1

Chemical Process Quantitative Risk Analysis

Chemical process quantitative risk analysis (CPQRA) is a methodology designed to provide management with a tool to help evaluate overall process safety in the chemical process industry (CPI). Management systems such as engineering codes, checklists and process safety management (PSM) provide layers of protection against accidents. However, the potential for serious incidents cannot be totally eliminated. CPQRA provides a quantitative method to evaluate risk and to identify areas for cost-effective risk reduction.

The CPQRA methodology has evolved since the early 1980s from its roots in the nuclear, aerospace and electronics industries. The most extensive use of probabilistic risk analysis (PRA) has been in the nuclear industry. Procedures for PRA have been defined in the *PRA Procedures Guide* (NUREG, 1983) and the *Probabilistic Safety Analysis Procedures Guide* (NUREG, 1985).

CPQRA is a probabilistic methodology that is based on the NUREG procedures. The term "chemical process quantitative risk analysis" is used throughout this book to emphasize the features of this methodology as practiced in the chemical, petrochemical, and oil processing industries. Some examples of these features are

- Chemical reactions may be involved
- Processes are generally not standardized
- Many different chemicals are used
- Material properties may be subject to greater uncertainty
- Parameters, such as plant type, plant age, location of surrounding population, degree of automation and equipment type, vary widely
- Multiple impacts, such as fire, explosion, toxicity, and environmental contamination, are common.

Acute, rather than chronic, hazards are the principal concern of CPQRA. This places the emphasis on rare but potentially catastrophic events. Chronic effects such as cancer or other latent health problems are not normally considered in CPQRA.

One objective of this second edition is to incorporate recent advances in the field. Such advances are necessary and desirable as highlighted by the late Admiral Hyman Rickover:

We must accept the inexorably rising standards of technology, and we must relinquish comfortable routines and practices rendered obsolete because they no longer meet the new standards.

Many hazards may be identified and controlled or eliminated through use of qualitative hazard analysis as defined in *Guidelines for Hazard Evaluation Procedures,* Second Edition (CCPS, 1992). Qualitative studies typically identify potentially hazardous events and their causes. In some cases, where the risks are clearly excessive and the existing safeguards are inadequate, corrective actions can be adequately identified with qualitative methods. CPQRA is used to help evaluate potential risks when qualitative methods cannot provide adequate understanding of the risks and more information is needed for risk management. It can also be used to evaluate alternative risk reduction strategies.

The basis of CPQRA is to identify incident scenarios and evaluate the risk by defining the probability of failure, the probability of various consequences and the potential impact of those consequences. The risk is defined in CPQRA as a function of probability or frequency and consequence of a particular accident scenario:

$$\text{Risk} = F(s, c, f)$$

s = hypothetical scenario
c = estimated consequence(s)
f = estimated frequency

This "function" can be extremely complex and there can be many numerically different risk measures (using different risk functions) calculated from a given set of s, c, f. The major steps in CPQRA, as illustrated in Figure 1.1 (page 4), are as follows:

Risk Analysis:

1. Define the potential event sequences and potential incidents. This may be based on qualitative hazard analysis for simple or screening level analysis. Complete or complex analysis is normally based on a full range of possible incidents for all sources.
2. Evaluate the incident outcomes (consequences). Some typical tools include vapor dispersion modeling and fire and explosion effect modeling.
3. Estimate the potential incident frequencies. Fault trees or generic databases may be used for the initial event sequences. Event trees may be used to account for mitigation and postrelease events.
4. Estimate the incident impacts on people, environment and property.
5. Estimate the risk. This is done by combining the potential consequence for each event with the event frequency, and summing over all events.

Risk Assessment:

6. Evaluate the risk. Identify the major sources of risk and determine if there are cost-effective process or plant modifications which can be implemented to reduce risk. Often this can be done without extensive analysis. Small and inexpensive system changes sometimes have a major impact on risk. The evaluation may be done against legally required risk criteria, internal corporate guidelines, comparison with other processes or more subjective criteria.

7. Identify and prioritize potential risk reduction measures if the risk is considered to be excessive.

Risk Management:

Chemical process quantitative risk analysis is part of a larger management system. Risk management methods are described in the CCPS *Guidelines for Implementing Process Safety Management Systems* (AIChE/CCPS, 1994), *Guidelines for Technical Management of Chemical Process Safety* (AIChE/CCPS, 1989), and *Plant Guidelines for Technical Management of Chemical Process Safety* (AIChE/CCPS, 1995).

The seven steps in Figure 1.1 are typical of CPQRA. However, it is important to remember that other risks , such as financial loss, chronic health risks and bad publicity, may also be significant. These potential risks can also be estimated qualitatively or quantitatively and are an important part of the management process.

This chapter provides general outlines for the major areas in CPQRA as listed below. The subsequent chapters provide more detailed descriptions and examples.

1. Definitions of CPQRA terminology (Section 1.1)
2. Elements that form the overall framework (Section 1.2)
3. Scope of CPQRA (Section 1.3)
4. Management of incident lists (Section 1.4)
5. Application of CPQRA (Section 1.5)
6. Limitations of CPQRA (Section 1.6)
7. Current practices (Section 1.7)
8. Utilization of CPQRA results (Section 1.8)
9. Project management (Section 1.9)
10. Maintenance of study results (Section 1.10)

CPQRA provides a tool for the engineer or manager to quantify risk and analyze potential risk reduction strategies. The value of quantification was well described by Lord Kelvin. Joschek (1983) provided a similar definition:

> a quantitative approach to safety . . . is not foreign to the chemical industry. For every process, the kinetics of the chemical reaction, the heat and mass transfers, the corrosion rates, the fluid dynamics, the structural strength of vessels, pipes and other equipment as well as other similar items are determined quantitatively by experiment or calculation, drawing on a vast body of experience.

CPQRA enables the engineer to evaluate risk. Individual contributions to the overall risk from a process can be identified and prioritized. A range of risk reduction measures can be applied to the major hazard contributors and assessed using cost–benefit methods.

Comparison of risk reduction strategies is a *relative* application of CPQRA. Pikaar (1995) has related relative or comparative CPQRA to climbing a mountain. At each stage of increasing safety (decreasing risk), the associated changes may be evaluated to see if they are worthwhile and cost-effective. Some organizations also use CPQRA in an *absolute* sense to confirm that specific risk targets are achieved. Further risk reduction, beyond such targets, may still be appropriate where it can be accomplished in a cost-effective manner. Hendershot (1996) has discussed the role of absolute risk guidelines as a risk management tool.

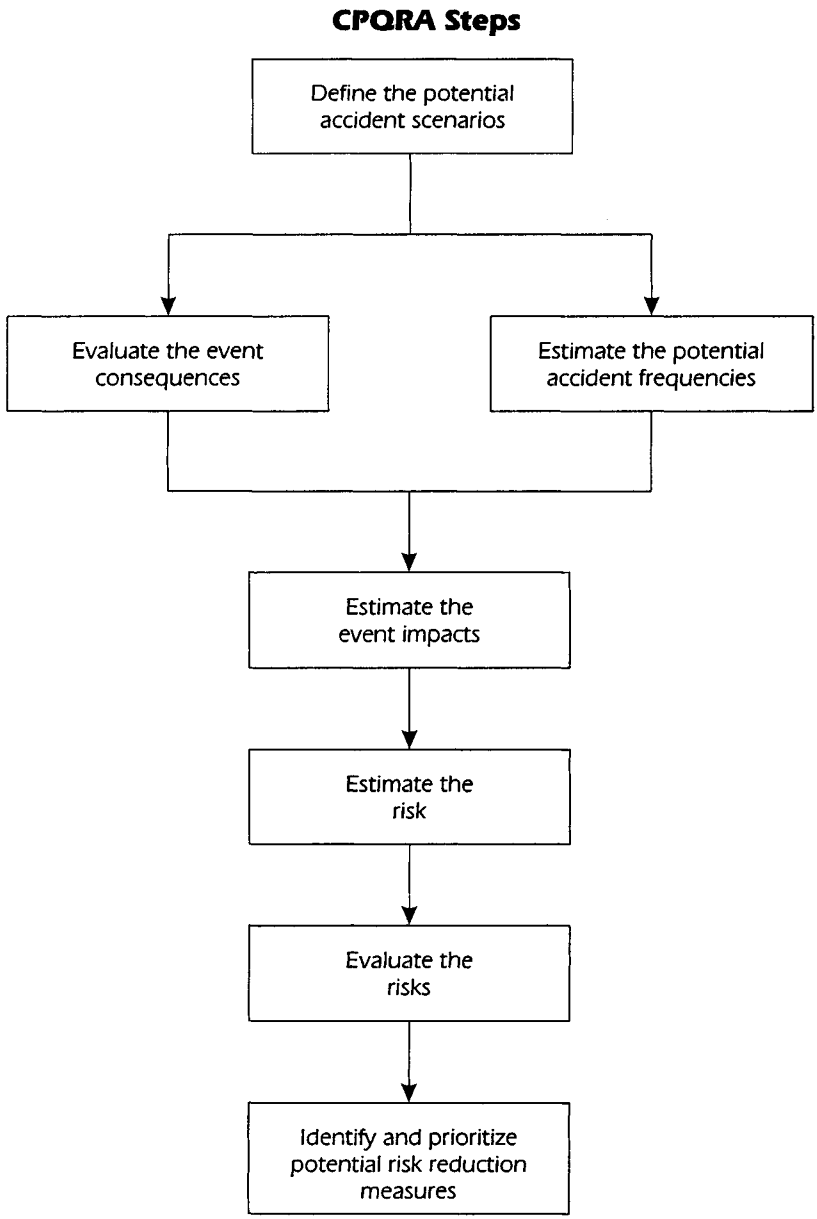

FIGURE 1.1 CPQRA Flowchart

Application of the full array of CPQRA techniques (referred to as component techniques in Section 1.2) allows a quantitative review of a facility's risks, ranging from frequent, low-consequence incidents to rare, major events, using a uniform and consistent methodology. Having identified process risks, CPQRA techniques can help focus risk control studies. The largest risk contributors can be identified, and recommendations and decisions can be made for remedial measures on a consistent and objective basis.

Utilization of the CPQRA results is much more controversial than the methodology (see Section 1.8). Watson (1994) has suggested that CPQRA should be considered as an argument, rather than a declaration of truth. In his view, it is not practical or necessary to provide absolute scientific rigor in the models or the analysis. Rather, the focus should be on the overall balance of the QRA and whether it reflects a useful measure of the risk. However, Yellman and Murray (1995) contend that the analysis "should be, insofar as possible, true—or at least a search for truth." It is important for the analyst to understand clearly how the results will be used in order to choose appropriately rigorous models and techniques for the study.

