29

ACCIDENT AND EMERGENCY MANAGEMENT

29.1 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 carrying the capability of disaster. 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 chances 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 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

Fluid Flow for the Practicing Chemical Engineer. By J. Patrick Abulencia and Louis Theodore

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. In the following pages, a number of accidents and disasters that took place before the advances of modern technology will be examined.

29.2 LEGISLATION

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.

Three other important topics as they relate to the subject of this chapter include the US Environmental Protection Agency's (USEPA's) Risk Management Program, the Occupational Heath and Safety Administration (OSHA), and potential environmental violations.

29.2.1 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*, properly known as the "Superfund," for the twofold 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 the 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 to human health and the environment. Citizen rights to sue are limited, however: (1) if USEPA 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 USEPA 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.

29.2.2 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 5 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 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.

29.3 HEALTH RISK ASSESSMENT[5–7]

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 scientists and health professionals to the world of risk assessments.

Since 1970, the field of risk assessment has received widespread attention within both the scientific and regulatory committees. It has also attracted the attention of the public. Properly conducted risk assessments have received fairly broad acceptance, in part because they put into perspective the terms toxic, hazard, and risk. Toxicity is an inherent property of all substances. It states that all chemical and physical agents can produce adverse health effects at some dose or under specific exposure conditions. In contrast, exposure to a chemical that has the capacity to produce a particular type of adverse effect, represents a hazard. Risk, however, is the probability or likelihood that an adverse outcome will occur in a person or a group that is exposed to a particular concentration or dose of the hazardous agent. Therefore, risk is generally a function of exposure or dose. Consequently, health risk assessment is defined as the process or procedure used to estimate the likelihood that humans or ecological systems will be adversely affected by a chemical or physical agent under a specific set of conditions.(8)

The term risk assessment is not only used to describe the likelihood of an adverse response to a chemical or physical agent, but it has also been used to describe the likelihood of any unwanted event. This subject is treated in more detail in the next section. These include risks such as: explosions or injuries in the workplace; natural catastrophes; injury or death due to various voluntary activities such as skiing, sky-diving, flying, and bungee jumping; diseases; death due to natural causes; and many others.(9)

Risk assessment and risk management are two different processes, but they are intertwined. Risk assessment and risk management give a framework not only for setting regulatory priorities, but also for making decisions that cut across different environmental areas. Risk management refers to a decision-making process that involves such considerations as risk assessment, technology feasibility, economic information about costs and benefits, statutory requirements, public concerns, and other factors. Therefore, risk assessment supports risk management in that the choices on whether and how much to control future exposure to the suspected hazards may be determined.

Regarding both risk assessment and risk management, this section will primarily address this subject from a health perspective; the next section will primarily address this subject from a safety and accident perspective.

The reader should note that two general types of potential health risk exist. These are classified as:

1. *Acute*. Exposures that occur for relatively short periods of time, generally from minutes to one or two days. Concentrations of (toxic) air contaminants are usually high relative to their protection criteria. In addition to inhalation, airborne substances might directly contact the skin, or liquids and sludges may be splashed on the skin or into the eyes, leading to adverse health effects. This subject area falls, in a general sense, in the domain of hazard risk assessment (HZRA).
2. *Chronic*. Continuous exposure occurring over long periods of time, generally several months to years. Concentrations of inhaled (toxic) contaminants are usually relatively low. This subject area falls in the general domain of health

risk assessment (HRA) and it is this subject that is addressed in this section. Thus, in contrast to the acute (short-term) exposures that predominate in hazard risk assessment, chronic (long-term) exposures are the major concern in health risk assessments.

Health risk assessments provide an orderly, explicit, and consistent way to deal with scientific issues in evaluating whether a hazard exists and what the magnitude of the hazard may be. This evaluation typically involves large uncertainties because the available scientific data are limited, and the mechanisms for adverse health impacts or environmental damage are only imperfectly understood. When one examines risk, how does one decide how safe is safe, or how clean is clean? To begin with, one has to look at both sides of the risk equation—that is, both the toxicity of a pollutant and the extent of public exposure. Information is required at both the current and potential exposure, considering all possible exposure pathways. In addition to human health risks, one needs to look at potential ecological or other environmental effects. In conducting a comprehensive risk assessment, one should remember that there are always uncertainties, and these assumptions must be included in the analysis.

