirected toward using expert systems in dynamic data situations where characteristics 1–4 seldom prevail. One area of this interest, on which this paper concentrates, is underground mine ventilation management. It is the purpose of this paper to advance the use of expert systems as part of underground mine ventilation management systems. Specifically, it focuses on extending a study undertaken by Kohler et al. (1986) at Pennsylvania State University.

The authors have developed an expert system (i.e., a smart manger) that controls a mine ventilation network. At present, the expert system interfaces with a physical (laboratory) model of a mine ventilation system. The interface is between the monitoring and control systems of the model (for flow, pressure, temperature, and gas readings) and the expert system itself. Among its functions, the expert system makes the necessary adjustments/modifications in the regulator settings to achieve the desired flow distribution.

The paper describes the design and development of the Mine Ventilation Manager (MVM). The main issues addressed by MVM are (1) mine modeling flexibility, (2) data simplification and storage efficiency, (3) relevant and timely use and inference of space-varying knowledge, and (4) integration of disparate system modules.

The remainder of this paper is organized as follows. A description of the requirements for a mine ventilation expert system is presented in the next section. These serve as criteria for judging the legitimacy of MVM and are discussed in detail in the third section.

REQUIREMENTS FOR MINE VENTILATION MANAGEMENT

The major objective of an underground mine ventilation system is to provide a safe and healthy environment for miners. The demand for the ventilation system (i.e., the airflow distribution throughout the mine) is based on a number of factors such as the rate of mining production, nature of liberated gases and dust, and characteristics of the airways. Control of the ventilation system is achieved through the adjustment of fan and regulator settings. Control of the system is asserted by management (operators) based on a number of constraints, regulated by statutory requirements, as well as operational objectives.

The quality of control exercised by management is limited by their ability to obtain timely information describing the state of the system and their capability to arrive at decisions based on that information. This limitation, of gathering timely information to support decision-making processes, has long been recognized and is the motivation for the development of automated mine monitoring and control systems.

Some aspects of automatic mine ventilation control fit nicely into traditional control techniques, especially when viewed in a *local* sense. The assertion of control in a *global* or minewide sense is based on more than measurements and their interrelationships. It is also based on judgment, intuition, and experience. This is particularly true during emergency conditions, such as situations subsequent to an explosion or during a mine fire. It is the inability of traditional control systems to utilize heuristics that has limited automatic control, as it is the strength of expert systems to utilize heuristics that will make possible safe and efficient control of the mine environment.

In addition to having standard controlling functions (for airflow rates, gas concentration, etc.) an expert system should allow one to make factual updates regarding structural changes in the mine itself. That is, a mine ventilation expert system needs to have a sound, readily available, comprehensive mine updating facility. For example, as a mine expands, an expert system should have the capability to create, validate, and represent the new mine configuration. Otherwise, the expert system runs the risk of becoming unreliable through retention of inaccurate or out-of-date information as part of its knowledge base.

The mine ventilation management process presents a number of challenging problems. One of the major ones is that, in addition to being time dependent, the mine monitoring data are space varying. Another aspect of mine ventilation is that its areas of expertise are multidimensional; that is, air flow in an underground mine has to be determined for a variety of different situations. This includes not only meeting operational requirements but also dealing with situations arising from buildup of dangerous gases, fires, cave-ins, and so forth. Even within one of these problem categories, such as fires, there are varying circumstances; fires may range from spontaneous combustion to an open fire, which would call for different responses.

By addressing these additional considerations, namely of space-varying data and a diversity of ventilation problems, Kohler et al. (1986) have begun to extend expert system use to underground mine ventilation management. The results of their work at present consist of a collection of various expert system modules and programs which together are referred to as a Ventilation Expert (VE).

Most of VE's production rules deal with diagnosing and advising about resolving drops in airflow. They also consider, as alternate problems, system failures (e.g., sensor or computer malfunction) and excess methane. In essence, VE operates toward reaching a conclusion that recommends a course of action, such as removal of debris, relocation of equipment, readjustment of a regulator, or revision of fan setting.

