Chapter 24

Accident and Emergency Management

INTRODUCTION

Accidents are a fact of life, whether they are a careless mishap at home, an unavoidable collision on the freeway, or a miscalculation at a chemical plant. Even in prehistoric times, long before the advent of technology, a club-wielding caveman might have swung at his prey and inadvertently toppled his friend in what can only be classified as an "accident."

As man progressed, so did the severity of his misfortunes. The "Modern Era" has brought about assembly lines, chemical manufacturers, nuclear power plants, and so on, all potentially capability of causing disasters. To keep pace with the changing times, safety precautions must constantly be upgraded. It is no longer sufficient, as with the caveman, to shout the warning, "Watch out with that thing!" Today's problems require more elaborate systems of warnings and controls to minimize the chance of serious accidents.

Industrial accidents occur in many ways—a chemical spill, an explosion, a nuclear power plant melt-down, and so on. There are often problems in transport, with trucks overturning, trains derailing, or ships capsizing. There are "acts of God," such as earthquakes, tsunamis and storms. The one common thread through all of these situations is that they are rarely expected and frequently mismanaged.

Most industrial process plants are safe to be around. Plant management, aided by reliable operators, who are in turn backed up by still-more-reliable automatic controls, does its best to keep operations moving along within the limits usually considered reasonably safe to man and machine. Occasionally, however, there is a "whoosh" or a "bang" that is invariably to the detriment of the operation, endangering investment and human life, and rudely upsetting the plant's loss expectancy.[1]

Accidents have occurred since the birth of civilization. Anyone who crosses a street, rides in a car, or swims in a pool, runs the risk of injury through carelessness, poor judgment, ignorance, or other circumstances. This has not changed throughout history. Current legislation plus a number of accidents and disasters that took place

before the advances of modern technology will be examined in the following pages. This will be followed by a number of illustrative examples, several of which draw heavily on probability and statistics.

LEGISLATION[4–7]

The concern for emergency planning and response is reflected in the legislation[2–4] summarized in this section. Although the Clean Air Act does not cover emergency planning and response in a clear and comprehensive manner, certain elements of the act are particularly significant. These include implementation plans and national emission standards for hazardous air pollutants. The Clean Water Act as well as other legislation pertaining to water pollution provides emergency planning and response that is more developed than it is for air. The Resource Conservation and Recovery Act (RCRA) and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) are two important pieces of legislation that are concerned with preventing releases, and with the requirements for the cleanup of hazardous and toxic sites. RCRA and CERCLA contain specific sections that address emergency planning and response. The Superfund Amendments and Reauthorization Act (SARA) is another important piece of legislation. SARA deals with the cleanup of hazardous waste sites as well as emergency planning and response. Title III, which is the heart of SARA, establishes requirements for emergency planning and "community right to know" for federal, state, and local government, as well as industry. Title III is a major stepping-stone in the protection of the environment, but its principal thrust is to facilitate planning in the event of a catastrophe. The Occupational Safety and Health Act (OSHAct) was enacted by Congress in 1970 and established the Occupational Safety and Health Administration (OSHA), which addressed safety in the workplace. Both EPA and OSHA are mandated to reduce the exposure of hazardous substances over land, sea, and air. The OSHAct is limited to conditions that exist in the workplace, where its jurisdiction covers both safety and health. Frequently, both agencies regulate the same substances but in a different manner as they are overlapping environmental organizations. Developed under the Clean Air Act's (CAA's) Section 112(r), the Risk Management Program (RMP) rule (40 CFR Part 68) is designed to reduce the risk of accidental releases of acutely toxic, flammable, and explosive substances. A list of the regulated substances (138 chemicals) along with their threshold quantities is provided in the Code of Federal Regulations at 40 CFR 68.130.

A brief overview of CERCLA, SARA, OSHA, and RMP is provided in the next four subsections.

Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 was the first major response to the problem of abandoned

hazardous waste sites throughout the nation. CERCLA was the beginning of the remediation of hazardous waste sites. This program was designed to:

1. Develop a comprehensive program to set priorities for cleaning up the worst existing hazardous waste sites.
2. Make responsible parties pay for these cleanups wherever possible.
3. Set up (initially) a $1.6 billion *Hazardous Waste Trust Fund*, known as the "Superfund," for the two-fold purpose of performing remedial cleanups when responsible parties could not be held accountable and responding to emergency situations involving hazardous substances.
4. Advance scientific and technological capabilities in all aspects of hazardous waste management, treatment, and disposal.

CERCLA requires the person in charge of a process or facility to notify the *National Response Center* (NRC) immediately when there is a release of a designated hazardous substance in an amount equal to or greater than a reportable quantity. CERCLA establishes the reportable quantity for releases of designated hazardous substances at one pound, unless otherwise specified. Such releases require notification to government officials to ensure that the need for response can be evaluated and any response can be undertaken in a timely fashion.

The development of the emergency planning and response actions under CERCLA is based primarily on a national contingency plan that was developed under the *Clean Water Act*. Although the actions of CERCLA have the capabilities to handle hazardous and toxic releases, the act was primarily directed toward the cleanup of abandoned hazardous waste sites.

Under Section 7003 of the RCRA legislation (1984), private citizens are authorized to bring legal action against companies, governmental entities, or individual citizens if past or present hazardous waste management practices are believed to pose an imminent danger. Section 7003 applies to past generators as well as to situations or sites where past acts or failures to act may have contributed to a present endangerment of human health and the environment. Citizen rights to sue are limited, however: (1) if the EPA or the state government is diligently bringing and prosecuting a related action under Section 7003 of RCRA or Section 106 of CERCLA, or (2) if the EPA or the state has settled a related action by entering into a consent decree. CERCLA was amended by the *Superfund Amendments and Reauthorization Act* (SARA) in 1986.

Superfund Amendments and Reauthorization Act of 1986 (SARA)

The *Superfund Amendments and Reauthorization Act of 1986* renewed the national commitment to correcting problems arising from previous mismanagement of hazardous wastes. While SARA was similar in many respects to the original law

(i.e., CERCLA), it also contained new approaches to the program's operation. The 1986 Superfund legislation:[5]

1. Reauthorized the program for five more years and increased the size of the cleanup fund from $1.6 billion to $8.5 billion.

2. Set specific cleanup goals and standards, and stressed the achievement of permanent remedies.

3. Expanded the involvement of states and citizens in decision-making.

4. Provided for new enforcement authorities and responsibilities.

5. Increased the focus on human health problems caused by hazardous waste sites.

The new law is more specific than the original statute with regard to remedies to be used at Superfund sites, public participation, and the accomplishment of cleanup activities. The most important part of SARA with respect to public participation is Title III, which addresses the important issues of community awareness and participation in the event of a chemical release.

As mentioned earlier, Title III of SARA addresses hazardous materials release; its subtitle is the *Emergency Planning and Community Right-to-Know Act of 1986*. Title III establishes requirements for emergency planning, hazardous emissions reporting, emergency notification, and "community right-to-know." The objectives of Title III are to improve local chemical emergency response capabilities, primarily through improved emergency planning and notification, and to provide citizens and local governments with access to information about chemicals in their localities. The major sections of Title III that aid in the development of contingency plans are as follows:

1. Emergency Planning (Sections 301–303).

2. Emergency Notification (Section 304).

3. Community Right To Know Reporting Requirements (Sections 311 and 312).

4. Toxic Chemicals Release Reporting—Emissions Inventory (Section 313).

Title III also developed time frames for the implementation of the Emergency Planning and Community Right-to-Know Act of 1986.

Sections 301–303 of Title III, which are responsible for emergency planning, are designed to develop state and local governments' emergency response and preparedness capabilities through better coordination and planning, especially within local communities.