1.1. CPQRA Definitions

Table 1.1 and the Glossary define terms as they are used in this volume. Other tabulations of terms have been compiled (e.g., IChemE, 1985) and may need to be consulted because, as discussed below, there currently is no single, authoritative source of accepted nomenclature and definitions. CPQRA is an emerging technology in the CPI and there are terminology variations in the published literature that can lead to confusion. For example, while risk is defined in Table 1.1 as "a measure of human injury, environmental damage or economic loss in terms of both the incident likelihood and the magnitude of the loss or injury," readers should be aware that other definitions are often used. For instance, Kaplan and Garrick (1981) have discussed a number of alternative definitions of risk. These include:

- **Risk** is a combination of **uncertainty and damage.**
- **Risk** is a ratio of **hazards to safeguards.**
- **Risk** is a triplet combination of **event, probability, and consequences.**

Readers should also recognize the interrelationship that exists between an incident, an incident outcome, and an incident outcome case as these terms are used throughout this book. An incident is defined in Table 1.1 as "the loss of containment of material or energy," whereas an incident outcome is "the physical manifestation of an incident." A single incident may have several outcomes. For example, a leak of flammable and toxic gas could result in

- a jet fire (immediate ignition)
- a vapor cloud explosion (delayed ignition)
- a vapor cloud fire (delayed ignition)
- a toxic cloud (no ignition).

A list of possible incident outcomes has been included in Table 1.2.

The third and often confusing term used in describing incidents is the incident outcome case. As indicated by its definition in Table 1.1, the incident outcome case specifies values for all of the parameters needed to uniquely distinguish one incident outcome from all others. For example, since certain incident outcomes are dependent on weather conditions (wind direction, speed, and atmospheric stability class), more than one incident outcome case could be developed to describe the dispersion of a dense gas.

TABLE 1.1. Selected Definitions for CPQRA

Frequency: Number of occurrences of an event per unit of time.

Hazard: A chemical or physical condition that has the potential for causing damage to people, property, or the environment (e.g., a pressurized tank containing 500 tons of ammonia)

Incident: The loss of containment of material or energy (e.g., a leak of 10 lb/s of ammonia from a connecting pipeline to the ammonia tank, producing a toxic vapor cloud) ; not all events propagate into incidents.

Event sequence: A specific unplanned sequence of events composed of initiating events and intermediate events that may lead to an incident.

Initiating event: The first event in an event sequence (e.g., stress corrosion resulting in leak/rupture of the connecting pipeline to the ammonia tank)

Intermediate event: An event that propagates or mitigates the initiating event during an event sequence (e.g., improper operator action fails to stop the initial ammonia leak and causes propagation of the intermediate event to an incident; in this case the intermediate event could be a continuous release of the ammonia)

Incident outcome: The physical manifestation of the incident; for toxic materials, the incident outcome is a toxic release, while for flammable materials, the incident outcome could be a Boiling Liquid Expanding Vapor Explosion (BLEVE), flash fire, unconfined vapor cloud explosion, toxic release, etc. (e.g., for a 10 lb/s leak of ammonia, the incident outcome is a toxic release)

Incident outcome case: The quantitative definition of a single result of an incident outcome through specification of sufficient parameters to allow distinction of this case from all others for the same incident outcomes. For example,a release of 10 lb/s of ammonia with D atmospheric stability class and 1.4 mph wind speed gives a particular downwind concentration profile, resulting, for example, in a 3000 ppm concentration at a distance of 2000 feet.

Consequence: A measure of the expected effects of an incident outcome case (e.g., an ammonia cloud from a 10 lb/s leak under Stability Class D weather conditions, and a 1.4-mph wind traveling in a northerly direction will injure 50 people)

Effect zone: For an incident that produces an incident outcome of toxic release, the area over which the airborne concentration equals or exceeds some level of concern. The area of the effect zone will be different for each incident outcome case [e.g., given an IDLH for ammonia of 500 ppm (v), an effect zone of 4.6 square miles is estimated for a 10 lb/s ammonia leak]. For a flammable vapor release, the area over which a particular incident outcome case produces an effect based on a specified overpressure criterion (e.g., an effect zone from an unconfined vapor cloud explosion of 28,000 kg of hexane assuming 1% yield is 0.18 km^2 if an overpressure criterion of 3 psig is established). For a loss of containment incident producing thermal radiation effects, the area over which a particular incident outcome case produces an effect based on a specified thermal damage criterion [e.g., a circular effect zone surrounding a pool fire resulting from a flammable liquid spill, whose boundary is defined by the radial distance at which the radiative heat flux from the pool fire has decreased to 5 kW/m^2 (approximately 1600 $Btu/hr\text{-}ft^2$)]

Likelihood: A measure of the expected probability or frequency of occurrence of an event. This may be expressed as a frequency (e.g., events/year), a probability of occurrence during some time interval, or a conditional probability (i.e., probability of occurrence given that a precursor event has occurred, e.g., the frequency of a stress corrosion hole in a pipeline of size sufficient to cause a 10 lb/s ammonia leak might be 1×10^{-3} per year; the probability that ammonia will be flowing in the pipeline over a period of 1 year might be estimated to be 0.1; and the conditional probability that the wind blows toward a populated area following the ammonia release might be 0.1)

Probability: The expression for the likelihood of occurrence of an event or an event sequence during an interval of time or the likelihood of occurrence of the success or failure of an event on test or demand. By definition, probability must be expressed as a number ranging from 0 to 1.

Risk: A measure of human injury, environmental damage or economic loss in terms of both the incident likelihood and the magnitude of the loss or injury

Risk analysis: The development of a quantitative estimate of risk based on engineering evaluation and mathematical techniques for combining estimates of incident consequences and frequencies (e.g., an ammonia cloud from a 10 lb/s leak might extend 2000 ft downwind and injure 50 people.
For this example, using the data presented above for likelihood, the frequency of injuring 50 people is given as $1 \times 10^{-3} \times 0.1 \times 0.1 = 1 \times 10^{-5}$ events per year)

Risk assessment: The process by which the results of a risk analysis are used to make decisions, either through a relative ranking of risk reduction strategies or through comparison with risk targets (e.g., the risk of injuring 50 people at a frequency of 1×10^{-5} events per year from the ammonia incident is judged higher than acceptable, and remedial design measures are required)

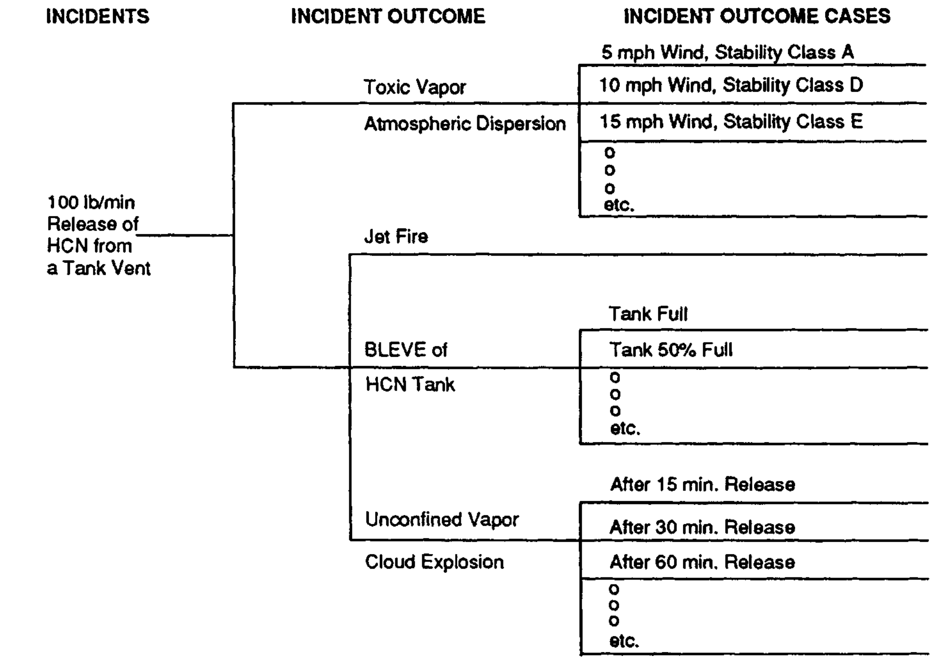

FIGURE 1.2. The relationship between incident, incident outcome, and incident outcome cases for a hydrogen cyanide (HCN) release.

The event tree in Figure 1.2 has been provided to illustrate the relationship between an incident, incident outcomes, and incident outcome cases. Each of these terms will be developed further in this chapter.

1.2. Component Techniques of CPQRA

It is convenient (for ease of understanding and administration) to divide the complete CPQRA procedure into component techniques (Section 1.2.1). Many CPQRAs do not require the use of all the techniques. Through the use of prioritized procedures (Section 1.2.2), the CPQRA can be shortened by simplifying or even skipping certain techniques that appear in the complete CPQRA procedure.

1.2.1. Complete CPQRA Procedure

A framework for the complete CPQRA methodology for a process system is given in Figure 1.3. This diagram shows

- the full logic of a CPQRA in more detail
- the relationship between a CPQRA and a risk assessment
- the interaction of a CPQRA with
  - –the analysis data base
  - –user requirements
  - –user reaction to risk estimates from a CPQRA

TABLE 1.2. CPQRA Hazards, Event Sequences, Incident Outcomes, and Consequences

	Event Sequences			
Process hazards	**Initiating events**	**Intermediate events**		**Incident outcomes**
Significant inventories of: Flammable materials Combustible materials Unstable materials Corrosive materials Asphyxiants Shock sensitive materials Highly reactive materials Toxic materials Inerting gases Combustible dusts Pyrophoric materials Extreme physical conditions High temperatures Cryogenic temperatures High pressures Vacuum Pressure cycling Temperature cycling Vibration/liquid hammering	Process upsets Process deviations Pressure Temperature Flow rate Concentration Phase/state change Impurities Reaction rate/heat of reaction Spontaneous reaction Polymerization Runaway reaction Internal explosion Decomposition Containment failures Pipes, tanks, vessels, gaskets/seals Equipment malfunctions Pumps, valves, instruments, sensors, interlock failures Loss of utilities Electrical, nitrogen, water, refrigeration, air, heat transfer fluids, steam, ventilation Management systems failure Human error Design Construction Operations Maintenance Testing and inspection External events Extreme weather conditions Earthquakes Nearby accidents' impacts Vandalism/sabotage	Propagating factors Equipment failure safety system failure Ignition sources Furnaces, flares, incinerators Vehicles Electrical switches Static electricity Hot surfaces/cigarettes Management systems failure Human errors Omission Commission Fault diagnosis Decision-making Domino effects Other containment failures Other material release External conditions Meteorology Visibility	Risk reduction factors Control/operator responses Alarms Control system response Manual and automatic emergency shutdown Fire/gas detection system Safety system responses Relief valves Depressurization systems Isolation systems High reliability trips Back-up systems Mitigation system responses Dikes and drainage Flares Fire protection systems (active and passive) Explosion vents Toxic gas absorption Emergency plan responses Sirens/warnings Emergency procedures Personnel safety equipment Sheltering Escape and evacuation External events Early detection Early warning Specially designed structures Training Other management systems	Analysis Discharge Flash and evaporation Dispersion Neutral or positively buoyant gas Dense gas Fires Pool fires Jet fires BLEVES Flash fires Explosions Confined explosions Vapor cloud explosions (VCE) Physical explosions Dust explosions Detonations Condensed phase detonations Missiles Consequences Effect analysis Toxic effects Thermal effects Overpressure effects Damage assessments Community Workforce Environment Company assets

Figure 1.3 also provides cross-references to other sections of this volume, where details of the techniques are given. The full logic of a CPQRA involves the following component techniques:

1. CPQRA Definition
2. System Description
3. Hazard Identification
4. Incident Enumeration
5. Selection
6. CPQRA Model Construction
7. Consequence Estimation
8. Likelihood Estimation
9. Risk Estimation
10. Utilization of Risk Estimates

A brief account of the role of each of the techniques is given below, and more detailed accounts are given in the sections indicated.