THE MINE VENTILATION MANAGER (MVM)

VE embodies important groundwork toward fulfilling the requirements for expert system capabilities discussed in the preceding section. In this section, MVM is introduced and examined.

The MVM expert system has its knowledge bases coded and processed under a production rule shell, INSIGHT2+, designed specifically for microcomputer use. MVM solves a broad range of ventilation problems; for example, it makes suggestions in response to drops in airflow and has the capability to check for device failures and methane buildup. In addition, MVM detects and provides consultations about potential or actual fire emergencies.

MVM strives to integrate various domains of mine ventilation expertise into one system whereby a user is provided with a consultation on any problem or combination of problems that arise in a mine. In this way, MVM attempts to address the issue of completeness in rule-based expert systems (e.g., see Suwa et al., 1984). MVM decides on and lines up consultations for whatever ventilation problems it discerns from the latest sensory data. Moreover, it is able to prioritize the consultations so that the ventilation officer is advised first about the more critical problems, such as open fire or high methane concentration, and later about less severe problems, such as a gradual drop in airflow.

A feature of MVM is its ability to determine optimal flow distribution (with respect to the amount of energy required to satisfy environmental constraints). To help fully exploit expert system reasoning about ventilation, it should be pointed out that mine ventilation networks (MVNs) must conform not only to a mine's physical structure but also to certain *ventilation requirements*, for example, direction-of-flow constraints. To ensure that these requirements are met, MVM provides a means by which a mine model, either proposed or assumed, is verified as viable for application of normal ventilation strategies. Finally, MVM's knowledge bases constitute an expert system that is applicable to any mine, the structure of which is described independently of the knowledge base itself.

Beyond merely indicating which regulators need readjustment, MVM determines the settings for the regulators to accommodate a new airflow distribution. MVM incorporates software with which to perform critical-path airflow calculations, from which the required regulator settings are computed.

Overview of MVM

The functional structure of the expert system is displayed in Fig. 1; as shown, the MVM knowledge-based expert system (KBES) is its central component. As described in the previous section, MVM consists of a hierarchy of production rule knowledge bases, coded in INSIGHT2+ procedure language