Occupational Safety and Health Act (OSHA)

Congress intended that OSHA be enforced through specific standards in an effort to achieve a safe and healthy working environment. A "general duty clause" was added to attempt to cover those obvious situations that were admitted by all concerned but for which no specific standard existed. The OSHA standards are an extensive

compilation of regulations, some that apply to all employers (such as eye and face protection) and some that apply to workers who are engaged in a specific type of work (such as welding or crane operation). Employers are obligated to familiarize themselves with the standards and comply with them at all times.

Health issues, most importantly, contaminants in the workplace, have become OSHA's primary concern. Health problems are complex and difficult to define. Because of this, OSHA has been slow to implement health standards. To be complete, each standard requires medical surveillance, record keeping, monitoring and physical reviews. On the other side of the ledger, safety hazards are aspects of the work environment that are expected to cause death or serious physical harm immediately or before the imminence of such danger can be eliminated.

Probably one of the most important safety and health standards ever adopted is the OSHA hazard communication standard, more properly known as the "right to know" laws. The hazard communication standard requires employers to communicate information to the employees on hazardous chemicals that exist within the workplace. The program requires employers to craft a written hazard communication program, keep *material safety data sheets* (MSDSs) for all hazardous chemicals at the workplace and provide employees with training on those hazardous chemicals, and assure that proper warning labels are in place.

USEPA's Risk Management Program

In the RMP rule, EPA requires a *Risk Management Plan* that summarizes how a facility is to comply with EPA's RMP requirements. It details methods and results of hazard assessment, accident prevention, and emergency response programs instituted at the facility. The hazard assessment shows the area surrounding the facility and the population potentially affected by accidental releases. EPA requirements include a three-tiered approach for affected facilities. A facility is affected if a process unit

Table 24.1   RMP Approach

Program	Description
1	Facilities submit RMP, complete registration of processes, analyze worst-case release scenario, complete 5-year accident history, coordinate with local emergency planning and response agencies; and, certify that the source's worst-case release would not reach the nearest public receptors.
2	Facilities submit RMP, complete registration of processes, develop and implement a management system; conduct a hazard risk assessment; implement certain prevention steps; develop and implement an emergency response program; and, submit data on prevention program elements.
3	Facilities submit RMP, complete registration of processes, develop and implement a management system; conduct a hazard risk assessment; implement prevention requirements; develop and implement an emergency response program; and, provide data on prevention program elements.

manufactures, processes, uses, stores, or otherwise handles any of the listed chemicals at or above the threshold quantities. The RMP approach is summarized in Table 24.1.

HAZARD RISK ASSESSMENT[7–10]

There are many definitions for the word risk. It is a combination of uncertainty and damage; a ratio of hazards to safeguards; a triplet combination of event, probability, and consequences; or even a measure of economic loss or human injury in terms of both the incident likelihood and the magnitude of the loss or injury. People face all kinds of risks everyday, some voluntarily and others involuntarily. Therefore, risk plays a very important role in today's world. Studies on cancer caused a turning point in the world of risk because it opened the eyes of risk engineers and health science professionals to the world of risk assessments.

Risk evaluation of accidents serves a dual purpose. It estimates the probability that an accident will occur and also assesses the severity of the consequences of an accident. Consequences may include damage to the surrounding environment, financial loss, or injury to life. This section is primarily concerned with the methods used to identify hazards and the causes and consequences of accidents. Issues dealing with health risks have been explored in the previous chapter. Risk assessment of accidents provides an effective way to help ensure either that a mishap does not occur or that the likelihood of an accident is reduced. The result of a hazard risk assessment allows concerned parties to take precautions to prevent an accident before it happens.

Regarding definitions, the first thing an individual needs to know is what exactly is an accident. An accident is an unexpected event that has undesirable consequences. The causes of accidents have to be identified in order to help prevent accidents from occurring. Any situation or characteristic of a system, plant, or process that has the potential to cause damage to life, property, or the environment is considered a hazard. A hazard can also be defined as any characteristic that has the potential to cause an accident. The severity of a hazard plays a large part in the potential amount of damage a hazard can cause if it occurs. Hazard risk is the probability that human injury, damage to property, damage to the environment, or financial loss will occur. An acceptable risk is a risk whose probability is unlikely to occur during the lifetime of the plant or process. An acceptable risk can also be defined as an accident that has a high probability of occurring, but with negligible consequences. Risks can be ranked qualitatively in categories of high, medium, and low. Risk can also be ranked quantitatively as an annual number of fatalities per million affected individuals. This is normally denoted as a number times one millionth, for example, 3×10^{-6}. This number indicates that on average three will die every year out of one million individuals. Another quantitative approach that has become popular in industry is the Fatal Accident Rate (FAR) concept. This determines or estimates the number of fatalities over the lifetime of 1000 workers. The lifetime of a worker is defined as 10^5 hours, which is based on a 40-hour work week for 50 years. A reasonable FAR for a chemical plant is 3.0 with 4.0 usually taken as a maximum. A FAR of 3.0 means that there are 3 deaths for every 1000 workers over a 50-year period. Interestingly, the FAR for an individual at home is
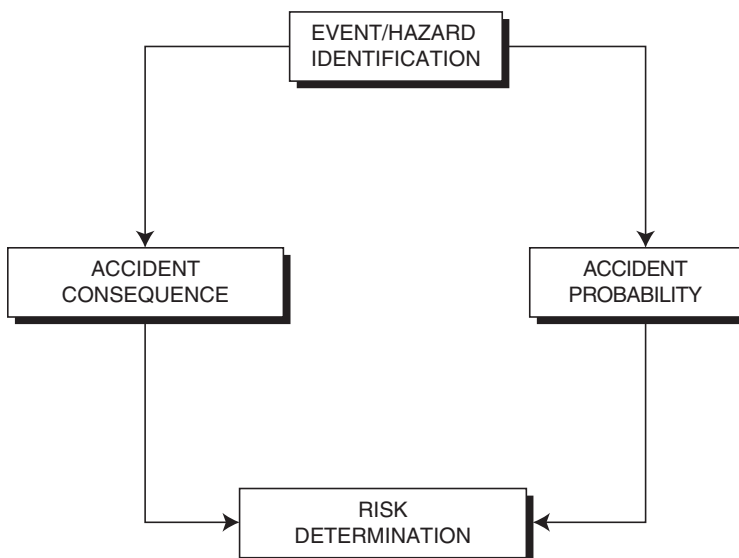
Figure 24.1   Hazard risk assessment flowchart.

approximately 3.0. Some of the illustrative examples later in this chapter compliment many of the concepts described below with technical calculations and elaborations.

As with Health Risk Assessment (HRA), there are four key steps involved in a Hazard Risk Assessment (HZRA). These are presented in Figure 24.1. A more detailed flowchart is presented in Figure 24.2 if the system in question is a chemical plant. These steps are detailed below:

1. A brief description of the equipment and chemicals used in the plant is needed.

2. Any hazard in the system has to be identified. Hazards that may occur in a chemical plant include:

   a. Fire
   b. Toxic vapor release
   c. Slippage
   d. Corrosion
   e. Explosions
   f. Rupture of pressurized vessel
   g. Heat exchanger failure
   h. Runaway reactions

3. The event or series of events that will initiate an accident has to be identified. An event could be a failure to follow correct safety procedures, improperly repaired equipment, or a safety mechanism.