- **CPQRA Definition** converts user requirements into study goals (Section 1.9.1) and objectives (Section 1.9.2). Risk measures (Section 4.1) and risk presentation formats (Section 4.2) are chosen in finalizing a scope of work for the CPQRA. A depth of study (Section 1.9.3) is then selected based on the specific objectives defined and the resources available. The need for special studies (e.g., the evaluation of domino effects, computer system failures, or protective system unavailability) is also considered (Chapter 6). CPQRA definition concludes with the definition of study specific information requirements to be satisfied through the construction of the analysis data base.
- **System Description** is the compilation of the process/plant information needed for the risk analysis. For example, site location, environs, weather data, process flow diagrams (PFDs), piping and instrumentation diagrams (P&IDs), layout drawings, operating and maintenance procedures, technology documentation, process chemistry, and thermophysical property data may be required. This information is fed to the analysis data base for use throughout the CPQRA.
- **Hazard Identification** is another step in CPQRA. It is critical because a hazard omitted is a hazard not analyzed. Many aids are available, including experience, engineering codes, checklists, detailed process knowledge, equipment failure experience, hazard index techniques, what-if analysis, hazard and operability (HAZOP) studies, failure modes and effects analysis (FMEA), and preliminary hazard analysis (PHA). These aids are extensively reviewed in the *HEP Guidelines*, Second Edition (AIChE/CCPS, 1992). Typical process hazards identified using these aids are listed in Table 1.2. Additional information on common chemical hazards is given in Bretherick (1983), Lees (1980), and Marshall (1987).
- **Incident Enumeration** is the identification and tabulation of all incidents without regard to importance or initiating event. This, also, is a critical step, as an incident omitted is an incident not analyzed (Section 1.4.1).
- **Selection** is the process by which one or more significant incidents are chosen to represent all identified incidents (Section 1.4.2.1), incident outcomes are identi-

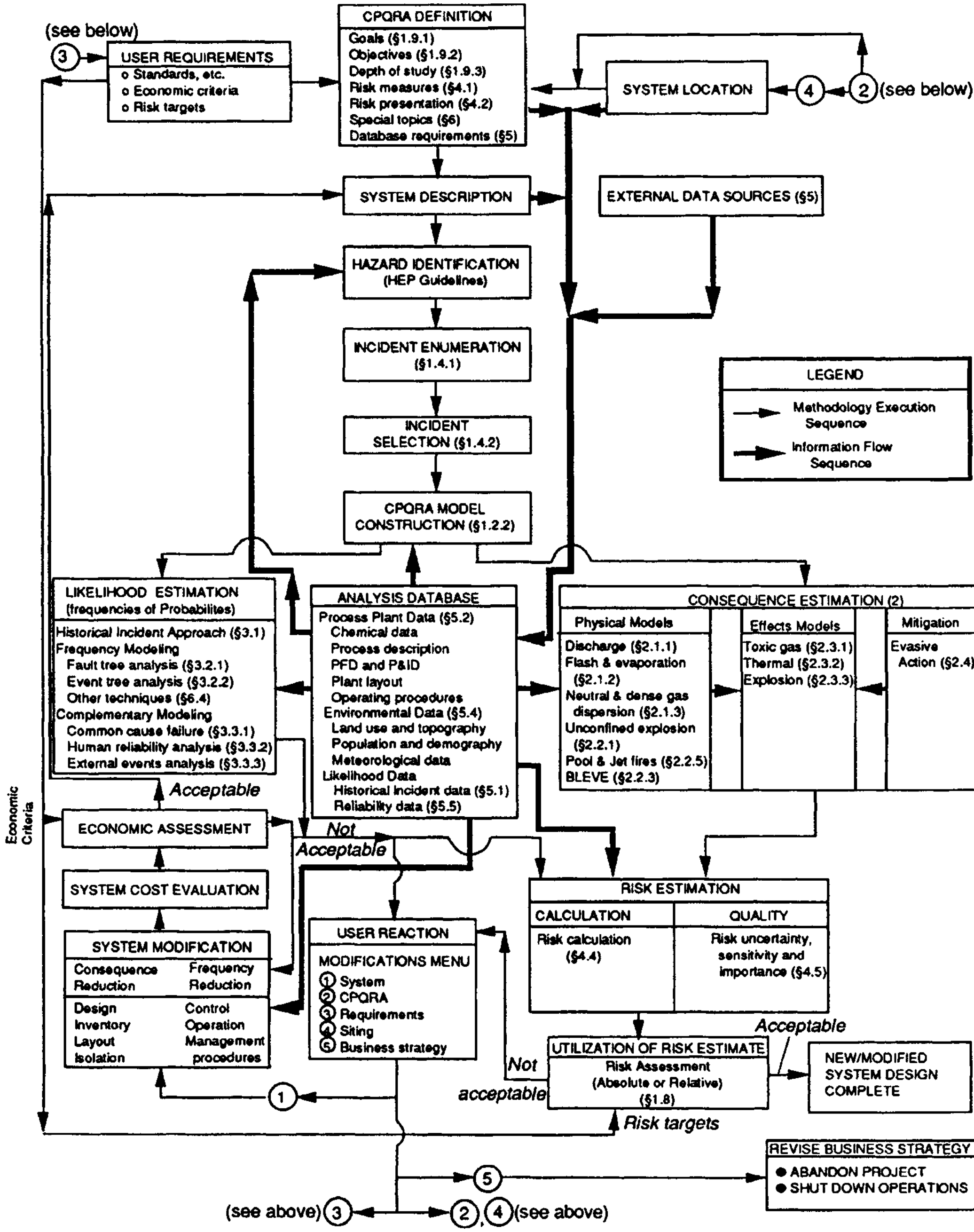

FIGURE 1.3. Framework for CPQRA methodology and chapter/section headings.

fied (Section 1.4.2.2), and incident outcome cases are developed (Section 1.4.2.3).

- **CPQRA Model Construction** covers the selection of appropriate consequence models (Chapter 2), likelihood estimation methods (Chapter 3) and their integration into an overall algorithm to produce and present risk estimates (Chapter 4) for the system under study. While various algorithms can be synthesized, a prioritized form (Section 1.2.2) can be constructed to create opportunities to shorten the time and effort required by less structured procedures.
- **Consequence Estimation** is the methodology used to determine the potential for damage or injury from specific incidents. A single incident (e.g., rupture of a pressurized flammable liquid tank) can have many distinct incident outcomes [e.g., unconfined vapor cloud explosion (UVCE), boiling liquid expanding vapor explosion (BLEVE), flash fire]. These outcomes are analyzed using source and dispersion models (Section 2.1) and explosion and fire models (Section 2.2). Effects models are then used to determine the consequences to people or structures (Section 2.2). Evasive actions such as sheltering or evacuation can reduce the magnitude of the consequences and these may be included in the analysis (Section 2-3)
- **Likelihood Estimation** is the methodology used to estimate the frequency or probability of occurrence of an incident. Estimates may be obtained from historical incident data on failure frequencies (Section 3.1), or from failure sequence models, such as fault trees and event trees (Section 3.2). Most systems require consideration of factors such as common-cause failures [a single factor leading to simultaneous failures of more than one system, e.g., power failure (Section 3.3.1), human reliability (Section 3.3.2), and external events (Section 3.3.3)].
- **Risk Estimation** combines the consequences and likelihood of all incident outcomes from all selected incidents to provide one or more measures of risk (Chapter 4). It is possible to estimate a number of different risk measures from a given set of incident frequency and consequence data, and an understanding of these measures is provided. The risks of all selected incidents are individually estimated and summed to give an overall measure of risk. The sensitivity and uncertainty of risk estimates and the importance of the various contributing incidents to estimates are discussed in Section 4.5.
- **Utilization of Risk Estimates** is the process by which the results from a risk analysis are used to make decisions, either through relative ranking of risk reduction strategies or through comparison with specific risk targets.

The last CPQRA step (utilization of risk estimates) is the key step in a *risk assessment.* It requires the user to develop risk guidelines and to compare the risk estimate from the CPQRA with them to decide whether further risk reduction measures are necessary. This step has been included as a CPQRA component technique to emphasize its overall influence in designing the CPQRA methodology, but it is not discussed in this book. Guidelines for decision analysis are contained in *Tools for Making Acute Risk Decisions* (AIChE/CCPS, 1995).

Before discussing the remaining functions and activities shown in Figure 1.3, it is important to recognize that all of the component techniques introduced above have not been developed to the same depth or extent, nor used as widely for the same length of time. Consequently, it is helpful to classify them according to "maturity," a term used here to combine the concepts of degree of development of the technique and years in use in the CPI. Greater confidence and less uncertainty are associated with the more mature component techniques, such as hazard identification and consequence estimation. Discomfort and uncertainty increase as maturity decreases. Frequency estimation is much less developed and practiced and accordingly classified, along with incident enumeration and selection techniques, as less mature than hazard identification and consequence estimation. The most underdeveloped and newest technique to the CPI of those listed, risk estimation, is the least mature of any of the CPQRA component techniques. Accordingly, the most uncertainty associated with any component technique accompanies risk estimates.

By reviewing the maturity scale, it is easy to rank the component techniques according to their development potential. While consequence estimation techniques are fairly sophisticated and some may argue "well-developed," frequency estimation techniques offer developmental challenges and enhancement necessities. Risk estimation techniques, especially companion methodologies such as uncertainty analysis, require substantial development and refinement, and much greater exposure before becoming widely accepted and "user friendly." The subject of the maturity of the techniques will be revisited in Section 1.2.2 as one driving force in the precedence ordering of CPQRA calculations.