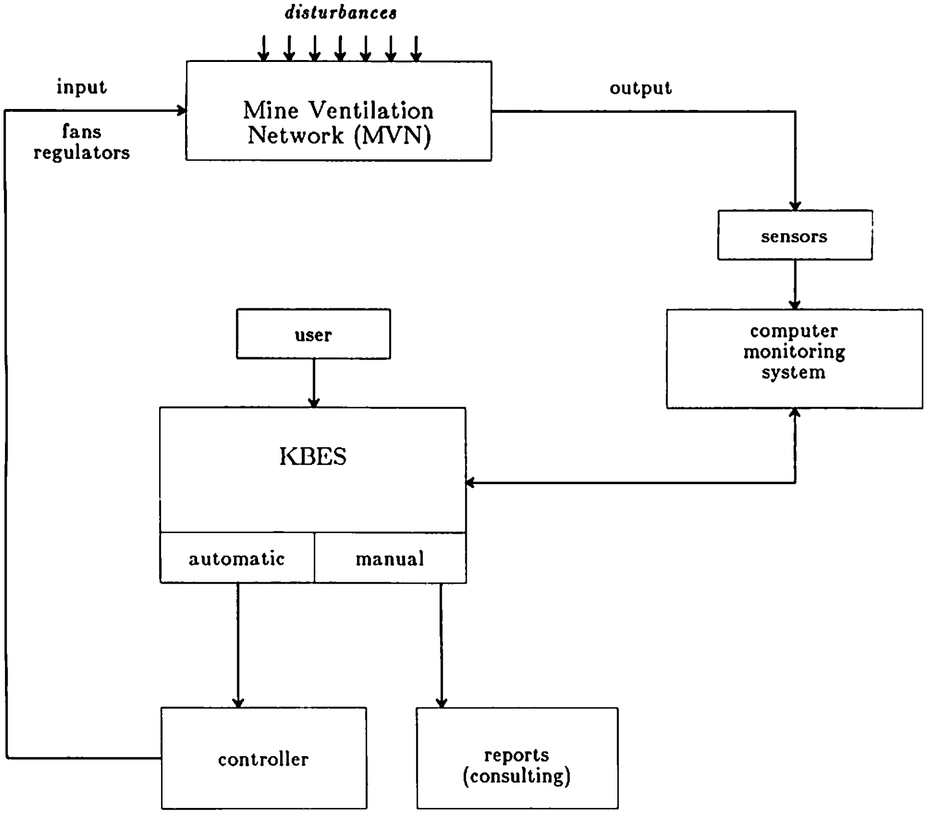

FIGURE 1. General structure of the Mine Ventilation Manager (MVM).

(PL), and a set of Pascal procedures called by production rule actions within these knowledge bases. Below, MVM is described in terms of how its component knowledge bases and Pascal programs interact, as diagrammed in Fig. 2.

At the top of the knowledge base hierarchy is MVNMGR, which prompts a user to select one of four consultations:

1. Establish a mine ventilation system (MVS)—*buildmvn*.
2. Update the parameters for an existing MVS—*updtmvn*.
3. Analyze the created MVS using simulators—*vent*, *fire*, and control of MVS through adjustment of regulator settings—*CPM*.
4. Monitor and respond to the latest group of sensor readings—*MVNDRIVE*.

In the first option MVNMGR calls a program, *buildmvn*, to assign initial data parameters to the network and then analyzes the submitted data to determine whether they form a valid mine ventilation network in terms of the canonical

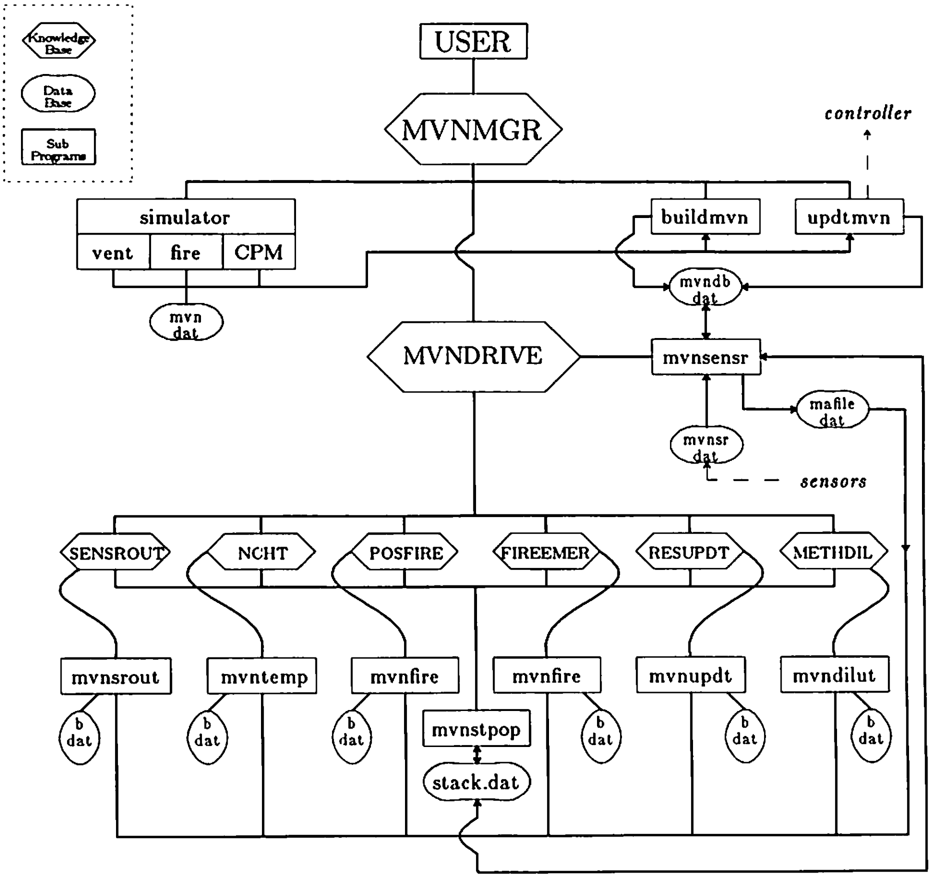

FIGURE 2. The knowledge-based expert system (KBES).

