A Practical Safety Analysis System for Hazards Control

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In any hazardous operation, safety is of paramount importance. By contributing to accident avoidance, proper safety measures can result in increased production and reduced operating expense. In contrast, artificially imposed restrictions are often an actual handicap. Thus, there is a need for methods to evaluate suggested safety measures and to arrive at optimum safety procedures. A practical, easy-to-use safety analysis system for the quantitative characterization of the risk inherent in a hazardous situation and for a quantitative evaluation of proposed safety procedures is described in this report. The system is based on comparison of circumstances in a given situation with those for reference situations. The analysis can be performed either algebraically or graphically by using nomographs and provides both numerical values and descriptive terms that are meaningful to personnel in safety, operations, and management. The nomographs also provide written documentation of the analysis. Sample calculations relating to the explosives industry are included, but the methods apply equally well to all hazardous situations.

Safety programs are extremely important in industrial operations, particularly in the ordnance industry. Whether or not a safety program is beneficial, however, depends a great deal on the approach taken by those in charge. A safety program that consists primarily of supervisors chiding workers with a "you can't do that" policy may well impede production and contribute little to the reduction of risks. On the other hand, there is the positive approach to safety which emphasizes a safe working environment and safe operating procedures.

The positive approach to a safety program distinguishes between "hazard" and "risk," and attempts to reduce the overall risk of an operation rather than attack a few selected hazards. Here, *hazard* is defined as *some potential danger beyond one's immediate control*. Some everyday hazards include (1) riding in an automobile, (2) working at an industrial job, or (3) just sitting at a desk all day. *Risk* is defined as *the chance that injury or damage will result from that particular hazard* (i.e., the degree of risk from a hazardous situation). For the hazards mentioned above, the risks might be (1) the probability of being killed or injured in an automobile accident, (2) the probability of being killed or disabled on the job, or (3) the probability of dying from a heart attack as a result of being overweight or out of physical condition due

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This work was supported in part by the Detonation Physics Division, Naval Weapons Center. The special assistance of Mr. R. G. S. Sewell of that Division and Mr. A. D. Wiruth of the Safety Department is gratefully acknowledged.

TABLE 1
RISKS OF FATALITY FROM VARIOUS HAZARDS (1975)[a]

HAZARD	NUMBER OF DEATHS IN U.S. PER YEAR	INDIVIDUAL RISK PER YEAR
Motor vehicle	55,791	1:4,000
Falling	17,827	1:10,000
Fires and hot substances	7,451	1:25,000
Drowning	6,181	1:30,000
Firearms	2,309	1:100,000
Air travel	1,778	1:100,000
Falling objects	1,271	1:160,000
Electrocution	1,148	1:160,000
Lightning	160	1:2,000,000
Tornadoes	91	1:2,500,000
Hurricanes	93	1:2,500,000
Nuclear power plant incidents	0	>0
All accidents	111,992	1:1,600

[a]From "Risks of Fatality from Various Hazards," *Business Week*, July 5, 1976.

to a sedentary job. Thus, *hazards* are events or situations that can possibly go wrong, and *risks* are quantitative statistical items (probabilities) that characterize the potential results of a hazard.

An optimum, positive safety program adheres to three maxims that can be compared with the axioms of geometry. These are:

1. All hazard and all risk can *never be completely eliminated.*
2. Risks from ever present hazards can be *reduced.*
3. The optimum safety program provides *overall risk reduction* rather than complete elimination of a few selected risks.

Since all hazards cannot be eliminated, it is desirable to reduce the risks associated with any ever present hazards to acceptable levels. An *acceptable risk* can be defined as *that real risk from some hazard, but one that does not deter a knowledgeable and prudent person.* For example, as Table 1 shows, the individual risk of fatality while riding in an automobile is about 1:4,000 per year ("Risks of fatality," 1976), yet one still rides to work in an automobile. The chance of being killed by lightning is about 1:2,000,000 per year, yet some golfers persist in endangering themselves by playing golf in a thunderstorm. For workers in the ordnance industry, the chances of a fatality were 1:359 for the year 1973 (U.S. Department of Commerce, 1975, 1976), yet most persons in this industry obviously consider this an acceptable level of risk.

