Int. J. Man–Machine Studies (1987) **27**, 587–598

Accidents at sea: Multiple causes and impossible consequences

WILLEM A. WAGENAAR AND JOP GROENEWEG
Leiden University, Leiden, The Netherlands

Accidents are the consequences of highly complex coincidences. Among the multitude of contributing factors human errors play a dominant role. Prevention of human error is therefore a promising target in accident prevention. The present analysis of 100 accidents at sea shows that human errors were not as such recognizable before the accident occurred. Therefore general increase of motivation or of safety awareness will not remedy the problem. The major types of human error that contribute to the occurrence of accidents are wrong habits, wrong diagnoses, lack of attention, lack of training and unsuitable personality. These problems require specific preventive measures, directed at the change of undesired behaviors. Such changes should be achieved without the requirement that people comprehend the relation between their actions and subsequent accidents.

Accidents in complex man–machine systems are usually caused by a multitude of events which occur in a coincidental manner that was never foreseen. These events, or causes, may vary from uncontrollable 'acts of God', unforeseeable technical mishap, to human negligence or failure. It is the thesis of this study that among these causes human error is the category which is most simply controlled. However, such a control can be exerted only by change of the work environment, consisting of hardware systems, machinery, tools, procedures and schedules. A change of human behavior through selection of better personnel, through safety training programs or increase of motivation will be of little avail. Such measures assume that the chains of events leading to accidents can be overseen by the people who are a part of them, and that not preventing the chain is the result of stupidity. However, making the mistakes people tend to make is only stupid in hindsight. Psychologists are talking moonshine if they claim that accident-prone people can be removed through psychological testing. There is no well-controlled study that has convincingly shown that a decrease of accident rate can be obtained through general safety-training or motivation programs (cf. Kletz, 1985, p. 68).

Nevertheless, in this paper prevention of human error is proposed as the option that will be the most successful remedy of accidents because human error is involved in the large majority of accidents, because human error is basically quite invariant, and because many forms of human error are invited by the design of hardware and software.

In this study we will supply some results of an analysis of 100 accidents at sea, which support the theses presented above. The chains of causes leading to the

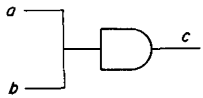
Address for correspondence: Willem A. Wagenaar, Unit of Experimental Psychology, Psychology Department, Leiden University, P.O. Box 9509, 2300 RA Leiden, the Netherlands.
A valuable contribution to this text was made by Patrick Hudson and Angie Pleit-Kuiper. The data concerning accidents at sea are borrowed from a study performed in cooperation with the Institute of Perception TNO for the Foundation of Coordinated Maritime Research.

0020-7373/87/050586 + 12$02.00/0

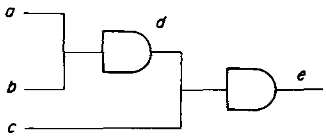
accidents will be presented by logical conjunctions, in order to arrive at a measure of their complexity. Subsequently, the human errors that are part of these conjunctions will be classified according to the categorization proposed by Feggetter (1982). The nature of these errors will give some insight into the underlying processes and, hopefully, provide a clue as how to prevent errors. The remaining of this paper will consist of five parts. First we will present a short exposition on the construction of causal networks as used in this study. Next a brief summary of Feggetter's classification system is presented. Subsequently the application of the method will be illustrated by one example. Then the results of an analysis of 100 accidents at sea is presented, and finally it will be investigated to what extent the results support the theses exposed above.

1. Causal networks

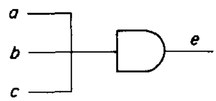
The causal networks used for the schematization of scenarios leading to accidents contain events connected by logical AND-gates and OR-gates. AND-gates are presented as follows†



The causes *a* and *b* lead to result *c* if they are both present. Therefore, *a* and *b* are both necessary but insufficient causes. A more complicated structure might look like this:



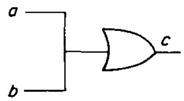
In this structure *a, b,* and *c* are root causes, while *d* is an intermediate cause. Since the set of *a, b,* and *c* is both necessary and sufficient, the structure is logically equivalent with:



The only difference is the intermediate cause *d*. When there is an appreciable time interval between the coincidence of *a* and *b* that caused *d*, and the subsequent coincidence of *c* and *d*, causing *e*, the structure containing *d* is preferred, since *d* could represent a preventable condition. Here is an example: a visitor on an oil tanker wants to smoke (a), and does not know smoking is strictly forbidden (b). Hence he smokes (d). Due to operations there are combustable gasses (c), which explode because of the cigarette (e). This event could be reduced to: a visitor wanting to smoke (a) and not knowing the rules (b), caused the combustible gas (c) to explode (e). But the smoking of the cigarette (d) existed for a certain period, and could have been detected by other people or by a smoke detection system. Hence, leaving out the smoking would without necessity restrict the range of preventive measures.

