GUIDELINES FOR EVALUATING PROCESS PLANT BUILDINGS FOR EXTERNAL EXPLOSIONS, FIRES, AND TOXIC RELEASES

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GUIDELINES FOR EVALUATING PROCESS PLANT BUILDINGS FOR EXTERNAL EXPLOSIONS, FIRES, AND TOXIC RELEASES

Second Edition

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GUIDELINES FOR EVALUATING PROCESS PLANT BUILDINGS FOR EXTERNAL EXPLOSIONS, FIRES, AND TOXIC RELEASES

Second Edition

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GLOSSARY

Accident: An unplanned event or sequence of events that results in an undesirable consequence.

Acute: Single, short-term exposure (less than 24 hours).

Aggregate Risk: Societal risk for on-site workers in occupied buildings (API 752).

Blast: A transient change in the gas density, pressure, and velocity of the air surrounding an explosion point. The initial change can be either discontinuous or gradual. A discontinuous change is referred to as a shock wave, and a gradual change is known as a pressure wave.

Blast Load: The load applied to a structure or object from a blast wave, which is described by the combination of overpressure and either impulse or duration.

BLEVE (Boiling Liquid, Expanding Vapor Explosion): The explosively rapid vaporization and corresponding release of energy of a liquid, flammable or otherwise, upon its sudden release from containment under greater-than-atmospheric pressure at a temperature above its atmospheric boiling point. A BLEVE is often accompanied by a fireball if the suddenly depressurized liquid is flammable and its release results from vessel failure caused by an external fire. The energy released during flashing vaporization may contribute to a shock wave.

Building: A rigid, enclosed structure.

Building Siting Evaluation: The procedures used to evaluate the hazards and establish the design criteria for new buildings and the suitability of existing buildings at their specific locations.

Building Geographic Risk: The risk to a person who occupies a specific building 24 hours/day, 365 days/year.

Combustible: Capable of burning.

Confinement: Solid surfaces that prevent movement of unburnt gases and a flame front in one or more dimensions.

Congestion: Obstacles in the path of the flame that generate turbulence.

Consequence: The undesirable result of an incident, usually measured in health and safety effects, environmental impacts, loss of property, and business interruption costs. For building siting, consequence refers to building damage and occupant vulnerability from the potential effects of an explosion, fire, or toxic material release. Consequence descriptions may be qualitative or quantitative.

Consequence Based Approach: The methodology used for building siting evaluation that is based on consideration of the impact of explosion, fire and toxic material release which does not consider the frequency of events.

Deflagration: A propagating chemical reaction of a substance in which the reaction front advances rapidly into the unreacted substance, but at less than sonic velocity in the unreacted material.

Detonation: A propagating chemical reaction of a substance in which the reaction front advances into the unreacted substance at or greater than sonic velocity in the unreacted material.

Essential Personnel: Personnel with specific work activities that require them to be located in buildings in or near a process area for logistical and response purposes.

Explosion: A release of energy that causes a blast.

Flammable: A gas that can burn with a flame if mixed with a gaseous oxidizer such as air or chlorine and then ignited. The term *flammable gas* includes vapors from flammable or combustible liquids above their flash points.

Flame Speed: The speed of a flame burning through a flammable mixture of gas and air measured relative to a fixed observer, that is, the sum of the burning and translational velocities of the unburned gases.

Flammable Limits The minimum and maximum concentrations of combustible material in a homogeneous mixture with a gaseous oxidizer that will propagate a flame.

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

F-N Curve: A plot of cumulative frequency versus consequences (expressed as number of fatalities).

Hazard: An inherent physical or chemical characteristic (e.g. flammability, toxicity, corrosivity, stored chemical energy, or mechanical energy) that has the potential for causing harm to people, property, or the environment.

HVAC: Heating, Ventilating and Air Conditioning.

Impulse: A measure that can be used to define the ability of a blast wave to do damage. It is calculated by the integration of the pressure-time curve.

Incident: An unplanned event with the potential for undesirable consequences.

Individual Risk: The risk to a person in the vicinity of a hazard. This includes the nature of the injury to the individual, the likelihood of the injury occurring, and the time period over which the injury might occur.

LFL (Lower Flammability Limit): The concentration of a combustible material in air below which ignition will not occur. It is often referred to as the Lower Explosive Limit (LEL). Mixtures below this limit are said to be "too lean."

Lookup Table Approach: See "Spacing Table Approach"

MCE (Maximum Credible Event): A hypothetical explosion, fire or toxic event that has the potential maximum consequence to the occupants of the building under consideration from among the major scenarios evaluated. The major scenarios are realistic and have a reasonable probability of occurrence considering the chemicals, inventories, equipment and piping design, operating conditions, fuel reactivity, process unit geometry, industry incident history, and other factors. Each building may have its own set of MCEs for potential explosion, fire or toxic material release impacts.

MOC (Management of Change): A system to identify, review and approve all modifications to equipment, procedures, raw materials and processing conditions other than replacement in kind," prior to implementation. [Management of Change is an element of the U.S. Occupational Health and Safety Administration (OSHA)'s Process Safety Management (PSM) regulation.]

Occupant Vulnerability: Proportion of building occupants that could potentially suffer an injury or fatality if a postulated event were to occur. The level of injury is defined according to the technical basis of the occupant vulnerability model being used.

On-site Personnel: Employees, contractors, visitors, service providers, and others present at the facility.

Overpressure: Any pressure above atmospheric caused by a blast.

Permanent Building: Rigid structures intended for permanent use in fixed locations.

Portable Building: Rigid structure that can be easily moved to another location within the facility.

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

Process Area: An area containing equipment (e.g. pipes, pumps, valves, vessels, reactors, and supporting structures) intended to process or store materials with the potential for explosion, fire, or toxic material release.

Probit: A random variable with a mean of 5 and a variance of 1, which is used in various effect models.

PSM (Process Safety Management): A program or activity involving the application of management principles and analytical techniques to ensure the safety of chemical process facilities. Sometimes called *process hazard management*. Each principle is often termed an "element" or "component" of process safety. [This can also refer to the U.S. Occupational Health and Safety Administration (OSHA)'s Process Safety Management (PSM) regulation 29 CFR 1910.119.]

Qualitative: Based primarily on description and comparison using historical experience and engineering judgment, with little quantification of the hazards, consequences, likelihood, or level of risk.

QRA (Quantitative Risk Assessment): The systematic development of numerical estimates of the expected frequency and/or consequence of potential accidents associated with a facility or operation based on engineering evaluation and mathematical techniques.

Reflected Pressure: Impulse or pressure experienced by an object facing a blast.

Risk Based Approach: A quantitative risk assessment methodology used for building siting evaluation that takes into consideration numerical values for both the consequences and frequencies of explosion, fire, or toxic material release.

Risk Based Inspection: A risk assessment and management process that is focused on loss of containment of pressurized equipment in processing facilities, due to material deterioration. These risks are managed primarily through equipment inspection.

Scenario: An unplanned event or incident sequence that results in a loss event and its associated impacts, including the success or failure of safeguards involved in the incident sequence.

Semi-quantitative: Risk analysis methodology that includes some degree of quantification of consequence, likelihood, and/or risk level.

Shelter-in-Place: A process for taking immediate shelter in a location readily accessible to the affected individual by sealing a single area (an example being a room) from outside contaminants and shutting off all HVAC systems.

Side-on Pressure: The impulse or pressure experienced by an object as a blast wave passes by it.

Spacing Table Approach: The use of established tables to determine minimum separation distances between equipment and buildings intended for occupancy. Industry groups, insurance associations, regulators and owner/operator companies have developed experience-based spacing tables for minimum building spacing for fire.

Toxic Material: An airborne agent that could result in acute adverse human health effects.

Vapor Cloud Explosion: The explosion resulting from the ignition of a cloud of flammable vapor, gas, or mist in which flame speeds accelerate to sufficiently high velocities to produce significant overpressure.

1 INTRODUCTION

Catastrophic accidents in the chemical process industries, while uncommon, may affect buildings in or near processing facilities. The likelihood of serious events involving hazardous materials can and has been effectively reduced through the application of process safety management. Specifically, the CCPS Guidelines for Technical Management of Chemical Process Safety (CCPS, 1989a) states:

As the chemical process industries have developed more sophisticated ways to improve process safety, we have seen the introduction of safety management systems to augment process safety engineering activities.

Management systems for chemical process safety are comprehensive sets of policies, procedures, and practices designed to ensure that barriers to major incidents are in place, in use, and effective. The management systems serve to integrate process safety concepts into ongoing activities of everyone involved in operations — from the chemical process operator to the chief executive officer.

These process safety management systems help ensure that facilities are designed, constructed, operated, and maintained with appropriate controls in place to prevent serious accidents. Despite these precautions, buildings close to process plants have presented serious risks to the people who work in them. This observation is prompted by the fact that some buildings that were not designed and constructed to be blast resistant have suffered heavy damage, and in some instances have collapsed when subjected to blast loads from accidental explosions. Serious injury or fatality to the occupants resulted from the building damage. Experience indicates that personnel located outdoors and away from such buildings, if subjected to the same blast, may have a lower likelihood of serious injury or fatality. Building occupants have also been exposed to toxic vapors that enter through forced or natural convection ventilation, and thermal hazards that result from fires near buildings.

Industry associations and insurers have proposed building design and siting guidelines as a means of improving personnel safety. The resulting standards, however, are not universally applicable to all industry sectors and do not ensure consistent levels of safety. Consequently, the chemical processing industries recognizes the need for guidance on a uniform approach to the design and siting of buildings intended for occupancy. The chemical process industries also recognizes that this guidance needs to be practical and consistently applicable across the spectrum of interested industries, and take into account the specific operations and conditions existing at any particular site.

The purpose of this book, *Guidelines for Evaluating Process Plant Buildings for External Explosions, Fires and Toxic Releases, Second Edition* is to provide guidance to building siting evaluations. The first edition of this book was written in conjunction with the first edition of American Petroleum Institute (API) Recommended Practice (RP) 752, "Management of Hazards Associated with Location of Process Plant Permanent Buildings," issued in 1995. API developed a recommended practice specific to siting of portable buildings in 2007. The new recommended practice was designated API RP-753 and named "Management of Hazards Associated with Location of Process Plant Portable Buildings" (API, 2007). API completed a major revision of API RP-752 in December 2009 (API, 2009). Development of API RP-753 and revision of API RP-752 prompted updating of this book. This book has an expanded role in providing the guidance for all phases of the building siting evaluation process.

API RP-752 was first published in 1995 and provided a three-stage framework for conducting a building siting evaluation. API RP-752 also included examples of numerical occupancy level criteria that could be used to screen buildings from siting evaluation, and some simplified consequence and risk analysis data. The 2009 edition transformed API RP-752 into a management process for siting evaluations, and removed most technical content. Portable buildings were removed from the scope of API RP-752 when API RP-753 was issued, and the scope of API RP-752 was clarified to encompass new and existing rigid structures intended to be permanently placed in fixed locations. Tents, fabric enclosures, and other soft-sided structures are therefore outside the scope of API RP-752.