diagram structure described by Wala and Altman (1987). Once the ventilation network is completely specified and validated, *buildmvn* stores its description in a file called *mvndb.dat*.

The second option presented by MVNMGR updates an existing ventilation network's parameters. With this option, MVNMGR calls a program *updtmvn*, which prompts the user for possible revisions of the network's database records and then updates them accordingly.

In option 3, the automated control of airflow distribution in the MVS is carried out by regulator and fan adjustments. These are determined with the help of a simulator subprogram called CPM (critical path method) and implemented by the control system. The remaining two subprograms *vent* and *fire* are used in the analysis and modeling of MVS under certain conditions to support decision-making processes for ventilation control.

Finally, in option 4, sensor readings from the mine are analyzed and the user is advised about any problems or emergencies discerned. To do this, MVNMGR *chains to,* or invokes, another knowledge base, MVNDRIVE, which in turn calls a program, *mvnsensr.* This program reads a file of sensor records, each containing values for the latest (1) air flow rate, (2) methane concentration, (3) carbon monoxide concentration, (4) carbon dioxide concentraiton, (5) oxygen concentraiton, and (6) temperature in the mine ventilation network. Based on these readings, potential problems are identified and classified.

The problems are then addressed and resolved by calling MVNDRIVE knowledge base, which responds by displaying a message identifying the problem and then invokes a knowledge base that advises about the current problem. A diagram illustrating MVM's decision logic for a particular problem (methane concentration) is provided in Fig. 3.

Mine Modeling

This section describes how *buildmvn* validates the structure of a mine ventilation network and, together with *updtmvn,* establishes and updates the mine ventilation network database. Also included is the usage of simulator subprograms *vent, fire,* and CPM in modeling and flow determination.

Ventilation Network Construction, Validation, and Updating

As mentioned in the last section, the first option invokes program *buildmvn,* whose main processing steps are as follows:

1. From the input branch records, construct two dual sets of adjacency lists, AJL and RAJL, where AJL represents the mine network as a directed graph whose edges proceed from their original tail node to their original head node and RAJL represents the same network as AJL, except in reverse, that is, as a directed graph whose edges proceed from their original head node to their original tail node.
2. Determine if the created network has a viable structure, according to criteria described in Wala and Altman (1987).
3. Conduct a depth-first search of AJL to generate, record, and store individual branch data.
4. Produce a report listing the following information for each branch: natural resistance, flow, cross-sectional area, and pressure loss. For the basic branches, regulator settings are included.
5. Finally, store the above information in a database file called *mvndb.dat.*

Program *mvnupdt* is used to revise parameters for a model mine already created by *buildmvn.* Essentially, *mvnupdt* serves as a vehicle through which one can modify the mine ventilation network parameters.