4. The probability that the accident will occur has to be determined. For example, if a chemical plant has a given life, what is the probability that the temperature in a heat exchanger will exceed the specified temperature range? The
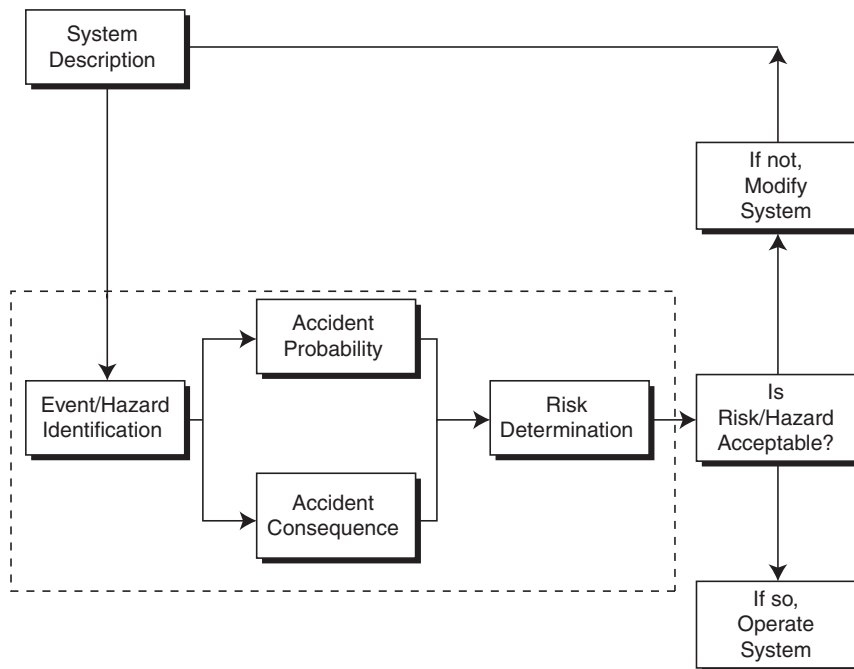
Figure 24.2   Chemical plant hazard risk assessment flowchart.

probability can be ranked from low to high. A low probability means that it is unlikely for the event to occur during the life of the plant. A medium probability suggests that there is a possibility that the event will occur. A high probability means that the event will probably occur during the life of the plant.

5. The severity of the consequences of the accident must be determined.

6. The information from (4) and (5) are combined. If the probability of the accident and the severity of its consequences are low, then the risk is usually deemed acceptable and the plant should be allowed to operate. If the probability of occurrence is too high or the damage to the surroundings is too great, then the risk is usually unacceptable and the system needs to be modified to minimize these effects.

The heart of the hazard risk assessment algorithm provided is enclosed in the dashed box of Figure 24.2. The algorithm allows for re-evaluation of the process if the risk is deemed unacceptable (the process is repeated starting with either step one or two).

As evident in the lessons from past accidents, it is essential for industry to abide by stringent safety procedures. The more knowledgeable the personnel, from the management to the operators of a plant, and the more information that is available to them, the less likely a serious incident will occur. The new regulations, and especially Title III of 1986, help to ensure that safety practices are up to standard. However, these regulations should only provide a minimum standard. It should be up to the companies, and

specifically the plants, to see that every possible measure is taken to ensure the safety and well-being of the community and the environment in the surrounding area. It is also up to the community itself, under Title III, to be aware of what goes on inside local industry, and to prepare for any problems that might arise.

APPLICATIONS

The remainder of this chapter is devoted to illustrative examples, many of which contain technical developmental material. A good number of applications have been drawn from National Science Foundation (NSF) literature,[11–16] and two other sources.[6,18]

ILLUSTRATIVE EXAMPLE 24.1

Consider the release of a toxic gas from a storage tank. List and discuss possible causes for the release.

SOLUTION: Some possible causes for a toxic gas release from a storage tank are:

1. Rupture in storage tank.
2. Fire in tank farm.
3. Explosion of storage tank.
4. Collapse of tank due to earthquake.
5. Rupture in main line.
6. Leak in line or from tank. ■

ILLUSTRATIVE EXAMPLE 24.2

What are potential consequences if a pinhole leak develops in a tube in a reboiler of a distillation column?

SOLUTION: Potential consequences of a pinhole leak include:

1. Changes in pressure.
2. Changes in temperature.
3. Chemical reaction, with accompanying over-pressure, over-temperature, and formation of other phases.
4. Leakage of toxics/flammables to an undesirable location.
5. Corrosion, embrittlement, or similar effect. ■

ILLUSTRATIVE EXAMPLE 24.3

Discuss the three major factors that often influence equipment (such as heat exchangers) failure rates.

SOLUTION: The variation of equipment failure rate with time-in-service is usually represented by three regions:

1. At initial start up, the rate of equipment failure is high due to factors such as improper installation or problems as a result of defective equipment.

2. The rate of failure declines when the equipment is under normal operation. At this point, failures are chance occurrences.

3. The rate of failure increases as the equipment ages. This can be termed as wear-out failure.

This failure rate with time is discussed later in Illustrative Example 24.8; its graphical representation is known as the "bathtub curve" (or Weibull distribution to statisticians) because of its shape.[16]   ■

ILLUSTRATIVE EXAMPLE 24.4

Calculate the upper flammability limit (UFL) and the lower flammability limit (LFL) of a gas mixture that consists of 30% methane (m), 50% ethane (e), and 20% pentane (p) by volume. Employ the following equation:

$$\text{FL(mixture, } n \text{ components)} = \sum_{i=1}^{n} \frac{1}{(f_i/\text{FL}_i)}; \quad f_i = \text{mole fraction } i \qquad (24.1)$$

SOLUTION: Use the expanded form of the equation provided above:

$$\text{LFL(mix)} = \frac{1}{(f_m/\text{LFL}_m) + (f_e/\text{LFL}_e) + (f_p/\text{LFL}_p)}$$

Substituting,

$$\text{LFL(mix)} = \frac{1}{(0.30/0.046) + (0.5/0.35) + (0.2/0.014)} = 0.0285 = 2.85\%$$

$$\text{UFL(mix)} = \frac{1}{(f_m/\text{UFL}_m) + (f_e/\text{UFL}_e) + (f_p/\text{UFL}_p)}$$

Substituting,

$$\text{UFL(mix)} = \frac{1}{(0.30/0.142) + (0.5/0.151) + (0.2/0.078)} = 0.125 = 1.25\% \qquad ■$$

ILLUSTRATIVE EXAMPLE 24.5

Two boiler tubes are drawn in succession from a lot of 100 tubes, of which 10 are defective. What is the probability that both tubes are defective if (a) the first is replaced before the second is drawn and (b) the first is not replaced before the second is drawn.

SOLUTION: The probability of event A, $P(A)$, can be interpreted as a theoretical relative frequency; i.e., a number about which the relative frequency of event A tends to cluster as n, the number of times a random experiment (on the event) is performed, increases indefinitely. This is the objective interpretation of probability. Probability can also be interpreted subjectively as a measure of the degree of belief, on a scale from 0 to 1, that the event A occurs. This interpretation

is frequently used in ordinary conversation. For example, if someone says, "The probability I (the author) will go to the racetrack today is 90%," then 90% is a measure of the person's belief that he or she will go to the racetrack. This interpretation is also used when, in the absence of concrete data needed to estimate an unknown probability on the basis of observed relative frequency, the personal opinion of an expert is sought to provide the estimate.

The conditional probability of event B given A is denoted by $P(B \mid A)$ and defined as follows:

$$P(B \mid A) = P(AB)/P(A) \qquad (24.2)$$

where $P(AB)$ is the probability that events A and B will occur. $P(B \mid A)$ can be interpreted as the proportion of A occurrences that also feature the occurrence of B.