API RP 752 (API, 2009) and RP 753 (API, 2007) have a set of guiding principles for building siting evaluations. API RP 752 guiding principles are shown below. API RP 753 has a similar set, but modified to be more suitable to portable buildings. The API RP-752 guiding principles are:

- Locate personnel away from process areas consistent with safe and effective operations;
- Minimize the use of buildings intended for occupancy in close proximity to process areas;
- Manage the occupancy of buildings in close proximity to process areas;
- Design, construct, install, modify, and maintain buildings intended for occupancy to protect occupants against explosion, fire and toxic material releases;
- Manage the use of buildings intended for occupancy as an integral part of the design, construction, maintenance, and operation of a facility.

Figure 1.1 depicts the relationship between API RP-752 and API RP-753. Blast resistant modular buildings (BRM) can potentially fall within the scope of either API RP-752 or API RP-753 depending on the intended use of the BRM. BRMs that are intended for permanent installation in a fixed location fall within the scope of API RP-752, whereas all temporary applications fall within the scope of API RP-753. This book addresses both permanent and temporary buildings and provides analysis methods that support both of the API recommended practices.

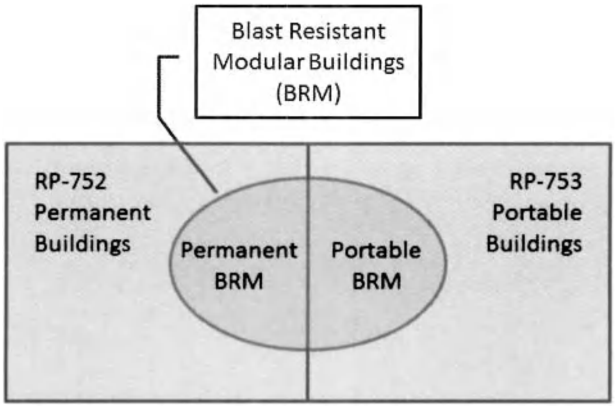

Figure 1.1. Relationship between API RP-752 and API RP-753

API RP-753 includes restrictions on personnel who can be located in portable buildings in certain circumstances. Only essential personnel are allowed in selected portable buildings close to and within process units (API RP-753 Zone 1) when the building has been subjected to a detailed analysis for the hazards at the building location. No such personnel restrictions are included in API RP-752 for permanent buildings; instead, all buildings intended for occupancy undergo a detailed analysis for explosion hazards.

It is not the role of this book to create any additional building siting requirements beyond those defined in API RP-752 and API RP-753. The reader should review both recommended practices before reading this book. Guidance on all aspects of the building siting evaluation process can be found in this book. This book serves as a roadmap to references including CCPS documents.

A wide variety of technical and process safety management issues are referenced throughout this book. Detailed coverage of these issues is outside the scope of this book, however, and readers are referred to other CCPS books for more information. These include, in particular:

- Guidelines for Technical Management of Chemical Process Safety (CCPS, 1989a)
- Guidelines for Hazard Evaluation Procedures, Third Edition, with worked examples (CCPS, 2008b)
- Guidelines for Chemical Process Quantitative Risk Analysis (CCPS, 2000)
- Guidelines for Vapor Cloud Explosion, Pressure Vessel Burst, BLEVE and Flash Fire Hazards (CCPS, 2010)
- Guidelines for Use of Vapor Cloud Dispersion Models (CCPS, 1987)

- Guidelines for Vapor Release Mitigation (CCPS, 1988)
- Guidelines for Facility Siting and Layout (CCPS 2003a)
- Guidelines for Developing Quantitative Safety Risk Criteria (CCPS 2009b)
- Guidelines for Fire Protection in Chemical, Petrochemical, and Hydrocarbon Processing Facilities (CCPS, 2003b).
- Guidelines for Risk Based Process Safety (CCPS, 2007)

Additionally, the following references also provide guidance:

- U.S. Army, "Structures to Resist the Effects of Accidental Explosions" (U.S. Army, 1991)
- American Society of Civil Engineers, *Design of Blast Resistant Buildings in Petrochemical Facilities* (ASCE, 2010)
- American Society of Civil Engineers, *Structural Design for Physical Security* (ASCE, 1999)
- "Single Degree of Freedom Structural Response Limits for Antiterrorism Design," (U.S. Army COE, 2006)

1.1 OBJECTIVE

The objective of these guidelines is to provide a practical approach to implementing a building siting evaluation for process plant buildings in accordance with API RP-752 and RP-753. Note that API RP-752 and RP753 provide the process by which building siting evaluations are conducted for permanent and portable buildings, respectively. However, these recommended practices do not provide the technical methods needed to conduct a building siting evaluation.

API RP-752 now requires a building siting evaluation of all permanent buildings intended for occupancy that are located on sites covered by the OSHA PSM regulation (29 CFR 1910.119). The analysis methods described in this book are not limited to U.S. OSHA PSM covered facilities and can be used for any buildings an owner/operator wishes to evaluate; in fact, other countries may have regulatory requirements that differ from the U.S. This book is applicable to on-shore facilities and does not address circumstances that exist in offshore installations. API RP-753 has similar requirements for detailed analysis of portable buildings unless a portable building is sited beyond a distance determined by a conservative simplified analysis method for vapor cloud explosions (VCE). Even the API RP-753 simplified method requires site-specific data in terms of process unit congested volume to calculate the siting distance.

The purpose of this book is to provide the methods to address the explosion, fire and toxic impacts to process plant buildings and occupants occurring as a result of hazards associated with operations external to the building.

Discussion of the following hazards is beyond the scope of this book:

- natural hazards;
- terrorist attack;
- fire and toxic impacts to off-site personnel and on-site personnel in open areas or within non-building structures; and
- secondary or "knock-on" effects that develop relatively slowly, allowing sufficient time for personnel to evacuate buildings.

1.2 BUILDING SITING EVALUATION PROCESS

This book is organized around the overall building siting evaluation process in API RP-752 as depicted in Figure 1.2. Readers are encouraged to read this entire guideline before starting or revising a building siting evaluation. Chapter numbers that provide guidance for each step are shown in parentheses.

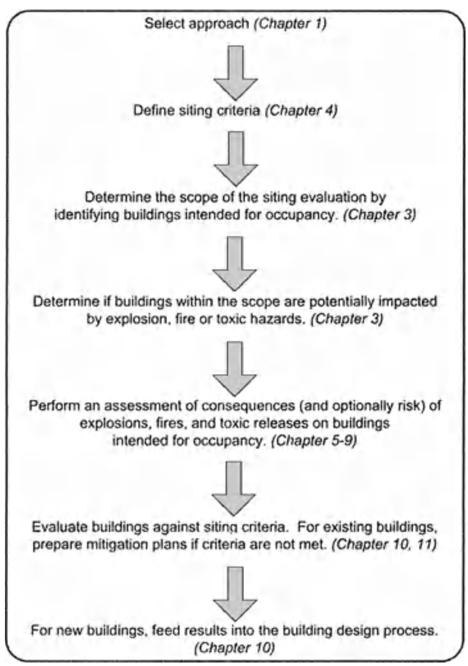

Figure 1.2. Overall Process for a Building Siting Evaluation

1.3 SELECTION OF APPROACH

The building siting process begins with selection of the approach that will be followed. The approach may be consequence-based or risk-based as explained in Chapter 2, Section 2.1.3. A consequence-based methodology does not include consideration of the frequency with which an explosion, fire or toxic scenario may occur; rather, the analysis is limited to computation of the damage or injury that may result from the postulated scenario. Risk-based analysis considers a range of scenarios and incorporates the frequency associated with each scenario. The risk to occupants of buildings is the sum of the risk posed by all of the scenarios impacting the building.

1.4 BACKGROUND

Prior accidents have prompted improvements to the approach to address risks to process plant buildings and their occupants. Table 1.1 provides a selected list of serious incidents involving buildings in process plants. A significant percentage of the fatalities occurred in buildings for the incidents shown in Table 1.1.

Table 1.1. Selected Accidents Involving Buildings in Process Plants

Date	Location	Fatalities	Description
1996	Cactus, Chiapas Mexico	7 (2 in buildings)	Liquefied petroleum gas (LPG) was released during maintenance when a valve was opened before flanges were bolted tight. The flammable cloud filled one liquefaction unit and half of the neighboring unit.
2001	Toulouse, France	29 (28 on-site, one off-site)	Off spec ammonium nitrate in prill form detonated in a large bulk warehouse. Approximately 400 metric tons of product were in the warehouse on the day of the explosion.
1993	Port Neal, Iowa	4 (none in buildings)	An ammonium nitrate (AN) reactor in a temporary shutdown suffered a runaway reaction. The AN plant was destroyed and numerous tanks were compromised by airblast and fragments. Fatalities resulted from ammonia and nitric acid vapor inhalation.
2007	Jacksonville Florida	4 (2 in a building)	A runaway reaction of a batch of methylcyclopentadienyl manganese tricarbonyl caused the reactor to burst, A loss of sufficient cooling lead to uncontrolled pressure and temperature. The contents ignited after the reactor burst.
1992	La Mede, France (Heller, 1993)	6 (most in buildings)	A liquefied petroleum gas (LPG) leak in the gas concentration section of a catalytic cracking unit resulted in an explosion that destroyed the unit and demolished the adjacent control room.

Table 1.1., Continued

Date	Location	Fatalities	Description
1992	Castleford, England (HSE, 1994)	5 (5 in buildings)	Heat-sensitive and unstable nitrotoluene residue was overheated during the preparation for maintenance. A runaway reaction caused a jet flame that destroyed a wooden control room.
1988	Norco, Louisiana (Hagar, 1988)	7 (6 in buildings)	A corrosion-induced propane leak in a fluid catalytic cracking unit resulted in an explosion that destroyed the control room. Six fatalities occurred in or near the control room; the seventh was caused by a falling brick wall.
1978	Texas City, Texas (Davenport, 1986)	7 (unknown number in buildings)	An isobutane storage sphere was overfilled and overpressured during a pipeline transfer operation. The sphere cracked at a defective weld, releasing isobutane. The release subsequently ignited and flashed back to the sphere. The sphere then failed catastrophically, resulting in a large fireball. Multiple BLEVEs of adjacent LPG storage vessels followed. Isolated glass breakage occurred as far as 2 mi (3.2 km) from the facility. A masonry control house less than 260 ft (80 m) away was destroyed by a missile fragment.
1978	Denver, Colorado (Lenoir, 1993; Garrison, 1988)	3 (0 in buildings)	A propane release at a polymerization unit in a process plant resulted in a blast that destroyed the process unit. The blast-resistant control house, located only 98 ft (30 m) from the blast center, sustained little damage.
1975	Beek, The Netherlands (Marshall, 1987)	14 (6 in buildings)	A propylene leak resulted in an explosion that caused severe blast and fire damage to the control house. All controls and plant records were lost.
1970	Linden, New Jersey (Lenoir, 1993; Garrison, 1988)	0	A 2,500 psig (170 bar) reactor of a hydrocracking unit failed explosively due to localized overheating. The blast caused widespread damage over a 900-ft (275-m) radius, including an adjoining unit, where the roof of a nearby building collapsed. Other units were safely shut down from a blast-resistant control building, which sustained minor damage.
1966	Montreal, Quebec (Garrison, 1988)	9 (all in or near buildings)	A release of styrene from a polymerization reactor through a rupture disk and/or a failed sight glass formed a vapor cloud inside and outside the building housing the reactor. The subsequent explosion demolished the three-story reactor building, and a warehouse, guard house, and garage were destroyed by fire. Six other buildings were also damaged.