While not considered a component technique, the development of the analysis data base is a critical early step in a CPQRA. In addition to the data from the system description, this data base contains various kinds of environmental data (e.g., land use and topography, population and demography, meteorological data) and likelihood data (e.g., historical incident data, reliability data) needed for the specific CPQRA. Much of this information must be collected from external (outside company) sources and converted into formats useful for the CPQRA. Chapter 5 discusses the construction of the analysis data base, and details the various sources of data available.

As shown in Figure 1.3, user reaction to the results of a risk assessment using the CPQRA estimate can be summarized as a menu of modification options:

- systems modification through engineering/operational/procedural changes
- amendment of the goals or scope of the CPQRA
- relaxation of user requirements
- alternative sites
- adjustments to basic business strategy.

Systems modification involves the proposal and evaluation of risk reduction strategies by persons knowledgeable in process technology. Risk estimation provides insight into the degree of risk reduction possible and the areas where risk reduction may be most effective. Proposed risk reduction strategies can incorporate changes to either system design or operation, in order to eliminate or reduce incident consequences or frequencies. As shown in Figure 1.3, such proposals need to be shown to meet all business needs (e.g., quality, capacity, legality, and cost) before being reviewed by CPQRA techniques. The other user options are self-explanatory and are more properly treated in a discussion of the risk assessment process and related risk management program.

1.2.2. Prioritized CPQRA Procedure

Most applications of the CPQRA methodology will not need to use all of the available component techniques introduced in Section 1.2.1. CPQRA component techniques are flexible and can be applied selectively, in various orders. Consequence estimation can be used as a screening tool to identify hazards of negligible consequence (and therefore a negligible risk) to avoid detailed frequency estimation. Similarly, frequency estimation can identify hazards of sufficiently small likelihood of occurrence that consequence estimates are unnecessary. The procedure outlined in Figure 1.4 has been constructed to illustrate one way to prioritize the calculations. It has been designed to provide opportunities to shorten the time and effort needed to achieve acceptable results. These opportunities arise naturally due to the ordering of the calculations. The criteria for establishing the priority of calculations are based on the maturity of the component techniques and their ease of use. The more mature consequence estimation techniques are given highest priority. These techniques are also the most easily executed. The degree of effort increases through the procedure, along with uncertainties as the maturity of the component techniques decreases.

The prioritized CPQRA procedure given in Figure 1.4 involves the following steps:

Step 1—Define CPQRA.
Step 2—Describe the system.
Step 3—Identify hazards.
Step 4—Enumerate incidents.
Step 5—Select incidents, incident outcomes, and incident outcome cases

These five steps are the same as the corresponding steps in Figure 1.3, and are discussed in Section 1.2.1.

- **Step 6 Estimate Consequences.** If the consequences of an incident are acceptable at any frequency, the analysis of the incident is complete. This is a simplification of the risk analysis, in which the probability of occurrence of the incident within the time period of interest is assumed to be 1.0 (the incident is certain to occur). For example, the overflow of an ethylene glycol storage tank to a containment system poses little risk even if the event were to occur. If the consequences are not acceptable, proceed to Step 7.
- **Step 7 Modify System to Reduce Consequences.** Consequence reduction measures should be proposed and evaluated. The analysis then returns to Step 2 to determine whether the modifications have introduced new hazards and to reestimate the consequences. If there are no technically feasible and economically viable modifications, or if the modifications do not eliminate unacceptable consequences, proceed to Step 8.
- **Step 8 Estimate Frequencies.** If the frequency of an incident is acceptably low, given estimated consequences, the analysis of the incident is complete. If not, proceed to Step 9.
- **Step 9 Modify System to Reduce Frequencies.** This step is similar in concept to Step 7. If there are no technically feasible and economically viable modifications to reduce the frequency to an acceptable level, proceed to Step 10. Otherwise, return to Step 2.

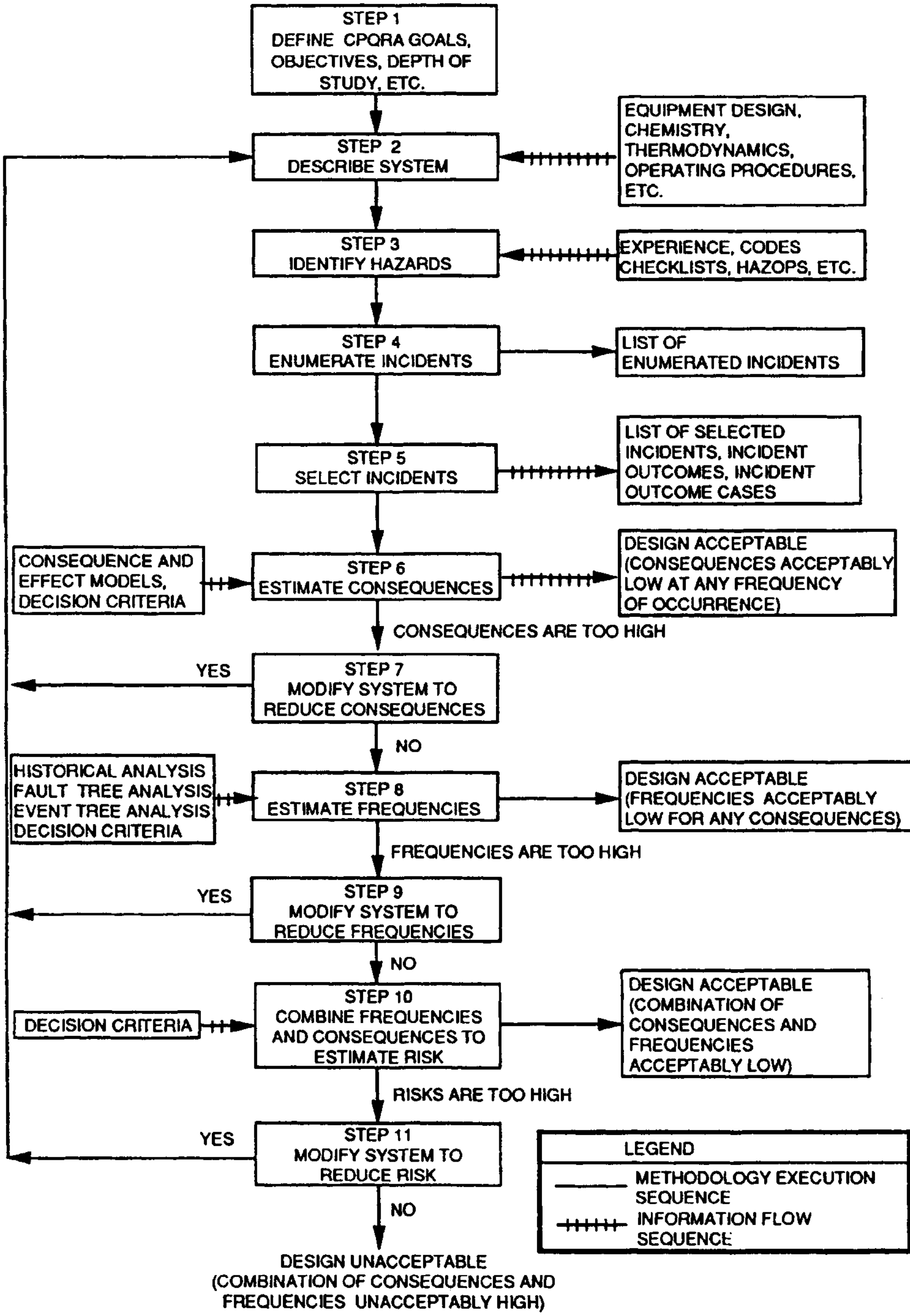

FIGURE 1.4. One version of a prioritized CPQRA procedure.

- **Step 10 Combine Frequency and Consequences to Estimate Risk.** If the risk estimate is at or below target or if the proposed strategy offers acceptable risk reduction, the CPQRA is complete and the design is acceptable.
- **Step 11 Modify System to Reduce Risk.** This is identical in concept to Steps 7 and 9. If no modifications are found to reduce risk to an acceptable level, then fundamental changes to process design, user requirements, site selection, or business strategy are necessary.

In summary, Figure 1.3 presents the overall structure of CPQRA, and Figure 1.4 illustrates one method of implementation. A complete CPQRA as illustrated in Figure 1.3 may not be necessary or feasible on every item or system in a given process unit. Guidance on the selection and use of CPQRA component techniques is presented later in this chapter.

1.3. Scope of CPQRA Studies

It is good engineering practice to pay careful attention to the scope of a CPQRA, in order to satisfy practical budgets and schedules; it is not unusual for the work load to "explode" if the scope is not carefully specified in advance of the work and enforced during project execution. This section introduces the concept of a study cube (Figure 1.5) to relate scope, work load, and goals (Section 1.3.1) and then gives typical goals for CPQRAs of various scopes (Section 1.3.2).

1.3.1 The Study Cube

CPQRAs can range from simple, "broad brush" screening studies to detailed risk analyses studying large numbers of incidents, using highly sophisticated frequency and consequence models. Between these extremes a continuum of CPQRAs exists with no rigidly defined boundaries or established categories. To better understand how the scope ranges for CPQRAs it is useful to show them in the form of a cube, in which the axes represent the three major factors that define the scope of a CPQRA: risk estimation technique, complexity of analysis, and number of incidents selected for study. This arrangement also allows us to consider "planes" through the cube, in which the value of one of the factors is held constant.

1.3.1.1. THE STUDY CUBE AXES

For this discussion, each axis of the Study Cube has been arbitrarily divided into three levels of complexity. This results in a total of 27 different categories of CPQRA, depending on what combinations of complexity of treatment are selected for the three factors. Each cell in the cube represents a potential CPQRA characterization. However, some cells represent combinations of characteristics that are more likely to be useful in the course of a project or in the analysis of an existing facility.