First, determine the probability that the first tube is defective, $P(A)$. Since 10 out of 100 are defective:

$$P(A) = (10/100)$$

Determine the probability that the second tube is defective if the first is replaced, $P(B)$. Since the first tube is replaced, the probability for the defective tube is the same:

$$P(B) = (10/100)$$

Determine the probability that the two tubes are defective if the first is replaced, that is, $P(AB)$:

$$P(AB) = P(A)P(B)$$
$$= (10/100)(10/100)$$
$$= 1/100$$

Determine the probability that the second tube is defective if the first tube is not replaced, that is, $P(B \mid A)$. Since the remaining lot contains 99 tubes:

$$P(B \mid A) = 9/99$$

Finally, determine the probability that both tubes are defective if the first tube is not replaced, that is, $P'(AB)$:

$$P'(AB) = P(A)P(B \mid A)$$
$$= (10/100)(9/99)$$
$$= 1/110$$

Conditional probability can be used to formulate a definition for the independence of two events A and B. Event B is defined to be independent of event A only if $P(B \mid A) = P(B)$. Similarly, event A is defined to be independent of event B if and only if $P(A \mid B) = P(A)$. From the definition of conditional probability, one can deduce the logically equivalent definition of the independence of event A and event B if and only if $P(AB) = P(A) \times P(B)$.   ∎

ILLUSTRATIVE EXAMPLE 24.6

The difference between the magnitude of a large earthquake at a nuclear power plant, on the Richter scale, and the threshold value of 3.25, is a random variable X having the following

probability distribution function (pdf):

$$f(X) = 1.7 \exp(-1.7X); \quad X > 0$$
$$= 0; \qquad\qquad\qquad \text{elsewhere}$$

Find the probability that X will have a value between 2 and 6; that is, $P(2 < X < 6)$.

SOLUTION: The probability distribution of a random variable concerns the distribution of probability over the range of the random variable. The distribution of probability is specified by the probability distribution function (pdf). The random variable may be discrete or continuous. Special pdfs finding application in risk analysis are considered in later problems. The pdf of a continuous random variable X has the following properties:

1. $\displaystyle\int_a^b f(x)\,dx = P(a < X < b)$

2. $f(x) \geq 0$

3. $\displaystyle\int_{-\infty}^{\infty} f(x)\,dx = 1$ (24.3)

where $P(a < X < b)$ = probability assigned to an outcome or an event corresponding to the number x in the range of X between a and b

$f(x)$ = pdf of the continuous random variable X.

Property (1) indicates that the pdf of a continuous random variable generates probability by integration of the pdf over the interval whose probability is required. When this interval contracts to a single value, the integral over the interval becomes zero. Therefore, the probability associated with any particular value of a continuous random variable is zero. Consequently, if X is continuous,

$$P(a \leq X \leq b) = P(a < X \leq b)$$
$$= P(a < X < b)$$ (24.4)

Property (2) restricts the values of $f(x)$ to non-negative numbers. Property (3) follows from the fact that:

$$P(-\infty < X < \infty) = 1$$ (24.5)

Calculate the probability that X will have a value between 2 and 6:

$$P(2 < X < 6) = \int_2^6 f(x)\,dx$$

$$= \int_2^6 1.7 \exp(-1.7x)\,dx$$

Since $\int \exp(ax)\,dx = (1/a)\exp(ax)$,

$$P(2 < X < 6) = -\exp(-1.7x)\big|_2^6$$

$$= \exp[(-1.7)(2)] - \exp[(-1.7)(6)]$$

$$= 0.0333 \qquad\qquad \blacksquare$$

The pdf of a discrete (rather than a continuous) random variable X is specified by $f(x)$ where $f(x)$ has the following essential properties:

1. $f(x) = P(X = x)$

    $\qquad$ = probability assigned to the outcome corresponding to the

    $\qquad\qquad$ number x in the range of X

2. $f(x) \geq 0$ $\hfill$ (24.6)

ILLUSTRATIVE EXAMPLE 24.7

A coolant sprinkler system in a reactor has 20 independent spray components each of which fails with a probability of 0.1. The coolant system is considered to "fail" only if four or more of the sprays fail. What is the probability that the sprinkler systems fails?

SOLUTION: Several probability distributions figure prominently in reliability calculations. The binomial distribution is one of them. Consider n independent performances of a random experiment with mutually exclusive outcomes which can be classified "success" or "failure". The words "success" and "failure" are to be regarded as labels for two mutually exclusive categories of outcomes of the random experiment. They do not necessarily have the ordinary connotation of success or failure. Assume that P, the probability of success on any performances of the random experiment, is constant. Let $q = 1 - P$ be the probability of failure. The probability distribution of x, the number of successes in n performances of the random experiment is the binomial distribution with probability distribution function specified by:

$$f(x) = \frac{P^x q^{n-x} n!}{x!(n-x)!}; \quad x = 0, 1, 2, \ldots, n \hfill (24.7)$$

where $f(x)$ is the probability of x successes in n performances and n is the number of independent performances of a random experiment. The binomial distribution can therefore be used to calculate the reliability of a redundant system. A redundant system consisting of n identical components is a system which fails only if more than r components fail. Typical examples include single-usage equipment such as missile engines, short-life batteries, and flash bulbs which are required to operate for one time period and are not reused.

$\qquad$ Assume that the n components are independent with respect to failure, and that the reliability of each is $1 - P$. One may associate "success" with the failure of a component. Then x, the

number of failures, has a binomial pdf and the reliability of the random system is:

$$P(x \leq r) = \sum_{x=0}^{r} \frac{P^x q^{n-x} n!}{x!(n-x)!} \tag{24.8}$$

Let x denote the number of components which fail. Identify the value of n, P, and q from the problem statement.

$$n = 20$$
$$P = 0.1$$
$$q = 0.9$$

Calculate the probability that the sprinkler system fails (i.e., $P(X \geq 4)$) by using the binomial distribution equation:

$$P(X \geq 4) = \sum_{x=4}^{20} \{P^x q^{n-x} n! / [x!(n-x)!]\} \tag{24.8}$$

Note that calculation can be simplified by the fact that $P(X \geq 4) = 1 - P(X \leq 3)$. Therefore,

$$P(X \geq 4) = 1 - P(X \leq 3)$$

$$= 1 - \sum_{x=0}^{3} (0.1)^x (0.9)^{20-x} 20! / [x!(20-x)!]$$

$$= 0.13 = 13\% \qquad \blacksquare$$

ILLUSTRATIVE EXAMPLE 24.8

Assume the time to failure (in hours), t, of a tube in a heat exchanger has a Weibull distribution with $\alpha = 1.3 \times 10^{-3}$ and $\beta = 0.77$. Find the probability that a tube in a heat exchanger will fail in 1000 hours.

SOLUTION: Frequently, and as discussed earlier, the failure rate of equipment exhibits three states: a break-in stage with a declining failure rate, a useful life stage characterized by a fairly constant failure rate, and a wear out period characterized by an increasing failure rate. A failure rate curve exhibiting these three phases is called a *bathtub curve*. The Weibull distribution provides a mathematical model of all three states of the bathtub curve. The probability distribution function is given by:[16]

$$f(t) = \alpha \beta t^{\beta-1} e^{-\int_{0}^{t} \alpha \beta t^{\beta-1} dt}$$

$$= \alpha \beta t^{\beta-1} e^{-\alpha t^{\beta}}; \quad t > 0, \alpha > 0, \beta > 0 \tag{24.9}$$

where a and b are constants.

The pdf for the heat exchanger tube is then defined as

$$f(t) = \alpha \beta t^{\beta-1} e^{-\alpha t^{\beta}} = 1.3 \times 10^{-3}(0.77)(t^{0.77-1})(e^{(-1.3 \times 10^{-3})(t^{0.77})}); \quad t > 0$$

The probability that a heat exchanger will fail within 100 hours (i.e., $P(t < 1000)$), can now be calculated

$$P(t < 1000) = \int_{0}^{1000} f(t)\,dt = 1 - e^{(-1.3 \times 10^{-3})(1000^{0.77})} = 0.23$$

∎

ILLUSTRATIVE EXAMPLE 24.9

The measurement of the pitch diameter of an acceptable thread of a boiler tube is normally distributed with mean of 0.4008 inch and standard deviation of 0.0004 inch. The specifications are given as 0.4000 ± 0.0010. What is the probability of a "defect" occurring?