However, as indicated by the accidents in Denver, Colorado, and Linden, New Jersey, proper design and siting of occupied buildings can substantially reduce the risks of fatality.

For accidents affecting process plant buildings, the potential for serious or fatal injury to building occupants is the foremost concern. Additionally, in cases where buildings house critical controls or equipment, proper design and siting may also help reduce indirect safety impacts (e.g., due to loss of process control or emergency response capability), as well as business interruption costs and property loss from such events.

The following case histories further illustrate the risks to building occupants in structures not designed to be blast resistant and the ramifications of these incidents on changes to regulations and industry standards.

1.4.1 Flixborough, UK: Vapor Cloud Explosion in Chemical Plant

On June 1, 1974, a cyclohexane vapor cloud was released after the rupture of a pipe bypassing a reactor. HSE described the vapor cloud explosion that occurred in the reactor section of the caprolactam plant of the Nypro Limited, Flixborough Works (HSE, 1975). The Flixborough Works is situated on the east bank of the River Trent (Figure 1.3). The nearest villages are Flixborough (800 meters or one-half mile away), Amcotts (800 meters or one-half mile away), and Scunthorpe (4.9 km or approximately three miles away).

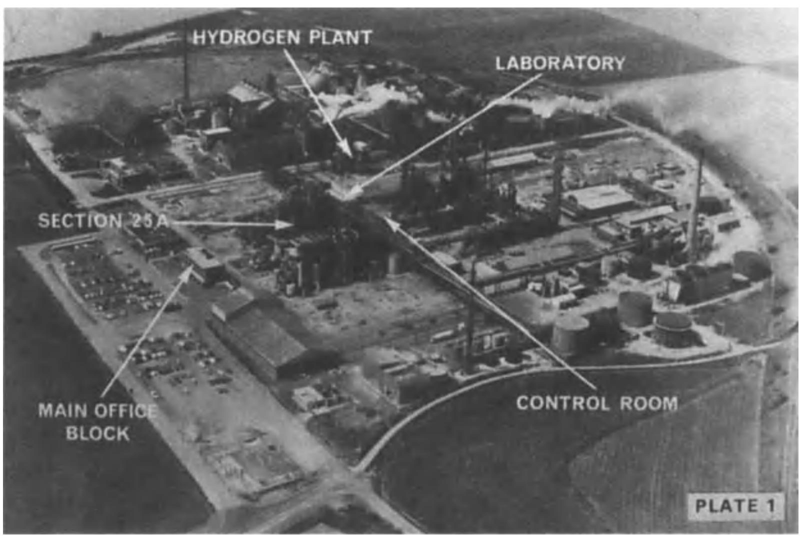

Figure 1.3. Flixborough Works Prior to the Explosion

The cyclohexane oxidation plant contained a series of six reactors. The reactors were fed by a mixture of fresh cyclohexane and recycled material. The reactors were connected by a pipe system, and the liquid reactant mixture flowed from one reactor into the other by gravity. Reactors were designed to operate at a pressure of approximately 9 bar (130 psi) and a temperature of 155°C (311°F). In March 1974, one of the reactors began to leak cyclohexane, and it was, therefore, decided to remove the reactor and install a bypass. A 0.51 m (20 in) diameter bypass pipe was designed and installed by plant personnel to connect the two flanges of the reactors. Bellows originally present between the reactors were left in place. Because reactor flanges were at different heights, the pipe had a dog-leg shape.

On May 29, 1974, the bottom isolating valve on a sight glass on one of the vessels began to leak, and a decision was made to repair it. On June 1, 1974, start-up of the process following repair began. As a result of poor design, the bellows in the bypass failed and a release of an estimated 33,000 kg (73,000 lb) of cyclohexane occurred, most of which formed a flammable cloud of vapor and mist (HSE, 1975).

After a period of 30 to 90 seconds following release, the flammable cloud was ignited. The time was then about 4:53 P.M. The explosion caused extensive damage and started numerous fires. The blast shattered control room windows and caused the collapse of its roof. It demolished the brick-constructed main office block, only 25 m (82 ft) from the explosion center. Fortunately, the office block was unoccupied at the time of the incident. None of the buildings had been constructed to protect the occupants from the effects of an explosion. Twenty-eight people died, and thirty-six were injured. Eighteen of the fatalities were in the control room at the time. If the incident had occurred during a week day rather than on a Saturday afternoon, over 200 people would have been working in the main office block. The plant was totally destroyed (Figure 1.4 and Figure 1.5) in addition to damaging 1,821 houses and 167 shops and factories in the vicinity of the plant.

Figure 1.4. Aerial View of Damage to the Flixborough Works

Figure 1.5. Damage to the Office Block and Process Areas at the Flixborough Works

Sadée et al. (1976–1977) gives a detailed description of structural damage due to the explosion and derived blast pressures from the damage outside the cloud. Several authors estimated the TNT mass equivalence based upon the damage incurred. Estimates vary from 15,000 to 45,000 kg (33,000 to 99,000 lb) of TNT. These estimates were performed at a time when TNT equivalence was the predominant prediction method, which is not recommended today.

The Flixborough incident brought initial focus to the potential hazards of vapor cloud explosions and the brittle response of unreinforced masonry (block) construction buildings. Subsequently, research was undertaken in a number of countries to improved understanding of vapor cloud explosions, develop blast prediction methods, and improve design of buildings to withstand blast loads.

1.5 PHILLIPS, PASADENA, TEXAS USA: PROPYLENE HDPE UNIT VCE AND BLEVES

On October 23, 1989, an explosion and a fire occurred at the Phillips 66 Company's Houston Chemical Complex located near Pasadena, Texas. This incident was caused by an accidental release of 40,000 kg (85,000 lbs) of a mixture containing ethylene, isobutane, hexene and hydrogen in a low density polyethylene unit (Figure 1.6). In this incident, 23 persons were killed and 314 people were injured.

Figure 1.6. Phillips Pasadena Plant Prior to the Incident

An OSHA report (OSHA, 1990) described the accident. On Sunday, October 22, 1989, a contractor crew started the maintenance procedure on the valves of a high density polyethylene reactor. Polyethylene was produced in loop reactors, which were supported by tall steel frame structures (Figure 1.6). The maintenance procedure consisted of disassembling and clearing a leg that had become clogged with polyethylene particles. On Monday afternoon (October 23) at about 1:00 P.M., a release occurred when the valve upstream of the discharge leg was accidentally opened. Almost all the contents of the reactor, approximately 40,000 kg (85,000 lbs) of high reactivity materials, were dumped. A large vapor cloud formed in a few seconds and moved downwind through the plant. Within two minutes, this cloud was in contact with an ignition source and exploded with the force of 2,400 kg (5,300 lbs) of TNT.

Following this VCE, two other major explosions occurred. The second explosion occurring 10 to 15 minutes after the initial explosion and involved BLEVEs of two 75 m^3 (20,000 U.S. gal) isobutene storage tanks (Figure 1.7). The third explosion occurred 25 to 45 minutes later, which was the catastrophic failure of the ethylene plant reactor. Damage to the process unit and nearby buildings is shown in Figure 1.8.

Figure 1.7. BLEVE at the Phillips Pasadena Site

Figure 1.8. Phillips Pasadena Area Damage (Courtesy of FM Global)

The initial blast destroyed the control room and caused the rupture of the adjacent vessels containing flammable materials and the water lines. The proximity between the process equipment and the buildings contributed to the intensity of the blast. Twenty-two of the victims were found within 76 m (250 ft) of the release point, 15 of which were within 45 m (150 ft). Most of the fatalities were within buildings, but the actual number was not reported.

The Phillips Pasadena 1989 incident, along with the 1984 Bhopal, India, 1988 Shell Norco, 1987 Arco Channelview, and 1989 Exxon Baton Rouge incidents, triggered the U.S. Congress to enact the Clean Air Act of 1990 with a requirement for both OSHA and EPA to develop process safety regulations. OSHA promulgated their standard first in 1992 as Process Safety Management (PSM) for Highly Hazardous Chemicals (29 CFR 1910.119) followed in 1996 by the EPA producing Section 112(r) of the Clean Air Act (CAA), which requires documentation of a site Risk Management Plan (RMP).

1.5.1 BP, Texas City, Texas USA: Discharge from Atmospheric Vent Resulting in a VCE

On March 23, 2005 at 1:20 P.M., an explosion and fire occurred at the BP Texas City Refinery Isomerization (ISOM) plant. In this incident, 15 people were killed and 180 were injured. During the incident, a shelter-in-place order was issued that required 43,000 people in the surrounding community to remain indoors.

According to the report by BP Products North America (Mogford, 2005) and the U.S. Chemical Safety and Hazard Investigation Board (CSB, 2007), on the morning of the accident, the raffinate splitter tower in the ISOM unit was restarted after a maintenance outage. During the procedure, the night shift charged the raffinate splitter to 100% of normal operating range (equivalent to 3.1 m [10 ft 3 inches]) height above the bottom tangent line in the 50 m (164-ft) tall tower and stopped flow. The day shift resumed pumping raffinate into the tower for over three hours without any liquid being removed, introducing an additional 397 m^3 (105,000 U.S. gal). As a consequence, the tower was overfilled, and the liquid overflowed into the overhead pipe at the top of the tower. The pressure relief valves opened at about 1:14 P.M. for 6 minutes and discharged an estimated 175 m^3 (46,000 U.S. gal) of flammable liquid to a blowdown drum with a vent stack open to the atmosphere. This blowdown drum overfilled after about 4½ minutes, which resulted in a geyser-like release that reached 6 m (20 ft) above the top of the stack at about 1:18 P.M. An estimated 8 m^3 (2,000 U.S. gal) of the hydrocarbon liquid overflowed from the blowdown drum stack. The flammable cloud was predominately on the west side of the unit to the south of the release point; the flammable cloud did not reach the eastern leg of the ISOM unit.

The vapor cloud was ignited at about 1:20 P.M. by an undetermined ignition source. A diesel pickup truck by the road on the north side of ISOM was observed to have its engine racing, and was a high potential ignition source.

In the explosion, 15 workers in or near trailers sited to the west of the ISOM unit were killed. Three occupants in a single-wide trailer perished, and 12 of 20 workers inside a double-wide trailer were killed; the others were seriously injured. Trailer locations are shown in Figure 1.9. Debris from the destroyed double-wide trailer is shown in Figure 1.10. The temporary office trailers were light wood construction. The cause of death for all 15 was blunt force trauma, probably resulting from being struck by structural components of the trailers. A total of 180 workers at the refinery reported injuries.