Risk Estimation Technique. Each of the components of this axis corresponds to a study exit point in Figure 1.4. The complexity and level of effort necessary increase

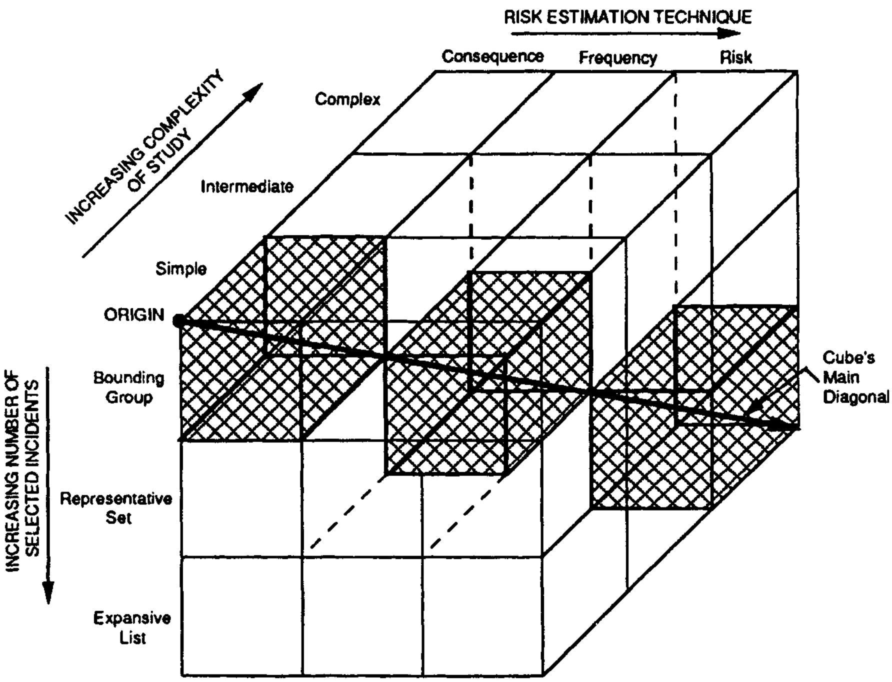

FIGURE 1.5. The study cube. Each cell in the cube represents a particular CPQRA study with a defined depth of treatment and risk emphasis. For orientation purposes, the shaded cells along the main diagonal of the cube are described in Table 1.5.

along the axis—from consequence through frequency to risk estimation—but not necessarily linearly.

In another sense, the representation of estimation by consequence, frequency, and risk is indicative of the level of maturity of these techniques. Quantification of the consequences from an incident involving loss of containment of a process fluid has been extensively studied. Once a release rate is established, the development of the resulting vapor cloud can be fairly well described by various source and dispersion models, although gaps in our understanding—particularly for flashing or two-phase discharges, near-field dispersion, and local flow effects—do exist. Quantification of the frequency of an incident is less well understood. Where historical data are not available, fault tree analysis (FTA) and event tree analysis (ETA) methods are used. These methods rely heavily on the judgment and experience of the analyst and are not as widely applied in the CPI as consequence models. Much remains to be learned about how to produce a truly representative risk estimate with minimum uncertainty and bias.

Complexity of Study. This axis presents a complexity scale for CPQRAs. Position along the axis is derived from two factors:

- the complexity of the models to be used in a study
- the number of incident outcome cases to be studied

Model complexity can vary from simple algebraic equations to extremely complex functions such as those used to estimate the atmospheric dispersion of dense gases. The number of incident outcome cases to be studied is the product of the number of incident outcomes selected and the number of cases to be studied per outcome. The number of cases to be studied may range from one—assuming uniform wind direction and a single wind speed—to many, using various combinations of wind speed, direction, and atmospheric stability for each incident outcome.

Figure 1.6 illustrates how model complexity and the number of incident outcome cases are combined to produce the simple, intermediate, and complex zones in the study cube.

Number of Incidents. The three groups of incidents used in Figure 1.5—bounding group, representative set, and expansive list—can be explained using the three classes of incidents in Table 1.3.

The bounding group contains a small number of incidents. Members of this group include those catastrophic incidents sometimes referred to as the worst case. The intent of selecting incidents for this group is to allow determination of an upper bound on the estimate of consequences. This approach focuses attention on extremely rare incidents, rather than the broad spectrum of incidents that often comprises the major portion of the risk. The representative set can contain one or more incidents from each of the three incident classes in Table 1.3 when evaluating risks to employees. When evaluating risk to the public, the representative set of incidents would probably only include selections from the catastrophic class of events because small incidents do not normally have significant impact at larger distances. The purpose of selecting representative incidents is to reduce study effort without losing resolution or adding substantial bias to the risk estimate. The expansive list contains all incidents in all three classes selected through the incident enumeration techniques discussed in Section 1.4.1.

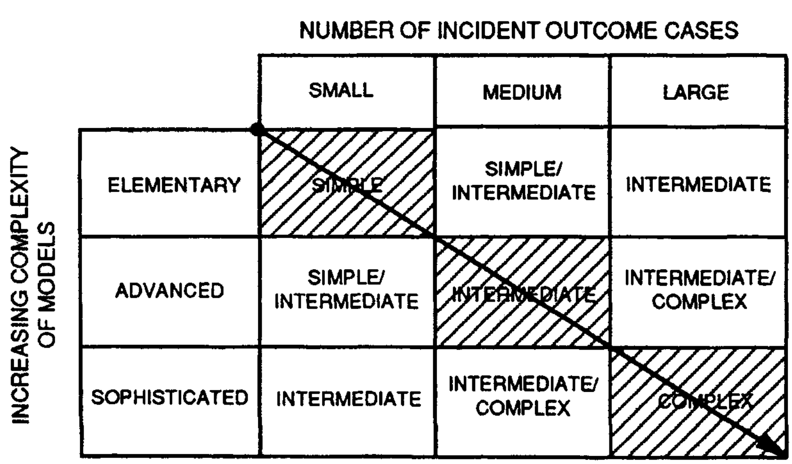

FIGURE 1.6. Development of complexity of study axis values for the Study Cube. The main diagonal values (shaded cells) correspond with the "complexity of study values" used in Figure 1.5.

1.3.1.2. PLANES THROUGH THE STUDY CUBE

The study cube provides a conceptual framework for discussing factors that influence the depth of a CPQRA. It is arbitrarily divided into 27 cells, each defined by three factors, and qualitative scales are given for each factor or cube axis.

In addition to considering cells in the study cube, it is convenient to refer to planes through the cube, especially through the risk estimation technique axis. A separate plane exists for consequence, frequency, and risk estimation. Anywhere within one of these planes, the risk estimation technique is fixed. Referring to consequence plane studies, there are nine combinations of the complexity of study and number of selected incidents. The use of the plane concept when describing CPQRAs is intended to reinforce the notion that several degrees of freedom exist when defining the scope of a CPQRA study, and it is not enough to cite only the risk estimation technique to be used when discussing a specific level of CPQRA.

1.3.2. Typical Goals of CPQRAs

Examples of typical goals of CPQRAs are summarized in Table 1.4, which highlights incident groupings that are appropriate to achieve each goal. Ideally, all incidents would be considered in every analysis, but time and cost constraints require optimizing the number of incidents studied. Consequently, incident groups other than the expansive list are preferred.

Goals that are appropriate early in an emerging capital project will be constrained by available information. However, for a mature operating plant, sufficient information will usually be available to satisfy any of the goals in Table 1.4. The amount and quality of information available for a CPQRA depend on the stage in the process' life when the study is executed. This effect is illustrated conceptually in Figure 1.7. A specific depth of study can be executed only if the process information available equals or exceeds the information required.

Each of the 27 depths of study shown in the Study Cube has specific information requirements. The information required for a CPQRA is a function of not only the position of the corresponding cell in the study cube (depth of study) selected, but also the specific study objectives. In general, information needs increase as

- the number of incidents increases,
- the complexity of study (number of incident outcome cases and complexity of models) increases,
- the estimation technique progresses from consequence through frequency to risk estimation calculations.

TABLE 1.3. Classes of Incidents

Localized incident	Localized effect zone, limited to a single plant area (e.g., pump fire, small toxic release)
Major incident	Medium effect zone, limited to site boundaries (e.g., major fire, small explosion)
Catastrophic incident	Large effect zone, off site effects on the surrounding community (e.g., major explosion, large toxic release)

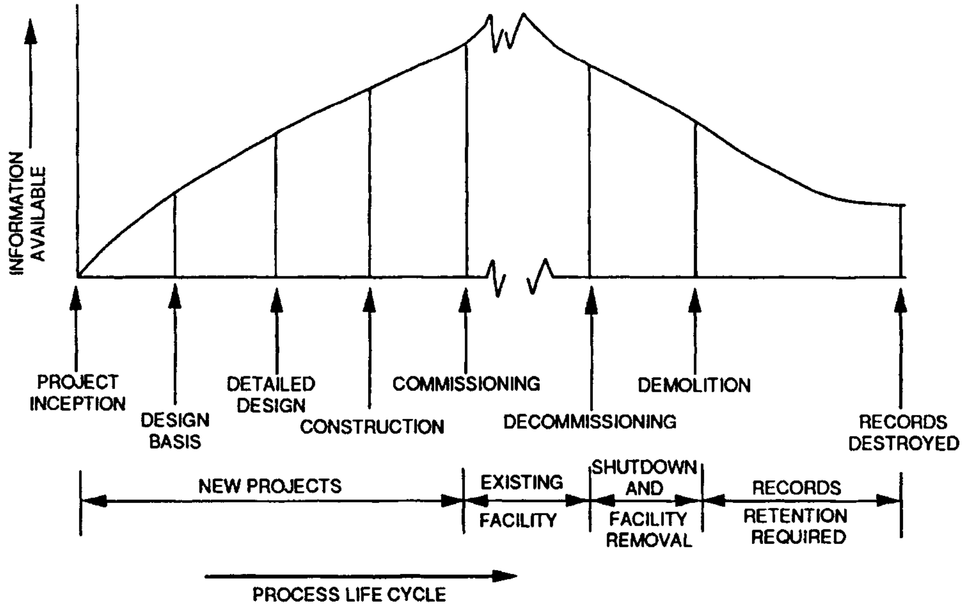

FIGURE 1.7. Information availability to CPQRA along the life of a chemical process.

Conceptually, information requirements increase moving from the origin along the main diagonal of the Study Cube. Specific study objectives are developed from the CPQRA goals by project management (Section 1.9.2). These specific objectives may add information requirements (often unique) to those established by the position in the cube.

In order to discuss important issues of study specification, it is convenient to limit attention to three of the 27 cells in the cube. These three cells are a simple/consequence CPQRA, intermediate/frequency CPQRA, and complex/risk CPQRA (Table 1.5). They occupy the main diagonal of the cube as illustrated in Figure 1.5. The cells are defined in terms of increasing CPQRA resolution. The choice of these cells in no way implies that they represent the most common types of risk studies. They are only presented to explain the general parameters of this form of presentation of CPQRA study depth. Further information on CPQRA studies for different cells in the study cube is given in Chapter 7, where a number of qualitative examples are presented. Chapter 8 presents more specific, quantitative case studies.