29.3.1 Risk Evaluation Process for Health

In recent years, several guidelines and handbooks have been produced to help explain approaches for doing health risk assessments. As discussed by a special National Academy of Sciences committee convened in 1983, most human or environmental health hazards can be evaluated by dissecting the analysis into four parts: hazard identification, dose-response assessment or hazard assessment, exposure assessment, and risk characterization (see Fig. 29.1). For some perceived hazards, the risk assessment might stop with the first step, hazard identification, if no adverse effect is identified or if an agency elects to take regulatory action without further analysis.(8) Regarding hazard identification, a hazard is defined as a toxic agent or a set of conditions that has the potential to cause adverse effects to human health or the environment. Hazard identification involves an evaluation of various forms of information in order to identify the different hazards. Dose-response or toxicity assessment is required in an overall assessment: responses/effects can vary widely since all chemicals and contaminants vary in their capacity to cause adverse effects. This step frequently requires that assumptions be made to relate experimental data for animals and humans. Exposure assessment is the determination of the magnitude, frequency, duration, and routes of exposure of human populations and ecosystems. Finally, in risk characterization, toxicology and exposure data/information are combined to obtain a qualitative or quantitative expression of risk.

Risk assessment involves the integration of the information and analysis associated with the above four steps to provide a complete characterization of the nature and magnitude of risk and the degree of confidence associated with this characterization. A critical component of the assessment is a full elucidation of the uncertainties associated with each of the major steps. Under this broad concept of risk assessment

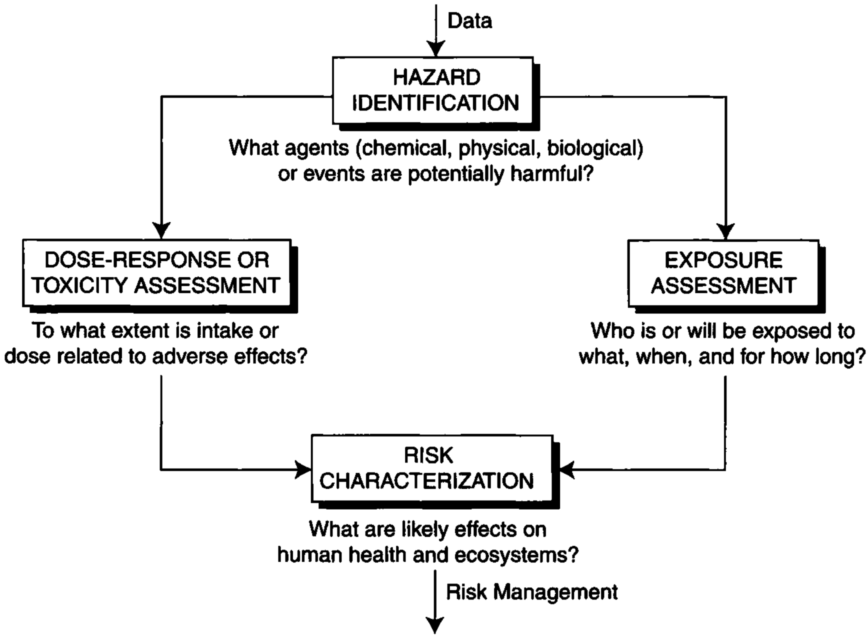


Figure 29.1 The health risk evaluation process.

are encompassed all of the essential problems of toxicology. Risk assessment takes into account all of the available dose-response data. It should treat uncertainty not by the application of arbitrary safety factors, but by stating them in quantitatively and qualitatively explicit terms, so that they are not hidden from decision-makers. Risk assessment, defined in this broad way, forces an assessor to confront all the scientific uncertainties and to set forth in explicit terms the means used in specific cases to deal with these uncertainties.[10]

29.4 HAZARD RISK ASSESSMENT[4–7]

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 the 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. 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, 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 workers 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 approximately 3.0. Some of the Illustrative Examples in Section 29.5 compliment many of the concepts described below with technical calculations and elaborations.

29.4.1 Risk Evaluation Process for Accidents

As with Health Risk Assessment (HRA), there are four key steps involved in a Hazardous Risk Assessment (HZRA). These are presented below in Fig. 29.2.