† Contrary to the usual convention, the diagrams are to be read from left to right.

A second possibility of combining causes is the logical OR-gate, represented as follows:



The causes *a* and *b* lead to result *c* whenever at least one is present. Either one of the two causes is therefore sufficient but neither is necessary. OR-gates play no role in backward analyses, as used in the present study, but later on our discussion will employ a structure containing some OR-gates.

The translation of accident scenarios into logical trees is a tricky business, because there are many ways in which one and the same scenario can be represented. Therefore we tried to establish the interrater reliability index, between two independent raters, using 14 accidents not included in this study. Although occasionally a substantial difference between raters was observed, the overall indexes of reliability were quite satisfactory. The reliability index for *Numbers of causes* was $r = 0{\cdot}84$. For *number of AND-gates* we found $r = 0{\cdot}66$. One of the problems encountered was the setting of a time horizon. How far back in history should the analysis go? In the corpus of accidents at sea a simple decision rule was provided by the fact that all accident scenarios were drawn from reports by the Dutch Shipping Council, the national authority responsible for the legal investigation of accidents at sea. Our event trees simply reflected the limits with respect to time, adopted by the Council.

2. Classification of human error

The root causes and intermediate causes which enter the conjunction are quite often the acts of humans. The diagnosis of what people actually do wrong will be greatly helped by a classification of these actions. One classification schedule was proposed by Feggetter (1982). A slightly adapted version of this schedule used in the present study, is presented in Table 1. The classification is of course somewhat arbitrary, and many others have been proposed and applied (cf. Rasmussen, 1982). For the present purpose we have been quite satisfied with Feggetter's classification, because it allowed us to make the verifications necessary for the support of our theses. In the future a more refined classification might provide further insights, but only if more data about accidents are available.

Categorization of errors is, like the contruction of event trees, somewhat arbitrary. Smoking on board a tanker could be classified as lack of training, when it is assumed that the perpetrator did not know the regulation, or did not understand the consequences. But it can also be classified as a wrong habit, when it appears that smoking on board occurred frequently. Or as lack of motivation, when ill will or laxity is perceived as the cause. An estimate of reliability between those making the ratings was again obtained by comparison of classifications made by two independent judges, rating 14 accidents that were not part of this study. The index was $r = 0{\cdot}87$ for the number of human errors identified in each accident. The reliability index for usage of human error categories was $r = 0{\cdot}80$.

TABLE 1

Classification of human error, according to Feggetter (1982)

1	*Cognitive System*
1.1	Human Information Processing
1.1.1	Senses
1.1.2	Perception
1.1.3	Attention
1.1.4	Memory
1.1.5	Decision
1.1.6	Risk taking & action
1.1.7	Monitoring
1.1.8	Feedback
1.2	Visual Illusions
1.3	False Hypothesis
1.4	Habits
1.5	Motivation
1.6	Training
1.7	Personality
1.8	Fear
2	*Social System*
2.1	Social Pressure
2.2	Role
2.3	Life Stress
3	*Situational System*
3.1	Physical Stress
3.1.1	Physical condition
3.1.2	State of nutrition
3.1.3	Drugs
3.1.4	Smoking
3.1.5	Alcohol
3.1.6	Fatigue
3.1.7	Sleep loss
3.2	Environmental Stress
3.2.1	Visibility
3.2.2	Glare
3.2.3	Temperature
3.2.4	Noise
3.2.5	Vibration
3.3	Ergonomic Aspects
3.3.1	Design of controls
3.3.2	Design of displays
3.3.3	Presentation of material
3.3.4	Policy for dealing with emergencies