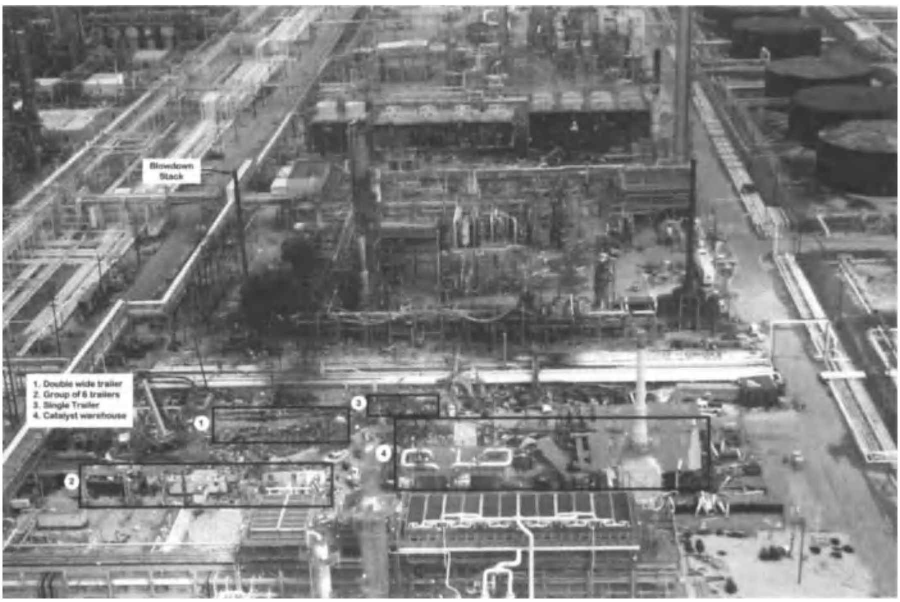

Figure 1.9. Aerial View of the ISOM unit after the Explosion (CSB, 2007)

The trailers were placed about 46 m (150 ft) west of the blowdown stack in the open area next to a pipe rack that was about 1 m (3 ft) above grade. The pipe rack provided congestion between the western edge of the ISOM unit and the trailers. The flammable cloud extended west past the pipe rack and trailers, resulting in the trailers adjoining a congested area that was involved in the VCE.

Figure 1.10. Destroyed Trailers West of the Blowdown Drum (arrow in upper left of the figure)

The BP Texas City incident showed the conventional office trailers were not as strong as previously believed and should not be sited near process units with potential explosion hazards. Portable buildings are often sited for convenience for temporary operations, such as turnarounds, and for permanent staff who need expedient work locations. Siting of portable buildings needs to consider all surrounding hazards, not just the hazards of the operations with which the portable buildings are associated. Industry response to CSB's urgent recommendation was the development of API RP-753, the first guideline that explicitly addressed siting of portable buildings.

1.5.2 Hickson & Welch Ltd, Castleford, UK; Jet Fire

On September 21, 1992 at 1:20 PM, a jet fire occurred at the Hickson & Welch Ltd. Chemical plant in Castleford, UK. The jet severely damaged a control room and impacted a more distant main office block. Five people died, all of whom were located in buildings.

The incident occurred during clean out of a batch still to remove residues. The batch still was part of the nitrotoluenes area of the plant. This vessel, shown in Figure 1.11, had never been cleaned since it was installed in 1961. The sludge was estimated to have a depth of 34 cm (14 in). The sludge was tar-like with the consistency of soft butter and had entrained liquid. The sludge was not analyzed nor was the atmosphere checked for flammable vapors. It was mistakenly thought that the material was a thermally stable tar. The investigation later revealed that the sludge contained flammable dinitrotoluene and nitrocresols, and covered one of the vessel's steam heating elements.

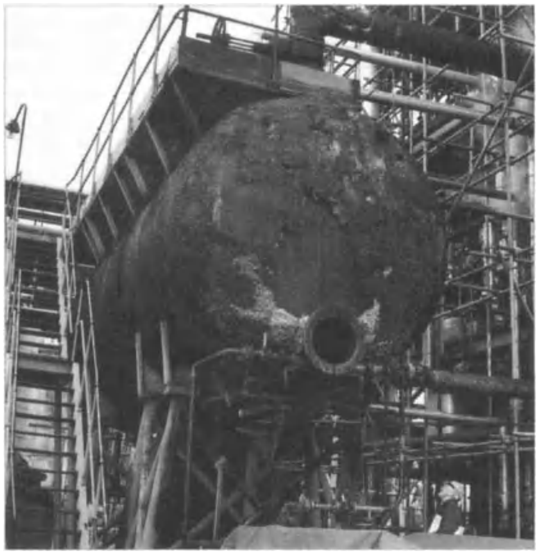

Figure 1.11. Vessel Involved in the Hickson & Welch Incident

Steam was applied to the bottom heating element to soften the sludge, with the temperature not to exceed 90°C. The clean out operation was started using a metal rake through an open manhole at one end of the vessel (see Figure 1.11). After about one hour, a longer rake was used to reach further into the vessel. Once the vessel's temperature gauge in the control room was reported to be reading 48 °C, instructions were given to isolate the steam.

At approximately 1:20 PM, a number of employees involved in the raking left the base of the vessel. One person left on the scaffold had stopped raking. He noticed a blue light, which turned instantly to an orange flame. As he leapt from the scaffold, an incandescent conical jet erupted from the manhole. This jet projected horizontally over 50 m, breaching and passing through the plant control building into the main office block. A second, vertical jet of burning vapors shot out of the top rear vent to the height of the distillation column nearby.

Investigations suggested that the sludge decomposed in an exothermic reaction that produced enough heat to ignite the vapors in the tank. The jet fire lasted for approximately one minute before subsiding. The force of the jet destroyed the scaffold, threw the manhole cover into the control building, and severely damaged this building and then impacted the main office block causing a number of fires to start inside the building. Damage to the control room and office block are shown in Figure 1.12 and Figure 1.13.

All of the casualties were located in the control building and main office block. Two of the five people in the control building died at the scene. Two others in the control room were badly burned and died later in hospital. The fifth victim, located in the main office, died of smoke inhalation.

Figure 1.12. Damage to the Control Building from the Jet Flame at Hickson & Welch

Figure 1.13. Damage to the Control Room and Impact on the Office Block from the Jet Flame at Hickson & Welch

1.6 EVOLUTION OF DESIGN AND SITING PRACTICES FOR BUILDINGS IN PROCESS PLANTS

Chemical process design and controls have often dictated the design and siting of buildings. This section contains a brief review of industry practices on the design and siting of process plant buildings.

1.6.1 Brief History of Building Designs

As process plant designs and management practices have evolved, building functions and locations have changed to reflect the new operating requirements, often leading to an increase in the number of buildings and personnel that were in or near the process units. For example, control facilities have typically been located within or adjacent to the process plants to provide effective control. Other buildings, such as maintenance facilities, are also sometimes located adjacent to process plants to allow prompt support of operations.

In *continuous-process* industries such as petroleum refining, petrochemicals, industrial chemicals, and fertilizers, the siting and size of buildings have been influenced by factors such as the following (Marshall, 1987):

- Increased unit capacities resulted in larger equipment. These units could no longer be enclosed in buildings.
- Outside location of process units or equipment required separate control buildings. Initially, their function was limited to displaying process variables. World-scale, single-train units, coupled with advances in automation, led to the use of servomechanisms for valve plug positioning.
- Signal transmission limitations of pneumatic control systems made it necessary to limit the distance between the control house and the transmitter or control valve. As a result, early control houses were located within or at the periphery of the process unit.
- The development of electronic and/or computer controls made it possible to control several process units from a centralized control center, leading to continued concentration of equipment and personnel in control rooms.
- Support services such as administration, engineering, and laboratory functions were moved closer to process units to facilitate operations. These functions were often located in the control center or in separate buildings adjacent to process areas.

Also, many batch processes, such as those in the specialty chemical industry (e.g., pharmaceuticals, paints, and plastic end-products), have typically located the control and support functions adjacent to the process. In a typical arrangement, the process plant building contains all or most of the process, with the control function frequently housed in a centrally located room within the plant building or an adjacent building.

1.6.2 Standards for Building and Equipment Siting and Separation

Many companies, as well as industry insurers, trade associations, and standards organizations, have developed specific criteria for spacing between plants, buildings, equipment, and property lines. These criteria were meant to reduce the impact of explosions or fires on major equipment and facilities, including adjacent units and buildings.

The wide ranges in spacing criteria are available from various organizations including CCPS, NFPA, API, IRI, and FM Global. For example, the spacing between control houses and process units ranges from 50 to 1200 ft (15 to 365 m), reflecting the diversity of potential hazards as well as the different objectives of the various organizations that developed the criteria. In general, insurance industry standards are designed to protect property and minimize business interruption in the event of an incident. NFPA standards are designed to prevent the occurrence of a fire and reduce the spread of fire to adjacent structures. Individual company or trade association standards may attempt to address both of these objectives as well as personnel safety. Due to the large variations in the types of processing facilities, materials handled, and objectives (i.e., equipment protection versus personnel protection), no single spacing standard is appropriate for all applications.

1.6.3 Standards and Criteria for Building Design, and the Need for Site-Specific Evaluation

Design guidelines for buildings in process plants have also evolved over the years in response to major incidents. These guidelines typically specify the desired building response to design criteria blasts, such as those resulting from a TNT detonation or a vapor cloud explosion of an assumed size and distance from an occupied building. A specific standard, for example, might specify that a building be designed to withstand a blast equivalent of 1 ton (900 kg) of TNT at 200 ft (61 m) from the blast source. Another standard might require that a building be designed for a 3 psi (0.21 bar) positive blast overpressure, 1 psi negative pressure, and 100 ms duration for a vapor cloud explosion hazard.

Many of these building design and siting criteria are based upon broad plant design guidelines and not upon an evaluation of specific materials, release conditions, or plant geography. While effective in many applications, this approach can lead to designs that are overly conservative in some instances or that fail to provide the desired degree of protection in other instances. The approach proposed by this book allows the use of appropriate building design and siting standards that have evolved over the years and takes into account site-specific conditions. These include an evaluation of the materials being handled, process conditions, building location and occupancy, building design and materials of construction, and effectiveness of process safety management systems.

The proposed approach in these guidelines allows process plant owners and operators to assess their sites and plant buildings based on these site-specific conditions. This allows building design and siting issues to be managed at the local level without imposing prescriptive standards that may not be appropriate to a specific facility. This approach has the overall result of providing informed, cost-effective management of the risks associated with buildings in process plants.

1.7 ORGANIZATION OF THE BOOK

The book is organized around the building siting process depicted in Figure 1.2. An overview of the entire process is provided for management in Chapter 2, with emphasis on the role of management in the process. Chapter 3 addresses inclusion or exclusion of buildings; both permanent and portable, in a building siting evaluation. Managers involved in company risk management and subject matter experts are the intended audiences for Chapter 3. Chapter 4 presents building siting criteria, which is technical material for subject matter experts.

Chapters 5, 6 and 7 present hazard assessment methodologies for explosions, fires and toxic material releases, respectively. Consequence analysis subject matter experts are the audience for these chapters.

Risk analysis is presented in Chapters 8 (Frequency Assessment) and 9 (Risk Assessment). Subject matter experts in risk analysis are the audience for these chapters.

Chapter 10 addresses mitigation plans and risk reduction strategies, as well as the need for an ongoing process to manage occupancy and building in addition to any changes that may trigger management of change (MOC). Subject matter experts and managers are the audiences for Chapter 10.

Chapter 11 addresses documentation of a building siting evaluation.

2 MANAGEMENT OVERVIEW

This chapter serves three distinct purposes:

- Provides management personnel an overview of the approach described in this book for identifying, evaluating, and managing the process safety considerations associated with explosions, fires, and toxic material releases external to buildings in process plants. Various consequence and risk assessment tools are used to help identify buildings that may present a significant risk to occupants or that may be of concern for other reasons, such as possible business interruption losses. Guidelines for applying the results of the analysis to make risk-based decisions on building design and siting are also discussed.
- Highlights management's responsibilities in accordance with API RP-752 and RP-753.
- Demonstrates that building siting evaluations fit a number of management objectives, including process safety, business and insurance risk management.

