Information Circular 9178

A Catastrophe-Theory Model for Simulating Behavioral Accidents

By William E. Souder

UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
David S. Brown, Acting Director

Information Circular 9178

A Catastrophe-Theory Model for Simulating Behavioral Accidents

By William E. Souder

UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
David S. Brown, Acting Director

Library of Congress Cataloging-in-Publication Data

Souder, William E.
A catastrophe-theory model for simulating behavioral accidents.

(Information circular / United States Department of the Interior, Bureau of Mines ; 9178)
Bibliography: p. 18-19
Supt. of Docs. no.: I 28.27:

1. Mine accidents—Psychological aspects. I. Title. II. Series: Information circular (United States. Bureau of Mines) ; 9178 .

TN295.U4 [TN311] 622 s [622'.8] 87-600371

CONTENTS

ILLUSTRATIONS

TABLES

A CATASTROPHE-THEORY MODEL FOR SIMULATING BEHAVIORAL ACCIDENTS

By William E. Souder [1]

ABSTRACT

Behavioral accidents are a particular type of accident. They are caused by inappropriate individual behaviors and faulty reactions. Catastrophe theory is a means for mathematically modeling the dynamic processes that underlie behavioral accidents. Based on a comprehensive data base of mining accidents, a computerized catastrophe model has been developed by the Bureau of Mines. This model systematically links individual psychological, group behavioral, and mine environmental variables with other accident causing factors. It answers several longstanding questions about why some normally safe behaving persons may spontaneously engage in unsafe acts that have high risks of serious injury. Field tests with the model indicate that it has three important uses: It can be used as an effective training aid for increasing employee safety consciousness; it can be used as a management laboratory for testing decision alternatives and policies; and it can be used to help design the most effective work teams.

[1] Operations research analyst, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA (now professor of industrial engineering and director of the technology management studies institute, The University of Pittsburgh).

INTRODUCTION

The following are four examples of normally safe-behaving persons who suddenly stepped out of character and knowingly committed unsafe acts. Their acts had disastrous consequences for them.

1. Three experienced divers and life-saving instructors ignored normal safety procedures to go on a night dive, incompletely equipped, in an unexplored underwater cave. All three drowned.

2. An experienced 45-yr-old supervisor assisting a work crew suddenly turned and walked into the path of the crew's bulldozer and was crushed before anyone could stop him.

3. A 40-yr-old senior electrician who was completing his work shift suddenly swung an iron wrecking bar over his shoulder and abruptly turned to return it to the toolcrib. The end of the bar struck the 400,000-V overhead cable he had just installed, killing him instantly.

4. An experienced mine employee knowingly walked under a bad roof, pointing out various roof flaws to his companion. He was crushed by a sudden fall of that roof.

What caused these reckless behaviors? These were not rational acts: there were few rewards and enormous personal risks in these acts. These were not inexperienced and untrained personnel. They were mature, intelligent, and responsible individuals. They behaved safely all their lives, espoused safe behaviors, and served as role models for their peers. The puzzling, unanswered question remains: why did they do these things?

These are examples of a particular type of accident: the behavioral accident. In a behavioral accident, the primary cause is an inappropriate reaction or maladjustive behavior of the individual to external stimuli. Behavioral accidents involve complex interactions among individual perceptions, attitudes, personalities, values, tolerances, prior experiences, and work environments. As the four cases suggest, individual and group phenomena may contribute to behavioral accidents. Elements of carelessness, inattention, thoughtlessness, poor habits, machoism, bandwagon effects, and thrill seeking are suggested within these cases. Because of their many causal factors, the diagnosis and prevention of behavioral accidents is often elusive and difficult.

This Bureau of Mines report describes research to define, empirically measure, and model behavioral accidents. Perhaps a greater degree of understanding of the phenomenon can lead to its prevention.

BACKGROUND

Human error often results from a mismatch between individual capacities and workloads. Overloading employees beyond their capacities can set up stresses that cause them to make errors. Conversely, underloading employees may not arouse them sufficiently, causing them to make errors as a result of boredom and inattention.

However, real-life situations are much more complex than these simple statements might imply. Everyone's capacity for work differs. Moreover, people's capacities may change as a result of their most recent experiences, daily variations, and other factors. One of these factors is the individual's perception of an overload. For example, it may not matter what the ergonomic standards say: if a person perceives he or she is overloaded then these perceptions will guide his or her behavior. Since individual perceptions can be highly variable, the capacity-workload equilibrium is likely to be correspondingly variable. To further complicate matters, some persons can adjust to work overloads while others cannot. For example, some experienced automobile drivers automatically adjust to fatigue and adverse road conditions by increasing their intensity of concentration and alertness. But not everyone can so easily adjust their behaviors in this fashion. Thus, the capacity-workload equilibrium is a complex, dynamic, individual phenomenon (*14, 18*).[2]

Figure 1 depicts the system of factors that have been found to relate to human errors (*14, 18*). If the capacity-workload equilibrium is disturbed by some combination of the factors shown in figure 1, a human error may occur. Whether or not an error does in fact occur is a function of the individual's adjustive behaviors. Individuals who accordingly adjust their behaviors to changes in supervision, work groups, external stimuli, and the other factors shown in figure 1 may moderate the effects of these changes, thereby avoiding a human error.

Note that even if a human error does occur it will not necessarily lead to an accident, as illustrated in figure 1. The external conditions may not be right for an accident to happen. For example, adjustive behaviors may enable a driver to compensate for a slick spot on the highway, thus avoiding skidding into an oncoming automobile. But if there is no oncoming automobile, then conditions are not right for a collision and adjustive behaviors are relatively less important.

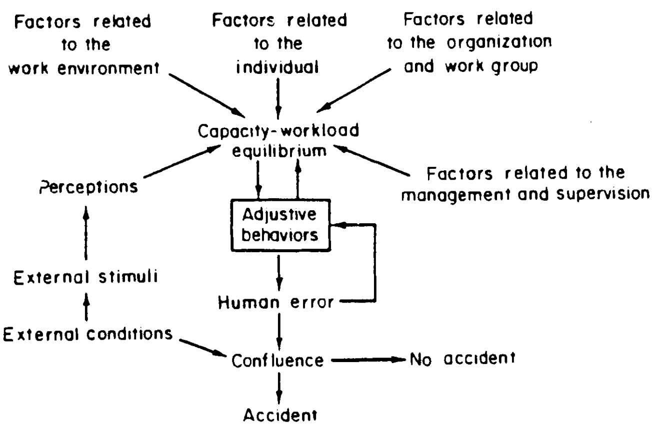

Figure 1.—Behavioral accident model.

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

FOCUS AND SCOPE OF THIS STUDY

The focus of this study was on individual adjustive behaviors and their relationships with the variables system shown in figure 1. Why, how, and when individuals successfully adjust and the consequences of failures to adjust were the topics of this research.

The adjustive behaviors of underground miners were studied by analyzing a sample of fatal-accident reports. Based on these analyses, and the use of catastrophe theory concepts (*20, 22*), a computer model was constructed that simulates behavioral accident systems. The model was tested and evaluated by a sample of mine employees. Recommendations were made for routinely using the model within mine operating firms.

METHODOLOGY

ACCIDENT SAMPLE

Mine Safety and Health Administration (MSHA) reports of fatal underground bituminous coal mine accidents from April 1979 to March 1985 were selected as the target population for the study of behavioral accidents. The choice of this target population was a compromise. Accident reports for earlier periods frequently lacked the necessary detailed information. On the other hand, a long enough time span was needed to cover a range of economic conditions. And it was desirable to include the most recent time periods in order to capture the latest conditions within the industry.

This target population was refined by selectively removing various reports. Reports with inadequate writeups or incomplete information were removed. Since the focus was on individual psychological and behavioral phenomena, reports involving multiple fatalities, equipment failures, and inadequate training or inexperience of the victim were removed. Reports from mines with injury rates over 50 pct above the industry average were also removed. The objective was to obtain a population where many of the traditional accident causes were absent, yet fatalities still occurred because of inappropriate individual adjustive behaviors.

These procedures resulted in a population of 358 fatal accident cases. Since this population was too large to be thoroughly studied within the available staffing and time constraints, sampling was used. The population was stratified by accident type, victim skill class, geographic location of the mine, and mine size. Accident reports were then randomly sampled from each stratum in numerical proportion to their occurrence in the 358 accident case population.

These procedures resulted in 60 fatal-accident cases for study. The stratification and random sampling insured that a range of important phenomena were present within a representative sample of 60 cases. As noted later in this report, these careful sampling procedures permitted the behavioral accident phenomena to be distinguished from the multitude of other confounding causes and factors. Behavioral accident phenomena are likely to be an important component of most accidents. However, their presence may remain undected because they are obscured by a multitude of other causes.

VARIABLES AND RATING SCALES

Based on an in-depth analysis of selected literature (*5, 12, 14, 18*), the 20 variables listed in table 1 were chosen for this study. Each of these variables relates to accident phenomena with individuals, and each is reported to be empirically measurable (*5, 12, 14, 18, 21*).

Some of the variables in table 1 are objectively measurable; examples are age, experience, and size. Others are highly subjective, such as carefulness, alertness, and confidence. Many of these variables can be measured by observation, supervisor's ratings, peer ratings, or personnel records. Others require carefully standardized rating scales, for example, field dependency. The so-called field-dependent individual is unable to extract salient information from a complex background (*12, 21*). For example, an individual who is unable to distinguish a zebra that is standing in front of a striped background evidences field dependency. Standard tests have been developed for measuring degrees of field dependency (*21*).

Rating scales were devised for measuring each variable, as illustrated in table 2. In pilot tests of interrater reliability, a panel of 10 qualified judges applied these scales in nine different exercises. After a brief training and learning period, the judges ratings showed no statistically significant differences (using Cochran Q, binomial, and kappa statistical tests of agreement (*11, 17*)). Moreover, in various trials of the scales, the author correctly repeated the results with 94 pct accuracy. Thus, it appears that the rating scales are highly reliable and repeatable (*11, 17–18*).