Sometimes the concept of acceptable risk may seem a bit strange. Nevertheless, the principle is well recognized in many areas. One example involves an accident at a lead azide processing and testing plant (Sewell, 1976). Lead azide is a detonating explosive and one of the hazards involved in its screening is that it may explode. The associated risk is that there is a finite probability that any manipulation of lead azide can set off an explosion that may do damage. In the example cited, one pound of the explosive was being screened inside a remotely operated cell. It exploded, doing about $3,000 worth of damage to the screening equipment and frangible blowout walls of the cell, although no personnel were injured. The safety management of the operation stated in the accident report that this loss was "fully within the known and acceptable risk" of the operation.

RISK ANALYSIS

In order to analyze the risk involved in a hazardous situation, three contributing factors are identified and a numerical value assigned to each. An overall risk score is determined as a product of the three individual factors (Kinney & Wiruth, 1976). This approach is similar in principle to that described by Fine (1971). The three factors that enter into the risk analysis are: (1) the *likelihood* that some hazardous event will occur; (2) the *exposure* to that particular

TABLE 2
ASSIGNED VALUES FOR HAZARDOUS EVENT LIKELIHOODS

NUMERIC	DESCRIPTIVE
10[a]	Might well be expected
6	Quite possible
3	Unusual, but possible
1[a]	Only remotely possible
0.5	Conceivable, but highly unlikely
0.2	Practically impossible
0.1[a]	Virtually impossible

[a]Defined reference point.

TABLE 3
ASSIGNED VALUES FOR
EXPOSURE FACTORS

NUMERIC	DESCRIPTIVE
10[a]	Continuous
6	Daily during working hours
3	Weekly or occasionally
2	Monthly
1[a]	A few times per year
0.5	Very rare

[a]Defined reference point.

hazardous situation; and (3) the possible *consequences* should the hazardous event actually occur.

Likelihood factor. The likelihood of occurrence of a hazardous event is related to the mathematical probability that it might actually occur. For purposes here, however, likelihoods are expressed in alternative terms of expectations. Likelihoods that may be encountered in practical safety situations range from that for a completely unexpected and unanticipated, but remotely possible, event to that for an event that might well be expected at some future time. These two likelihoods are established as defined reference points. The former is arbitrarily assigned a likelihood value of unity, the latter a likelihood value of 10. Situations between these two likelihoods are readily assigned intermediate values. For example, an event that "could happen" is assigned a likelihood value of six, and an event that would be "unusual, but still quite possible" is assigned a likelihood value of three.

Safety considerations must provide not only for all such possible situations, however, but also for events that are practically impossible. The absolutely impossible event should thus be assigned a likelihood value of zero. However, since no event that can be described can be considered absolutely impossible, no event can have a mathematical probability of zero. Rather, the probability can approach zero so closely that the event is virtually impossible. A defined reference likelihood value of .10 is assigned to this virtually impossible situation. Thus, the two-decade scale for the likelihood factors ranges from a value of .10 for a virtually impossible event, through a value of unity for an unexpected but remotely possible event, up to a value of 10 for an expected event. These defined reference points, plus interpolated values, are given in Table 2.

Exposure factor. The greater the exposure to a potentially dangerous situation, the greater the associated risk. The value of 10 is therefore assigned to the situation of continuous exposure, and the value of unity is assigned to the situation of rather rare exposure occurring only a few times per year. Interpolation between these two reference points allows for intermediate values. Thus, the value of three is assigned to the situation of weekly or only occasional exposure. Extrapolation provides for the situation of very rare exposure, and the value of zero would be assigned were there no exposure at all. These exposure factors are given in Table 3.