A more detailed flowchart is presented in Fig. 29.3, 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. Runaway reactions.

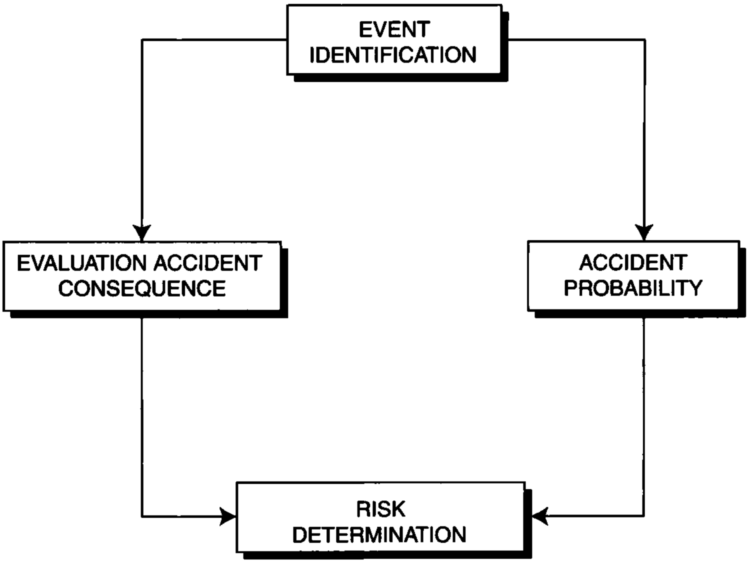


Figure 29.2 Hazard risk assessment flowchart.

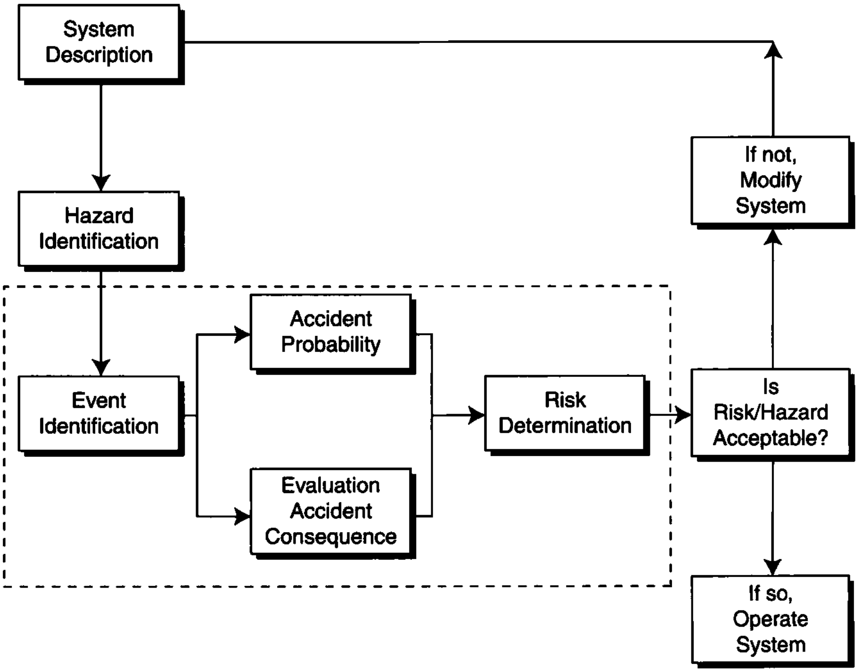


Figure 29.3 Chemical plant hazard risk assessment flowchart.

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 a pump will fail? The probability can be ranked from low to high. A low probability means that it is unlikely for the event to occur in 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 Fig. 29.3. The algorithm allows for reevaluation 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.

29.5 ILLUSTRATIVE EXAMPLES

The remainder of this chapter is devoted to Illustrative Examples, many of which contain technical development material. A good number of applications have been drawn from National Science Foundation (NSF) literature,[11–16] and two other sources.[6,17]

Illustrative Example 29.1 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; explosion of storage tank.
3. Collapse of tank due to earthquake.
4. Rupture in main line.
5. Leak in line or from tank.