CONTENT ANALYSES MEASUREMENTS

Each of the 60 MSHA reports was carefully read and summarized to highlight its contents. In following established procedures (*1, 8*), each report was then reread and rated by the author on each of the variables listed in table 1, using scales like the one illustrated in table 2. While this approach of reading and rating text based on the reader's impressions may be open to some arbitrariness, it is a seriously accepted methodology. Two other readers who were trained in content analyses methods reproduced the author's ratings with 90- to 96-pct accuracy, using random

Table 1.—Summary list of variables

Name	Definition	Number [1]
	INDIVIDUAL FACTORS	
Age	Victim's age	3
Safety	Percentage of safe behaviors demonstrated by victim	5
Carefulness	Extent to which victim showed carefulness in task behaviors	6
Initiative	Extent to which victim demonstrated safety initiatives	7
Alertness	Extent to which victim correctly observed danger signals that preceded accident.	8
Evasiveness	Extent to which victim acted to avoid or evade a potential accident situation	9
Training	Recentness of training received by victim	12
Field dependency	Extent to which victim was psychologically field dependent for perceptual information processing.	14
Self-control	Extent to which victim maintained restraint over emotions	15
Impulsivity	Extent to which victim demonstrated impulsive behaviors	16
Experience	Victim's level of experience	19
	WORK ENVIRONMENT	
Commitment	Extent to which firm demonstrated commitment to safety	10
Size	Size of firm	13
Rate	Injury rate at firm	20
Policy	Number of safety policies promulgated by firm	17
	ORGANIZATION AND WORK GROUP	
Integration	Degree to which victim was integrated with work group	4
Confidence	Degree of confidence in crew members shown by supervisor	18
	MANAGEMENT AND SUPERVISION	
Attitude	Top management attitude toward safety	1
Norm	Safety norm of immediate supervisor	2
Enforcement	Extent to which safety policies were enforced	11

[1]Identification number assigned for subsequent discussion and analysis.

Table 2.—Example of a rating scale for the norm [1] variable

Indicators	*Rating*
Supervisor cautioned crew members to be aware of poor roof	High safety norm or +.
Supervisor admonished crew to constantly check to see that cables were neatly stowed.	Do.
Supervisor frequently held informal safety meetings	Do.
Supervisor stopped the work to remove a possible hazard	Do.
Supervisor did not hold any regular safety meetings	Low safety norm or −.
Supervisor seldom stressed carefulness and safety	Do.
Supervisor often took chances and behaved carelessly	Do.
Supervisor permitted crew to take shortcuts	Do.
Inadequate information provided about supervisor's safety norm.	Inadequate data or 0.

[1]See table 1 for definition.

samplings of text from the reports. This is a relatively high interrater statistic that lends more confidence to the results presented here. Additional standard precautions were also taken to increase the validity of the results (*1, 8, 19*).

In addition to the content rating data, various contributing factors, such as failure to comply with safe operating procedures and failure of management, were often cited in the MSHA reports by the investigating teams. These items were carefully noted and recorded for further analyses.

CONTENT ANALYSES RESULTS

DATA REDUCTION

The content analyses produced a string of 60 +, −, or 0 scores (one for each accident case) for each variable listed in table 1. Five of the twenty variables were then eliminated from further consideration because their degree of causal involvement (DCI) was too low. The *ith* variable was eliminated when DCI_i, defined as

$$[60 - N_i(0)]/60 \qquad (1)$$

was less than or equal to 0.60. Here, $N_i(0)$ is the number of times the *ith* variable was rated 0 for inadequate data in the content analyses (see table 2). Equation 1 effectively eliminates any variables that could not clearly be scored either + or − in at least 60 pct of the accident cases in the content analyses. Although this was a rather intuitive approach to data reduction, it was effective. The five variables thus eliminated were variables 1, 4, 5, 17, and 18 from table 1.

UNIVARIATE ANALYSES

Of the 15 variables that survived the degree of causal involvement test, 9 occurred often enough among the 60 accident cases to be statistically significant. These results are summarized in table 3. Thus, the accident cases examined were characterized by some problem or some deficiency in these nine aspects. That is, low supervisor safety norms, carelessness, low safety initiatives, lack of alertness, poor evasiveness, poor enforcement, high field dependency, poor self-control, and impulsivity characterized the cases. These results are consistent with the conventional wisdoms about accident causation (*14, 18*).

On the other hand, table 4 presents results that are not consistent with the conventional wisdoms. The conventional wisdoms hold that youthful employees, weak safety commitments by the firm, lack of employee training, lack of employee experience, large firm size, and an environment of high injury rates are primary causes of fatalities (*14, 18*). As the results in table 4 show, the sample of fatal accidents examined was not characterized by these attributes. The sample was purposely selected in such a way that these attributes were removed from it (see "Accident Sample" section). The victims were not young, inexperienced, and deficient in training. Over half of the firms were large, accident rates at the firms were not above average, and management commitments to safety were strong. Nevertheless, fatal accidents occurred. Clearly some other factors must have caused the accidents studied.

These results thus support the central thesis of this study: the victim's own inadequate adjustive behaviors can be the primary cause of an accident. Such behavioral accidents can occur in spite of the fact that other variables and factors all point to a generally safe, potentially accident-free environment.

CONTRIBUTING FACTORS

Table 5 shows the incidence, I_j, and statistical significance of the *jth* contributing factors cited in the reports by the investigating teams. The incidence is given by

$$I_j = (NC_j/60), \tag{2}$$

where NC_j is the number of times the *jth* contributing factor was cited. As with equation 1, this is a rather intuitive approach to reducing the data.

As table 5 shows, the incidence of failures of management (failure to enforce safety commitments made by the firm, failure to eliminate known hazards, etc.) and failures to comply with approved safe operating procedures were statistically significant. That is, the investigators cited these factors a significant number of times. Similarly, as table 5 shows, the investigating teams cited faulty employee judgments and lax supervisors, who permitted unsafe practices, as significant contributing factors. These results are consistent with the conventional wisdoms. These are precisely the factors that research has repeat-

Table 3.—Statistically significant variables [1]

Name	Comments	Number [2]
Norm	In 76 pct of fatalities, immediate supervisor evidenced a low safety norm.	2
Carefulness	In 80 pct of fatalities, victims did not show careful behaviors in performing various tasks.	6
Initiative	Safety initiatives were absent in 80 pct of fatalities	7
Alertness	In 86 pct of fatalities, victims apparently failed to correctly observe pertinent danger signals that preceded the accident.	8
Evasiveness	In 98 pct of fatalities, victims failed to act to avoid or evade pending danger.	9
Enforcement	In 81 pct of fatalities, supervisor did not enforce established safety rules and practices.	11
Field dependency	In 95 pct of fatalities, victims appeared unable to extract salient information from a complex background (high field dependency)	14
Self-control	In 89 pct of fatalities, victims evidenced low self-control	15
Impulsivity	In 79 pct of fatalities, victims demonstrated impulsive behaviors, with little foresight into consequences and little regard for personal safety.	16

[1]Binomial statistical test, with level of significance for rejection set at 0.10. See reference 17 (pp. 36–42) for binomial test used. Note that in this test, $N = N_i(+) + N_i(-)$, where $N_i(+)$ and $N_i(-)$ are the number of times the *ith* variable was scored + and −, respectively.

[2]Identification number assigned for subsequent discussion and analysis.

Table 4.—Nonsignificant variables [1]

Name	Comments	Number [2]
Age	About half (45 pct) of victims were over 35 yr old, thus youthfulness was not a significant factor in the fatalities studied.	3
Commitment	Over half (52 pct) of cases were characterized by a strong safety commitment by firm.	10
Training	In over half (51 pct) of the fatalities, victims had received formal training for job within prior 3 months. Thus, recentness of training did not deter the fatalities studied.	12
Size	Over half (52 pct) of firms studied were large size (annual outputs above industry mean).	13
Experience	Over half (59 pct) of victims had more than 10 yr experience	19
Rate	Over half (53 pct) of sites had injury rates below industry mean	20

[1]Binomial statistical test, with level of significance for rejection set at 0.10. See reference 17 (pp. 36–42) for binomial test used. Note that in this test, $N = N_i(+) + N_i(-)$, where $N_i(+)$ and $N_i(-)$ are the number of times the *ith* variable was scored + and −, respectively.

[2]Identification number assigned for subsequent discussion and analysis.

Table 5.—Contributing factors

Factor [1]	Number [2]	I_i	Significance [3]
Failure of management	21	0.500	0.01
Failure to comply with approved safe operating procedures	22	.783	< .01
Employees used unsafe judgment	27	.800	< .01
Supervisors permitted unsafe practices	28	.600	.01
Chance events	23	.133	NS
Equipment failures	24	.250	NS
Faulty equipment designs	25	.317	NS
Desire for output at the expense of safety	26	.233	NS

NS Not statistically significant.
[1]Each accident may have more than 1 contributing factor.
[2]Identification number assigned for subsequent discussion and analysis.
[3]Binomial statistical test, with level of significance for rejection set at 0.10; x = NC, N = 60 in the binomial test.

edly shown to be accident contributors. When these items are present, they foster other events and behaviors that cause accidents (*18*).

The last four factors listed in table 5 were not cited a statistically significant number of times. One of these factors was chance events. Chance events or acts of nature were cited in only about one-sixth of the cases. Two other factors, equipment failures and faulty equipment designs, were cited in fewer than one-third of the cases examined. The fourth factor, emphasis on output at the expense of safety, was cited in less than one-fourth of the cases. Thus, neither chance events, equipment failures, faulty equipment design, nor output pressures were significant contributors to the fatal accidents studied. This result runs counter to some prevalent beliefs that these factors are common causes of accidents (*13, 18*). However, they did not cause the accidents studied. Rather, the accidents studied appear to have been caused by something else. In this sense, these results provide further support for the thesis that at least some serious accidents are the result of poor adjustive behaviors of individuals.

STATISTICAL ANALYSES OF SIGNIFICANCE

MULTIVARIATE ANALYSES

The preceding procedures resulted in a total of 13 variables and factors that characterized the accident cases. How do these variables and factors interrelate as a system of accident causes?

In answer to this question, table 6 presents the results from a binomial test of the pairwise interrelatedness of the statistically significant items from tables 3 and 5. The statistical significance of a relationship between any pair of variables was determined from the binomial equation for p(x):

$$p(x) = \binom{N}{x} P^x Q^{N-x}. \qquad (3)$$

Here P = Q = 1/2, x is the frequency of content score mismatches between that pair of variables, N is the total number of pairs of nonzero scores for that variable pair from the content analyses, and p(x) is the probability of occurrence of x. A content score mismatch is the case of a + score in one variable and a − score in the other variable from the content analyses. Only values of p(x) less than or equal to 0.10 are acceptable. For more details on the binomial equation and the binomial statistical test see Siegel (*17*).