SOLUTION: When time to failure, t, has a normal distribution, its pdf is given by:

$$f(t) = \frac{1}{(2\pi)^{1/2}\sigma} e^{-0.5[(t-\mu)/\sigma]^{1/2}} \tag{24.10}$$

where μ is the mean value of t and σ is the standard deviation of t. Thus, if t is normally distributed with mean μ and standard deviation σ, then the random variable, $(t - \mu)/\sigma$, is also normally distributed with mean 0 and standard deviation 1. The term $(t - \mu)\sigma$ is called a standard normal variable (designated by Z) and the graph of its pdf is called a standard normal curve. Table 24.2 provides a tabulation of areas under a standard normal curve to the right of Z_0 for non-negative values of Z_0.[16] From this table, probabilities about a standard normal variable, Z, can be determined. This may now be applied to the solution at hand.

In order to calculate the probability of a defect occurring, the probability of meeting the specification must first be calculated. Determine the standard normal variable, Z:

$$\begin{aligned} Z &= (X - \mu)/\sigma \\ &= (X - 0.4008)/0.0004 \end{aligned} \tag{24.11}$$

Determine the lower and upper limits of the probability of meeting specification:

$$\text{Lower limit (LL)} = 0.4000 - 0.0010 = 0.3990$$
$$\text{Upper limit (UL)} = 0.4000 + 0.0010 = 0.4010$$

Determine the probability of meeting specification, P_s, from the area under the standard normal curve between the lower and upper limits:

$$\begin{aligned} P_s &= P[(LL - \mu)/\sigma < Z < (UL - \mu)/\sigma] \\ &= P\{[(0.3990 - 0.4008)/(0.0004)] \\ &\quad < Z < [(0.4010 - 0.4008)/(0.0004)]\} \\ &= P(-4.5 < Z < 0.5) \end{aligned}$$

From Table 24.2

$$P_s = 0.5 + 0.191 = 0.61 = 61\%$$

Table 24.2 Standard Normal Variables

				Next decimal place of Z_0					
Z_0	0	1	2	3	4	5	6	7	8	9
0.0	0.500	0.496	0.492	0.488	0.484	0.480	0.476	0.472	0.468	0.464
0.1	0.460	0.456	0.452	0.448	0.444	0.440	0.436	0.433	0.429	0.425
0.2	0.421	0.417	0.413	0.409	0.405	0.401	0.397	0.394	0.390	0.386
0.3	0.382	0.378	0.374	0.371	0.367	0.363	0.359	0.356	0.352	0.348
0.4	0.345	0.341	0.337	0.334	0.330	0.326	0.323	0.319	0.316	0.312
0.5	0.309	0.305	0.302	0.298	0.295	0.291	0.288	0.284	0.281	0.278
0.6	0.274	0.271	0.268	0.264	0.261	0.258	0.255	0.251	0.248	0.245
0.7	0.242	0.239	0.236	0.233	0.230	0.227	0.224	0.221	0.218	0.215
0.8	0.212	0.209	0.206	0.203	0.200	0.198	0.195	0.192	0.189	0.187
0.9	0.184	0.181	0.179	0.176	0.174	0.171	0.189	0.166	0.164	0.161
1.0	0.159	0.156	0.154	0.152	0.149	0.147	0.145	0.142	0.140	0.138
1.1	0.136	0.133	0.131	0.129	0.127	0.125	0.123	0.121	0.119	0.117
1.2	0.115	0.113	0.111	0.109	0.107	0.106	0.104	0.102	0.100	0.099
1.3	0.097	0.095	0.093	0.092	0.090	0.089	0.087	0.085	0.084	0.082
1.4	0.081	0.079	0.078	0.076	0.075	0.074	0.072	0.071	0.069	0.068
1.5	0.067	0.066	0.064	0.063	0.062	0.061	0.059	0.058	0.057	0.056
1.6	0.055	0.054	0.053	0.052	0.051	0.049	0.048	0.047	0.046	0.046
1.7	0.045	0.044	0.043	0.042	0.041	0.040	0.039	0.038	0.038	0.037

(Continued)

Table 24.2 *Continued*

Z_0					Next decimal place of Z_0					
	0	1	2	3	4	5	6	7	8	9
1.8	0.036	0.035	0.034	0.034	0.033	0.032	0.031	0.031	0.030	0.029
1.9	0.029	0.028	0.027	0.027	0.026	0.026	0.025	0.024	0.024	0.023
2.0	0.023	0.022	0.022	0.021	0.021	0.020	0.020	0.019	0.019	0.018
2.1	0.018	0.017	0.017	0.017	0.016	0.016	0.015	0.015	0.015	0.014
2.2	0.014	0.014	0.013	0.013	0.013	0.012	0.012	0.012	0.011	0.011
2.3	0.011	0.010	0.010	0.010	0.010	0.009	0.009	0.009	0.009	0.008
2.4	0.008	0.008	0.008	0.008	0.007	0.007	0.007	0.007	0.007	0.006
2.5	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.005	0.005
2.6	0.005	0.005	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
2.7	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
2.8	0.003	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
2.9	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.001	0.001	0.001

Detail of tail ($0._2135$, for example, means 0.00135)

Z_0	0	1	2	3	4	5	6	7	8	9
2	$0._1228$	$0._1179$	$0._1139$	$0._1107$	$0._2820$	$0._2621$	$0._2466$	$0._2347$	$0._2256$	$0._2187$
3	$0._2135$	$0._3968$	$0._3687$	$0._3483$	$0._3337$	$0._3233$	$0._3159$	$0._3108$	$0._4723$	$0._4481$
4	$0._4317$	$0._4207$	$0._4133$	$0._5854$	$0._5541$	$0._5340$	$0._5211$	$0._5130$	$0._6793$	$0._6479$
5	$0._6287$	$0._6170$	$0._7996$	$0._7579$	$0._7333$	$0._7190$	$0._7107$	$0._8599$	$0._8332$	$0._8182$
0	1	2	3	4	5	6	7	8	9	

Finally, calculate the probability of a defect occurring, P_d:

$$P_d = 1 - P_s$$
$$= 1 - 0.69$$
$$= 0.31 = 31\%$$ ■

ILLUSTRATIVE EXAMPLE 24.10

Three thermometers (A, B, C) are positioned near the outlet of a heat exchanger. Assume that the individual thermometer component lifetimes are normally distributed with means and standard deviations provided in Table 24.3.

Using the following random numbers, simulate the lifetime (time to failure) of the temperature recording system and estimate its mean and standard deviation. The lifetime to failure is defined as the time (in weeks) for one of the thermometers to "fail".

Monte Carlo simulation is a procedure for mimicking observations on a random variable that permits verification of results that would ordinarily require difficult mathematical calculations or extensive experimentation. The method normally uses computer programs called *random number generators*. A *random number* is a number selected from the interval (0, 1) in such a way that the probabilities that the number comes from any two subintervals of equal length are equal. For example, the probability the number is in the sub-interval (0.1, 0.3) is the same as the probability that the number is in the subinterval (0.5, 0.7). Thus, random numbers are observations on a random variable X having a uniform distribution on the interval (0, 1). This means that the pdf of X is specified by:

$$f(x) = 1; \quad 0 < x < 1$$
$$= 0; \quad \text{elsewhere}$$

The above pdf assigns equal probability to subintervals of equal length in the interval (0, 1). Using random number generators, Monte Carlo simulation can generate observed values of a random variable having any specified pdf. For example, to generate observed values of T, the time to failure, when T is assumed to have a pdf specified by $f(t)$, first use the random number generator to generate a value of X between 0 and 1. The solution is an observed value of the random variable T having pdf specified by $f(t)$. Additional information on Monte Carlo methods is provided in Chapter 26.

SOLUTION: Let T_A, T_B, and T_C denote the lifetimes of thermometer components A, B, and C, respectively. Let T_S denote the lifetime of the system. First determine the values of standard normal variable Z and T_A for component A using the 10 random numbers given. Note that the random number generated is the cumulative probability shown in Table 24.4. Also note that $T = \mu + (\sigma)(Z)$.