Illustrative Example 29.2 Consider the probability distribution of the number of defectives in a sample of five pumps drawn with replacement from a lot of 1000 pumps, 50 of which are defective. Associate "success" with drawing a defective pump from the lot. Then the result of each drawing can be classified as success (defective pump) or failure (non-defective pump). The sample of pumps is drawn with replacement (i.e., each item in the sample is returned before the next is drawn from the lot; therefore, the probability of success remains constant at 0.05). Calculate the probability that the sample contains exactly three defective pumps.

Solution The probability distribution of x, the number of successes in n performances of the random experiment, is the binomial distribution, with probability distribution function (pdf) specified by[16]

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

where $P(x)$ is the probability of x successes in n performances.

Substituting the values $n = 5$, $p = 0.05$, and $q = 0.95$ into the pdf,

$$P(x) = \frac{n!}{x!(n! - x!)} p^x q^{n-x} = \frac{5!}{x!(5! - x!)} (0.05)^x (0.95)^{5-x}$$

Therefore,

$$P(x = 3) = \frac{5!}{3!(5! - 3!)} (0.05)^3 (0.95)^{5-3} = 0.11\%$$

Illustrative Example 29.3 An iron foundry has four work stations that are connected to a single duct. In order to reduce the possibility of an accident, each work station has a hood that transports 3000 acfm of air flow. The duct length is 400 feet and the pressure loss at the hood entrance is 0.5 in H_2O. There also is a cyclone air cleaner that creates 3.5 in H_2O pressure drop. Determine the diameter of the duct to ensure adequate transport of the dust. Also determine the power required for a combined blower/motor efficiency of 40%.

Solution Determine the minimum air velocity required for general foundry dust

$$v_{\text{air}} = 4000\ \text{ft/min}$$
$$= 66.67\ \text{ft/s}$$

Calculate the total air flow required in acfm.

$$q_{\text{air}} = (3000)(4)$$
$$= 12{,}000\ \text{acfm}$$

Calculate required cross-sectional area in ft^2.

$$A = q_{\text{air}}/v_{\text{air}}$$
$$= (12{,}000)/(4000)$$
$$= 3\ \text{ft}^2$$

Calculate the duct diameter.

$$D = (4A/\pi)^{1/2}$$
$$= [(4)(3)/3.14]^{1/2}$$
$$= 1.9544\ \text{ft}$$
$$= 24\ \text{in}$$

In order to determine power requirements, the pressure drop across the system needs to be calculated first. Calculate the Reynolds number for the above duct.

$$\text{Re} = Dv\rho/\mu$$
$$= (1.9544)(66.67)(0.075)/(1.21 \times 10^{-5})$$
$$= 8.08 \times 10^5$$

The pressure drop in the duct in lb$_f$/ft^2 is then (for $f = 0.003$ since Re > 20,000).

$$\Delta P_{\text{duct}} = 4\,fLv^2\rho/2g_cD$$
$$= (4)(0.003)(400)(66.67)^2(0.075)/[(2)(32.2)(1.9544)]$$
$$= 12.7\ \text{lb}_f/\text{ft}^2$$

Calculate the total system pressure drop.

$$\begin{aligned}\Delta P_{tot} &= \Delta P_{duct} + \Delta P_{hood} + \Delta P_{cyc}\\ &= 12.7 + (0.5)(5.2\,\text{lb}_f/\text{ft.}^2\text{-in H}_2\text{O}) + (3.5)(5.2\,\text{lb}_f/\text{ft.}^2\text{-in H}_2\text{O})\\ &= 33.5\,\text{lb}_f/\text{ft}^2\end{aligned}$$

Finally, calculate the power required in hp.

$$\begin{aligned}\text{hp} &= 3.03 \times 10^{-5}\,\Delta P_{tot} q_{air}/\eta\\ &= 3.03 \times 10^{-5}(33.5)(12{,}000)/0.4\\ &= 30.5\,\text{hp}\end{aligned}$$

Illustrative Example 29.4 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 complete preparative work.
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.
   f. Determine possible causes for the deviation.
   g. Determine possible consequences of the deviation.
   h. Recommend action(s) to be taken.
6. Issue meeting report.
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 29.5 Consider a water pumping system consisting of two pumps (A and B), where A is the pump ordinarily operating and B is a standby unit that automatically takes over if A fails. A control valve in both cases regulates flow of water through the pump. Suppose that the top event is no water flow, resulting from the following basic events: failure of pump A and failure of pump B, or failure of control valve. Prepare a fault tree diagram for this system.[4,17]