As may be seen from table 6, some of the variables were found to be unrelated (blank cell), some were not statistically significantly related, and others were statistically significantly related (values of 0.10 or less). Many of

Table 6.—Pairwise data matrix[1]

Variable or factor[2]	2	6	7	8	9	11	14	15	16	21	22	27	28
2		9/47	10/39			10/44			14/36	13/50	19/44	15/66	5/28
6	0.001		7/39	6/40	8/40	7/44	8/34	13/35	10/36	10/25	7/30		8/28
7	.001	0.001		8/36	6/36		8/31	11/35	3/22	4/31	10/39	5/28	
8		.001					4/34	7/34	7/32	5/31	5/32	6/39	8/21
9		.001	0.001				6/37	4/29	7/34	6/19	2/29	4/35	3/21
11	.001	.001	.001						13/34	3/20			
14		.001		0.001	0.001			8/36	5/35			3/38	
15		.058	.001	.017	.001		0.001		13/35			5/34	
16	NS	.002	.001	.001	.001	0.036	.001	NS				8/38	
21	.001	.096	.001	.001	NS	.001					21/40	19/44	13/29
22	NS	.001	.001	.001	.001					NS			17/50
27	.001		.001	.001	.001		.001	0.001	0.001	NS			18/52
28	.001	.002	.001	NS	.001					NS	NS	0.002	

NS Not statistically significant (p(x) > 0.10).
[1]Data above the diagonal are x/N, where x = frequency of score mismatches and N = total number of pairs of nonzero scores from the content analyses for that variable pair. A score mismatch is the case of + in 1 variable and − in the other. A blank cell indicates either insufficient data to suggest a relationship or no logical reason for computing x/N statistic. Insufficient data were considered to exist where either x ≥ 24 or N ≤ 18. Data below the diagonal are p(x) computed from equation 3. See Siegel (17) for additional information.
[2]See tables 1 and 5 for definitions of variables and factors.

the variables were related at the 0.001 level of statistical significance.

It was decided to eliminate from further consideration any relationships that were not significant at the 0.002 level or less. This rule eliminated 4 of the 44 relationships shown in table 6, while maintaining a highly desirable level of confidence that the remaining relationships were in fact the important ones.

PATH ANALYSES

By using a path analysis procedure and the 0.002 level of significance rule, causal chains were deduced from the data in table 6 (*2–3, 17, 19*). Figure 2 was then constructed from these results.

The numbered nodes in figure 2 represent the variables and factors from tables 3 and 5 that survived the content ratings and statistical analyses. Three types of variables survived, as noted in figure 2; psychological variables, behavioral variables, and management variables. The arrows in figure 2 depict the causal pathways that were deduced from the path analysis procedures. For example, the arrow running from node 6 (carefulness) to node 7 (initiative), near the center of figure 2, indicates that carefulness influences the extent to which individuals demonstrate safety initiatives in their behaviors. Moreover, this relationship holds true on the average in 998 or more cases out of 1,000, because of the 0.002 level of significance rule. The path analysis procedures deduced that the causality runs from node 6 to node 7 and not from node 7 to node 6 (*1–3, 17*). This happens to be the most intuitively logical causality for these two variables. In other cases, the causality could have gone either way and the path analysis procedure was used to make the final determination of the direction (*2–3, 8, 18*).

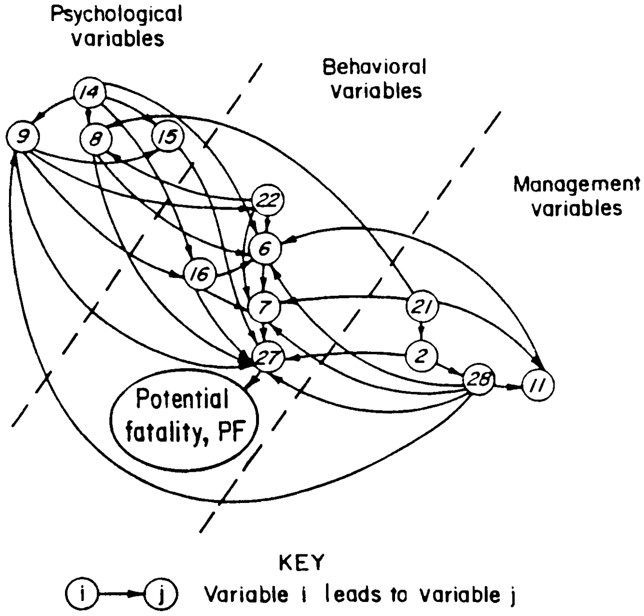

Figure 2.—Path analysis network (see tables 1 and 5 for definitions of nodes).

The path analyses resulted in node 27 as the terminal node in the network, as shown in figure 2. That is, node 27 does not lead to any other subsequent nodes. Therefore, the descriptor potential fatality, variable PF, was attached directly to this node in figure 2. Thus, figure 2 represents the system of variables that were found to lead to the potential for a fatal accident.

SYSTEMS MODEL OF BEHAVIORAL ACCIDENTS

BEHAVIORAL ACCIDENTS

As the preceding results have shown, serious accidents can and do happen to well-trained, highly experienced and mature personnel working in mines that have good safety records and strong safety commitments. Chance events, equipment failures, and pressures to produce were not the causes. Rather, these accidents appeared to be caused by the inappropriate decisions and adjustive behaviors of the victims themselves in response to hazardous conditions. In short, these were behavioral accidents.[3]

These results suggest that behavioral accidents may represent a hardcore type of accident that is highly resistant to conventional treatments. Enormous amounts of time and money are being spent on conventional safety and training programs. Yet serious accidents continue to occur and accident rates stubbornly resist falling below some threshold levels. It may be that the bulk of accidents that could be eliminated through conventional treatments has now been eliminated. What remains may be the hard core of behavioral accidents. More powerful, innovative means may be needed to eliminate them. The systems model shown in figure 2 is a basis for these more innovative approaches.

[3] As previously noted, 60 behavioral accident cases were found from a total population of 358 fatal accident cases. Though this is not a relatively high rate of occurrence, it represents a great cost in terms of human life. Moreover, since all accidents would seem to have some behavioral content, the importance of behavioral accident phenomena may be much greater than this statistic might indicate.

RELATIVE IMPORTANCE OF THE VARIABLES

Figure 2 can be used to determine the relative importance of various variables with respect to the potential for a fatality. Knowledge of the relative importance of the variables is the first step in taking actions to control them.

Table 7 presents an analysis of the numbers of arrows (paths) entering and exiting each variable (node) in figure 2. The total number of exiting paths from the psychological variables set is 12. The management set has the same number of exiting paths. This is a relatively large number of exiting paths for a network of this size, thus indicating that these variable sets are relatively important. That is, both the psychological and management variables affect several others. They are important *affecting* variables.

Table 7.—Numbers of entering and exiting paths for each variable in figure 1

Variable set and variable or factor	Number[1]	Number of paths[2]							
		Entering from—				Exiting to—			
		P	B	M	Total	P	B	M	Total
Psychological:									
Field dependency	14	0	0	0	0	3	2	0	5
Evasiveness	9	1	1	1	3	1	3	0	4
Alertness	8	1	1	1	3	0	2	0	2
Self-control	15	2	0	0	2	0	1	0	1
Sums	NAp	4	2	2	8	4	8	0	12
Behavioral:									
Impulsivity	16	3	0	0	3	0	3	0	3
Failure to comply with approved safe operating procedures	22	1	0	0	1	2	2	0	4
Carefulness	6	2	2	2	6	0	1	0	1
Initiative	7	0	3	2	5	0	1	0	1
Employees used unsafe judgment	27	3	2	2	7	0	0	0	0
Sums	NAp	6	7	6	22	2	4	0	9
Management:									
Failure of management	21	0	0	0	0	1	1	2	4
Norm	2	0	0	1	1	0	1	1	2
Supervisor permitted unsafe practices	28	0	0	1	1	1	3	1	5
Enforcement	11	0	0	2	2	0	1	0	1
Sums	NAp	0	0	4	4	2	6	4	12

NAp Not applicable.

[1] See tables 1 and 5 for definitions of variables and factors.

[2] P, psychological variable; B, behavioral variable; M, management variable. Variable 14 and factor 27 are the origination and termination, respectively, for this network.

Similarly, the total number of paths entering the behavioral variables set is 22, as noted in table 7. Thus, the behavioral variables set is a relatively important *affected* set of variables.

Similarly, table 7 shows that the behavioral variables carefulness, initiative, and employee judgment are the most important affected variables. The most important affecting variables are the psychological variables field dependency and evasiveness, the behavioral variable failure to comply, and the management variables failure of management and supervisor permitted.

These aspects determine the way in which the psychological, behavioral, and management variables dynamically interact to culminate in the potential for a fatality. Starting from any node (variable) in figure 2, the effects of a change in that variable can be tracked as it cascades its way through the network like a ball in a pinball machine, impacting other variables, compounding their effects, and building a potential for an accident.

CASCADING NETWORK EFFECTS: AN EXAMPLE

Let us examine the effects of two management factors: the failure of management to implement strong safety policies (21) and the failure of supervisors to eliminate unsafe practices (28). As figure 2 shows, these two factors directly affect two important psychological variables: alertness and evasiveness (variables 8 and 9). This result says that lax safety management and supervision can directly cause employees to fail to recognize, interpret, and act upon subtle cues and danger signs of an imminent accident. This is a very reasonable finding. Employees who are not sensitized to accident cues by their management are likely to either not see those cues or fail to act on them, or both.

Note that this finding has some very significant implications. It says that lax management affects the deep-seated psychological variables that control an individual's long term behaviors, *not* just the individual's situational safety behaviors. This may have some very serious and far-reaching consequences. For example, once an individual's alertness and evasive mechanisms have been dulled by lax management practices, this may spill over into other aspects of his or her behavior. The individual may tend to behave unsafely in all aspects of his or her life. Retraining may thus not be effective under these circumstances. In fact, conventional training, which is directed at behavior modification, may have any little effect on a person whose alertness and evasiveness have been dulled (*14, 18–19*).

These effects may be seen from the model in figure 2. The impacts of low alertness (variable 8) and impaired evasive abilities (variable 9) are shown to continue to cascade throughout the network, building and amplifying themselves as they go. Impaired evasive abilities lead the individual to impulsive behaviors and poor judgments (variable 16 and factor 27). If the individual involved happens to be highly field dependent (variable 14—unable to extract salient information from a complex environment), then the effects of the low alertness and impaired evasive abilities are further magnified. The individual's self-control (variable 15) becomes diminished and the individual's judgment (factor 27) is further impaired. Under these conditions, the individual becomes less likely to comply with approved safe operating procedures (factor 22). Thus, his or her awareness of dangers and his or her ability to avoid them (variables 8 and 9) are further dulled in a kind of feedback-reinforcement cycle. Careful behaviors (variable 6) thus rise and fall in proportion to the strengths of these influences. As a result, the individual is further pushed toward a fatal accident. Recall that all of this began by seemingly trivial failures by management and by the supervisor.