Management should have a role in four key decisions regarding building siting evaluations. They are:

1. The approach used in the building siting evaluation processes, including consequence or risk-based evaluation, a phased approach that starts with a consequence-based evaluation and transitions to risk-based, and an approach for existing versus new buildings;
2. A process for selection of explosion, fire and toxic release scenarios;
3. The criteria for evaluating building performance; and
4. Sequencing of the use of various approaches, such as a phased approach beginning with simplified analyses, followed by selection of more detailed analyses.

Each of the decision areas is discussed in more detail in this chapter.

2.1 PROCESS OVERVIEW

2.1.1 Explosion, Fire and Toxic Release Phenomena

An accident can be defined as "an unplanned event or sequence of events that results in an undesirable consequence." For the purposes of this book, undesirable consequence is defined as an explosion, fire, or toxic release.

Before an explosion, fire or toxic material release occurs, certain conditions must exist. First, hazards that can lead to explosions, fires, or toxic material releases must be present. In the case of explosions, this means that flammable, combustible, or reactive materials, or process conditions capable of producing explosive events, must be present. Second, an initiating event must occur to begin the accident sequence. Examples are human error and equipment failure. Third, intermediate events must occur, allowing the accident sequence to proceed toward an outcome. Intermediate events fall into two categories: propagating events or factors, and mitigating events or factors.

An event can proceed to various incident outcomes, depending on the sequence of intermediate events. A release of flammable vapor could result in a pool fire, jet fire, fireball, flash fire, vapor cloud explosion, or flammable cloud dispersion without ignition. Incident outcomes that this book addresses are depicted in Figure 2.1.

Examples of incident outcomes that could result from the release of a hazardous material are as follows:

- If the release results in limited evaporation of the flammable liquid, a pool will form on the ground. If vapors from the release are ignited, material will burn above the liquid surface resulting in a pool fire. Heat from the fire accelerates evaporation from the pool, which sustains the fire. Damage from pool fires is usually localized and results from radiant heat and direct flame contact.
- If the release burns at the source of the leak and the system is operating at sufficiently high pressure, it may create a jet fire. The extent of damage is limited to the area in the vicinity of the flame. High-velocity jets are largely unaffected by wind, while low-velocity jets can be tilted and shortened by the wind. For a liquid or two-phase jet, a portion of the liquid may "rain" out of the jet stream, giving rise to a pool fire.
- If the release mixes with air and forms a flammable vapor cloud before ignition occurs, and turbulence is developed in the ignited flammable cloud (for example, by the flame front propagating through a process unit), the flame speed can accelerate sufficiently to cause an explosion. This event is referred to as a vapor cloud explosion. In addition to airblast effects, radiant heat and flame contact effects may also occur. Flashback to the source may cause a pool and/or jet fire.
- If the release forms a vapor that mixes sufficiently with air to create a flammable mixture, and upon ignition there is not sufficient turbulence or confinement to accelerate the flame and produce a blast wave, a flash fire results. Damage is caused by radiant heat and direct flame contact. The affected area may be much larger than for a pool or jet fire.
- If ignition of fuel-rich mixture occurs, the release will burn as a fireball. Burning will occur primarily in the outer layer of the fuel-rich cloud. As the buoyancy of the hot gases increases, the burning cloud rises, expands,

and assumes a spherical shape. Damage is caused by direct flame contact and radiant heat.

- If the release forms a vapor cloud of toxic material that does not ignite (either because a material is not flammable or a flammable material did not contact an ignition source), a toxic cloud will disperse. Concentrations at which many chemicals produce acute toxic effects are considerably less than flammable concentrations; as a result, a toxic cloud typically extends much further downwind than a flammable cloud. Exposure of building occupants occurs by infiltration of vapors into the building through openings or air handling systems. Exposure of occupants varies with time as vapors mix with air inside the building and as the outside concentration changes.

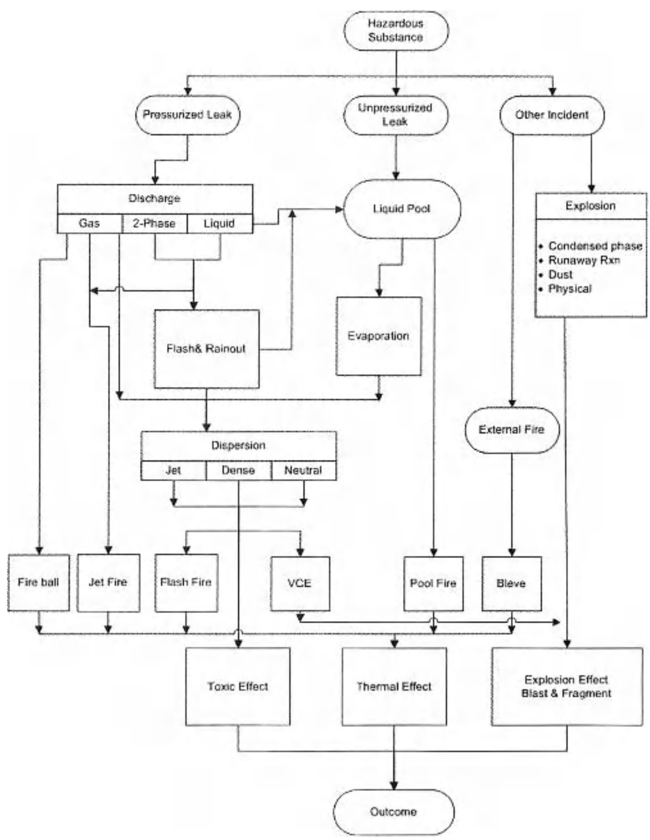

Figure 2.1. Potential Outcomes of a Hazardous Material Release (Pitblado, 1996)

Additional events of concern are condensed-phase explosions, uncontrolled chemical reactions, boiling liquid expanding vapor explosions (BLEVEs), pressure-volume (PV) ruptures, physical explosions, and confined explosions. BLEVEs, PV ruptures and physical explosions may not involve flammable or combustible materials. These are briefly described below:

- Uncontrolled chemical reactions (e.g., polymerization) can release sufficient energy to cause a failure of the containment system, leading to blast and fragment effects.
- A rapid loss of containment of a pressurized gas or vapor (not necessarily flammable material), called a PV rupture (a type of physical explosion), may produce fragment effects as well as a blast wave as the rapidly expanding fluid compresses the surrounding air. If the material released is flammable, a PV rupture may also be followed by a fireball.
- Failure of a vessel containing a liquid at a temperature above its atmospheric boiling point may produce a BLEVE, with resulting blast and fragment effects. If flammable material is involved, a BLEVE may also produce a fireball. A common BLEVE scenario is fire exposure that heats the vessel contents and softens the vessel shell, in which case there may be sufficient time to evacuate buildings.
- Another type of physical explosion can occur upon rapid vaporization of a liquid when contacted with a significantly hotter material (e.g., water added to vessel containing hot oil). This is also referred to as a rapid phase transition explosion. Rapid phase transition explosion can also occur when vey cold material encounters warmer elements such as an LNG spill into water. In addition to blast, physical explosions can also generate fragments when initially confined.
- Some substances can release significant heat if they decompose. Under certain conditions, this decomposition can cause a condensed-phase explosion, which can cause a failure of the containment system, creating blast as well as fragment effects. Some condensed-phase materials decompose in a detonative manner and are capable of producing blast effects even when not initially confined.
- A confined explosion occurs when there is a rapid combustion of a fuel and an oxidizer inside an enclosure (e.g., building, vessel, or duct), developing sufficient pressure to cause the enclosure to rupture. Examples of confined explosions include gas or dust explosions inside buildings, storage tanks, or process equipment.

Any of the above blast, fire, or fragment effects have the potential to impact process plant buildings and their occupants.

2.1.2 Statement of the Problem

Building occupants can be subjected to a range of impacts, depending upon the type of building construction, building features that mitigate risk, building location relative to hazards, process conditions, materials being handled, and other risk mitigation measures. The purpose of a building siting evaluation is to manage the risk to occupants of all buildings in a facility from potential explosions, fires or toxic releases.

When a building does not meet company-established criteria, various mitigation options may be appropriate. These options may include one or more of the following:

- Modifying the process to eliminate or reduce the hazards.
- Enhancing process safety management effectiveness.
- Strengthening buildings to withstand possible events of concern.
- Eliminating or mitigating debris hazards from roofs, walls, windows, doors, ceilings, and mechanical services.
- Relocating occupants away from the buildings subject to serious damage.
- Relocating the buildings to locations where damage will not occur.

These options may involve major cost or feasibility constraints, and would require conducting an analysis prior to implementation.

Building siting evaluations take into account the need for a cost-effective approach that allows facilities to focus and prioritize resources on those buildings that do not meet the owner/operator building siting evaluation criteria.

2.1.3 Analysis Approach Selection

Evaluating risk to building occupants can be accomplished through a consequence-based or risk-based assessment. A building siting evaluation is not limited to one of these approaches; both approaches may be used as discussed below.

A consequence-based assessment evaluates potential damage to building and/or potential injury to occupants without consideration of the likelihood that the postulated scenario will occur. The consequence-based method requires selection of maximum credible event (MCE) scenarios to represent each applicable type of hazard (explosion, fire and toxic material release). Since the scenario selection process establishes an implicit risk position for the owner/operator, it is highly recommended that management understand and are engaged in development of the process and criteria for evaluation and selection of the scenarios. Process plant buildings may be impacted by hazards from a number of process units. Consequence analysis involves detailed calculations of the potential damage or occupant injury from hazards in each process unit, and determination of the MCE from among all of the major scenarios analyzed. Damage or occupant injury predictions are compared to consequence criteria that are established before the study is undertaken.

A risk-based assessment evaluates the impact of a wide range of scenarios from small to large and incorporates the likelihood of each scenario. The risk to occupants of a building is calculated as the sum of the risks from all of the scenarios. Risk criteria are first established using risk metrics such as risk to an individual building occupant and risk to occupants as a group (aggregate risk).

An owner/operator may opt for a phased approach to building siting evaluation with the level of detail increasing with each step. This phased approach may consist of a consequence-based assessments using conservative assumptions as an initial step. More detailed consequence analyses that use process-specific information may be used as a subsequent step to "sharpen the pencil." A quantitative risk assessment may also be performed subsequent to the consequence analyses.

The selected approach is applicable to either new or existing buildings. The type of assessment and the building performance criteria may vary among assessments of existing buildings, design of upgrades to existing buildings, and new buildings.

2.1.4 Steps in the Process

The first step in the analysis is to obtain necessary information to support the type of evaluation being performed. This can include information about the materials being handled, the process conditions, and other site-specific information such as the type of building construction, occupancy, plant layout, and equipment location.

An initial survey can be performed to identify the types and quantities of materials or other process conditions present that have the potential to result in explosions, fires, or toxic material releases that could impact nearby buildings. If materials of concern are present in quantities insufficient to be a credible hazard to building occupants, or if process conditions of concern do not exist, then little or no risk is posed to the building occupants, and no further evaluation is required. If materials or process conditions do pose potential hazards to building occupants, then an assessment of the hazards is needed.