3. An example: the impossible accident on the Farmsum

On 14 December 1982 on board the Farmsum sailing on the Atlantic Ocean, four men were busy cleaning hold 6. Suddenly the 15 meter high and 25 meter wide partition between hold 5 and 6 collapsed and 6000 tons of water flooded over the unsuspecting men. Three sailors were thrown up against a metal wall by the torrent and drowned. The bosun was miraculously saved. It is absolutely certain that all the men assumed that hold 5 was empty. In everyone's opinion the accident was

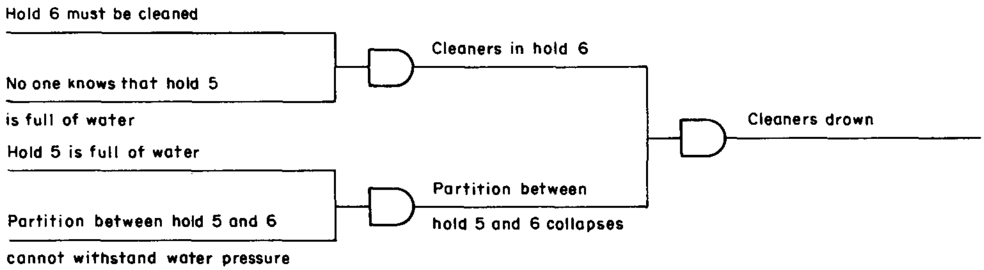


FIG. 1. Causes leading to the drowning of cleaners in hold 6.

impossible. An analysis of the investigation following the accident revealed a complex chain of causes leading to the accident.

Cleaners were working in hold 6 while hold 5 was full of water. No one was aware of this fact, and the wall between hold 5 and 6 was not designed to withstand this pressure. The situation is represented as shown in Fig. 1.

How could hold 5 be full of water without anyone being aware of it? The ship sailed with water in hold 4 as ballast. Due to bad weather, a leak had sprung between hold 4 and 5. Thus hold 5 filled up with water from hold 4. It had been noticed that water was disappearing from hold 4, but the first mate had a very plausible explanation for this. While cleaning hold 6, sluice water had been used. However, it appeared to be impossible to pump this water out because the sluice valve in hold 4 had been left open by mistake. This caused the sluice pump not to pump from hold 6 but from hold 4. The first mate responded to this by refilling hold 4. Thus, more than 24 hours before the accident we see the chain of causes shown in Fig. 2.

It seems rather absurd that the first mate thought the large amount of water missing from hold 4 could have been pumped out by a low capacity sluice pump. However, we must realize that the first mate did not know how long the pumping had been going on, or how much water had been removed. At that point this was not so important because the officer was busy trying to solve a very different problem. He tried to explain why the water could not be pumped from hold 6. Initially he thought that the sluice pump was broken. The men in the machine room knew that this pump definitively had worked. The discovery of the open valve in hold 4 offered a new hypothesis and the missing water confirmed this hypothesis. It is known that people accept hypotheses on the grounds of confirming information, without critically testing the hypotheses (Lord, Lepper & Ross, 1979). The first mate was satisfied with the confirmation, shut off the sluice valve and started to fill hold 4.

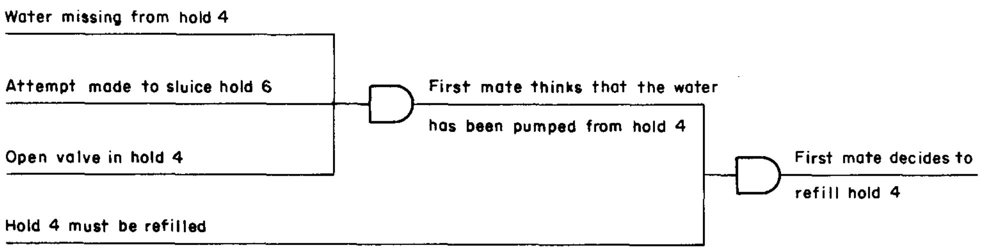


FIG. 2. Chain of causes leading to the first mate refilling hold 4.