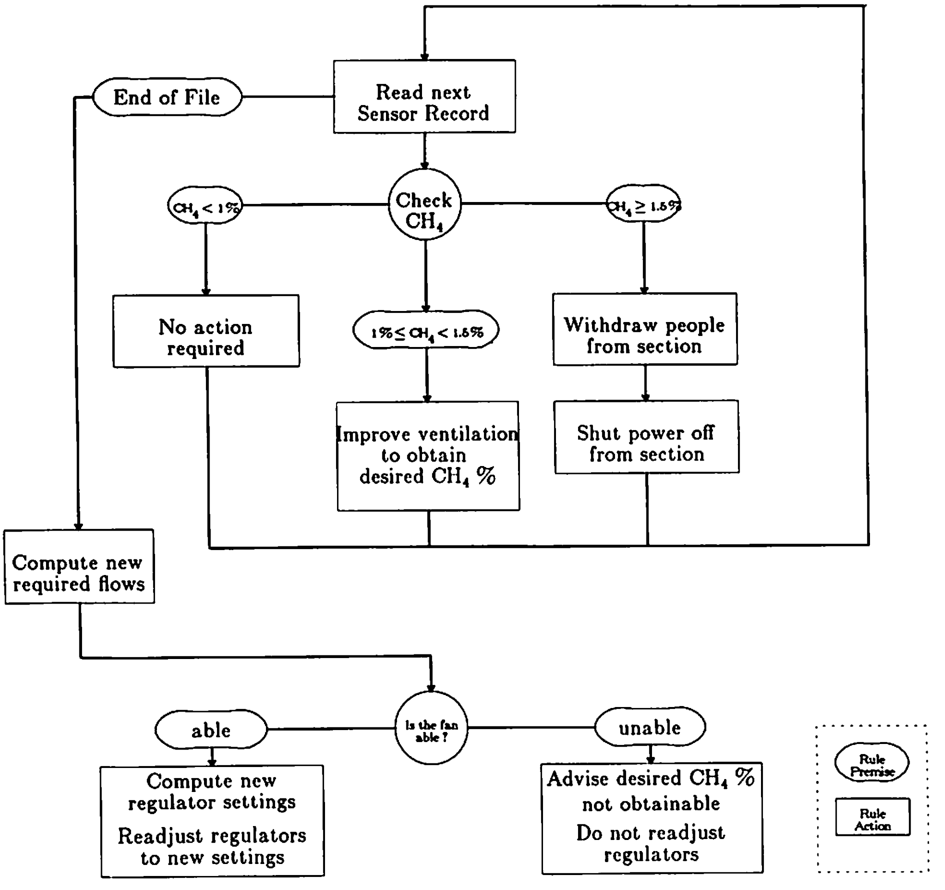

FIGURE 3. Logic diagram for methane (CH_4) consultation.

MVS Modeling and Simulation

The simulation program relies heavily on the three subprograms *vent, fire,* and CPM. Each one of them can be selected individually for modeling purposes such as:

1. Analysis of MVS behavior. The *vent* subprogram serves as a simulator of MVS to test consequences (in terms of flow distribution) of actions suggested in response to major disturbances and/or emergencies. This modeling capability is used during the interactive consultation sessions and is meant to help the ventilation manager in the decision-making process.

2. Fire simulation. The *fire* subprogram can be invoked to simulate the development of an open fire and its effect on the distribution of fumes and temperature increases in the MVS. This capability allows the ventilation man-

ager to predict the dynamics of a fire (e.g., how fast and in what direction it will spread) during the fire fighting operation.

3. Automated control of MVS. The CPM subprogram is used to determine the regulator and fan settings that satisfy the flow distribution requirements, while minimizing the energy used for ventilation. The critical path method is used to implement this, and it allows the ventilation manager to know, a priori, the effects of modifications in regulator/fan settings.

Advisor Modules

MVM arranges a series of consultations, dealing with detected and identified problems in order of their severity. Hence, from the standpoint of mine monitoring, MVM can be viewed as a collection of expert advisors, each giving advice in its particular problem domain. Examples of how some of these expert modules arrive at their recommendations are detailed below.

Faulty Sensor Advisor

Basically, there are three types of responses associated with sensors:

1. Normal signal response—returned measurements are within the *expected ranges.*
2. *Abnormal signal response—the measurements are not* within expected ranges but one still theoretically possible.
3. Unacceptable signal response—the measurements have ranges that are theoretically impossible.