Table 24.3   Thermometer Failure Data; Illustrative Example 24.10

	A	B	C
Mean (weeks)	100	90	80
Standard deviation (weeks)	30	20	10

Table 24.4   Random Numbers; Illustrated Example 24.10

For A		For B		For C	
0.52	0.01	0.77	0.67	0.14	0.90
0.80	0.50	0.54	0.31	0.39	0.28
0.45	0.29	0.96	0.34	0.06	0.51
0.68	0.34	0.02	0.00	0.86	0.56
0.59	0.46	0.73	0.48	0.87	0.82

Random No.		Z	T_A
0.52	From Table 24.4;	0.05	$T_A = 100 + 30(0.05) = 102$
0.80		0.84	125
0.45		-0.13	96
0.68		0.47	114
0.59		0.23	107
0.01		-2.33	30
0.50		0.00	100
0.29		-0.55	84
0.34		-0.41	88
0.46		-0.10	97

Next, determine the values of standard normal variable Z and T_B for component B using the 10 random numbers given.

Random No.		Z	T_B
0.77	From Table 24.4;	0.74	$T_B = 90 + 20(0.74) = 105$
0.54		0.10	92
0.96		1.75	125
0.02		-2.05	49
0.73		0.61	102
0.67		0.44	99
0.31		-0.50	80
0.34		-0.41	82
0.00		-3.90	12
0.48		-0.05	89

Determine the values of standard normal variable Z and T_C for component C using the 10 random numbers given.

Random No.		Z	T_C
0.14	From Table 24.4;	-1.08	$T_C = 80 + 10(-1.08) = 69$
0.39		-0.28	77
0.06		-1.56	64
0.86		1.08	91
0.87		1.13	91
0.90		1.28	93

0.28	−0.58	74
0.51	0.03	80
0.56	0.15	81
0.82	0.92	89

For each random value (10) of each component (A, B, C), determine the system lifetime, T_S.

T_A	T_B	T_C	T_S	
102	105	69	69	(minimum of A, B, and C)
125	92	77	77	
96	125	64	64	
114	49	91	49	
107	102	91	91	
30	99	93	30	
100	80	74	74	
84	82	80	80	
88	12	81	12	
97	89	89	89	
			Total = 635	

Calculate the mean value of T_S.

$$\text{Mean} = 635/10$$
$$= 63.5 \text{ weeks}$$

Calculate the standard deviation of T_S.

T_S	$(T_S - \mu)^2$
69	$(69 - 63.5)^2 = 30.25$
77	182.25
64	0.25
49	210.25
91	756.25
30	1122.25
74	110.25
80	272.25
12	2652.25
89	650.25
	Total = 5987.00

By definition,

$$\text{Standard deviation} = \left(\frac{\sum (T_s - \mu)^2}{n - 1}\right)^{0.5} ; n = 10 = (5987/9)^{0.5}$$

$$= 25.8 \text{ weeks} \qquad \blacksquare$$
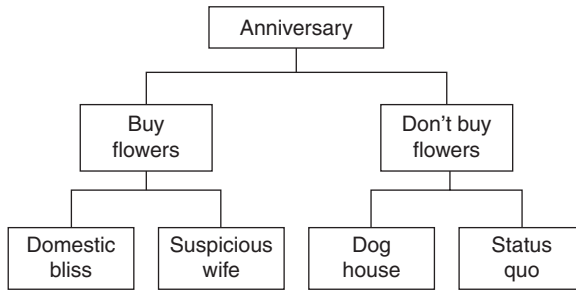
Figure 24.3   Event tree; Illustrative Example 24.11.

ILLUSTRATIVE EXAMPLE 24.11

Construct a decision tree, given the following sequence of events.

> Date: a married couple's anniversary
>
> Husband's decisions: buy flowers or do not buy flowers
>
> Consequences (buy flowers): domestic bliss or suspicious wife
>
> Consequences (do not buy flowers): status quo or wife in tears/husband in doghouse

SOLUTION: A *decision tree* provides a diagrammatic representative of sequences that begin with a so-called initiating event and terminate in one or more consequences. It finds application in many engineering and accident management calculations.

The bottom four events provided in Figure 24.3 evolve from what may be defined as *resolution of uncertainty points*. This is an example of an "event" tree. In contrast to a "fault" tree which works backward from a consequence to possible causes, an event tree works forward from the initiating (or top) event to all possible consequences.   ■

ILLUSTRATIVE EXAMPLE 24.12

If a building fire occurs, a smoke alarm sounds with probability 0.9. The sprinkler system functions with probability 0.7 whether or not the smoke alarm sounds. The consequences are minor
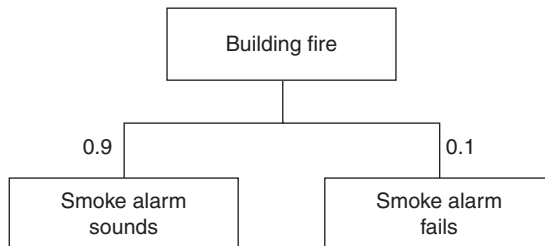
Figure 24.4   Event tree I; Illustrative Example 24.12.

fire damage (alarm sounds, sprinkler works), moderate fire damage with few injuries (alarm sounds, sprinkler fails), moderate fire damage with many injuries (alarm fails, sprinkler works), and major fire damage with many injuries (alarm fails, sprinkler fails). Construct an event tree and indicate the probabilities for each of the four consequences.

SOLUTION: As described in the previous illustrative example, an event tree provides a diagrammatic representation of event sequences that begin with a so-called *initiating* event and terminate in one or more undesirable consequences. In contrast to a fault tree (considered in the next illustrative example) which works backward from an undesirable consequence to possible causes, an event tree works forward from the initiating event to possible undesirable consequences. The initiating event may be equipment failure, human error, power failure or some other event that has the potential for adversely affecting the environment or an ongoing process and/or equipment.

1. Determine the first consequence(s) of the building fire and list the probabilities of the first consequence. See Figure 24.4.
2. Determine the second consequence(s) of the building fire and then list the probabilities of the consequence(s). See Figure 24.5.
3. Determine the final consequences and calculate the probabilities of minor fire damage, moderate fire damage with few injuries, moderate fire damage with many injuries, and major fire damage with many injuries. See Figure 24.6.

Note that for each branch in an event tree, the sum of probabilities must equal 1.0. Note again that an event tree includes the following: (1) works forward from the initial event, or an event that has the potential for adversely affecting an ongoing process, and ends at one ore more undesirable consequences, (2) is used to represent the possible steps leading to a failure or accident, (3) uses a series of branches which relate the proper operation and/or failure of a system with the ultimate consequences, (4) provides a quick identification of the various hazards which could result from a single initial event, (5) is beneficial in examining the possibilities and consequences of a failure, (6) usually does not quantify (although it can) the potential of the event occurring, and (7) can be incomplete if all the initial events are not identified.
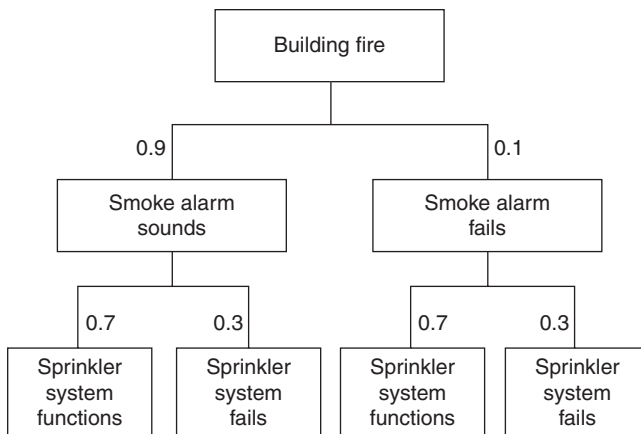