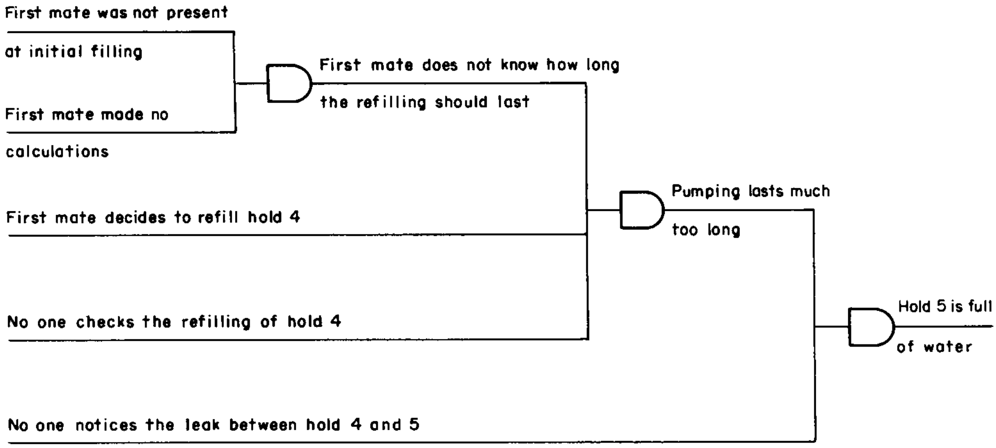


FIG. 3. Chain of events leading to hold 5 being full of water.

Approximately 3300 tons of water were missing from hold 4. The first mate did not notice that this had been replenished by a total of 6600 tons, almost more than hold 4 could accommodate. Naturally the explanation was that hold 4 as well as hold 5 were filled. The fact that the first mate was not present during the original filling of hold 4 takes its revenge here. He could not know that this had only lasted a few hours and he did not make a rough calculation on the grounds of pump capacity. He did not order someone to keep an eye on the refilling of hold 4. This chain of events is represented in Fig. 3.

The accident on the Farmsum has a total of 35 causes, combined in a conjunction of 17 AND-gates. If we only count the root causes then we still have 20 different causes, including a leak between hold 4 and 5, a negligent captain, the absence of a ship's carpenter for daily gauging, ship's officers who did not keep one another informed, a valve which remained stuck in the open position while the broken indicator showed it as closed. There were at least five actors in the drama, each of whom could only oversee one part of the scenario. And this is exactly the downfall of a conjunction which only contains AND-gates: none of the causes as such provide cause for alarm. The human errors contributing to this accident were classified as shown in Table 2.

A few cautionary remarks have to be made. First it should be stressed that a backward analysis after the facts will always result in conjunctions with no OR-gates, because only the causes that *did* happen are included. Causes that could have happened but did not, appear only in an analysis of effects when causes are unknown. Thus the first mate's attempt to explain why sluicing of hold 6 was unsuccessful could be represented as in Fig. 4.

The causal network representing the actual occurrence of the accident is not a model of the strategic processes in the heads of those involved. More will be said about this problem later.

The second remark I would like to make is that the large number of causes can only be considered typical of accidents in a fully developed technological environment. Everyday accidents such as falling from a ladder or causing a collision could be different.

TABLE 2
Classification of human errors in the Farmsum accident

No.	Category	Behavior
1.3	False hypothesis	First mate assumes that water disappeared from hold 4 through sluicing
1.4	Habits	First mate never gauges the water level in the holds
1.6	Training	Captain did not know how to handle the ship
1.7	Personality	Captain is negligent (cf. he knows that the daily gauging is neglected but does not take any counter measures)
1.7	Personality	Second mate is a headstrong and negligent person
1.7	Personality	First mate is so selfconfident that he ignores any information not confirming his own hypothesis.
2.1	Social pressure	First mate dislikes the captain and he does not give him all required information
2.1	Social pressure	Bosun thinks 'he is not in the position' to question the first mate's gauging habits
3.3.1	Design of controls	There is no way to check the water level in hold 4 without taking extensive measures
3.3.1	Design of controls	It is not possible to see whether a very important valve is open or closed.