In case 1, obviously no action is taken. For 2, a number of consistency and verification checks are made. For example, it would be highly unlikely for only one sensor to show a rapid rise in temperature (or an extreme pressure drop) while the neighboring sensors indicate no noticeable changes. Also, the measurements have the property that one can, through extrapolation, actually *predict* the next expected measurement. As part of the monitoring system, the returned measurements are cross-checked against their previous values, as well as the readings of neighboring sensors. If a particular sensor is suspected of returning inconsistent or unreliable data, it is placed on a list of faulty sensors and its signals are disregarded until it is checked and adjusted. Finally, in case 3, the sensor is simply placed on a list of unoperational sensors. Whenever a sensor is detected to be unreliable or unoperational, an appropriate message (advice) is forwarded to the user.

Change of Flow Advisor

When airflow readings change by more than the allowed limit within a specified time period, a problem of inadequate airflow is indicated. A number of factors may cause unexpected fluctuations of airflow in a particular branch, including people and machinery moving through the mine, a malfunctioning regulator, a door left open, and so forth.

When a deficiency in airflow is detected in areas of significance, such as where the miners are working, the new settings for regulators and fan(s) can be determined by the CPM subprogram when invoked by the simulator. This advisory information is then used to adjust the regulator/fan settings until the flow rates meet their requirements. These actions, however, are carried out by the regulator/fan control system only after the operator's approval.

Potential Fire Advisor

Four basic measurements suggest the possibility of a potential fire. On comparing previous and current branch readings for temperature, CO, CO_2, and O_2 concentrations, a potential fire warning is given if there is (1) a temperature rise of 5 degrees or a rise beyond 28 °C, (2) >50% relative rise in CO together with O_2 depletion, or (3) >50% relative rise in CO_2 together with O_2 depletion.

Program POSFIRE checks for branches with the above signs of a potential fire hazard. If such a branch is found, an appropriate message is issued identifying that and neighboring branches as a likely source of possible fire. Once the presence and location of fire are detected, the *fire* subprogram is invoked by the simulator and its computations can be used to predict the effect of the fire as well as help with the fire fighting operations. In cases where multiple branches have been reported as having fire symptoms, a branch that is the closest common predecessor of these branches (determination of which will not be discussed here) is identified as the likely source of a possible fire and the Open Fire advisor is invoked.

Other Advisors

MVN has a number of additional modules. These include Temperature, Methane Buildup, and Open Fire advisors. Their tasks and responsibilities are self-explanatory and it would serve no purpose to discuss them here in detail. As the system expands, additional advisors may be added without the need to overhaul the existing ones.

As a note of interest, the Escape/Rescue advisor was added after the advisors mentioned above were already in place. The escape/rescue paths are determined using procedures that implement an adaptation of Dijkstra's shortest-path algorithm (e.g., see Aho et al., 1974, p. 207). There, one determines the optimal paths from a given location to predetermined available escape ways. The algorithms computes the best path from the identified location of a fire to a head node of a branch upstream to the fresh air (intake). In other words, an escape path, as it is being formed, terminates at the first branch found not to be downstream of air flowing through the fire source branch.

CONCLUDING REMARKS

At present, MVM is a prototype expert system that has made a number of advances toward implementation beyond the pioneering work of Kohler et al. In summary, these advances are in

1. Expansion of the areas of expertise (e.g., fire detection).
2. Mine modeling and validation of ventilation network structure.
3. Integration of problem-specific subsystems into one system.
4. Conformance to efficient monitoring and control policies.
5. Independence of mine model's representation from the knowledge bases.
6. Automated regulator and fan control.

Additional developments needed to make MVM a more complete expert require a deeper interface between knowledge engineering and mine ventilation theory. A possible enhancement is a refinement of the basis for determining the best escape pathways from mine fires. Factors such as length and incline of the branches as well as the probability of a branch being subjected to reverse airflow as a fire develops should be assessed and included in the determination of optimal escape routes.

Although MVM is not complete, enough has been said to testify to its overall degree of systematic coherence such that the location of new features can readily be ascertained, for instance, to specific knowledge bases or programs to be modified. Nonetheless, while MVM's modularity is an asset for planning enhancements, it also harbors some problems concerning rule consistency. For example, one must consider the possibility of multiple simultaneous problems occurring in a mine for which the expert system suggests conflicting emergency-handling advice.

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