1.4. Management of Incident Lists

Effective management of a CPQRA requires enumeration (Section 1.4.1) and selection (Section 1.4.2) of incidents, and a formal means for tracking (Section 1.4.3) the incidents, incident outcomes, and incident outcome cases. Enumeration attempts to ensure that no significant incidents are overlooked; selection tries to reduce the incident outcome cases studied to a manageable number; and tracking ensures that no selected incident, incident outcome, or incident outcome case is lost in the calculation procedure.

TABLE 1.4. Typical Goals of CPQRAs

To Screen or Bracket the Range of Risks Present for Further Study. Screening or bracketing studies often emphasize consequence results (perhaps in terms of upper and lower bounds of effect zones) without a frequency analysis. This type of study uses a bounding group of incidents.
To Evaluate a Range of Risk Reduction Measures. This goal is not limited to any particular incident grouping, but representative sets or expansive lists of incidents are typically used. Major contributors to risk are identified and prioritized. A range of risk reduction measures is applied to the major contributors, in turn, and the relative benefits assessed. If a risk target is employed, risk reduction measures would be considered that could not only meet the target, but could exceed it if available at acceptable cost.
To Prioritize Safety Investments. All organizations have limited resources. CPQRA can be used to prioritize risks and ensure that safety investment is directed to the greatest risks. A bounding group or representative set of incidents is commonly used.
To Estimate Financial Risk. Even if there are no hazards that have the potential for injury to people, the potential for financial losses or business interruption may warrant a CPQRA. Depending on the goals, different classes of incidents might be emphasized in the CPQRA. An annual insurance review might highlight localized and major incidents using a bounding group with consequences specified in terms of loss of capital equipment and production.
To Estimate Employee Risk. Several companies have criteria for employee risk, and CPQRA is used to verify compliance with these criteria. In principle, the expansive list of incidents could be considered, but the major risk contributors to plant employees are localized incidents and major incidents (Table 1.3). Rare, catastrophic incidents often contribute less than a few percent to total employee risk. A representative set or bounding group of incidents may be appropriate.
To Estimate Public Risk. As with employee risk, some internal-corporate and regulatory agency public risk criteria may have been suggested or adopted as "acceptable risk" levels. CPQRA can be used to check compliance. Where such criteria are not met, risk reduction measures may be investigated as discussed above. The important contributors to off-site, public risk are major and catastrophic incidents. A representative set or expansive list of incidents is normally utilized.
To Meet Legal or Regulatory Requirements. Legislation in effect in Europe, Australia, and in some States (e.g., NJ and CA) may require CPQRAs. The specific objectives of these vary, according to the specific regulations, but the emphasis is on public risk and emergency planning. A bounding group or representative set of incidents is used.
To Assist with Emergency Planning. CPQRA may be used to predict effect zones for use in emergency response planning. Where the emergency plan deals with on-site personnel, all classes of incidents may need to be considered. For the community, major and catastrophic classes of incidents are emphasized. A bounding group of incidents is normally sufficient for emergency planning purposes.

1.4.1. Enumeration

The objective of enumeration is to identify and tabulate all members of the incident classes in Table 1.3, regardless of importance or of initiating event. In practice, this can never be achieved. However, it must be remembered that omitting important incidents from the analysis will bias the results toward underestimating overall risk.

The starting point of any analysis is to identify all the incidents that need to be addressed. These incidents can be classified under either of two categories, loss of containment of material or loss of containment of energy. Unfortunately, there is an infinite number of ways (incidents) by which loss of containment can occur in either category. For example, leaks of process materials can be of any size, from a pinhole up to a severed pipe line or ruptured vessel. An explosion can occur in either a small container or a large container and, in each case, can range from a small "puff" to a catastrophic detonation.

TABLE 1.5. Definitions of Cells Along the Main Diagonal of the Study Cube (Figure 1.5)

Simple/Consequence CPQRA

Estimation Technique—Consequence

Complexity of Study
Number of Incident Outcome Cases—Small
Complexity of Model—Elementary

Number of Incidents—Bounding Group

This is a CPQRA that is useful for screening or risk bounding purposes. It requires the least amount of process definition and makes extensive use of simplified techniques. In terms of Figure 1.4, it consists of consequence calculations only (Steps I through 7). A Simple/Consequence CPQRA is suitable for screening at any stage of the project: in the case of an existing plant, screening might highlight the need to consider further study; at the design stage, it might aid in optimizing siting and layout.

Intermediate/Frequency CPQRA

Estimation Technique—Frequency

Complexity of Study
Number of Incident Outcome Cases—Medium
Complexity of Model—Advanced

Number of Incidents—Representative Set

This is a more detailed CPQRA that corresponds to Steps I through 9 in Figure 1.4. It cannot be applied until the design is substantially developed, unless historical frequency techniques are applied. It may be applied at any time after process flow sheet definition. Complete descriptions of the process and equipment are not usually necessary. A Representative Set of incidents is chosen. In principle, the results of an Intermediate/Frequency CPQRA should approximate a detailed study, but have less resolution.

Complex/Risk CPQRA

Estimation Technique—Risk

Complexity of Study
Number of Incident Outcome Cases—Large
Complexity of Model—Sophisticated

Number of Incidents—Expansive List

This is the most detailed CPQRA. It employs the full methodology described in Figure 1.4. It may be applied to operating plants or to capital projects, but only after detailed design has been completed, when sufficient information is available. Where appropriate, it would employ the most sophisticated analytical techniques reviewed in Chapters 2 and 3. However, it would be unlikely to apply the most sophisticated techniques to all aspects of the study—only to those items that contribute most to the result. Due to the number of incidents, incident outcomes and incident outcomes cases considered, this study level provides the highest resolution.

The *HEP Guidelines*, Second Edition (AIChE/CCPS, 1992) outlines the roles of HAZOP, FMEA, and What-If in hazard assessment. The supplemental "Questions for Hazard Evaluation" shown in Appendix B of the *HEP Guidelines* can be helpful for identifying hazards, initiating events, and incidents. While none of these hazard identification techniques directly produces a list of incidents, each provides a methodology from which initiating events can be developed. Proper scenario selection is extremely important in CPQRA and the results of the analysis are no better than the scenarios selected.

In addition to the above techniques, Table 1.2 can be used as a checklist to assist in further incident enumeration through listing candidate initiating events, intermediate events, and incident outcomes and consequences. It should be understood that there is

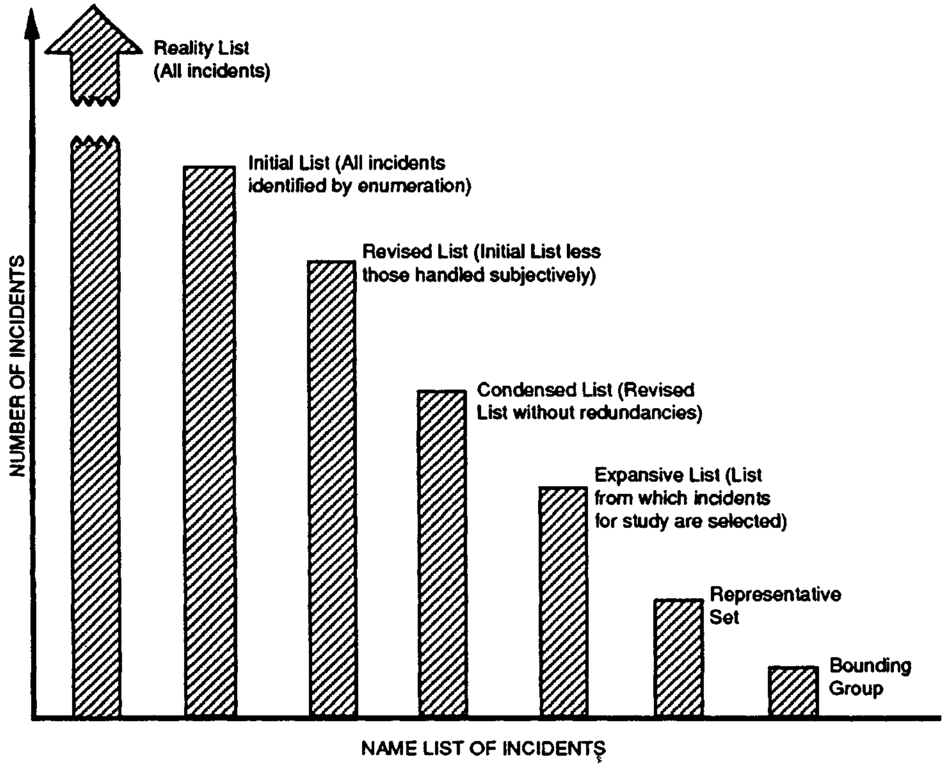

FIGURE 1.8. Incident lists versus number of incidents (comparison of lists developed through incident selection to the reality list).

no single technique whose application guarantees the comprehensive listing of all incidents (i.e., the reality list of Figure 1.8 is unattainable). Nonetheless, use of hazard identification techniques and Table 1.2 can lead to the identification of a broad spectrum of incidents, sufficient for defining even the expansive list of incidents (Section 1.4.2.1).

Other approaches for enumeration of major incidents and their initiating events have been developed. One of these uses fault tree analysis (FTA). The fault tree is a logic diagram showing how initiating events, at the bottom of the tree, through a sequence of intermediate events, can lead to a top event. This analysis requires two knowledge bases: (1) a listing of major subevents which contribute to a top event of loss of containment, and (2) the development of each subevent to a level sufficient to describe the majority of initiating events. For enumeration, this process is executed without any attempt to quantify the frequency of the top event. However, this fault tree can serve as a means for obtaining frequencies later in the CPQRA. The success of this technique is principally dependent on the expertise of the analyst. An example is given by Prugh (1980).

The "Loss of Containment Checklist" included in this book as Appendix A can be applied to enumerate credible incidents. This checklist considers causes arising from nonroutine process venting, deterioration and modification, external events, and process deviations. Sample incidents include the following:

- overpressuring a process or storage vessel due to loss of control of reactive materials or external heat input
- overfilling of a vessel or knock-out drum
- opening of a maintenance connection during operation
- major leak at pump seals, valve stem packings, flange gaskets, etc.
- excess vapor flow into a vent or vapor disposal system
- tube rupture in a heat exchanger
- fracture of a process vessel causing sudden release of the vessel contents
- line rupture in a process piping system
- failure of a vessel nozzle
- breaking off of a small-bore pipe such as an instrument connection or branch line
- inadvertently leaving a drain or vent valve open.

The reader should note, however, that the loss of containment checklist should not be considered exhaustive, and other enumeration techniques should be considered in developing an expansive list of incidents.

Another way to generate an incident list is to consider potential leaks and major releases from fractures of all process pipelines and vessels. The enumeration of incidents from these sources is made easier by compiling pertinent information (listed below), relevant to all process and storage vessels. This compilation should include all pipework and vessels in direct communication, as these may share a significant inventory that cannot be isolated in an emergency.