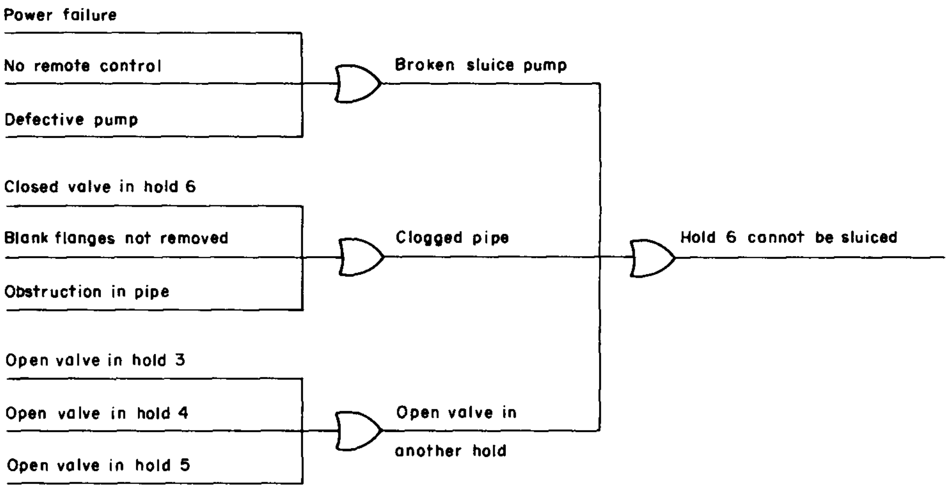


FIG. 4. Representation of the first mate's attempt to explain the unsuccessful sluicing of hold 6.

4. Analysis of 100 accidents

The 100 accidents at sea are cases all heard by the Dutch Shipping Council between 1982 and 1985. The choice of this set was inspired foremost by the fact that the Council issues detailed reports, including testimony of all people involved, and a usually quite sophisticated analysis by the Inspector. Besides, it can be argued that shipping accidents constitute a fair representation of accidents in other industrial environments, having a well-balanced mix of rough hardware and high technology; of coarse, dangerous work and sophisticated strategic planning.

The number of causes in the 100 accidents ranged from 7 to 58 with a median of 23. The median number of 12 gates per network indicates that the number of steps between the remotest causes and the final consequence was fairly large. Much bigger than even a very experienced chess player would consider in deciding about the next move.

The total number of causes underlying the accidents was 2250. Out of this total 345 were forms of human error. This ratio could suggest that human error is a minor factor in the origin of accidents at sea. Such a conclusion would be rash and ill-considered. The 345 human errors were all necessary conditions, and therefore crucial. In fact only four of the 100 accidents occurred without any preceding human error. The proportion of human error is also not small when placed in the perspective of the essential task of man in complex systems, which is to prevent or counteract the other errors. In 96 out of 100 cases the people involved could and should have prevented the accident, but did not. The number of human errors per accident and the number of erring people are presented in Table 3.

From this table it is clear that accidents are typically caused by more than one human error. Usually the errors are made by one or two people. One can guess about the reasons for this. Possibly it means that hardware and procedures on board are designed such that single human errors cannot cause troubles. But the coincidence of errors is unanticipated and causes couplings against which the system has no defense (cf. Perrow, 1984). The coupling could have been detected when all errors were made by the same person. But in the 51 cases in which errors were distributed over more people timely detection was bound to fail.

This mechanism is also illustrated by the number of errors per person. In one-person accidents there are 2·8 errors per person. This number is reduced to 1·9,

TABLE 3
Number of human errors and erring persons in 100 *accidents at sea*

No. of people involved	Number of human errors											
	0	1	2	3	4	5	6	7	8	9	10	Total
0	4	—	—	—	—	—	—	—	—	—	—	4
1	—	3	18	14	6	4	—	—	—	—	—	45
2	—	—	4	11	16	7	2	1	—	—	—	41
3	—	—	—	1	—	3	2	1	1	—	—	8
4	—	—	—	—	—	—	1	—	—	—	1	2
Total	4	3	22	26	22	14	5	2	1	0	1	100

TABLE 4
Classification of human errors in 100 accidents at sea, according to Feggetter's classification system

No.	Feggetter's category	Overall frequency of errors	Number of accidents in which the errors occur
	Cognitive system		
1.1	Human information processing	44	35
1.2	Visual illusions	2	2
1.3	False hypothesis	60	51
1.4	Habits	50	46
1.5	Motivation	1	1
1.6	Training	41	35
1.7	Personality	43	35
1.8	Fear	0	0
Subtotal (%)		70%	93%
	Social system		
2.1	Social pressure	20	17
2.2	Role	2	2
2.3	Life stress	2	2
Subtotal (%)		7%	21%
	Situational system		
3.1	Physical stress	18	12
3.2	Environmental stress	22	17
3.3	Ergonomic aspects	39	34
Subtotal (%)		23%	56%

1·9 and 1·8 for accidents involving two, three or four people. If one person can oversee the complete scenario there is a possibility for correction; only the more complex scenarios remain unchecked. When the formation is distributed across more people it becomes hard to realize the consequences of the errors.