Solution Generally, a fault tree may be viewed as a diagram that shows the path that a specific accident takes. Fault tree analysis (FTA) begins with the ultimate consequence and works backward to the possible causes and failures. It is based on the most likely or most credible events that lead to the accident. FTA demonstrates the mitigating or reducing effects, and can include causes stemming from human error as well as equipment failure. The task of constructing a fault tree is tedious and requires a probability background to handle common mode failures, dependent events, and time constraints.

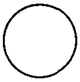
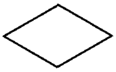
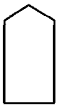
Fault tree analysis seeks to relate the occurrence of an undesired event, the "top event," to one or more antecedent events, called "basic events." The top event may be, and usually is, related to the basic events via certain intermediate events. A fault tree diagram exhibits the casual chain linking the basic events to the intermediate events and the latter to the top event. In this chain, the logical connection between events is indicated by so-called "logic gates." The principal logic gates are the AND gate, symbolized on the fault tree by AND, and the OR gate symbolized by OR.

The fault tree symbols and their definitions are presented in Table 29.1. The construction of the fault tree for a tank overflow example is demonstrated in Fig. 29.4.

Details on event trees are available in the literature.[16,17]

Illustrative Example 29.6 A baghouse has been used to clean a particulate gas stream for nearly 30 years. There are 600, 8-inch diameter bags in the unit. 50,000 acfm of dirty gas at 250°F enters the baghouse with a loading of 5.0 grains/ft^3. The outlet loading is 0.3 grains/ft^3. Local EPA regulations state that the maximum allowable outlet loading is 0.4 grains/ft^3. If the system operates at a pressure drop of 6 in. H_2O, how many bags can fail before the unit is out of compliance? The Theodore–Reynolds equation (see below) applies and all the contaminated gas emitted through the broken bags may be assumed the same as that passing through the tube sheet thimble.

Table 29.1 Fault tree symbols[a]

Basic Event 	Standard Usage: Basic initiating fault requiring no further development Modified ADL Usage: Represents initiating event and therefore has a yearly rate of occurrence
Undeveloped Event 	Standard Usage: Event which is not developed any further as it is not required or data is unavailable Modified ADL Usage: Represents contributing events having taken place
External Event 	Standard Usage: Event normally expected to occur Modified ADL Usage: Not used as even events normally expected to occur can lead to an undesired outcome and data may not be any more accurate than for any other type of event
Intermediate Event 	Standard and ADL Usage: Intermediate level event caused by more primary events developed below
And Gate 	Standard and ADL Usage: Logic gate where output fault occurs only if all input faults/events occur
Or Gate 	Standard and ADL Usage: Logic gate where output fault occurs if at least one of the input faults/events occurs

[a]ADL = Alternate Digital Logic.

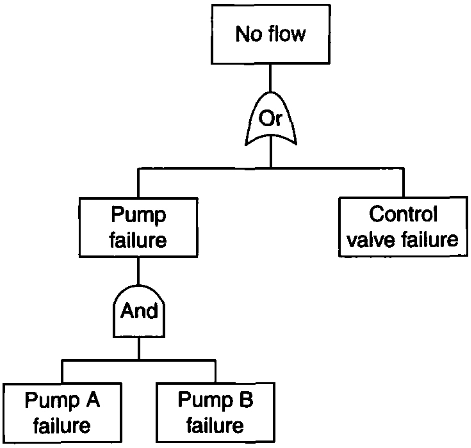


Figure 29.4 Fault tree diagram for a water pumping system consisting of two pumps (A and B).

The effect of bag failure on baghouse fractional penetration (or efficiency) can be described by the following equation:

$$P_t^* = P_t + P_{tc}$$

$$P_{tc} = \frac{0.582(\Delta P)^{1/2}}{\phi}$$

$$\phi = \frac{q}{[LD^2(T + 460)^{1/2}]}$$

where P_t^* = penetration after bag failure
P_t = penetration before bag failure
P_{tc} = penetration correction term; contribution of broken bags to P_t^*
ΔP = pressure drop, in. H_2O
ϕ = dimensionless parameter
q = volumetric flow rate of contaminated gas, acfm
L = number of broken bags
D = bag diameter, inches
T = temperature, °F

Note: $P = 1 - E$; E = fractional efficiency.