A determination of the consequences resulting from the MCEs may be used to identify those process plant buildings that meet the owner/operator's building siting evaluation criteria. These buildings may be removed from further evaluation, although continued management of risk is still required to ensure that changes do not cause a building to exceed the owner/operator's criteria in the future. If the consequence analysis indicates that some buildings do not meet company selected consequence criteria, the user may either proceed directly to risk mitigation or choose to perform a more detailed evaluation.

Quantitative risk assessment may be performed instead of, or in addition to, a consequence-based assessment. The quantified risk is then compared with risk criteria to determine if risk-reduction measures are warranted. If it is found after conducting a risk assessment that buildings do not exceed risk criteria, no further evaluation is required. Otherwise, a risk mitigation plan is developed.

Risk management is a process of identifying, evaluating, and controlling risk. Since risk is a function of both the consequences and the likelihood of the undesired event, risk can be reduced by either reducing the consequences or the likelihood. the user of a consequence-based assessment will identify and implement consequence-reduction measures. Alternatively, the user of a risk assessment has the option of addressing either the consequence or the frequency of the event to reduce the risk to building occupants.

Risk management may include an evaluation of a number of options to determine the most cost-effective means of reducing risk. In each case, after identifying those options, the user will return to the appropriate step to evaluate the effectiveness of the options.

2.2 MANAGEMENT RESPONSIBILITIES UNDER API RP-752 AND API RP-753

2.2.1 Meeting Expectations – Management's Role in the Process

API RP-752 and RP-753 allow owner /operators significant latitude in setting performance criteria for both the consequence- and risk-based approaches to building siting. Performance criteria are selected for each type of hazard (explosion, fire and toxic release). Management sets the criteria considering their corporate values and how building siting is integrated into the balance of their process safety program. Regulations in some countries prescribe risk criteria, but not in the U.S. Companies may establish different approaches to modeling and evaluating nearly identical scenarios. For example:

- One company may elect to use a consequence-based approach and a "filled unit" assumption to identify the major scenarios at a facility, and then use a Building Damage Level as the acceptance criteria.
- A second company may also select the consequence-based approach but elect to model specific releases that may not fill a unit or may fill more than one unit, select the maximum consequence among the scenarios modeled, and then use Occupant Vulnerability as the acceptance criteria.
- A third company may elect to use a risk-based approach and use a numerical risk tolerance criteria.

Management identifies the appropriate criteria for use and whether to use a consequence- or risk-based approach. RP-752 requires the selection of the criteria prior to the completion of the assessments. This approach prevents assessment results from influencing the study criteria.

A risk-based approach allows for a quantification of the current risk and the risk reduction that can be achieved by various countermeasures. When selecting a consequence-based approach, management acknowledges the residual but unquantified risk associated with scenarios that are more severe than the scenarios selected for inclusion in the study, but assures a selected level of protection from scenarios that are addressed.

Once the criteria and approach are selected, management assures that the personnel performing the study are qualified to do so. A building siting evaluation is a complex undertaking that requires expertise in the areas of process operations, explosion, flammable and toxic hazards, and structural response. Personnel involved in the building siting evaluation need to be competent in the aspects for which they are responsible. Among the areas of competency that may be needed are:

- hazard identification,
- scenario development,
- frequency assessment,
- flammable and toxic gas dispersion modeling,
- fire modeling,
- explosion modeling,
- blast response of buildings,
- fire resistance of buildings,
- toxic gas ingress into buildings,
- occupant vulnerability, and
- quantitative risk assessment techniques.

Upon completion of the siting study, management is accountable for assuring mitigation of hazards at buildings that meet or exceed the company criteria. RP-752 requires the development of a mitigation plan that includes a schedule for implementation.

2.2.2 Maintaining the Process

Since occupied building siting involves an ongoing process and is not limited to a single event, the need for systems to maintain the process is evident.

Management control systems may need to be modified to assure that buildings not intended for occupancy do not change functional status and become intended for occupancy. Management of change (MOC) procedures should identify the events that could trigger a need to re-evaluate the siting for the affected areas. Such events could include the addition or removal of units, or significant process or material changes.

RP-752 has specific requirements for maintaining building systems or features that are relied upon to assure the risk to occupants meets the criteria. For example, if a building is deemed suitable as protection from a toxic release due to a filtration system, RP-752 requires that the filtration system is properly installed and maintained.

3 DETERMINING THE SCOPE OF THE BUILDING SITING EVALUATION

3.1 INTRODUCTION

This chapter provides guidance on determining the scope of the building siting evaluation. The selection of the buildings and potential incident scenarios defines the scope of an evaluation.

A significant change from the previous edition of this book is the inclusion of all buildings intended for occupancy in the assessment, rather than a reliance on occupancy screening to eliminate buildings from consideration.

The first step in the assessment process is to determine if a building is, in fact, potentially subjected to an event of concern. If no event that could significantly impact the building can occur, no further evaluation is necessary.

3.2 BUILDINGS CONSIDERED

Only enclosed structures with rigid walls and a roof are considered buildings. The scope of this guideline is limited to on-shore buildings. Offshore platforms, docks, ships, barges and other marine structures are outside the scope of this guideline.

All buildings used by on-site personnel are evaluated for inclusion in the building siting evaluation. This includes both existing permanent and portable buildings as well as new buildings. A building is considered intended for occupancy if it is an assigned work location or if it is used for a recurring group function. Similarly, buildings that do not clearly meet these criteria may still be included on a case-by-case basis, such as buildings that contain key safety or economically valuable equipment.

3.2.1 Buildings Intended for Occupancy

Buildings specifically identified as intended for occupancy include:

- Buildings used as shelter in place, since personnel are instructed to gather within such a building. Hence the building is intended for occupancy, even if it is not routinely used to house personnel.
- Change houses, since personnel will gather at these locations on a regular basis (e.g. twice per shift). Hence while these buildings may be lightly occupied or unoccupied for a substantial portion of the day, they are used for a recurring group function.
- Conference rooms, under the recurring group function rule.

- Operator shelters that have personnel assigned. Many companies refer to these as satellite control rooms.
- Guard houses, due to having personnel assigned.
- Laboratories with assigned personnel.
- Lunchrooms, due to the recurring group function rule.
- Maintenance shops with assigned personnel.
- Offices, because of the assigned personnel. A single office in an otherwise unoccupied building is considered intended for occupancy.
- Orientation rooms, because of the recurring group function.
- Warehouse buildings with assigned personnel.
- Buildings within buildings may be included because of the personnel assigned to a specific area. An example is an office within a warehouse.
- Rooms intended for occupancy within an enclosed process area.

The list above mentions buildings with personnel assigned. "Assigned to a building" means that the building is the person's primary work location; the person is resident in the building.

Work assignments do not necessarily mean a person is assigned to a building. For example, a technician assigned to calibrate an instrument in an analyzer shelter on a monthly basis, or an operator assigned to enter a warehouse to extract supplies about once a day are not considered assigned to a building.

EXAMPLE 1
Identification of a building intended for occupancy

Background

A warehouse has no personnel assigned. However, the center floor of the warehouse is open and is used on a regular basis for contractor safety meetings at the start of each shift.

Approach

Since the warehouse is being used for a recurring group function, it is considered as intended for occupancy and should be included in the building siting evaluation.

3.2.2 Buildings that may be Excluded from the Siting Study

Buildings that are not intended for occupancy and thus may be excluded from the building siting evaluation in accordance with the API RPs include:

- Structures with roofs and no walls intended to protect personnel from weather. These structures are excluded since they do not meet the definition for a building. Examples of such structures are:
  - Bus stops
  - Pavilions
  - Welding covers
  - Truck loading canopies
  - Covered walkways
  - Smoking canopies
- Buildings that do not have personnel assigned and require at most only intermittent access. Individual personnel may have to enter these buildings to take a measurement or read an instrument or perform a field test on a material. The primary function of these buildings is to protect equipment, and personnel enter to interface with the equipment. Note that these buildings are not expected to serve a recurring group function. Examples of such structures include:
  - Analyzer buildings
  - Field sampling stations
  - Electrical buildings
  - Remote instrument enclosures
  - Equipment enclosures
  - Abandoned buildings
- Enclosed process areas where personnel perform activities similar to those performed at an outside process area.
- Buildings that primarily house materials, and no personnel are assigned.
- Operator shelters with intermittent use.

Some portable buildings may also be excluded in accordance with RP-753 as not intended for occupancy:

- Tool trailers or sheds without attendants, since these buildings do not have personnel assigned.
- Portable decontamination facilities that are not part of a site's permanent infrastructure.
- Control equipment enclosures, since no personnel are assigned.
- Analyzer sheds, provided no personnel are assigned to the building.

- Portable electrical substations and portable electric generators housed in portable buildings (typically cargo van type structures) are excluded.

RP-753 also excludes occupied portable structures that are used to support temporary work activities within covered process areas, and which are often mandated by regulatory requirements. Current technology is typically not sufficient to provide the capability to remotely perform these activities. Examples include:

- Mobile environmental monitoring stations
- Supplied air trailers
- Inert entry life support trailers
- Vehicles housing equipment stations (e. g., trucks or vans with X-ray equipment)

Once a building has been excluded from the siting assessment, the owner must take steps to prevent it from becoming occupied. This is discussed in Chapter 2, Section 2.2.2 of this book.

EXAMPLE 2
Identification of a warehouse not intended for occupancy

Background

Personnel enter the warehouse periodically to store or remove material but no person has an office in the warehouse or enters on other than an intermittent basis, and people are not present the majority of the time per work shift.

Approach

Since the warehouse is being used for its intended purpose and it does not house personnel, it is excluded from the building siting assessment.

EXAMPLE 3
Identification of an analyzer shelter not intended for occupancy

Background

An analyzer shelter in a process unit houses instruments that monitor composition of various process streams. An instrumentation technician enters the shelter once a month to perform calibrations, which takes about 2 hours. No personnel are assigned to the shelter.

Approach

Since the function of the shelter is to house equipment, no personnel are assigned to the shelter, and it is accessed on an intermittent basis, the shelter is excluded from the building siting evaluation.

EXAMPLE 4
Identification of an enclosed process not intended for occupancy

Background

A process unit located in a cold weather region is housed in a building intended to protect the equipment from the environment. Operators enter the process building making scheduled rounds to monitor the equipment and process conditions. Maintenance personnel enter the process building to perform periodic maintenance as well as repair equipment on a non-routine basis. No personnel are assigned to the process building. A control room is located near to the process building, and operators are assigned to the control room.

Approach

Since the process building serves to house process equipment and no personnel are assigned to or housed in this building, it is excluded from the siting evaluation.

3.2.3 Buildings Evaluated on a Case-by-Case Basis

Buildings with no personnel assigned but occupied by individuals for a short duration may be evaluated on a case-by-case basis. Factors to be considered in the decision to include or exclude these structures may include, size, construction, and regularity of occupancy.

Examples are:

- Smoking shelters
- Weather shelters
- Dock attendant stations
- Loading rack personnel stations
- Restroom buildings

EXAMPLE 5
Identification of a case-by-case building evaluation

Background

A plant has two types of smoking shelters. Type A shelters are small canopies with three solid sides that are located throughout the plant and do not provide seating. Type B shelters are enclosed structures and include vending machines, tables and chairs. Type B shelters are located in the parking lots for the administrative buildings.