A classification of errors is presented in Table 4. The most frequent categories are false hypotheses and habits. Both were present in about half of the accidents. The overall category of cognitive problems accounted for 70% of the errors, and was present in 93% of the accidents. The implications of these numbers will be discussed later. At this moment it is already useful to inspect the last column of Table 4 closely, since it indicates what the effect on accident rate would be if a particular type of problem could be redressed. Elimination of false hypotheses has as an upper limit the effect of preventing half of the accidents. Improved training may result in a 35% decrease of accidents, and improvement of ergonomic design in a 34% decrease. Increase of motivation may exclude 1% of the accidents.

A count of coincidence of errors within one accident revealed that two combinations occur more frequently than expected by chance ($P < 0{\cdot}0005$). One of these combinations is an error of information processing and high situational stress.

The eighteen errors in this joint category were almost exclusively related to lack of attention during bad visual conditions. In fog or other adverse visual conditions one needs a lookout on the front of the ship, more personnel on the bridge to monitor radar and other equipment. Frequently these extra precautions are not taken; in a number of cases ships were sailing through mist without anyone watching. It is as if the invisibility of other traffic creates the soothing suggestion that there is no other traffic. The other frequent combination is of personality and social pressure. These 21 combinations are all clear examples of corrupted psychological conditions on board. Discipline is weak, the captain tolerates all sorts of malpractice (among which the use of alcohol), and the execution of jobs is dictated more by social pressure than by the formal rules.

5. Impossible accidents and their prevention

One can look at accidents from the perspective of risk-taking. In this view the behaviour of people is a consequence of a more or less conscious process of risk evaluation. The possible occurrence of accidents is realized, but outweighed by other factors such as economical advantage or minimization of effort. If this were true it could be attempted to reduce accident rate by influencing the risk evaluation process through selection of personnel or increase of motivation. The results presented above do not support this notion. Accidents appear to be the result of highly complex coincidences which could rarely be foreseen by the people involved. The unpredictability is caused by the large number of causes and by the spread of information over participants. Also the nature of the errors that are made indicates lack of understanding rather than lack of motivation or risk propensity. Accidents occur because the behaviour that causes them is not seen as risky. Errors of information processing (mostly lack of attention) are made frequently, but are, under normal conditions, not punished by accidents. Hypotheses that proved to be false in the reported incidents were usually correct in previous instances, and that is exactly the reason why they are adopted again, even when the contrary information is available (cf. Reason, 1986). Habits that contribute to the origin of accidents could become habits because they were not negatively rewarded before. The same can be said about lack of training and unsuitable personality. These factors, lack of attention, false hypotheses, wrong habits, lack of training and adverse personality were at the bottom of 93 out of 100 accidents. Each of these factors interferes with risk evaluation because people have no insight in the complex conjunctions of which the factors form the necessary ingredients. Accidents do not occur because people gamble and lose, they occur because people do not believe that the accident about to occur is at all possible.

Many accidents are outrageous and bizarre, not because people take outrageous risks, but because people assume that the bizarre will not occur. Here are some examples from our set.

On two ships about to meet, both mates were changing the paper roll of the Deccaplotter, the radiographic position-finding apparatus. Neither of the officers requested extra help. Both had problems changing the paper roll. While they were busy with the plotters no one was standing watch and the ships collided. Another captain was sailing in a thick fog with no one available to stand watch. Nevertheless, he did not turn on the radar because he liked to use the equipment sparingly. The result was a collision. Another captain sailed with a defective automatic steering mechanism. Still he employed this mechanism and used signals as a safety measure to warn others that he could not steer the ship. He hoped that other ships would stay well out of his path. They did stay clear, but due to the defective mechanism the ship ran aground instead. One last example: because of hazardous cargo no smoking was allowed on the wings, but it was allowed in the wheelhouse. This lead to the unwritten rule that no watchman was required on the wings. Thus the safety measure promoted unsafe behaviour and the result was a collision.