A detailed development of the above equation is provided in the literature.(18)

Solution Calculate the efficiency, E, and penetration, P, before bag failure(s):

$$\begin{aligned} E &= \text{(inlet loading} - \text{outlet loading)/(inlet loading)} \\ &= (5.0 - 0.03)/(5.0) \\ &= 0.9940 = 99.40\% \end{aligned}$$

$$\begin{aligned} P_t &= 1 - 0.9940 \\ &= 0.0060 = 0.60\% \end{aligned}$$

Calculate the efficiency and penetration, P_t^*, based on regulatory conditions:

$$\begin{aligned} E &= (5.0 - 0.4)/(5.0) \\ &= 0.9200 = 92.00\% \end{aligned}$$

$$\begin{aligned} P_t^* &= 1 - 0.9200 \\ &= 0.0800 = 8.00\% \end{aligned}$$

Calculate the penetration term, P_{tc}, associated with the failed bags:

$$\begin{aligned} P_{tc} &= 0.0800 - 0.0060 \\ &= 0.0740 \end{aligned}$$

Write the equation(s) for P_{tc} in terms of the number of failed bags, L:

$$P_{tc} = \frac{0.582(\Delta P)^{1/2}}{\phi}$$

where

$$\phi = \frac{q}{\left[LD^2(T + 460)^{1/2}\right]}$$

Calculate the number of bag failures that the system can tolerate and still remain in compliance:

$$\begin{aligned} L &= \frac{qP_{tc}}{(0.582)(\Delta P)^{0.5}(D)^2(T+460)^{0.5}} \\ &= (50{,}000)(0.074)/(0.582)(6)^{0.5}(8)^2(250+460)^{0.5} \\ &= 1.52 \end{aligned}$$

Thus, if two bags fail, the baghouse is out of compliance.

Illustrative Example 29.7 A reactor is located in a relatively large laboratory with a volume of 1100 m^3 at 22°C and 1 atm. The reactor can emit as much as 0.75 gmol of hydrocarbon (HC) into the room if a safety valve ruptures. A hydrocarbon mole fraction in the air greater than 425 parts per billion (ppb) constitutes a health and safety hazard.

Suppose the reactor valve ruptures 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), 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 reactor?

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 (273K, 1 atm). Since the room temperature is not 273K,

$$\begin{aligned} n_{air} &= (1100\,m^3)\left(\frac{1\,gmol}{0.0224\,STP\,m^3}\right)\left(\frac{273K}{295K}\right) \\ &= 45{,}445\,gmol \end{aligned}$$

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

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

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

Since 16,500 ppb $\gg$ 850 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 substitution, a source reduction measure. Input substitution is the replacement of the material in the reactor with material with a lower vapor pressure.

REFERENCES

1. H. deHeer, "Calculating How Much Safety is Enough", Chemical Engineering, New York, February 19, 1973.
2. L. Theodore, M. Hyland, Y. McGuinn, L. Schoen, and F. Taylor, USEPA Manual, "Principles of Accident and Emergency Management", Air Pollution Training Institute, RTP, NC, 1988.
3. Personal notes:A. M. Flynn and L. Theodore, 1999.
4. A. M. Flynn and L. Theodore, "Health, Safety and Accident Management in the Chemical Process Industries", Marcel Dekker, New York (acquired by Taylor & Francis, 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. K. Theodore and L. Theodore, "Major Environmental Issues Facing the 21st Century," 2nd edition, CRC Press, 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, October, 1985, London.
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, Boca Raton, FL, 1998.

16. S. Shaefer and L. Theodore, "Probability and Statistics for Environmental Scientists", CRC Press, 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 J. Reynolds, "Effect of Baghouse Failure and Baghouse Outlet Loading", *J. Air Poll. Control.*, 29, 870–872, 1979.

NOTE: Additional problems are available for all readers at www.wiley.com. Follow links for this title.