SOME IMPLICATIONS

What do these results tell about how to decrease underground mine fatalities? Since management actions and styles were found to *directly* influence employee carefulness, safety initiatives, and judgments, it is clear that management quality is a key leverage point for reducing accidents. This is not new: the effects of management quality on employees are well known. What is new here is the finding that management quality *directly* influences two important individual psychological factors: employee awareness of dangerous conditions and employee actions to avoid them.

Thus, there are three major implications. First of all, the preeminence of management as a factor in preventing accidents has been reaffirmed. Fatalities can be substantially reduced by improving the general quality of mine management and first-line supervision. Second, miner training should be more concentrated on improving miner pattern recognition skills and perceptual information processing abilities. The ability of miners to perceive ambiguous cues of pending accidents, e.g., poor roof conditions, is a key to accident prevention. Third, training mine supervisors to emphasize and reinforce alertness skills among their subordinates is an essential ingredient. This is important to cementing the linkage between management quality and individual behaviors.

Figure 2 suggests yet another way to decrease fatalities: change the psychological variables that lead an individual into accidents. At first, this may sound like some sort of recommendation aimed at psychologically altering the individual. But it is nothing quite so radical. Rather, *adjustive* behavior modification is the suggested approach. Employees can be trained to have greater self-control, to become less impulsive in crises, to be more alert, and to react more appropriately to accident situations. Though this is not a new idea, it is somewhat novel for the mining industry. Most training courses emphasize unitary behaviors and the one best way to do the job, rather than alternative ways and multiple roles in the work environment. The ability to flex to meet the situation and to select the most suitable response from a repertoire of many responses is essential in a complex environment like an underground mine.

These ideas all come directly from figure 2. They are innovative ideas. They are only a sampling of the kinds of recommendations and innovative approaches that an analysis of figure 2 can yield.

SIMULATING ACCIDENT CAUSES

Figure 2 may be viewed as a system flow model in which activities at any node (variable) create influences that flow along the paths (arrows) into other nodes. The volume or amount of any flow, VP_{ij}, along any path from node i to node j is given by

$$VP_{ij} = (N - x)/N. \tag{4}$$

The cumulative flow, VN_j, at any node j is given by

$$VN_j = \Sigma_i [(VN_i)(VP_{ij})]. \tag{5}$$

Here N and x are the corresponding items from table 6 for the path from node i to node j. The potential for a fatality, PF, is given by

$$PF = [VN_m/(VN_m)_{max}] \times 100, \tag{6}$$

where $(VN_m)_{max}$ is the maximum value of the *mth* node for the system being considered.

The VP_{ij} data for the network in figure 2 are shown in table 8. Note that the VP_{ij} data are computed only for those paths that resulted from the path analyses, as shown in figure 2. For example, table 6 shows x/N data for the relationship between node 2 and node 6. But the path analyses indicated that these data resulted from the indirect relationship of node 2 to node 6 that runs through nodes 28 and 11. There is no direct path between node 2 and node 6. Hence, there is no corresponding VP_{26} datum in table 8.

Table 9 presents the results of repetitively applying equations 4 and 5, starting with initial unitary activities in variable 14 and factors 22 and 21. For example, case 1 assumes that there is initially one act of field dependency on the part of some one individual. That is, case 1 assumes that the individual is unable to extract salient information from a complex or ambiguous environment in one instance. To illustrate, suppose the individual is standing in the pathway of an oncoming shuttle car, but he or she is unable to determine whether the shuttle car is approaching rapidly or is stopped. Case 1 shows what happens as a result of this one failure. This one act grows and compounds to an ultimate value at node 27 that is 8.23 times its initial unitary value. Using equation 6, this translates to a 54.9 pct potential for a fatality, PF, as noted in the last line of table 9.

The effects of other single acts are shown as cases 2, 3, and 4 in table 9. For example, in case 2, the effects of a one-time failure of the employee to comply with established safety policies is shown to compound to a 12.2-pct potential for a fatality. Case 3 shows that a one-time failure of management compounds to a 42.5-pct potential. The maximum potential for an accident when starting from variable 14 and factors 22 and 21 is 100 pct, as shown in case 4. Thus, for the variables set examined here, problems in the psychological variable (field dependency) are the most

Table 8.—VP_{ij} data [1]

Variable i	Variable j 2	6	7	8	9	11	14	15	16	21	22	27	28
2 ..		0	0	0	0	0	0	0	0	0	0	0.73	0.82
6 ..	0		.82	0	0	0	0	0	0	0	0	0	0
7 ..	0	0		0	0	0	0	0	0	0	0	.75	0
8 ..	0	.85	0		0	0	0	0	0	0	0	.85	0
9 ..	0	0	0	0		0	0	.76	.81	0	.93	.89	0
11 ..	0	.84	0	0	0		0	0	0	0	0	0	0
14 .	0	.76	0	.89	.84	0		.88	.86	0	0	0	0
15 .	0	0	0	0	0	0	0		0	0	0	.85	0
16 .	0	.73	.69	0	0	0	0	0		0	0	.79	0
21 .	.74	0	.87	.84	0	.85	0	0	0		0	0	0
22 .	0	.77	.88	.85	0	0	0	0	0	0		0	0
27 .	0	0	0	0	0	0	0	0	0	0	0		0
28 .	0	.71	.83	0	.86	1.00	0	0	0	0	0	.65	

[1] See tables 1 and 5 for definitions of variables and factors.

Table 9.—Network calculations

	Case 1	Case 2	Case 3	Case 4
INITIAL VALUES				
VN_{14}	1.0	0.0	0.0	1.0
VN_{22}	.0	1.0	.0	1.0
VN_{21}	.0	.0	1.0	1.0
COMPUTED VALUES				
VN_{2}	0.0	0.0	0.74	0.74
VN_{26}	.0	.0	.61	.61
VN_{11}	.0	.0	.85	1.46
VN_{9}	.84	.0	.52	1.36
VN_{22}	.78	1.0	.48	2.26
VN_{8}	1.55	.85	.84	2.58
VN_{15}	1.52	.0	.39	1.91
VN_{16}	1.54	.0	.42	1.96
VN_{6}	[1]3.80	.72	3.05	7.78
VN_{7}	4.87	1.47	4.58	9.98
VN_{27}	8.23	1.83	6.37	14.99
Fatality potential (PF) ..... pct	[1]54.9	12.2	42.5	100

[1]Sample calculation:

$$VN_6 = (VN_{22})(VP_{22,6}) + (VN_{11})(VP_{11,6}) + (VN_{26})(VP_{26,6}) + (VN_{14})(VP_{14,6}) + (VN_8)(VP_{8,6}) + (VN_{16})(VP_{16,6})$$

$$= (0.78)(0.77) + (0.0)(0.84) + (0.0)(0.71) + (1.0)(0.76) + (1.55)(0.85) + (1.54)(0.73) = 3.80.$$

$$\text{PF, case 1} = (VN_{27} \text{ for case 1}) / (VN_{27} \text{ for case 4}) = (8.23/14.99) \times 100 = 54.9 \text{ pct.}$$

likely to result in a fatality. Management failure is the next most likely cause of a fatality, and an individual failure to comply with an established safety procedure is the least likely to result in a fatality. Note that these results could be different for a different set of initial values and nodes.

The data from table 9 are plotted in figure 3 in such a way as to display the tracking of the contributions that each key variable makes to the potential for a fatality. Figure 3 clearly demonstrates the impact of the behavioral variables. In each of the four cases, the node flows, VN_j, are all relatively low until the behavioral variables are reached within the system. At that point, the node flows increase dramatically. This increase is greatest in case 4, where multiple interactions of the management, psychological, and behavioral variables occur.

Thus, it becomes apparent from these few sample calculations that the network model depicted in figure 2 and table 7 has many potentials for simulating accident situations. That model is further developed, in the following section, in order to make it more realistic and relevant for mining applications.

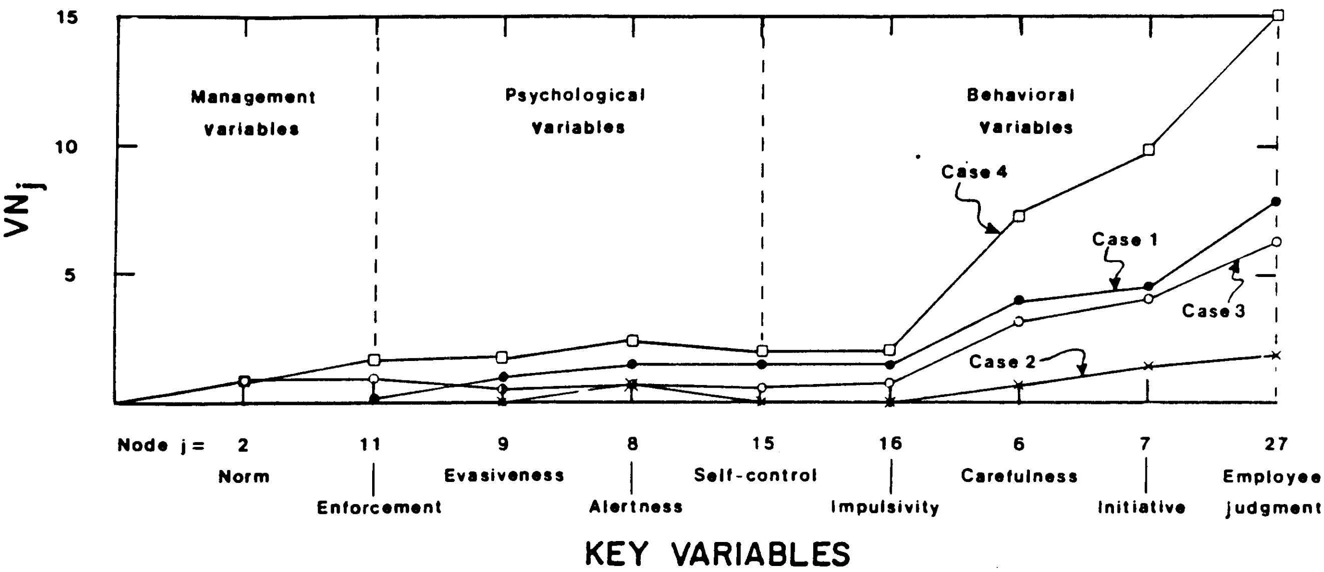

Figure 3.—Results of network calculations (table 9).