The reason why accidents that result from complex conjunctions are so difficult to foresee could be that prediction of unlikely events is not the normal task of an operator. Assume that on the Farmsum the following facts were known:

(a) It has been bad weather since 3 days.
(b) Hold 4 has lost 40% of its water.
(c) The sluice valve in hold 4 remains stuck in the open position.
(d) The position indicator of the valve is broken.
(e) The position indicator shows that the valve is closed.
(f) The attempt to empty hold 6 is given up after 4 hours.
(g) The sluice pump is not broken.
(h) The content of the holds is not gauged daily.
(i) The first mate was not present while hold 4 was being filled.
(j) The first mate does not calculate the total filling time.
(k) No one inspects the refilling of hold 4.

Would anyone attempt a logical concatenation of these facts in order to arrive at the conclusion that hold 5 is now full with water? Given the problems with sluicing in hold 6 and the loss of ballast, the first mate should have considered two causal networks. One of these networks, presented before, accounting for the problems with the sluice pump, is a fault tree analysis that runs backward from a symptom to possible causes. The other network should be a forward analysis, departing from the fact that the ship is sailing under adverse weather, with some ballast missing. We argue that the consequences of these conditions are also investigated by a backward analysis. Such an analysis starts with a hypothetical but not unlikely accident, and reasons back to possible causes, in order to find out whether the present condition of bad weather and missing ballast constitutes a sufficient cause. Thus the operator is using information for the recovery of diagnoses or for the prediction of likely accidents, but never for the prediction of the very unlikely accidents that do in fact happen.

It follows from the foregoing that accidents cannot be prevented just by telling people to act safely. The behaviours leading to accidents are not considered unsafe at the time. If these behaviours are to be prevented nonetheless, we should be prepared to change the environment by which they are elicited. It is possible to secure the attention of operators, for instance by providing them with continuous tasks and knowledge of results. The number of false hypotheses can be reduced by the introduction of intelligent support systems, like the IMAS system proposed by Embrey & Humphreys (1984). Undesirable habits can be largely eliminated, not by instruction or indoctrination (cf. Slovic, 1985) but by control and incentives.

Training can be improved and maintained. The effect of adverse personality and social pressure can be reduced through the creation of better working conditions. It would already make a big difference if the attractiveness of flags of convenience could be reduced.

The analysis of 100 accidents at sea has brought us to the conclusion that the acts which lead to an accident are part of a complex causal network that cannot be overseen by the actors. Errors do not look like errors at the time they are perpetrated, and the accidents that are caused by them look impossible beforehand. Still human error is the most promising target for those who want to reduce accidents. However, telling people to change their behaviour when facing accidents will not help, because they will rarely believe they are facing accidents. There are many other methods of successfully controlling human behavior. Time has come to accept the need for these methods.

References

EMBREY, D. E. & HUMPREYS, P. (1984). *Support for Decision Making and Problem Solving in Abnormal Conditions in Nuclear Power Plants.* Conference on Knowledge Representation for Decision Support Systems. International Federation for Information Processing, Durham, 1984.

FEGGETER, A. J. (1982). A method for investigating human factor aspects of aircraft accidents and incidents. *Ergonomics,* **25,** 1065–1075.

KLETZ, T. A. (1985). *An Engineer's View of Human Error.* Rugby, UK: The Institution of Chemical Engineers.

LORD, C., LEPPER, M. R., & ROSS, L. (1979). Biased assimilation and attitude polarization: The effects of prior theories on subsequently considered evidence. *Journal of Personality and Social Psychology,* **37,** 2098–2110.

FLEISHMAN, E. A. & QUAINTENANCE, M. K. (1984). *Taxonomies of Human Performance.* Orlando, FL: Academic Press.

PERROW, C. (1984). *Normal Accidents.* New York: Basic Books.

RASMUSSEN, J. (1982). Human errors. A taxonomy for describing human malfunction in industrial installations. *Journal of Occupational Accidents,* **4,** 311–333.

REASON, J. (1988). Cognitive under-specification: its varieties and consequences. In: BAARS, B. Ed., *The Psychology of Error: a Window on the Mind.* In press. New York: Plenum.

SLOVIC, P. (1985). Only new laws will spur seat-belt use. *The Wall Street Journal,* January 30.