- vessel number, description, and dimensions
- materials present
- vessel conditions (phase, temperature, pressure)
- connecting piping
- piping dimensions (diameter and length)
- pipe conditions (phase, pressure drop, temperature)
- valving arrangements (automatic and manual isolation valves, control valves, excess flow valves, check valves)
- inventory (of vessel and all piping interconnections, etc.)

This approach is discussed in more detail in the *Rijnmond Area Risk Study* (Rijnmond Public Authority, 1982) and the *Manual of Industrial Hazard Assessment Techniques* (World Bank, 1985). Of necessity, this approach excludes specific incidents and initiating events that would be generated by hazard identification methods (e.g., releases from emergency vents or relief devices). Freeman et al. (1986) describe a system that addresses both fractures and other initiating events. The list of incidents can also be expanded by considering each of the incident outcomes presented in Table 1.2 and proposing credible incidents that can produce them. Pool fires might result from releases to tank dikes or process drainage areas; vapor cloud explosions, flash fires, and dispersion incidents from other release scenarios; confined explosions (e.g., those due to polymerization, detonation, overheating) from reaction chemistry and abnormal process conditions; or BLEVE, from fire exposure to vessels containing liquids.

1.4.2. Selection

The goal of selection is to limit the total number of incident outcome cases to be studied to a manageable size, without introducing bias or losing resolution through overlooking significant incidents or incident outcomes. Different techniques are used to select incidents (Section 1.4.2.1), incident outcomes (Section 1.4.2.2), and incident outcome cases (Section 1.4.2.3). The risk analyst must be proficient in each of these techniques if a defensible basis for a representative CPQRA is to be developed.

1.4.2.1. INCIDENTS

The purpose of incident selection is to construct an appropriate set of incidents for the study from the initial list that has been generated by the enumeration process. An appropriate set of incidents is the minimum number of incidents needed to satisfy the requirements of the study and adequately represent the spectrum of incidents enumerated, considering budget constraints and schedule.

The effects of selection are shown graphically in Figure 1.8. The reality list contains all possible incidents. It approaches infinitely long. The initial list contains all the incidents identified by the enumeration methods chosen. The remaining lists are described in this section. Figure 1.8. shows the relative reductions in list size that are achieved by successive operations on the initial list.

One of the risk analyst's jobs is to select a subset of the Initial List for further analysis. This involves several tasks, each resulting in a unique list (Figure 1.8). Throughout the selection process, the risk analyst must exercise caution so that critical incidents, which might substantially affect the risk estimate, are not overlooked or excluded from the study. The initial list of incidents is reviewed to identify those incidents that are too small to be of concern (Step 4, Figure 1.4). Removing these incidents from the initial list produces a revised list (Figure 1.8).

To be cost effective and reduce the CPQRA calculational burden, it is essential to compress this revised list by combining redundant or very similar incidents. This new list is termed the condensed list (Figure 1.8). This list can and should be reduced further by grouping similar incidents into subsets, and, where possible, replacing each subset with a single equivalent incident. This grouping and replacement can be accomplished by consideration of similar inventories, compositions, discharge rates, and discharge locations.

The list formed in this manner is the expansive list and represents the list from which the study group is selected. A detailed or complex study would utilize the entire expansive list of incidents, while a screening study would utilize only one or two incidents from this list.

The expansive list can be reduced to one or both of two smaller "lists": the bounding group or the representative set (Section 1.3.1; and Figure 1.5). Selection of a bounding group of incidents typically considers only the subsets of catastrophic incidents on the expansive list. This may be further reduced by selecting only the worst possible incident or worst credible incident.

Selection of a representative set of incidents from the expansive list should include contributions from each class of incident, as defined in Table 1.3. This process can be facilitated through the use of ranking techniques. By allocating incidents into the three classes presented in Table 1.3, an inherent ranking is achieved. Further ranking of individual incidents within each incident class is possible. Various schemes can be devised to rank incidents within each incident class (e.g., preliminary ranking criteria based on the severity of hazard posed by released chemicals, release rate, and total quantity released). A ranking procedure is important in the selection of a representative set of incidents if the study is to minimize bias or loss of resolution.

Ranking can also be a useful tool if the study objectives (Section 1.9.2) exclude incidents below a specified cutoff value. One example is the establishment of a cutoff for loss of containment of material events by specifying a limited range of hole sizes for a wide range of process equipment (e.g., two for process pipework, one representing a full-bore rupture and the other 10% of a full bore rupture). This approach is presented in the *Manual of Industrial Hazard Assessment Techniques* (World Bank, 1985). Such a cutoff is arbitrary and a more fundamental approach is to identify, from consequence techniques (Chapter 2), the minimum incident size of importance for each of the materials used on-site. This ensures consistent treatment of materials of different hazards. Figure 1.9 (Hawksley, 1984) contains data on pipeline failures including the frequency distributions for holes of various sizes.

1.4.2.2 INCIDENT OUTCOMES

The purpose of incident outcome selection is to develop a set of incident outcomes that must be studied for each incident included in the finalized incident study list (i.e., the bounding group, representative set, or expansive list of incidents). Each incident needs to be considered separately. Using the list of incident outcomes presented in Table 1.2, the risk analyst needs to deter nine which may result from each incident. This process is not necessarily straightforward. While the analyst can decide whether an incident

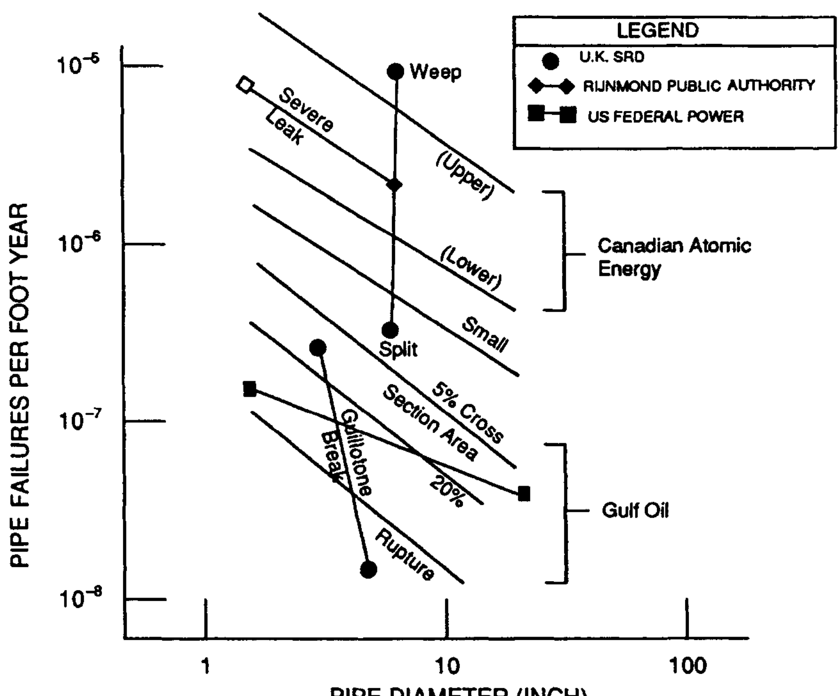

FIGURE 1.9. Summary of some pipe failure rate data. From Hawksley (1984). Reprinted with permission.

involving the loss of a process chemical to the atmosphere needs to be examined using dispersion analysis because of potential toxic gas effects, what happens if the same material is immediately ignited on release?

Figure 1.2 was presented to illustrate how one incident may create one or more incident outcomes, using the logical structure of an event tree. More detailed event trees have been developed in attempts to illustrate the complicated and often interrelated time series of incident outcomes that can occur. Figure 1.10 presents such an event tree developed by Mudan (1987) to show all potential incident outcomes from the release (loss of containment) of a hazardous chemical. Naturally, the properties of the chemical, conditions of the release, etc., all influence which of the logical paths shown in Figure 1.10 will apply for any specific incident. All such paths need to be considered in creating the set of outcomes to be studied for each incident included in the finalized study list. After examination, it soon becomes apparent that even Figure 1.10 is not detailed enough to cover all possible permutations of phenomena that can immediately result from a hazardous material release.

Detailed logical structures (see Figures 1.11 and 1.12) have been developed [e.g., see UCSIP (1985)] to try to account for the mix of incident outcomes that can result following an incident. No single comprehensive logic diagram exists. Various computer programs have been developed, however, to assist the analyst. Ultimately, the analyst must be satisfied that the set of outcomes selected for each incident in the finalized study list adequately represents the range of phenomena that may follow an incident.

1.4.2.3. INCIDENT OUTCOME CASES

As shown in Figure 1.2, for every outcome selected for study, one or more incident outcome cases can be constructed. Each case is defined through numerically specifying sufficient parameters to allow the case to be uniquely distinguished from all other cases developed for the same outcome.

An easy distinction between incident outcome cases is in the prevailing weather. When considering the dispersion of a cloud formed from the release of a process chemical to the atmosphere, the analyst must decide how the travel of the cloud "downwind" is to be studied. Various parameters—wind speed, atmospheric stability, atmospheric temperature, humidity, etc.—all need to be considered.

Once the risk analyst has identified all of the parameters that influence specification of an incident outcome, ranges of values for each parameter need to be developed, and discrete values created within each range. An incident outcome case is specified by the data set containing the analyst's selection of a unique value within the range developed for each parameter. The number of outcome cases that can be created equals the number of possible permutations of this data set using all of the discrete values for each of the parameters.