NETWORK PREPROCESSORS

In the simulation exercises, initial values of some key variables were simply assumed in order to determine the ultimate potential for a fatality under several conditions. In reality, several psychological, behavioral, managerial, and environmental conditions that naturally surround the network in figure 2 often determine the initial values of these key variables (*4, 6, 9, 15*). These conditions are natural preprocessors for the network. These preprocessors can be used to flexibly model particular real situations. These situations will then drive the fixed data base of relationships shown in table 8, which are the flow rates for the paths depicted in figure 2.

Seven preprocessors are used: psychological conditions (PC), behavioral conditions (BC), supervisor ability (FA), management concern for safety (MC), environmental conditions (EC), physiological state (PS), and adjustive behaviors (JB). These preprocessor variables are defined in table 10 and are presented as part of the network shown in figure 4. Note that the discussion here focuses on the development of these preprocessors, a subsequent section of this report discusses their use.

PSYCHOLOGICAL CONDITIONS (PC)

Research (*4, 6, 9, 19*) indicates that the three psychological conditions listed in table 10—pattern recognition skills, alertness, and discriminatory abilities—strongly impact a person's likelihood of acting to avoid an accident. For example, pattern recognition training teaches visual differences between faulty and safe roofs in a mine. Alert miners will observe these differences. Discriminating miners will know the appropriate actions to take based on these observations.

Research (*1–2*) suggests that pattern recognition skills (X_1), alertness (X_2), and discriminatory abilities (X_3) combine according to

$$PC = [(X_2/1.67) + (X_3/2.5)] - (X_1/2.0), \qquad (7)$$

where PC gives their combined effects. The parameter PC is an input to node 14 of the network in figure 4. The value of PC is the initial value of VN_{14} in calculations like those in table 9. Thus, a large value for PC will have a large impact on node 14; a small value will have a small impact. Recall that node 14 is the variable field dependency (psychological ability to distinguish salient cues from an ambiguous environment). When the value of PC is high, the flow into node 14 is high and field dependency is high. Similarly, when the value of PC is low, field dependency is necessarily low.

BEHAVIORAL CONDITIONS (BC)

The four behavioral conditions shown in table 10—volatility, machoism, consistency, and influence—can bias individual reactions to emergencies (*4, 6, 9*). For example, persons who characteristically act in a macho fashion may become involved with more accidents than those who do not. This may be especially true where others emulate the macho individual.

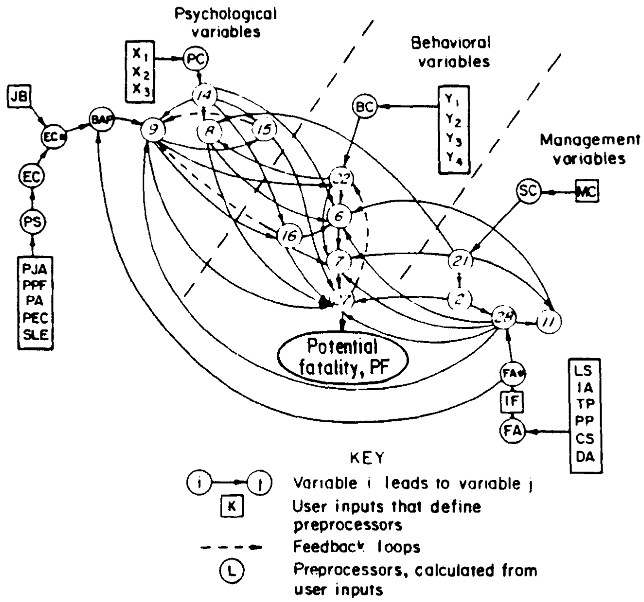

Figure 4.—Network with preprocessors.

Table 10.—Preprocessor variable definitions

Preprocessor	*Definition*
Psychological conditions (PC):	Extent to which individual—
Pattern recognition skills (X_1)	Has received formal training in pattern recognition.
Alertness (X_2)	Is an accurate observer.
Discriminatory abilities (X_3)	Knows appropriate actions to take in an emergency.
Behavioral conditions (BC):	Extent to which individual—
Volatility (Y_1)	Reacts irrationally to crises.
Machoism (Y_2)	Has compelling need to demonstrate his "manliness."
Consistency (Y_3)	Behaviors are consistent day to day.
Influence (Y_4)	Is emulated by others.
Supervisor ability (FA):	
Leadership skills (LS)	Ability to lead others.
Interpersonal abilities (IA)	Ability to get along with others.
Technical proficiency (TP)	Proficiency in technical aspects of work directed.
Planning skills (PP)	Ability to plan work of others.
Communication skills (CS)	Ability to communicate with others.
Directing abilities (DA)	Ability to direct work of others.
Management concern for safety (MC)	Extent to which top management evidences concern for safety.
Environmental conditions (EC):	
Perceived ambiguity of job-role (PJA)	Degree of understanding or lack of clarity about nature of the job.
Production pressure and fatigue (PPF)	Amount of perceived pressures to get out the product or produce at a high level.
Job physical annoyances (PA)	Extent to which employee feels job is dirty, noisy, or otherwise physically annoying.
Perceived economic climate (PEC)	Extent to which employee feels trapped in an underpaid and/or lowly esteemed job.
Stressful personal life events (SLE)	Extent to which employee appears to be affected on job by traumatic personal or family events.
Physiological state (PS)	Extent to which individual is physiologically qualified for particular job.
Adjustive behaviors (JB):	
Aggression	Misplaced direction of pent-up emotions, stubborn and persistent nonadjustive reaction in face of evidence that this is inappropriate or ineffectual behavior.
Projection	Attributing one's own failures to another person or thing, blaming others for own shortcomings.
Withdrawal	Use of fantasies, emotional flight, repression, or regression to infantile behaviors.
Sublimation	Replacing urge to vent one's anger and frustrations with higher level substitutes without ever fully resolving basic conflicts or issues.
Adaptation	Adjustments that accommodate the stimuli but fail to make permanent and complete internal reconciliation, so that recidivism is likely.
Consultation	Complete and thorough resolution of issues through consultative sessions between employee and supervisor or other affected parties.

Research (*18–19*) suggests that these four conditions combine according to

$$BC = [(Y_1 + Y_2)/2.0]\,(Y_3)\,(Y_4), \qquad (8)$$

where BC is their envelope. The parameter BC is the input to node 22, as shown in figure 4. The value of BC is the initial value of VN_{22} in computations like those illustrated in table 9.

SUPERVISOR ABILITY (FA) AND MANAGEMENT CONCERN FOR SAFETY (MC)

The six supervisor abilities listed in table 10 are generally felt to be important influences on employee accident behaviors (*13, 15*). Their envelope, FA, is

$$FA = LS + IA + TP + PS + CS + DA. \qquad (9)$$

The value of FA is part of the input to node 28 in figure 4.

Management concern for safety (MC), as defined in table 10, is generally believed to affect employee accident behaviors. Research (*18–19*) suggests that the effect is an inverse geometric one, i.e.,

$$SC = (1.0 - MC) + [(1.0 - MC)^2/2.0], \qquad (10)$$

where SC is simply an envelope.

The value of the parameter SC directly affects node 21 in figure 4. It is the initial value of VN_{21} in calculations like those in table 9.

ENVIRONMENTAL CONDITIONS (EC)

The five environmental conditions listed in table 10 have repeatedly been found to seriously affect employee work behaviors (*13–15*). An employee who perceives that his or her job is ambiguous, feels under pressure to get out the product, feels trapped in an underpaid job, or finds the physical environment annoying is more likely to have an accident than other employees who are not under these pressures. In addition, personal financial problems, family trauma, or other stressful life events can promote careless behaviors on the job. Holmes and Rahe (*7*) have devised a scale for measuring such events.

The envelope, EC, of these five environmental conditions is

$$EC = (PJA + PPF + PA + PEC + SLE)\,(PS), \qquad (11)$$

where PS is the individual physiological abilities state, as defined in table 10. The value of the parameter EC is part of the input to node 9 in figure 4.

ADJUSTIVE BEHAVIORS (JB)

Individuals may react to their environments in any of the six adjustive behaviors (JB) listed in table 10. Which of these behaviors actually occurs in any situation will depend on the individual's personality. But it will also depend in part on the supervisor's ability to successfully intervene. A highly skilled supervisor, i.e., one with a large FA value from table 10, may be able to intervene early enough in the sequence of events to neutralize dangerous adjustive behaviors such as aggression (*4, 10, 14–15*).

Let IF be an intervention factor such that IF = 1 if the supervisor successfully intervenes, and otherwise IF = 0. Then let

$$FA^* = F_1\,(IF, FA) \qquad (12)$$

and let

$$EC^* = F_2\,(JB, EC), \qquad (13)$$

where F_1 and F_2 are functions. Then FA* and EC* will respectively affect nodes 28 and 9 as shown in figure 4. The exact impacts of EC* and FA* are governed by the cusp catastrophe model described in the following section.

CUSP CATASTROPHE MODEL

THEORY AND EXAMPLE

Thom's catastrophe theory (*13, 20*) enables the combined influence of the environmental conditions, the supervisor's ability, the intervention factor, and the adjustive behaviors to be depicted as shown in figure 5. The behavioral accident potential, BAP, is given by

$$BAP = F_3\,(FA^*, EC^*), \qquad (14)$$

where F_3 is some function.

Zeeman (*22*) cites a vivid illustration of the cusp catastrophe theory model shown in figure 5 with a friendly dog that is teased to the point of biting. Starting at point B on the behavioral surface in figure 5, where the dog is friendly and affectionate, the dog is purposely teased by its master. Thus, the dog's environment is depreciated and a corresponding movement occurs from left to right along the 1–EC* axis in figure 5, where $0 \leq EC^* \leq 1$. The teasing also depreciates the relationship between the dog

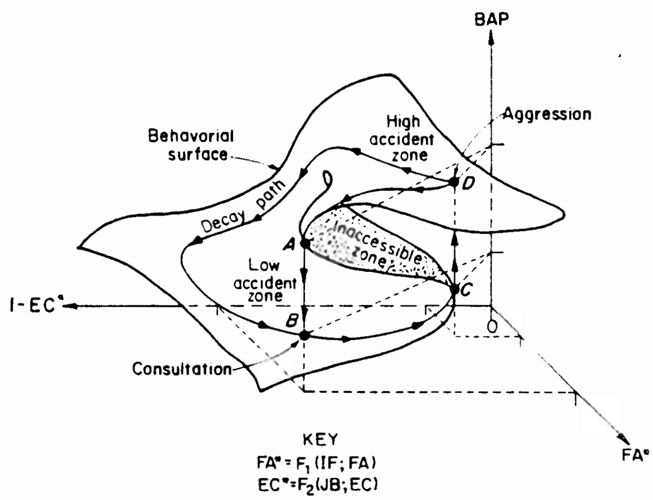

Figure 5.—Cusp catastrophe model.

and its master, so that a corresponding movement occurs toward the origin along the FA* axis in figure 5. The combined effects of these actions is to move the dog along the pathway from point B towards point C. As the teasing continues, the dog becomes increasingly more agitated. The dog reaches its threshold of tolerance at point C, where it suddenly jump shifts its behavior to point D on the upper surface of the cusp. Or, to put it bluntly, the dog bites its master.