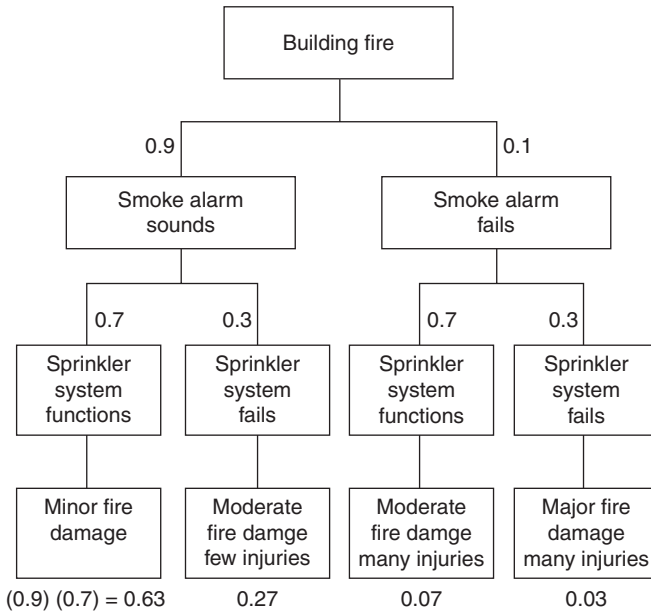**Figure 24.5** Event tree II; Illustrative Example 24.12.

Figure 24.6   Event tree III; Illustrative Example 24.12.

Thus, the use of an event tree is sometimes limiting for hazard analysis because it lacks the capability of quantifying the potential of the event occurring. As noted, it may also be incomplete if all the initial occurrences are not identified. Its use is beneficial in examining, rather than evaluating, the possibilities and consequences of a failure. For this reason, a fault tree analysis should supplement this model to establish the probabilities of the event tree branches. This topic is introduced in the next illustrative example.   ■

ILLUSTRATIVE EXAMPLE 24.13

A runaway chemical reaction can occur if coolers fail (A) *or* there is a bad chemical batch (B). Coolers fail only if both cooler #1 fails (C) *and* cooler #2 fails (D). A bad chemical batch occurs if there is a wrong mix (E) *or* there is a process upset (F). A wrong mix occurs if there is an operator error (G) *and* instrument failure (H). Construct a fault tree. If the following annual probabilities are provided by the plant engineer. Also calculate the probability of a runaway chemical reaction occurring in a year's time.

$$P(C) = 0.05$$
$$P(D) = 0.08$$
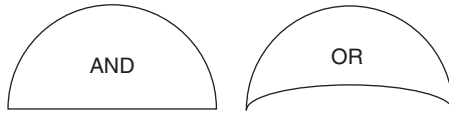$$P(F) = 0.06$$
$$P(G) = 0.03$$
$$P(H) = 0.01$$

Figure 24.7   AND and OR Gates.

Fault tree analysis seeks to relate the occurrence of an undesired event to one or more ante-cedent events. The undesired event is called the "top event" and the antecedent events called "basic events." The top event may be, and usually is, related to the basic events via certain inter-mediate events. The fault tree diagram exhibits the casual chain linking of the basic events to the intermediate events and the latter to the top event. In this chain, the logical connection between events is illustrated by so called "logic gates." The principal logic gates are the AND and OR gates, the symbols for which are shown in Figure 24.7.

SOLUTION: Construct the fault tree. See Figures 24.8–24.11.

Obtain the first branch of the fault tree, applying the logic gates.
Obtain the second branch of the fault tree, applying the logic gates.
Obtain the third branch of the fault tree, applying the logic gates.

Calculate the probability that the runaway reaction will occur.

$$P = (0.05)(0.08) + (0.01)(0.03) + 0.06 = 0.0643$$

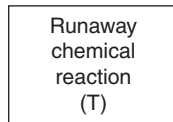Note that the major contribution to the probability comes from F (process upset).

Figure 24.8   Fault tree I; Illustrative Example 24.13.
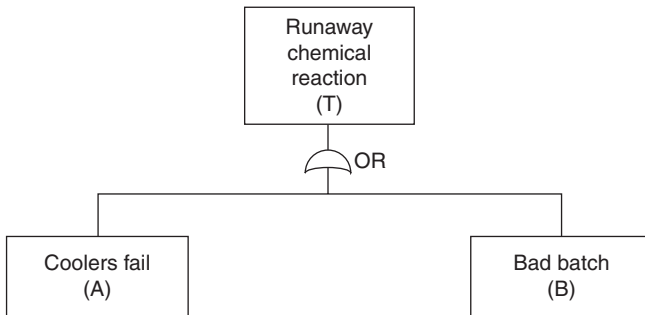

Figure 24.9   Fault tree II; Illustrative Example 24.13.
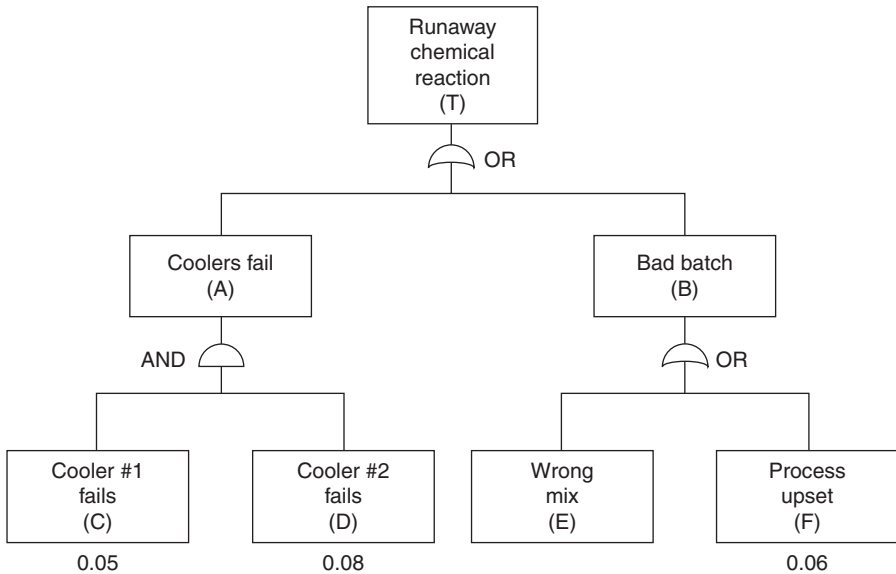
Figure 24.10   Fault tree III; Illustrative Example 24.13.

The reader should note that a fault tree includes the following:

1. Works backward from an undesirable event or ultimate consequence to the possible causes and failures.
2. Relates the occurrence of an undesired event to one or more preceding events.
3. "Chain links" basic events to intermediate events which in turn is connected to the top event.
4. Is used in the calculation of the probability of the top event.
5. Is based on the most likely or credible events which lead to a particular failure or accident.
6. Analysis includes human error as well as equipment failures.   ■

ILLUSTRATIVE EXAMPLE 24.14

Discuss the HAZOP (Hazard and Operability) procedure.