Possible consequences factor. Damage from a hazardous event can range from minor damage, which is barely noticeable, to catastrophic. This very wide range in damage is established as extending over two decades of numerical values. The relationship between material damage and the consequence factor is represented by the empirical formula, factor $= \left(\frac{\text{damage}}{100}\right)^{0.4}$. Thus, the value of unity is taken as a basis point that represents minor injury, possibly requiring first aid, or material damage of not more than a few hundred dollars. The catastrophe, assigned a value of 100, is a situation that results in many fatalities or a material loss of millions of dollars. Inter-

TABLE 4
ASSIGNED VALUES FOR
POSSIBLE CONSEQUENCES

NUMERIC	DESCRIPTIVE	MONETARY
100[a]	Catastrophe, many fatalities	$> \$10^7$
40	Disaster, multiple fatalities	$\$10^6 - 10^7$
15	Very serious, a fatality	$\$10^5 - 10^6$
7	Serious, serious injury	$\$10^4 - 10^5$
3	Important, disability	$\$10^3 - 10^4$
1[a]	Noticeable, first aid may be needed	$\$10^2 - 10^3$

[a]Defined reference point.

TABLE 5
RISK SCORE VALUES

NUMERIC	DESCRIPTIVE
>320	Very high risk; consider discontinuing operation.
160-320	High risk; immediate correction required.
70-160	Substantial risk; correction required.
20-70	Possible risk; attention needed.
<20	Some slight risk; perhaps acceptable.

mediate values are found by interpolation between these two reference points. Table 4 lists both numeric and descriptive factors for possible consequences.

Consequence factors have two rather different aspects. One is worker injury, fatality, or both; the other is material damage. In spite of possible objections, practicality (e.g., liability insurance) dictates a common scale for these two quite different types of consequences. This common scale also allows for situations where both personal injury and material damage might occur. The consequence factor is then a weighted sum of its two diverse aspects.

Risk Score. The risk score for some potentially hazardous situation is computed as the product of the above three factors. Computed risk scores are readily associated with risks observed for actual situations. For instance, experience indicates that a risk score as low as 20 represents a situation of low risk, one generally considered acceptable. Such risk is far less than the one we ordinarily accept in everyday situations, as when driving to work, mowing the lawn with a power mower, or riding a bicycle for exercise. Each of these activities is far more risky than an industrial situation with a risk score of 20 or below.

Experience also indicates that a situation with a risk score of 70 to 160 is one with definite risk and, according to our current social standards, one where correction is needed. Risk scores of 160 to 320 indicate high risk situations where correction is urgently needed. A very high risk score of more than 320 indicates a situation so risky that ceasing the operation should be considered, at least until interim measures to correct the deficiency have been implemented. If the operation can not be made safe, it should be permanently shut down.

Numerical risk scores and descriptions are listed in Table 5. The classifications are based on experience and are subject to adjustment when experience indicates that this is necessary. Nevertheless, it should be noted that the classifications in Table 5 are very conservative; they provide strong statements for the potential risks involved.

Sample risk score calculation. Imagine the following hypothetical hazardous situation:

> A building contains a number of presses being used to load bomblets with explosive. Historically, the explosive has been known to explode within the die while being pressed. The probability of explosion within the die seems to be related to the rate of compression of the explosive. The damage done by one of these explosions destroys the tool die and usually damages the press. It may cause operator injury, but there have been no operator fatalities. On a particular day, one of the presses is not operating smoothly but sticks at certain points and stalls until pressure is built up to send the tool rushing along. A result of this uneven compression rate can be an explosion which destroys the die and damages the press to the extent of about $5,000.

To determine the risk score for this situation, numerical values are assigned to each component of the risk.

1. *Likelihood.* For the particular scenario above, the likelihood corresponds to "quite possibly could happen," and is assigned a numerical value of six.