Several subsequent events are now possible. When the dog's master ceases the teasing and goes off to tend his or her wounds, the dog's aggressive behavior may gradually decay back to point B along the decay path DB. Or the dog's behavior may recede along path DA and jump shift back to point B. Or the dog may remain at point D for some time, as long as its master continues to maintain the corresponding EC* and FA* stimuli. Still other more complex outcomes are possible if this static model is permitted to undergo dynamic changes. For example, suppose the teasing permanently changes the dog's personality. It is not uncommon for a dog to be turned into a mean and vicious animal through repeated teasing. This could be modeled as a shift in the shape and location of the cusp. Or the cusp could collapse once point D has been reached, i.e., the dog only attacks once and then regresses into a totally submissive state (*19*).

It is clear from these discussions that this is a static model with some limitations. But it is also clear that this static model may be quite relevant for modeling accident behaviors.

APPLICATION TO BEHAVIORAL MINE ACCIDENTS

It is easy to see how the story of the teased dog can be analogous to the underground miner who becomes agitated. At point B in figure 5, either the individual is in harmony with his or her environment or the supervisor's intervention factor (IF) is high enough that the individual's adjustive behavior is adequate for him or her to cope. Change any of the variables that contribute to this equilibrium, i.e., give the individual a less skilled supervisor, a worse environment, a supervisor who is less able to intervene, etc., and dramatic things may happen. The individual's adjustive behaviors may jump shift to aggression at point D in figure 5. Once at point D, the individual could remain there for relatively long periods of time, since the behavioral surface is relatively flat in the vicinity of point D. Large changes in the environment or the supervisor's abilities may be required to move the individual away from point D. All the subsequent events reviewed above may now occur, i.e., the individual's behavior may decay back to point B, the individual may remain aggressive, the individual's behavior may jump shift to other positions, etc. It may be noted that in terms of the JB scale in table 10, point D is aggression, point C is projection, and point B is consultation. The other JB scale positions, i.e., adaptation, etc., are points along the path BC.

The output from figure 5 is a value for BAP, calculated according to equation 14. As shown in figure 4, the value of the parameter BAP goes directly into node 9 of the network. Recall that node 9 was the variable evasiveness (see table 1). Thus, BAP controls the ability of the individual to avoid an imminent accident.

BEHAVIORAL DYNAMICS

Even with the addition of the cusp catastrophe mechanism, the network in figure 4 is primarily a static model. However, one important dynamic aspect can easily be added: behavioral reinforcement.

Real, vicarious, or social experiences can reinforce unsafe behaviors. To illustrate, suppose a normally safe-behaving individual knowingly performs a familiar job in a careless manner and does not have an accident. This experience may reinforce the individual's deviant behavior and increase the likelihood that he or she will repeat the careless act. Or, to put it more bluntly, because he or she got away with it one time he or she will probably try it again. This same result can occur if the individual has never actually experienced the careless act, but thinks about it longingly (vicarious experience) or observes others doing it (social learning).

To account for such phenomena, three feedback loops are included in figure 4. One loop runs from node 15 to node 9, a second feedback loop runs from node 16 to node 9, and a third runs from node 27 to node 22. The first loop permits changes in self-control to feed into evasiveness. That is, as one's self-control decreases (or increases), one's evasive ability also decreases (or increases). The second feedback loop permits impulsivity to feed into evasiveness. The third loop permits individual judgments to feed into compliance behaviors, i.e., once poor judgments occur they can further cloud the individual's compliance behaviors. Many other feedback loops are possible. However, these three appeared to be the most prominent ones for the applications here (*16, 19*).

With feedbacks, the cumulative flows at any node j are given by

$$VN^*_j = VN_j + \Sigma_k (VN_k)(VP_{kj}), \tag{15}$$

where VN_i is the value at the kth node where the feedback originates and VP_{kj} is the value of the feedback path. Here

$$VP_{kj} = A\,(VP_{jk}), \tag{16}$$

for the case where

$$0 \leq A \leq 1.0. \tag{17}$$

The coefficient, A, is parametrically set to reflect particular situations. For example, if social learning is believed to influence an individual's behaviors by 20 pct, i.e., he or she is affected 20 pct of the time, then A would be set at 0.20 for that case. Different values of A may be used in each of the three feedback loops (*19*).

BEHAVIORAL ACCIDENT SIMULATOR (BAS)

A review of the literature and a consideration of the application here (*12, 16, 22*) suggested that the following functional forms of equations 13 and 14 should be used. In the high accident zone of figure 5,

$$BAP = [a_1(1 - EC^*)]^{a_2(1 - EC^*)}, \tag{18}$$

where

$$EC^* \geq a_3. \tag{19}$$

In the low accident zone,

$$BAP = [a_4(1 - EC^*)]^{e/2}, \tag{20}$$

where

$$EC^* < a_3. \tag{21}$$

In equations 18 through 20,

$$EC^* = a_5 EC - a_6 (x_1 JB + x_2 FA^*), \tag{22}$$

for $x_1 = 0$ or 1, when $x_2 = 1$ or 0, and when $e = 2.718+$. Note that equation 22 is simply a convenient functional way to combine equations 12, 13, and 14. By using equation 22, FA* becomes an input to EC* instead of an input to BAP as shown in figure 4. The coefficients a_1, a_2, etc., are parameters set by the model builder that control the positioning and length of the behavioral decay path (path DB in figure 5), the jump shift and return shift paths (paths CD and AB in figure 5), and the behavioral buildup path (path BC in figure 5).

The probability of a fatality (the output from node 27 of figure 4) is given by

$$CK = a(Z^{be})^{c + de} \tag{23}$$

where CK is the chance that an individual experiencing the conditions within the network will be killed and

$$Z = k\,[(VN_{27})/(VN_{27})_{max}], \tag{24}$$

where a, b, c, d and k are suitably chosen constants, and where $e = 2.718+$.

The model, as defined by equations 4 through 24, and the VP_{ij} data base shown in table 8, were programmed in conversational mode using the Fortran 77 language. This computer program, called the behavioral accident simulator (BAS), can be run on VAX, DEC–1099, and IBM personal computer systems (*19*). The BAS provides many different parametric options to the user, so that a variety of scenarios can be run and a variety of conditions can be simulated. Graphic outputs, tabular outputs, and several user-selected reports are available. The conversational nature of the BAS permits the user to flexibly interact with the program at the computer keyboard. Users can describe various situations and receive immediate printouts of the fatality probabilities and other statistics for those situations.

ILLUSTRATIVE APPLICATION OF THE BAS

FRANK: A HYPOTHETICAL CASE

To illustrate the use of the BAS, the following is a purely hypothetical case of Frank, an underground miner at the hypothetical XYZ mine. Frank is currently assigned to one of the dirtiest and least attractive jobs at the XYZ mine. He often works overtime, he believes he is generally underpaid, and he feels he is under a great deal of pressure to get out the product. Frank's life philosophy is: "you gotta fight everybody just to stay even in this world." He is currently contesting his third wife's divorce suit. Yesterday, his new Corvette was vandalized and over $1,000 of uninsured damage was done to the interior of the car. Frank is a generally aggressive person with many pent-up emotions. He is a poor observer, often flies off the handle, and is prone to react inappropriately to emergencies. He has a consistent need to demonstrate his macho self-image and he thinks training is for sissies. Unfortunately, Frank often influences his peers to act just like him. Frank's supervisor is technically competent, but he is an inadequate planner, director, and leader. The supervisor has poor interpersonal skills and does not communicate well with the crew. However, top management at the XYZ mine is very safety conscious.

CODING THIS CASE INTO THE BAS

It is apparent from this description that the hypothetical Frank has behavioral and psychological characteristics that incline him toward accidents. Moreover, he is currently experiencing some personal life stresses, a poor working environment, and an ineffective supervisor. By using scales that were designed to be used with the BAS (*7, 18*), Frank's situation was coded into the BAS on a personal computer as scenario A. For example, using the scales for the variables listed in tables 10, Frank's environmental conditions (EC) and stressful life events (SLE) were coded as follows in scenario A: PJA = 100, PPF = 100, PA = 100, PEC = 100, and SLE = 100. A score of 100 indicates the worst possible conditions. From table 10, Frank's behavioral conditions (BC) were coded as follows: volatility (V_1) = 1, machoism (V_2) = 1, consistency (V_3) = 0, and influence (V_4) = 1. These are the worst scores possible for these variables.

Four other scenarios were also similarly coded into the BAS. In scenario B, the impacts of changing Frank's supervisor were simulated by recoding the BAS with a superior-performing supervisor while leaving all the other data the same. In scenario C, the codes were altered to simulate the effects of transferring Frank and his coworkers to a cleaner and more attractive job environment. Scenario D simulates the effects of transferring Frank out of the work group, thus breaking up the work clique. Scenario E simulates the effects of retraining Frank in a way that would totally modify his behavior.

RESULTS FROM THE BAS

It should be noted here that the purpose of these exercises is not to get absolute answers about how to deal with Frank. Rather, the purpose is to gain insights about the impacts of various management alternatives and what-if conditions, as one way of learning more about the entire accident system. For example, there is an implication in scenario E that Frank can be totally retrained. In reality, this is highly unlikely. Yet, experimenting with this alternative enables one to learn a great deal about accident systems and how they operate.

Figure 6 plots the results of the above five scenarios from the BAS. Scenario A, the current situation, gives intolerable results: Frank's chances of being killed are extraordinarily high. Thus, it is clear that this current situation cannot be permitted to exist. Some changes must be made. Would things be better under a new supervisor? Scenario B responds to this question. As figure 6 shows, though Frank's chances of being killed are lessened under the new supervisor, his chances still remain intolerably high. Scenario C, transferring Frank and the crew to a better working environment, substantially lowers the chances of being killed. This result is shown in figure 6. But major decreases in the chances of being killed do not occur until scenario D, where Frank is transferred out of the work group and the work clique is broken up. Still, Frank's chances of being killed remain unacceptably high. It is apparent from the scenario E results that in this extreme example Frank himself must be changed if his chances of being killed are to be lowered to acceptable levels.