Approach

The type A shelters may be excluded from the siting assessment since they are not buildings under the definition provided in RP-752 and are analogous to a bus stop. Type B shelters are buildings and the presence of tables and chairs indicates they are intended for occupancy.

3.3 SCENARIO SELECTION

A scenario is an unplanned event or incident sequence that results in a loss event and its associated impacts. Scenarios in this book are incidents that lead to an explosion, fire or toxic release. The scope is limited to process hazards. Natural disasters, deliberate actions (sabotage and terrorist actions), airplane impact, and other scenarios not related to process hazards are beyond the scope of a building siting evaluation. Building siting evaluations typically do not involve a detailed sequence of events for the manner in which a scenario occurs; rather, the scenarios are usually simple descriptions of loss of containment (e.g., pipe rupture) or runaway reaction that causes an explosion and loss of containment.

A scenario may have multiple potential outcomes. For example, if a loss of containment of a flammable liquid is postulated, the potential outcomes are no ignition, prompt ignition, or delayed ignition. Prompt ignition will result a fire, whereas delayed ignition could result in a flash fire, fireball, or vapor cloud explosion. A consequence-based assessment assumes an outcome for each scenario, whereas a risk-based assessment determines frequencies for each of the potential outcomes.

A first step in the scenario selection process is to identify the materials being handled under site conditions that can result in fire, explosive, or toxic hazards. The materials handled may not be present in quantities to result in an event of concern. Because some materials have the potential to produce one or more type (fire, explosion or toxic) hazard, each possible incident outcome may need to be considered.

The scenario selection process for a consequence-based assessment or a risk-based assessment is similar in the types of scenarios that are addressed and the means of quantifying the effects of the scenarios. A consequence-based assessment relies on the use of a Maximum Credible Event (MCE). A risk-based assessment considers a wide range of potential scenarios including both smaller (and more likely) scenarios as well as larger (and less likely) scenarios, which may in some cases exceed the MCE used in the consequence-based approach. The use of the risk-based approach requires the ability to determine the frequency associated with each potential scenario.

The scenarios selected for the building siting evaluation are those that can potentially result in hazards to the building occupants on the site. The assessment of potential hazards to neighbors is outside of the scope of the building siting evaluation but is addressed by regulations in many countries and by industry programs such as the American Chemistry Council's Responsible Care® program (CMA, 2010).

An owner may choose to include scenarios that address the potential impacts from a neighboring facility, especially if the neighboring plant is adjacent to the site undergoing assessment. However, potential hazards resulting from scenarios outside the plant boundaries may be difficult to analyze to the same level of detail as on-site scenarios since the detailed process and material information may not be available.

3.3.1 Consequence-based Scenario Selection

The use of the consequence-based approach relies on the selection of the MCE. RP-752 defines MCE as:

> *"a hypothetical explosion, fire or toxic event that has the potential maximum consequence to the occupants of the building under consideration from among the major scenarios evaluated. The major scenarios are realistic and have a reasonable probability of occurrence considering the chemicals, inventories, equipment and piping design, operating conditions, fuel reactivity, process unit geometry, industry incident history and other factors. Each building may have its own set of MCEs for potential explosion, fire or toxic impacts."*

The first step in developing the MCE for a particular building is to identify the "major scenarios." Consideration should be given to the properties of major scenarios as defined in API RP-752:

- "Realistic" – the major scenarios are scenarios that behave by the laws of physics given the site conditions and chemicals present. For example it is not necessary to consider the entire contents of a liquid filled atmospheric storage tank instantly flashing to vapor. However, a spill may still have the potential to result in a vapor cloud explosion if there are sources of congestion or confinement present. Some facilities may consider a filled unit as a realistic limit on the energy term for a VCE major scenario; other facilities may not have enough material present to fill a unit with a flammable cloud. The use of the term "realistic" serves to eliminate scenarios such as those associated with the US EPA's RMP rule of worst case scenarios, where the mass of a flammable cloud released is equal to the entire quantity of material released regardless of the release conditions (EPA 1999). The release of a toxic material is tied to the release from a specific isolatable inventory, but does not need to address the release of all the material on site.
- "Reasonable probability of occurrence" – while scenarios that meet this definition are not provided in RP-752, the intent is to ensure companies do not eliminate all but the smallest events. RP-752 specifically identifies the need to consider past industry events and experience in lieu of only considering company or corporate history. Hence it would not be reasonable to assume that a VCE would not occur at a facility simply because it has not happened at that particular facility before, if such incidents have occurred at similar facilities in the past. However, the physical layout of the site and the amount of material released may be used to develop a scenario similar to past incidents without having to assume the same magnitude as the past incidents. See Table 1.1 for examples of past incidents.

Where to draw the line of what event has a "reasonable probability of occurrence" is complex and subject to judgment. Merriam Webster defines "reasonable" as "not extreme or excessive." The likelihood of a particular event (e.g. line rupture) occurring may be "reasonable" in one situation (high pressure/temperature, corrosive service, exposed to external impact, contains energetic/runaway reaction potential) and not reasonable in another (low severity operation, not exposed to external impacts). Examples of situations that might be considered "credible" or "non-credible" include but are not limited to the examples in Table 3.1.

Table 3.1. Examples of Credible and Non-Credible Situations for Building Siting Evaluations

"Credible"	Rupture of small bore piping
	Leak from process equipment
	Pump/compressor seal failure
	Gasket failure
	Loading/unloading hose rupture
	Loss of containment from operational activities such as filter changing
	Process upsets such as overfilling a vessel or tank
May or May Not Be "Credible"	Rupture of large bore piping or vessel/tank
	Pressure vessel structural failure at normal operating conditions
	Catastrophic failure of pump or compressor casing/valves
	Reaction runaway that exceeds the pressure relief system capacity
	Vehicle impact to exposed process equipment and piping
	Alternate case US EPA RMP scenario
"Non-Credible"	Events that are not physically possible (e.g., inventory of flammable material is insufficient to generate the scenario; unconfined pool fire in an area that has curbing and dikes)
	Multiple domino events when each event has a low likelihood
	A release of flammable gas filling more than one well-spaced process unit and acting as one large explosion
	Simultaneous release of multiple unconnected process inventories
	Worst-case U.S. EPA RMP scenario

Once the major scenarios are defined, the impacts of each are calculated for the occupants of each building. The major scenario that produces the greatest effect upon a building's occupants is the MCE for that building. The consequence-based method requires selection of MCE scenarios to represent each applicable type of hazard (explosion, fire and toxic)

It is important to understand that the MCE scenarios are not defined at the start of the assessment, but rather the identification of the MCEs is an outcome of the assessment. MCEs are the scenarios that have the maximum consequence among the major scenarios evaluated. As a result, the MCEs cannot be identified until the modeling and building assessments are complete.

The potential impacts of an explosion will depend on several factors, including the strength of the building. A scenario that results in a more energetic explosion but is farther away from a building may not be as detrimental to the building occupants as a smaller scenario that is closer to the building.

The release of a toxic material will not impair the integrity of a building envelope. The potential adverse effects of a toxic hazard on building occupants is influenced by the natural ventilation rate and the heating ventilating and air conditioning (HVAC) systems present, rather than type of building construction. RP-752 allows the owner/operator to assume that on-site buildings intended for occupancy can be impacted by releases of toxic materials or they may choose to carry out toxic gas dispersion modeling for each building intended for occupancy. If a user opts to model gas dispersion, the exterior toxic concentration of exposure may be selected as the measure by which scenarios will be evaluated, and the MCE for each building is selected once the dispersion analyses are complete. If the user selects a resulting internal concentration or exposure as the measure of severity, then the MCE cannot be finalized until the assessment of toxic intrusion into the building is complete.

The potential impacts from pool and jet fires are typically expressed in thermal radiation contours and associated durations. When either of these approaches is used, it is possible to readily identify the MCE for each building as soon as the thermal radiation levels and durations are developed or the fire sources are identified. Flash fires result in very short duration thermal pulses that generally do not represent a hazard to the occupants of a building provided the flammable gas does not enter the building. Fireballs result in thermal pulses that generally do not represent a hazard to occupants of buildings outside the fireball radius and constructed of fire resisting materials with no or small area of windows.

3.3.2 Risk-based Scenario Selection

When using the risk-based approach, a wide variety of scenarios is considered with a frequency of occurrence determined for each scenario. The determination of these frequencies is discussed in Chapter 8. Unlike the consequence approach where only the major scenarios providing the impact to the buildings are evaluated, the risk-based approach requires the evaluation of a range of small, medium and large scenarios of each type. For example, a consequence-based approach may only assess the potential impacts due to a release from a high pressure vapor line under the least favorable weather conditions, while a risk-based approach would evaluate impacts due to releases from multiple lines of various sizes and under various weather conditions.

3.3.3 Explosion Scenarios

An evaluation of materials and site conditions that can lead to an explosion requires an understanding of the chemical and physical properties of the materials being handled, a determination of the quantities handled, and an assessment of the site conditions that can contribute to an event. Refer to Chapter 5 for additional information on explosions.

Vapor Cloud Explosions. Lenoir and Davenport (Lenoir, 1993) have summarized some major VCEs worldwide from 1921 to 1991. The materials involved in these incidents suggest that certain hydrocarbons—such as ethane, ethylene, propane, and butane—demonstrate greater potential for VCEs. Several factors may contribute to these statistics. These materials are prevalent in industry and are often handled in large quantities, increasing the potential for an incident. Certain inherent properties of the materials also contribute to their potential for explosion. These include flammability, reactivity, vapor pressure, and vapor density (with respect to air).

These light hydrocarbons are not the only materials exhibiting the potential for a VCE. Under certain conditions, other materials, including heavier hydrocarbons such as cyclohexane, benzene, or gasoline, can cause VCEs with blast effects similar to those of LPG and other low-molecular weight materials. For example, if large quantities of heavier hydrocarbons are released at elevated temperatures, a vapor cloud may form. The overpressure from such a VCE can be significant, such as that involving cyclohexane at Flixborough (see Table 1.1 in Chapter 1 of this book and the Flixborough court inquiry report (HSE, 1975).

The key point is to determine if flammable or combustible materials are being processed under conditions of temperature and pressure such that, if a release occurs, a quantity of the material may be released into the air as either a gas, vapor, mist, or aerosol that is sufficient to cause damage to buildings if a VCE were to occur. If such conditions are present, appropriate VCE scenarios should be developed. Determining the release quantity of material that is required to result in a VCE capable of damaging process plant buildings is extremely site-specific. Important factors are the release conditions, the physical and chemical properties of the released material, the degree of confinement, obstacle density, and the geometry of the release area.

Internal Explosions. Situations where the ignitable vapors, mists, aerosols or dusts are dispersed inside a building, vessel, or other such enclosure may have the potential for an explosion. Prediction of blast loads from such an internal explosion on other buildings is difficult due to the effect of the confining structure on the blast pressure that leak outside. The authors are not aware of any published simplified prediction methods. Some computational fluid dynamic models can estimate potential external blast loads from an internal explosion. Often, the enclosure (e.g., vessel or building) limits damage to surrounding buildings due to preferential venting out of enclosure openings. There are a large number of possible variables in the determination, and even the use of computational fluid dynamic models may not address all of these variables, leading to uncertainty in the predicted blast loads. Also, many chemical processing facilities have other types of outdoor explosions that may have a greater influence on siting of occupied buildings.