2. *Exposure.* The situation occurs "daily." Exposure is thus assigned a value of six.

3. *Possible consequences.* The possible consequences seem to be intermediate between the "important, disability" and the "serious, serious injury." The intermediate value of five is assigned for possible consequences.

The numerical value for the risk score is computed at $6 \times 6 \times 5 = 180$. Such a risk score indicates substantial risk and that correction is required.

EVALUATION OF A PROPOSED RISK REDUCTION MEASURE

The larger the risk score for a situation, the more effective a proposed corrective action is; and the less that the proposed remedy costs, the greater is the justification. A quantitative index for this justification can be derived from numerical values assigned to each of three component factors. These three factors are: (1) the risk score itself, (2) the risk reduction multiplier, and (3) the cost divisor. The latter two factors and methods for calculating justification and cost effectiveness are discussed below.

The risk reduction multiplier. The risk reduction multiplier assigned to a proposed risk-reduction action is set at unity for complete elimination of risk and at zero for an action with no effect. Intermediate values are assigned accordingly. For example, a measure that would reduce risk by about 60% would be assigned a value of 0.6.

The cost divisor. Cost and justification bear an inverse relation. Thus, a cost factor is best expressed as a divisor whose numerical value increases with cost so that increased cost gives less justification.

Experience indicates that the cost divisor is approximately proportional to the cube root of the total dollar amount. These dollar amounts should include actual out-of-pocket cost and capitalized cost for increased operating or overhead expenses. The reference value of unity is assigned to the divisor that represents a total cost of \$100, and the value of 10 is assigned for correction costs of one thousand times greater, or \$100,000. The mathematical relationship can be expressed in the form of an equation:

$$\text{Divisor} = \sqrt[3]{\frac{\text{Total cost}}{100}}$$

Justification and cost effectiveness. A justification factor for a proposed risk-reduction action can be obtained by dividing the risk-reduction multiplier for the proposed action by the cost divisor and then multiplying by the risk score. This justification factor can be used as a measure of cost effectiveness for the proposed action. Numerical values for this have been correlated with experience. For instance, a justification value of less than about 10 indicates that a proposal is of doubtful merit. The risk reduction it provides does not justify the indicated expenditure of time, effort, and money. In this case, endeavors should be directed to other situations. Values between 10 and 20 indicate an action that is justified. Experience also suggests that a justification value greater than 20 indicates a highly worthwhile risk-reduction action.