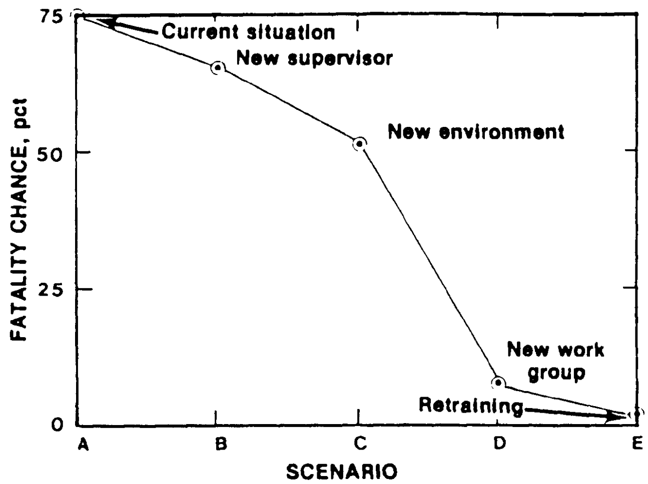

Figure 6.—Effects of various BAS scenarios.

PHILOSOPHY OF USING THE BAS

Though the example with Frank was purely hypothetical, it was nevertheless an informative and valuable exercise. The BAS demonstrated the relative effectiveness of several alternative management policies. The BAS showed that, under the given conditions, the most potent management action is to break up the work clique and form a new work group. Some other common alternatives, e.g., bringing in a new supervisor and altering the work environment, were found to be much less effective. These are valuable results. They show that time and effort should not be wasted on the other alternatives: they will not be effective. This was not intuitively apparent from the description given for Frank's case.

Thus, the BAS can make four valuable contributions. First, it encourages managers to explore a wide variety of creative new alternatives that they might not otherwise consider. The very nature of the BAS encourages managers to ask what-if questions. Its sole purpose is to simulate real world conditions as a basis for generating and experimenting with creative solutions. The BAS catalyzes a kind of brainstorming that encourages one to generate and try out a variety of conditions and scenarios. For example, in the hypothetical case with Frank, a natural question to ask is: "What would happen if we could make the mine perfectly clean and quiet?" Of course, this is not feasible. But by asking an exaggerated question of the BAS, the extreme cases can be tested. The result in scenario C, was highly revealing: even making the mine conditions perfect would not solve the problem. The BAS has indicated the need to look somewhere else for the solution. A more creative solution, breaking up the work group, was then tried in scenario D. This was found to be highly effective. Given these results, management can now try other proposed solutions—somewhere between the impossibly perfect mine conditions and the possible but impractical breakup of the work group. For example, what happens if we clean up the mine a little, provide some very directed training, and modify the work team somewhat? Such combinations can now be tested with the BAS, in order to move toward a solution that is both feasible and practical to implement.

Second, the BAS is a unique management laboratory where alternative actions can be tried before they are implemented. By using the BAS, the relative effectiveness of various alternatives can be studied as a basis for selecting the most cost-effective choices. For example, in the hypothetical case with Frank, bringing in a new supervisor is an intuitively appealing solution. But the BAS demonstrated that this would have been an ineffective and costly solution in this case. The BAS gives managers the opportunity to try new policies and actions before implementing them. This capability to test the impacts of new safety policies, organization designs, and changes in mine environments before developing or implementing them is clearly highly valuable.

Third, the BAS emphasizes the systems approach to accidents. It permits one to look at the total system of accident factors and to observe the ways in which they interact to cause accidents. BAS users acquire an important conceptual appreciation for the way various factors can interact, augment each other, or cancel each other. An understanding of the complex dynamics of human accident phenomena is essential to the selection of effective accident prevention policies. Focusing on only one or two factors in the hopes of eliminating accidents will not work. An understanding of the entire accident system dynamics is required. The BAS provides this understanding.

Fourth, the BAS is not only a management tool. It has been shown to be a highly effective self-learning or self-teaching tool for miners. Miners who used the BAS acquired a significantly improved sense of safety, and an appreciation for ways to avoid hazards.

One reason for much of the potency of the BAS is that it is not simply a theoretical model, designed in a vacuum. The network of variables that compose the heart of the BAS (fig. 4) was derived purely empirically, from actual MSHA accident cases. The preprocessor variables and other relationships in the BAS are all empirically based, from studies reported in the literature. Thus, everything within the BAS is a reflection of reality, at least to the extent that it has been captured in various accident reports and research studies.

Another feature that makes the BAS attractive is its ability to flexibly and realistically model a wide variety of circumstances. Many different individual, organizational, group, managerial, and mine conditions can be represented and tested.

LABORATORY TESTS OF THE BAS

Over 200 hypothetical cases have now been run on the BAS to demonstrate its utility. Figures 7, 8, and 9 present some of the more interesting results from these cases. For example, as figure 7 shows, the BAS can be used to test interactions between work environments and perceived levels of stress by individual miners. These BAS results indicate that the difference between high and low stress only becomes significant as the work environment degrades. However, in very poor work environments even low stresses are quite deleterious. As figure 8 demonstrates, the BAS can be used to test the effectiveness of various levels of supervisor competencies. As figure 9 demonstrates, the influence of several types of individual behavior profiles can also be readily tested with the BAS.

These results are informative and interesting. But the real test of the BAS is a matter of whether or not it actually improves mine safety.

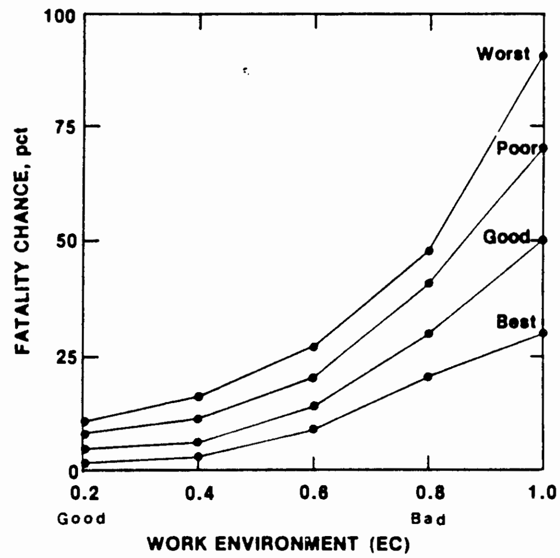

Figure 8.—Effects of supervisor abilities (FA).

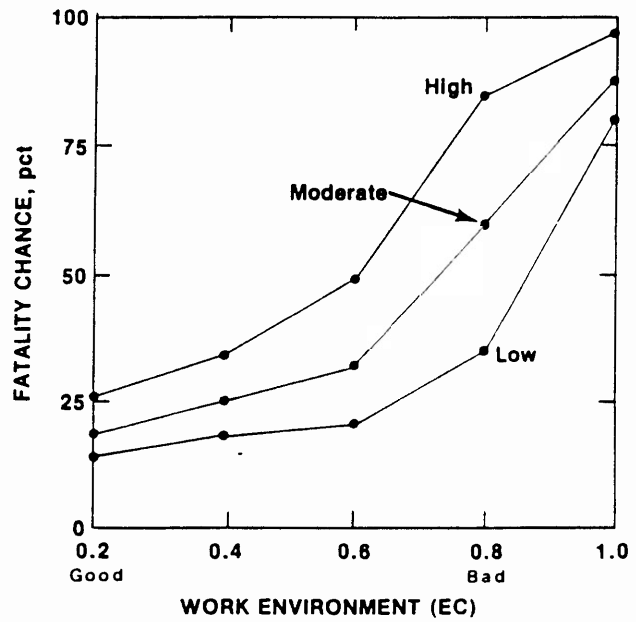

Figure 7.—Effects of stress (SLE).

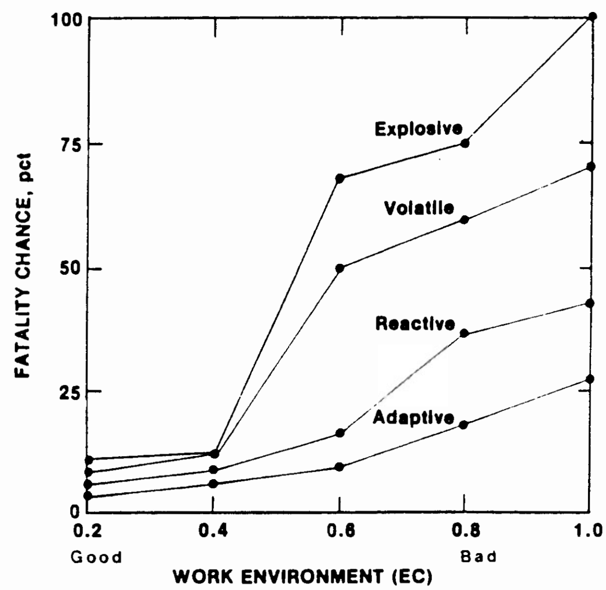

Figure 9.—Effects of various behavioral profiles (BC).

FIELD TESTS OF THE BAS

Twenty-eight persons from the mining industry experimented with the BAS on an individual basis. They included miners, mining engineers, and mine managers. Each subject used the BAS to generate scenarios of interest and observed the results. These scenarios included tests of various work environments, stresses, psychological conditions, behavioral conditions, management safety policies, supervisor abilities, crew composition, organizational arrangements, and employee adjustive behaviors.

Before experimenting with the BAS, each subject completed an attitude questionnaire. A postexperience questionnaire was then administered to each subject at the completion of the BAS session. Each session lasted from 2 to 3 h. Tables 11 and 12 present the results from the pre- and post-BAS experience questionnaires. The following are comments from post-BAS experience questionnaires (each comment is from a different subject).

1. Too many times management does not seem to exhaust all their alternatives before they try something. What I mean here is that they simply do not look at all the alternative things they could do. They just do whatever first comes to mind. If firing the employee comes to mind first, then that is what they do. The BAS says "wait a minute. Let's look at some other alternatives." And then it shows you what these alternatives can do. You get to see the effectiveness of each alternative before you do it. Now that is worthwhile. Even if some of the relations are made up in the model and not exact, they at least seem to go in the right direction. That's all you need.

2. Working with the BAS can be a useful experience for mine managers. It will help them do things that reduce mine accidents.