As discussed in Section 1.9.3, the combinatorial expansion of incident outcome cases can adversely affect resource requirements for a CPQRA without substantially adding to the quality of the resulting risk estimate or insights from the study. An experienced analyst will be able to limit the number of incident outcome cases to be studied. For example, problem symmetry may be exploited, worst case conditions assumed, plume centerline concentrations selected rather than developing complete cloud pro-

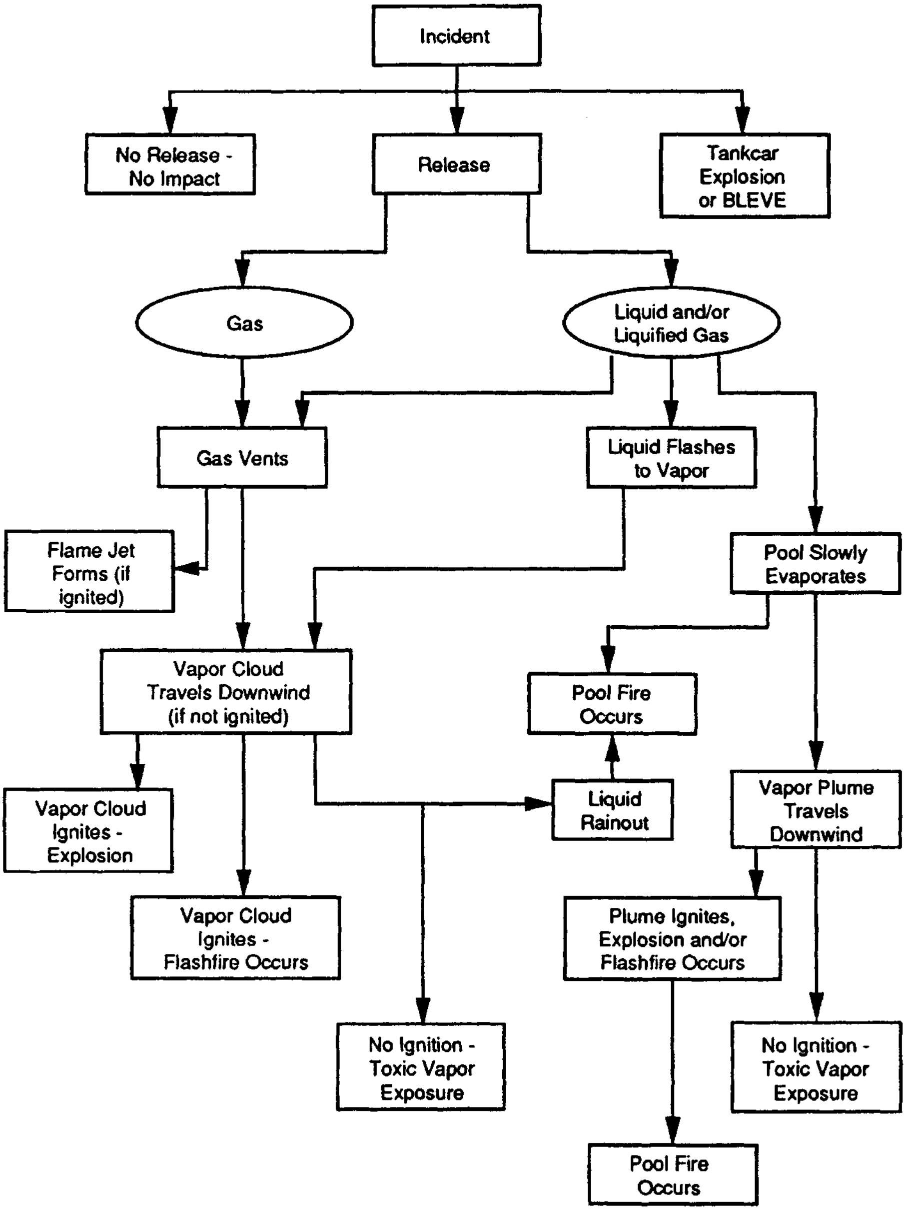

FIGURE 1.10. Typical spill event tree showing potential incident outcomes for a hazardous chemical release.

files, and a directional incident outcome assumed rather than study an omnidirectional incident. Each decision removes a multiplier from the number of cases to be studied.

It is the analyst's responsibility to ensure that sufficient definition results from the number of incident outcome cases specified to achieve study objectives. Decisions made concerning parameter selection and the range of values to be studied within each parameter need to be challenged through peer review and documented. Likewise the perceived importance of such parameters and their values can and should be checked through sensitivity studies following the development of an initial risk estimate. It is

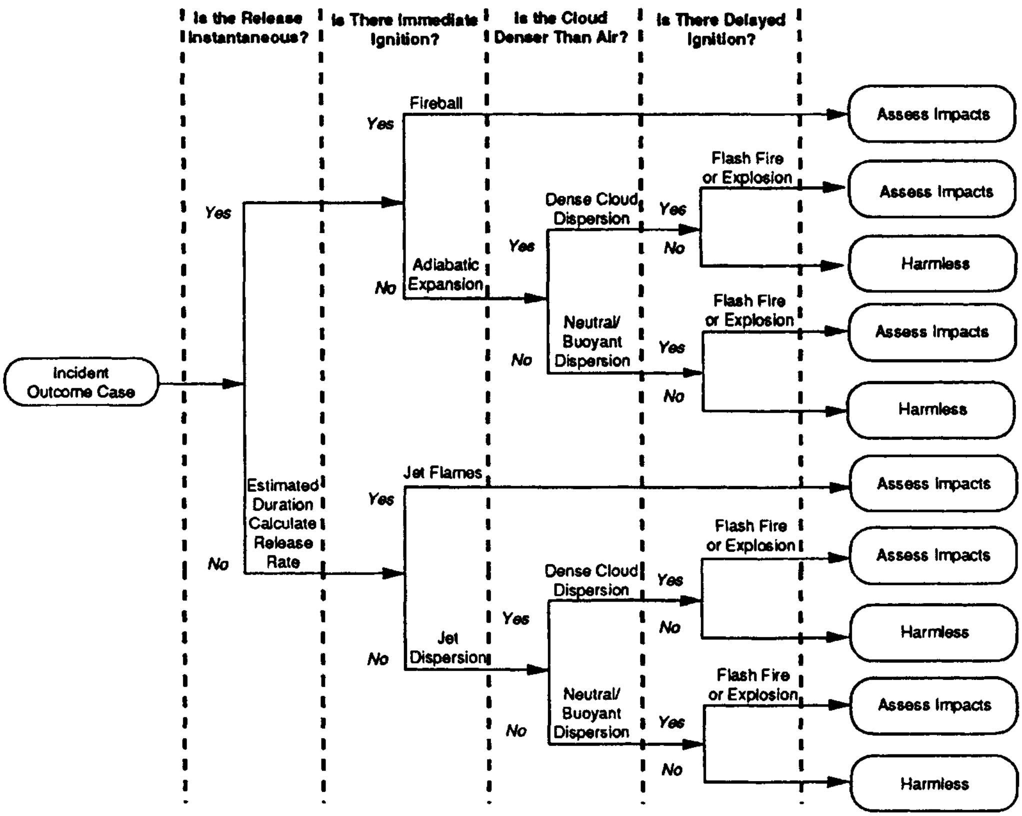

FIGURE 1.11. Spill event tree for a flammable gas release.

also the analyst's responsibility to recognize the sensitivity of the cost of the CPQRA to each parameter and avoid wasting resources.

One effective strategy is to screen the parameter value ranges and select a minimal number of outcome cases to complete a first pass risk estimate. Using sensitivity methods, the importance of each selected parameter value can be determined, and adjustments made in subsequent passes, maintaining control of the growth of the number of incident outcome cases while observing impacts on resulting estimates.

It is also useful to determine upper and lower bounds for the risk estimate using the parameter-value range available. This offers the analyst a reference scale against which to view any single point estimate, along with its sensitivity to changes in any given parameter. Various mathematical models are available for determining the upper and lower bounds for the parameter-value ranges available. These include techniques commonly used in the statistical design of experiments (e.g., see Box and Hunter, 1961; Kilgo, 1988). These methods can be used to identify critical parameters from all of the parameters identified. Linear programming techniques and min/max search strategies (e.g., see Carpenter and Sweeny, 1965; Long, 1969; Nelder and Mead, 1964; Spendley et al., 1962) can be used thereafter to find values for these critical parameters that will produce both the upper and lower bounds (maximum and minimum values) for the risk estimate.

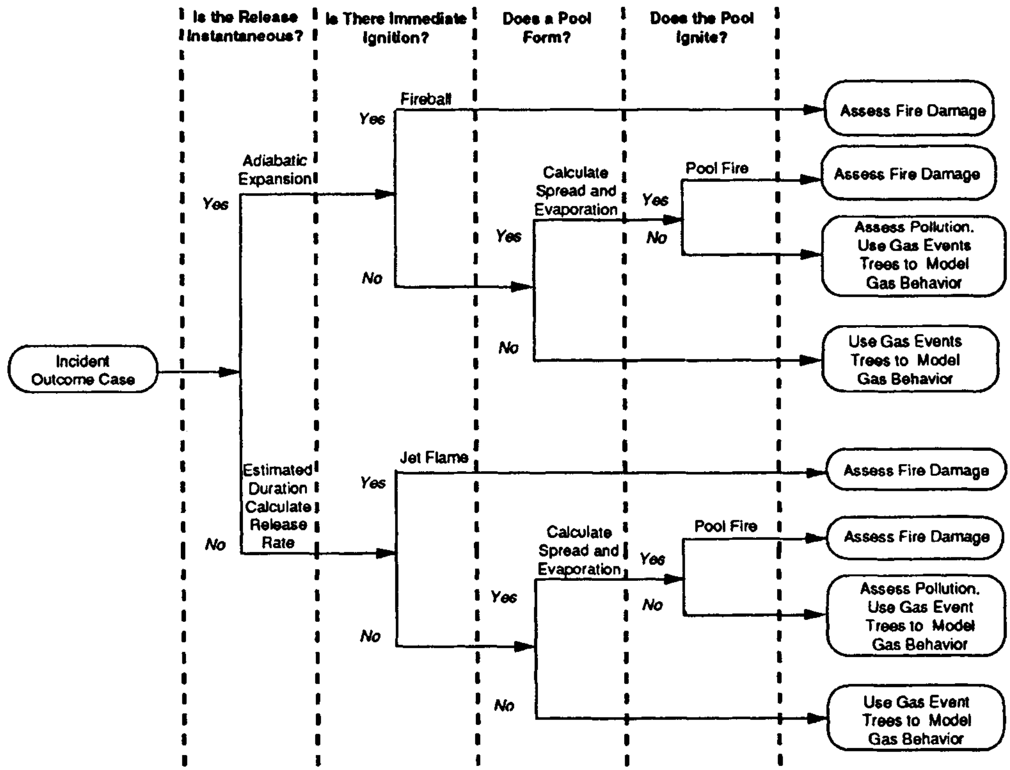

FIGURE 1.12. Spill event tree for a flammable liquid release.

Since these bounds can be established without exhaustively examining all of the incident outcome cases possible, the experienced analyst can manage the number of cases to be examined without compromising the desire to develop a quantitative understanding of the range—a feel for spread—of the risk estimate.

1.4.3. Tracking

The development of some risk estimates, such as individual risk contours or societal risk curves requires a significant number of calculations even for a simple analysis. This can be time consuming if a manual approach is employed for more than a few incident outcome cases. Chapter 4, Section 4.4, describes risk calculation methods and provides examples of various simplifiied approaches. The techniques are straightforward, however many repetitive steps are involved, and there is a large potential for error. A computer spreadsheet or commercial model is generally useful in manipulating, accounting, labeling, and tracking this information. The case studies of Chapter 8 illustrate these grouping, accounting, labeling, and tracking processes.

1.5. Applications of CPQRA

No organization or society has the resources to perform CPQRAs (of any depth) on all conceivable risks. In order to decide where and how to use the resources that are avail-

Next Page