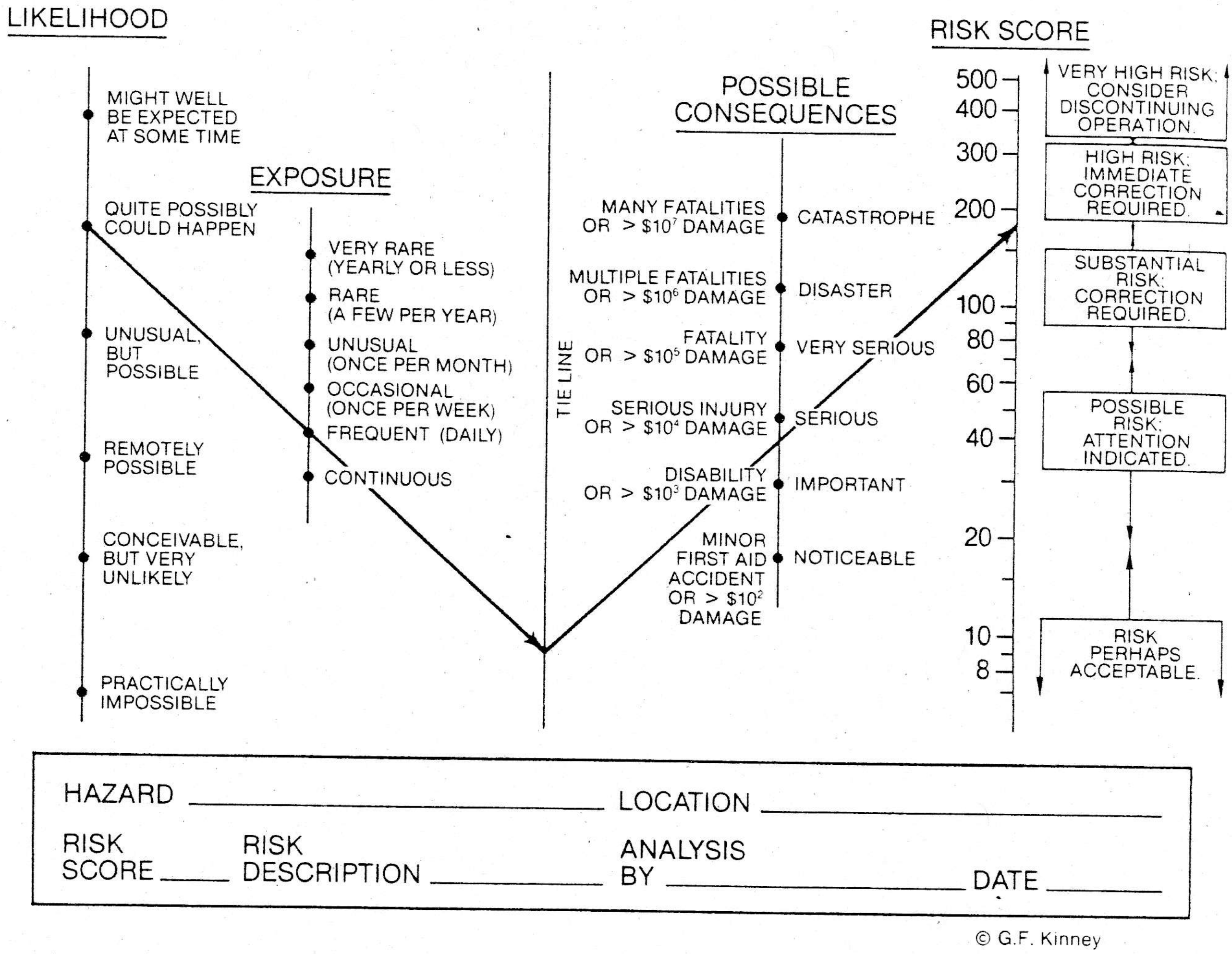
The above justification values provide reference points for an entire scale of justification and cost effectiveness factors. This scale permits ready comparison of the merits of various proposals for reduction of an identified risk. The scale also aids in establishing priorities within a broad risk-reduction program.

Cost effectiveness calculations. Cost effectiveness calculations may be illustrated using the hypothetical bomblet loading press example previously cited. The risk score assigned to that situation was 180, indicating substantial risk and a need for immediate corrective action. One solution might be to dismantle and repair the sticky shaft of the press. The risk reduction could be as much as 90%, so the assigned value for the risk reduction multiplier is 0.9. The cost for regrinding and labor could be as much as \$3,000, so the cost divisor for this solution is $(3{,}000/100)^{1/3} = 3.1$. The overall cost effectiveness factor is then $0.9/3.1 \times 180 = 52$. This is a highly worthwhile solution.

A second solution to the bomblet loading press problem might be to replace the press with a new one. The risk reduction would be at least 95%, so the assigned risk reduction value would be 0.95 or greater. The cost of a new press could be about \$15,000, so the cost divisor is $(15{,}000/100)^{1/3} = 5.3$. The corresponding cost effectiveness is $0.95/5.3 \times 180 = 32$. This is a worthwhile solution, but is less cost effective than having the shaft of the old press reground.