3. The BAS is a good tool for new employees. But it might end up as a tool for management to get rid of certain individuals, instead of trying to change things within the organization itself.

4. Most accidents seem to be caused by mental lapses, or at least a "hurry-up to get the job done" attitude. Safety meetings and films, as boring as they are, are helpful if you will only remember one small item from them and practice it.

5. Management and employees should look into this computer program and see how they can make changes based on what it might suggest to them.

6. The BAS is clearly useful to anyone dealing with hazards.

7. The BAS is a good device for mine managers and for foremen to learn skills that will improve their judgments in coping with problem employees and difficult situations.

8. Because there may be vast differences in individual receptiveness to safety messages, something like the BAS is a good idea as a training device. No matter how you feel about training, this thing is sort of interesting and it holds your attention.

9. The BAS gives management better insights into reducing accidents, improving work relations, and understanding employees.

10. I can see this as a very effective working tool in the mining industry. But management must be willing to take the time to care about their employees, to be willing to better understand human nature and to be willing to invest dollars to improve safety. This is a good tool for learning a lot about employees and how they act. But, if managers don't care about that, then your model is no good.

11. This is the first time I have ever seen all the accident factors put together like this. It really shows the relationships and gives you a feel for the whole thing.

Table 11.—Selected results from BAS experience questionnaires, percent

	Agreement
Pre-BAS questionnaire:	
High accident rates are inherent in the job	40
The miner's own behavior is seldom the cause of accidents	46
Conventional safety training is ineffective	38
Post-BAS questionnaire:	
The BAS clarifies behaviors that lead to accidents	92
The BAS is a useful training device for mine supervisors	92
The BAS is a useful training device for miners	88
The BAS is more effective than conventional training methods	88
The BAS sharpens a person's ability to recognize and avoid hazards	73
Use of the BAS could help reduce mine accident rates	76

Table 12.—Selected results from pre- and post-BAS questionnaires for BAS users who did not believe in training

	Averages[1]		Level of significance of change,[2] pct
	Pre-BAS	Post-BAS	
Individual miners can do very little to reduce accident rates	1.67	4.28	>99
Mine accidents are caused by a system of interacting factors	3.89	1.33	>99
Miners often take chances and do things that are not very safe	3.72	2.22	>95

[1] 1.0, strongly agree; 5.0, strongly disagree.

[2] Wilcoxian 1-tailed test of statistical significance; numbers represent confidence levels; e.g., 99 pct means there is 99-pct confidence that a real change in attitudes and beliefs has occurred.

12. This is a good thing to help analyze the human factors and how they influence safety in the mine. I hope the possibilities exist to make this available to all mining companies for training of their supervisors and employees.

13. The BAS gives good appreciation for the hazards and the miner's own reactions. It shows how one's own gut reactions in a time of crisis can be the wrong thing to do.

14. A very good program that should be made available to the industry for training supervisors as well as workers alike.

15. The whole problem is management. Until they will pay something for safety, nothing is going to help.

16. This should be required of all the employees who are known to work carelessly. You should pick out the ones who don't work safe and make them take this.

17. I had fun, but I would like to see how this correlates with real data and situations.

18. Like any training, just doing this does not make you a more safe person.

19. I doubt that this is useful in real situations. I don't see how this will be very useful. Some people just work safer than others, just like some people are more messy than others. You can't change people.

As table 11 shows, before working with the BAS, many of the subjects felt that high accident rates were inherent in mining. Thus, they seldom perceived that the miner's own behavior was a cause of accidents. Consistent with this, many of the subjects felt that conventional training was ineffective. However, as a result of using the BAS, these attitudes dramatically changed. As table 11 shows, over 80 pct of the subjects felt the BAS was a useful and effective training aid. Most of the subjects agreed that the BAS clarifies behaviors that lead to accidents and sharpens a person's ability to recognize and avoid hazards. Three-fourths of the subjects said that using the BAS could help reduce mine accident rates.

For some subjects, these attitude shifts were rather dramatic. Table 12 summarizes the attitude shifts for those subjects who stated in their pre-BAS experience questionnaires they did not believe conventional training was effective. Before their BAS experiences, these nonbelievers felt that individual miners could do little to prevent accidents. They had minimal appreciation for the ways that accidents could be caused by a system of interacting factors, and they generally denied that miners often take chances. Their BAS experiences caused statistically significant changes in these attitudes. After their BAS exercises, these nonbelievers had a much greater appreciation for mine accident systems. They became much more aware of the ways that miners unwittingly take risks and the ways in which individual behaviors are vitally important within the entire accident system. They still did not believe in *conventional* training. However, they thought the BAS was a potentially effective new approach to training.

The post-BAS experience questionnaire comments summarize both the favorable and unfavorable opinions. Three messages are clearly conveyed in these comments. One, the BAS was generally viewed as a potentially useful and effective device. It may be much more effective than many existing conventional training aids. Two, the BAS is a potentially useful device for managers to use in exploring alternative safety actions, work environment designs, and organization structures. Three, the actual effectiveness of the BAS in any application appears to depend greatly on the creativity of the users and the philosophy of use behind the BAS. The BAS is at best an information collection and decisionmaking aid. It can help the user gain numerous valuable insights, but it cannot be expected to make decisions or provide the ultimate answers.

SUMMARY AND CONCLUSIONS

A simulation model of human accident systems was developed based on an analysis of MSHA accident reports, some theories about human behavior, and a mathematical approach called catastrophe theory. A Fortran computer program, the behavioral accident simulator (BAS), was written for this model.

BAS users sit at a computer terminal or personal computer and experiment with various scenarios of their choosing. They observe the impacts of their decisions and their choices on accident rates and fatalities. The BAS enables the user to see the impacts of each decision and each behavior on every variable in the system. Users are able to vividly observe how these various factors cascade together to cause fatal accidents.

The BAS has been extensively tested in over 200 laboratory simulations and in a pilot field test with 28 coal mine industry personnel. These experiences demonstrated that the BAS is a highly valuable decision aid and training device. Mine managers can use the BAS as a kind of management laboratory to ask what-if questions about alternative organizational arrangements, working conditions, and other actions as a basis for choosing the best ones. Trainers can use the BAS as an innovative and effective way to teach mine management skills. Moreover, the BAS can be used by mine employees to improve their understanding of how their individual behaviors can cascade into serious accidents.

The BAS is a unique and innovative approach to the study and alleviation of human error accidents. It emphasizes experimentation with the entire system of individual, group, organizational, management, and mine variables to reduce accident rates. The pilot field test with mine employees demonstrated that this approach can significantly improve employee safety attitudes and mine management decisionmaking.

RECOMMENDATIONS FOR FURTHER RESEARCH

The success of the BAS encourages the development and implementation of advanced BAS-type models throughout the mining community. More sophisticated, precise, and powerful models should be developed, perhaps using stochastic variables and nonlinear dynamics techniques. Stochastic variables would permit more accurate modeling of actual human accident behaviors. Nonlinear dynamics techniques could be used to comprehensively treat the complex and varying interactions between these variables that are common in the real world. Because of its deterministic nature, the BAS is limited in its capabilities to handle these realities. However, now that its utility has been demonstrated, a step up to more elaborate models seems warranted. Because of their greater precision and power, more elaborate models would be both easier to validate and more useful to the mining community.

REFERENCES

1. Berelson, B. Content Analysis. Hafner (New York), 1971, pp. 5–70.

2. Blalock, H. M. Causal Inference in Nonexperimental Research. Univ. NC Press (Raleigh, NC), 1964, pp. 3–27.

3. Conway, J. R. Path Analysis Techniques for the Behavioral Sciences. Penton (London), 1983, pp. 21–105.

4. Denton, D. K. The Unsafe Act. Prof. Safety, July 1979, pp. 34–37.

5. Haddon, W., E. A. Suchman, and D. Klein (eds.). Accident Research. Harper & Row (New York), 1964, pp. 29–87.

6. Hale, A., and M. Hale. A Review of the Industrial Accident Literature. H. M. Stationary Office (London), 1972, 75 pp.

7. Holmes, T. H., and R. H. Rahe. The Social Readjustment Rating Scale. J. Psychosom. Res., No. 11, 1967, p. 216.

8. Kripendorff, K. Content Analysis: An Introduction to Its Methodology. Sage Publications (London), 1980, pp. 105–210.

9. Lykes, N. R. A Psychological Approach to Accidents. Vantage Press (New York), 1954, pp. 37–112.

10. McGlade, F. S., and L. Brody. Adjustive Behavior and Safe Performance. Thomas (Springfield), 1970, pp. 51–118.

11. Meister, D. Behavioral Analysis and Measurement Methods. Wiley (New York), 1985, pp. 304–310.

12. Mihal, W. L. Individual Differences in Perceptual-Information Processing and Their Relation to Accident Behavior. Ph. D. Thesis, Univ. Rochester, Rochester, NY, 1974, 205 pp.

13. Petersen, D. The Human Error Model of Accident Causation. Focus (Rochester, NY), July 1983, pp. 97–100.

14. ——. Human Error Reduction and Safety Management. Garland Press (New York), 1982, pp. 29–101.

15. Pfeifer, C. M., J. L. Stefanski, and C. B. Grether. Psychological, Behavioral, and Organizational Factors Affecting Coal Miner Safety and Health. Westinghouse Behavioral Services Center Tech. Rep. BSC-5, 1972, pp. 12–99, NTIS PB 275599.

16. Poston, T., and I. Stewart. Catastrophe Theory and Its Applications. Pitman (London), 1978, pp. 53–186.

17. Siegel, S. Nonparametric Statistics. McGraw-Hill (New York), 1956, pp. 36–44, 161–166.

18. Souder, W. E. The Behavioral Accident Phenomenon: Review and Models. Univ. Pittsburgh TMSG Study Rep., Feb. 22, 1984, 68 pp.

19. ——. A Catastrophe Model of Behavioral Accidents. Paper in Proceedings of the IEEE International Conference on Systems, Man & Cybernetics (Tucson, AZ, Nov. 12–15, 1985), pp. 514–516.

20. Thom, R. Structural Stability and Morphogenesis. Benjamin, 1975. pp. 5–87.

21. Whitkin, H. A. Psychological Differentiation and Forms of Pathology. J. Abnorm. Psychol., v. 70, 1965, pp. 317–336.

22. Zeeman, E. C. Catastrophe Theory. Sci. Am., v. 234, 1976, pp. 56–83.

U.S. GOVERNMENT PRINTING OFFICE: 1988 — 505-016/80.011

INT.-BU.OF MINES,PGH.,PA. 28693