SOLUTION: Specific details regarding this procedure are available in the literature.[4,17] The overall HAZOP method, however, is summarized in the following steps:

1. Define objective(s).
2. Define plant limits.
3. Appoint and train a team.
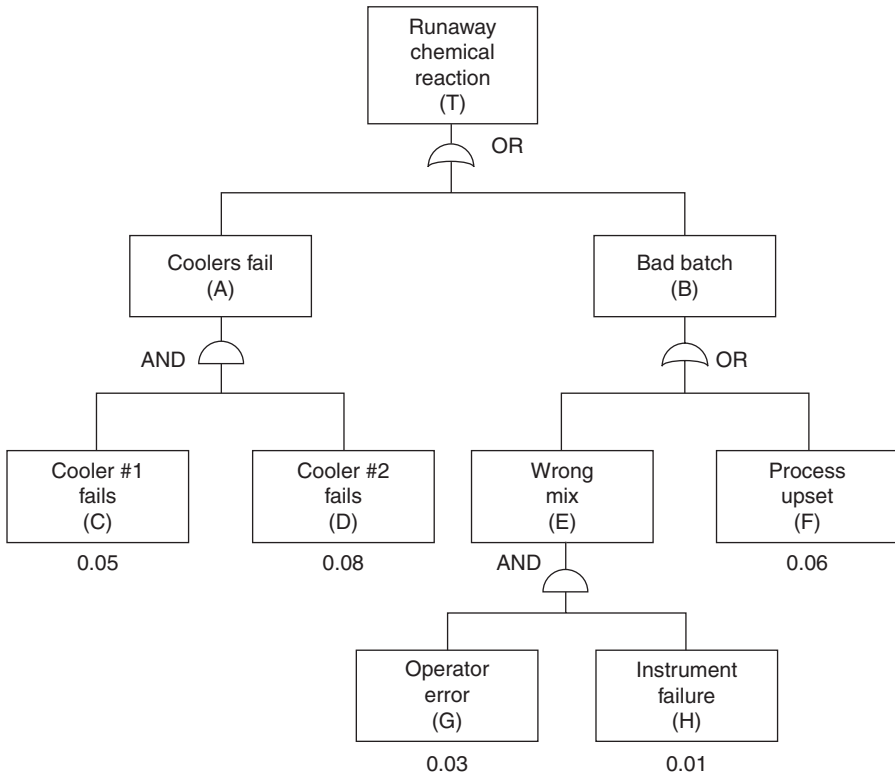4. Obtain (generate) complete preparative work.

Figure 24.11 Fault tree IV; Illustrative Example 24.13.

5. Conduct examination meetings in order to:
   a. Select a manageable portion of the process.
   b. Review the flowsheet and operating instructions.
   c. Agree on how the process is intended to operate.
   d. State and record the intention.
   e. Search for possible ways to deviate from the intention, utilizing the HAZOP "guide" words.[2,4,16,17]
   f. Determine possible causes for the deviation.
   g. Determine possible consequences of the deviation.
   h. Recommend action(s) to be taken.
6. Issue meeting reports.
7. Follow up on recommendations.

After the serious hazards have been identified with a HAZOP study or some other type of qualitative approach, a quantitative examination should be performed. Hazard quantification or hazard analysis (HAZAN) involves the estimation of the expected frequencies or probabilities of events with adverse or potentially adverse consequences. It logically ties together historical occurrences, experience, and imagination. To analyze the sequence of events that lead to an accident or failure, event and fault trees are used to represent the possible failure sequences. ■

ILLUSTRATIVE EXAMPLE 24.15

A heat exchanger is located in a relatively large laboratory with a volume of 1100 m^3 at $22°\text{C}$ and 1 atm. The exchanger can leak as much as 0.75 gmol of hydrocarbon (HC) from the flowing liquid into the room if the exchanger ruptures. A hydrocarbon mole fraction in the air greater than 425 parts per billion (ppb) constitutes a health and safety hazard.

Suppose the heat exchanger fails and the maximum amount of HC is released instantaneously. Assume the air flow in the room is sufficient to cause the room to behave as a continuously stirred tank reactor (CSTR[17–19]); i.e., the air composition is spatially uniform. Calculate the ppb of hydrocarbon in the room. Is there a health risk? From a treatment point-of-view, what can be done to decrease the environmental hazard or to improve the safety of the exchanger?

SOLUTION: Calculate the total number of gmols of air in the room, n_{air}. Assuming that air is an ideal gas, 1 gmol of air occupies 22.4 liters (0.0224 m^3) at standard temperature and pressure (273 K, 1 atm). Since the room temperature is not 273 K,

$$n_{\text{air}} = (1100 \text{ m}^3)\left(\frac{1 \text{ gmol}}{0.0224 \text{ STP m}^3}\right)\left(\frac{273 \text{ K}}{295 \text{ K}}\right)$$

$$= 45{,}445 \text{ gmol}$$

Note: STP m^3 indicates the volume (in m^3) that the gas would have at a specified standard temperature and pressure.

The mole fraction of hydrocarbon in the room, x_{HC}, is

$$x_{\text{HC}} = \frac{0.75 \text{ gmol HC}}{45{,}445 \text{ gmol air} + 0.75 \text{ gmol HC}} = 16.5 \text{ ppm} = 16{,}500 \text{ ppb}$$

Since $16{,}500 \text{ ppb} \gg 850 \text{ ppb}$, the hazard presents a significant health risk.

To implement safety measures, the potential rupture area should be vented directly into a hood or a duct to capture any leakage in the event of a rupture. Another alternative is input liquid substitution, a source reduction measure;[6] input substitution is the replacement of the fluid flowing in the heat exchanger. ■

REFERENCES

1. H. DE HEER, Calculating How Much Safety is Enough, *Chemical Engineering*, New York City, NY, February 19, 1973.
2. L. THEODORE, M. HYLAND, Y. MCGUINN, L. SCHOEN, and F. TAYLOR, *Principles of Accident and Emergency Management*, USEPA Manual, Air Pollution Training Institute, RTP, NC, 1988.
3. A. FLYNN and L. THEODORE: personal notes, 1999.
4. A. FLYNN and L. THEODORE, *Health, Safety and Accident Management in the Chemical Process Industries*, Marcel Dekker, New York City, NY (acquired by Taylor & Francis Group, Boca Raton, FL), 2002.
5. G. BURKE, B. SINGH, and L. THEODORE, *Handbook of Environmental Management and Technology*, 2nd edition, John Wiley & Sons, Hoboken, NJ, 2001.
6. L. STANDER and L. THEODORE, *Environmental Regulatory Calculations Handbook*, John Wiley & Sons, Hoboken, NJ, 2008.

7. M. THEODORE and L. THEODORE, *Introduction to Environmental Management*, CRC Press/Taylor & Francis Group, Boca Raton, FL, 2009.

8. D. PAUSTENBACH, *The Risk Assessment of Environmental and Human Health Hazards: A Textbook of Case Studies*, John Wiley & Sons, Hoboken, NJ, 1989.

9. Manual of Industrial Hazard Assessment Techniques, Office of Environmental and Scientific Affairs, The World Bank, London, October 1985.

10. J. RODRICKS and R. TARDIFF, *Assessment and Management of Chemical Risks*, ACS, Washington DC, 1984.

11. J. REYNOLDS, R. DUPONT, and L. THEODORE, *Hazardous Waste Incineration Calculations: Problems and Software*, John Wiley & Sons, Hoboken, NJ, 1991.

12. R. DUPONT, L. THEODORE, and J. REYNOLDS, *Accident and Emergency Management: Problems and Solutions*, VCH Publishers, New York, 1991.

13. L. THEODORE, R. DUPONT, and J. REYNOLDS, *Pollution Prevention: Problems and Solutions*, Gordon and Breach Publishers, Amsterdam, Holland, 1994.

14. K. GANESON, L. THEODORE, and J. REYNOLDS, *Air Toxics—Problems and Solutions*, Gordon and Breach Publishers, Amsterdam, Holland, 1996.

15. R. DUPONT, T. BAXTER, and L. THEODORE, *Environmental Management: Problems and Solutions*, CRC Press/Taylor & Francis Group, Boca Raton, FL, 1998.

16. S. SHAEFER and L. THEODORE, *Probability and Statistics Applications for Environmental Science*, CRC Press/Taylor & Francis Group, Boca Raton, FL, 2007.

17. J. REYNOLDS, J. JERIS, and L. THEODORE, *Handbook of Chemical and Environmental Engineering Calculations*, John Wiley & Sons, Hoboken, NJ, 2002.

18. L. THEODORE and R. DUPONT, *Health Risk and Hazard Risk Assessment Calculations*, CRC/Taylor & Francis Group, Boca Raton, FL, 2012.

19. L. THEODORE, *Chemical Reactor Principles and Design*, John Wiley & Sons, Hoboken, NJ, 2012 (in preparation).