Still another solution to the press loading problem might be to have the operator

FIGURE 1
GRAPHICAL CALCULATION OF RISK SCORE FOR
BOMBLET PRESS LOADING EXAMPLE, USING A NOMOGRAPH



oil the shaft frequently. This would be expected to reduce the risk by 10 or 15% and would have a capitalized cost of only about $500. The assigned effectiveness value is thus 0.125, and the cost divisor is $(500/100)^{1/3} = 1.7$. The cost effectiveness is $0.125/1.7 \times 180 = 13$. This solution is of doubtful merit compared to the other two solutions presented above.

APPLICATION TO SAFETY PROGRAMS

The numerical analyses described above for relative risk and for justification of a proposed procedure constitute important tools for use in safety programs (Fine, 1971). The tables of factors organized, constructed, and presented here simplify this overall approach and make it even more useful. It might seem at first that this constitutes a mere "numbers game," but that is far from correct. These sophisticated methods provide a basis for informed judgment in safety situations. They insure that no important factor has been overlooked and also provide a rating for any given situation in comparison with, and relative to, the many practical situations on which the tables are based. Priorities among possible alternatives may be established objectively. This can constitute a positive contribution to an overall safety program.

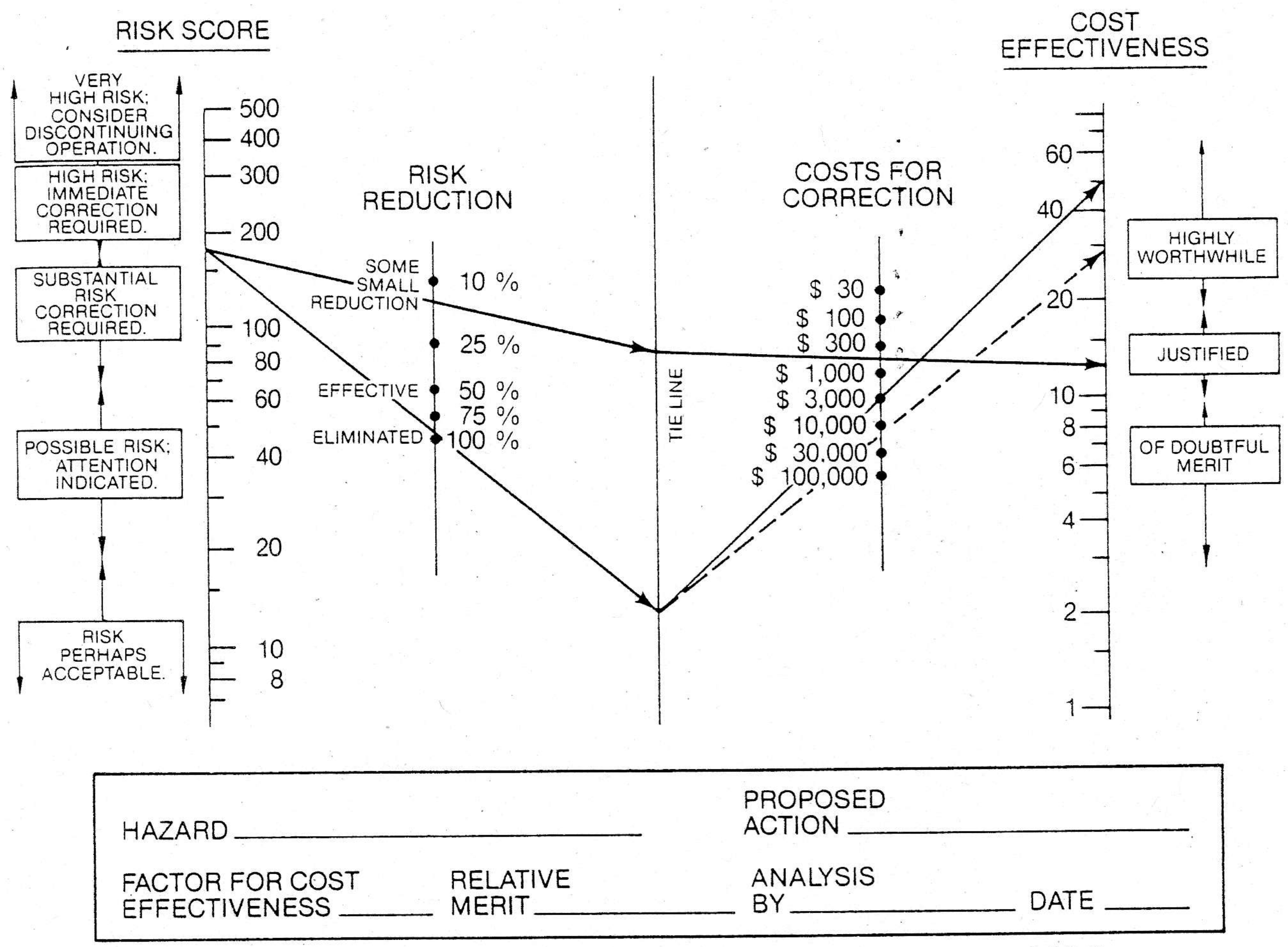
In the following section, a simple means of applying this method to benefit safety programs is demonstrated.

GRAPHICAL SOLUTIONS

The mathematical procedures above are fairly simple, but it is much more convenient to perform them graphically using nomographs.[1] In these nomographs, descriptively

[1]Copies of the nomographs described are available from the authors.

FIGURE 2
GRAPHICAL CALCULATION OF JUSTIFICATION FACTORS FOR BOMBLET PRESS LOADING EXAMPLE, USING A NOMOGRAPH



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labeled points are spaced along the component lines in accordance with the numerical scales already described. For risk score and cost effectiveness, numerical values are provided in addition to the descriptive labels. The use of nomographs in computing risk scores and cost effectiveness is illustrated below, using the bomblet loading press example.

Risk score nomograph. Figure 1 shows this graphical risk score computation. First, the point for a likelihood of "quite possibly could happen" is located along the likelihood axis, since this corresponds to the likelihood of a press explosion. Then, a line is drawn from this point through that for "daily" exposure and extended to the tie-line. Next, a line is drawn from the tie line through a point intermediate between the consequences of "disability" and "serious injury." Finally, extension of this line to the risk score axis indicates a "substantial risk, correction required," with the same numerical value (180) as obtained in the arithmetic computation.

Cost effectiveness nomograph. As Figure 2 shows, the graphical analysis for cost effectiveness is plotted much the same as that for the risk score. This nomograph begins with the risk score itself and proceeds through the estimated risk reduction (either as a percentage or in descriptive terms) and the cost for correction. The justification factor and associated cost effectiveness are then obtained both numerically and in descriptive terms.

SUMMARY

Mathematical methods have been developed for (1) evaluating the risk from a specific hazard and (2) comparing the effectiveness of possible procedures to reduce that risk. The methods demonstrate that risk (and the associated risk score) can be lowered by reducing any of three contributing factors: the *likelihood* of a hazardous event, the *exposure* to that event, and its *possible consequences*. Similarly, a justification or cost effectiveness analysis proceeds on the basis that there is greater justification for a particular safety measure the greater the risk score, the greater the risk reduction, and the less the proposed measure would cost. By such mathematical methods, individual bias is largely eliminated and an objective evaluation obtained. This is a key item in an effective safety engineering program.

A graphical method for performing risk and cost effectiveness analyses has been developed. This graphical method has the following advantages:

1. The analyses can be readily performed in the plant or the field by persons with minimal training because there is no need for involved computations.

2. The methods automatically provide documentation for the analyses and associated recommendations.

3. The numerical values resulting from the calculations enable ready assignment of relative priorities for attention to different unsafe situations.

4. The numerical results also provide a means of comparing benefits obtainable from alternative remedial steps.

5. The graphical method is understandable by operating and management personnel, and has been proven acceptable to both.

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