Condensed-phase Explosions/Other Uncontrolled Chemical Reactions. Processes that handle materials with high heats of decomposition or undergo other exothermic chemical reactions are candidates for explosive events. Chemical reactions that are exothermic may have an increased reaction rate under certain conditions (reaction runaway), as might result from process upsets or other system failures. Except in the case of detonating materials such as TNT, decomposing or reactive chemicals generally need some degree of confinement for significant explosion effects to occur. CCPS's Chemical Reactivity Evaluation Guidelines (CCPS, 1995b), and Emergency Relief Systems Using DIERS Technology by the Design Institute for Emergency Relief Systems (DIERS, 1992), provide guidance on chemical reactivity and on relief system designs for emergency venting of systems where the potential for explosion exists.

If the above types of materials and/or conditions exist in the area of process plant buildings, appropriate scenarios for the buildings are developed. Additional information on the development of explosion scenarios is presented in Chapter 5.

BLEVEs/Pressure-volume Ruptures/Physical Explosions. Rapid loss of containment of materials confined under pressure at temperatures above their normal boiling point may result in a BLEVE with blast and/or radiant heat effects (if flammable material is involved), as well as fragment effects. These effects can be experienced for considerable distances, depending upon the types and volumes of material stored.

Catastrophic rupture of a pressure vessel as a result of a PV rupture or physical explosion may also result in blast and fragment effects.

Additional information on the selection and analysis of explosion scenarios is provided in Chapter 5.

3.3.4 Fire Scenarios

When handling flammable or combustible material, the resulting consequences could involve fire. Also, it is not uncommon for explosions involving flammable or combustible materials to be followed by fire, increasing the potential impact to building occupants. When the spacing table approach is used for fires, the definition of fire scenarios is simply limited to the identification of potential fire sources. Occupied buildings are then deemed adequately sited if the separation distance from the fire source meets the spacing table requirements.

A detailed discussion on fire has not been included in this book because substantial literature is available on the effects of fire. Table 6.2 provides a number of references, including industry and insurance standards for guidance on spacing of equipment. Most of these references address potential fire impacts. Lees' Loss Prevention Handbook (Mannan, 2005) provides an extensive listing of fire references, including information on design considerations for buildings, and guidance on plant layout. In addition to spacing criteria, many standards provide requirements for building design and construction to provide fire resistance and protect occupants.

In general, fire scenarios fall into the following categories:

Pool Fires. Flammable and combustible liquids processed at temperatures such that they remain in a liquid state with limited evaporation upon release will form a pool. These materials, which have the potential for pool fire upon ignition, include NFPA Class I flammable liquids, such as gasoline, and NFPA Class II and Class III combustible liquids.

Jet Fires. Any flammable material and many combustible materials processed at elevated pressures may have the potential for a jet fire, depending upon the release conditions. If the processing pressures are low, and the building is sufficiently far away, little, if any, potential may exist for the building to be impacted by the jet flame.

Flash Fires. The same materials that can create a VCE can result in a flash fire if the congestion/confinement/turbulence conditions necessary for a VCE are not present.

Fireballs. A fireball results from releases that have limited mixing with air prior to ignition. Materials that can produce VCEs may also have the potential, for fireballs, depending upon the release quantity and dispersion characteristics. A BLEVE involving flammable or combustible materials also produces a fireball.

Additional information on fire scenarios is provided in Chapter 6.

EXAMPLE 6

Initial screening through identification of materials and conditions present at the specific site

Background

An indoor packaging facility handles lubricating oil (an NFPA Class IIIB liquid) in drums at atmospheric pressure and temperature. Prior to shipment, the drums are stored in pallets in a warehouse section of the facility. The explosion and fire potential that may be present from handling combustible liquid inside a building is to be evaluated. A lunchroom is adjacent to the packaging facility.

Approach

A Class IIIB is defined as one having a flash point above 93 °C (200 °F). Since the lube oil is not reactive and is handled at atmospheric temperatures, no potential exists for explosion. However, the potential for fire exists, but is extremely low and can also be eliminated from consideration in the building siting evaluation since the material is not handled above or near its flash point temperature and a release at atmospheric pressure will not form a mist.

3.3.5 Toxic Scenarios

Toxic release scenarios may be specifically identified or recognized as a site-wide hazard. For example, a plant with a large HF-Alkylation unit may consider exposure to HF a site-wide issue and not model specific release conditions. Release of toxic materials resulting in one or more of the following:

- Exterior concentrations exceeding a threshold value,
- Exterior exposures (concentration and time of exposure) exceeding a threshold value,
- Interior concentrations exceeding a threshold value,
- Interior exposures (concentration and time of exposure) exceeding a specified threshold value.

Toxic releases are discussed in more detail in Chapter 7.

4 BUILDING SITING EVALUATION CRITERIA

4.1 INTRODUCTION

Building siting evaluation criteria are established to determine how the potential exposure to personnel within buildings from postulated explosion, fire or toxic hazards compares to owner/operator policies and standards. There are multiple methods of expressing the siting criteria. The criteria used in a consequence based study may be either exposure based or consequence based. Siting criteria for a risk based study explicitly address both the consequence and frequency of the potential exposure. The selection of the criteria and the resulting level of protection are left to the owner/operator of a facility under API RP-752. API RP-753 does provide some specific numeric criteria for portable buildings.

Owners/operators electing to expand the scope of their building siting evaluation to include buildings not intended for occupancy will need to select criteria suitable for their specific objectives.

Criteria need to be consistent with the analysis approach used in the building siting evaluation. API RP-752 allows owner/operators to select a consequence-based approach or a risk-based approach for all hazards. The spacing table approach may only be used for fire hazards.

Criteria used in conjunction with a consequence based approach do not address the frequency of the hazardous event and may be either of the following types:

- Exposure Criteria – The magnitude of the hazard at the building location is limited to a specified value that has been established by the owner/operator. An example of an exposure criterion for buildings is limiting the maximum overpressure or thermal hazard that a building may be exposed to regardless of potential damage to the building or hazards to its occupants.
- Consequence Criteria – The potential impact of the hazard to the building or its occupants is limited to less than a specified value established by the owner/operator. For example, when building damage is used as a consequence criteria for explosion hazards, there is at least an implied correlation to the potential for injuries to building occupants.

Typically, risk based criteria are expressed in terms of risk to an individual or populations (CCPS, 2009b). There are no established risk criteria for the processing industries in the United States. The U.S. Department of Defense Explosives Safety Board has established risk criteria for high explosive operations for its internal and contractor operations (DDESB, 2009). Some non-U.S. jurisdictions have regulatory requirements that include specific risk criteria.

The criterion used with the spacing table approach is a simple pass-fail comparison to the separation distances provided by the spacing table.

Other techniques that take into account some site-specific conditions, such as the Dow Fire and Explosion Index (AIChE, 1994) and the Mond Index (ICI, 1985) have been used to prioritize buildings for evaluation. These indices do not compute actual exposure or consequence levels; as such, they are not consistent with the blast and toxic evaluation requirements of API RP-752 or API RP-753. However, the indices could be used to calculate spacing for fires, which meets the spacing table approach.

RP-752 recommends that the building siting criteria be established prior to determining the results of the building siting assessment. The approach used to establishing the criteria, its applicability to the study, and the specific values used as the decision points should be included in the documentation.

4.2 OCCUPANT VULNERABILITY

The term "occupant vulnerability" was not defined in the 1st and 2nd editions of API RP-752. The previous edition of this text defined occupant vulnerability as the probability of death or serious physical injury as a function of building type and overpressure exposure levels. The 3rd edition of RP-752 specifically defines occupant vulnerability as *"the proportion of building occupants that could potentially suffer a permanent disability or fatality if a potential event were to occur."* Occupant vulnerability is not defined within RP-753.

Since the purpose of this book is to provide guidance on the siting of occupied buildings potentially exposed to major process events and not to assess personnel safety, it is important to distinguish between different injury levels. QRA calculations are largely used to predict fatalities, since the prediction of less severe injuries is difficult, and not widely supported by data. The types of injuries that are consistent with the RP-752 definition are those with an Abbreviated Injury Scale (AIS) severity level of 5 or 6. The descriptions of AIS Severity Levels are provided in Table 4.1. By way of comparison, injury levels used in personal safety programs such as an OSHA recordable injury would typically have an AIS severity level of 2, and an OSHA lost time injury would typically have an AIS severity level of 2 through 5. Hence when selecting an occupant vulnerability model it is important to understand the level of injury the model is using to determine occupant vulnerability.

The presence of a building affects the occupant vulnerability in different ways for explosion, fire and toxic hazards. Buildings have the potential to become blast injury amplifiers in that personnel in the open can tolerate blast loadings that may severely damage or collapse a conventional building. A conventional building is one that is not specifically designed to resist a blast load. The potential for personnel injuries and deaths inside of buildings exposed to explosion hazards is directly related to the response (damage) of the building rather than the blast loading at the building location.

Without blast damage, almost any building will reduce the potential for immediate injuries from thermal or toxic exposures as compared to the potential for injury to personnel in the open. However, the presence of the building may delay personnel from immediately recognizing the potential hazard, or personnel may choose to remain in a building and miss an opportunity to safely leave the area. As a result, criteria for fire and toxic hazards may need to consider prolonged exposure if personnel remain in a building.

Chapters 5, 6, and 7 discuss the development of vulnerability models for explosion, fire and toxic hazards. Readers who wish to use occupant vulnerability criteria are encouraged to read these chapters before selecting the criteria.

Table 4.1. Abbreviated Injury Scale (AIS) Severity Levels

AIS Severity Level	Severity	Type of Injury
0	None	None
1	Minor	Superficial
2	Moderate	Reversible injuries; medical attention required
3	Serious	Reversible injuries; hospitalization required
4	Severe	Life threatening; not fully recoverable without care
5	Critical	Life threatening; non-reversible injury; not fully recoverable even with medical care
6	Virtually Unsurvivable	Fatal

4.3 CRITERIA FOR EXISTING BUILDINGS EXPOSED TO EXPLOSION HAZARDS

The criteria discussed in this section are applicable to existing buildings.

4.3.1 Building Exposure Criteria for Explosion

Building exposure criteria are based on the premise that there is a maximum blast loading that will cause a building response, which will result in tolerable consequences for the building occupants. To implement such a criterion, the characteristics of a specific building or construction type have to be well understood, and the exposure criteria set to limit the building response to within tolerable levels. An example of the use of exposure criteria is when a company purchases Blast Resistant Modules (BRMs) with a specified blast loading capability (identified in terms of pressure, impulse, and allowable response) and limits the siting of the modules to areas where the potential blast loadings will be below the rated blast loading capability. RP-753 uses exposure criteria as the basis for the zone boundaries in the simplified approach.

4.3.2 Building Consequence (Damage) Criteria

The use of Building Damage Levels (BDLs) is a common building siting evaluation criterion primarily used for evaluation of existing buildings. Building damage increases as the severity of the blast load increases and may be represented as a continuous or discrete function. When a continuous function is used, the scale is "percentage of damage" (DDESB, 2009). When the discrete approach is used, BDLs are categorized into a number of damage states ranging from minimal damage to collapse (Baker, 2000). BDLs are typically not used to site new buildings. New construction is designed to provide adequate protection from the potential hazards present at its intended location. This is discussed in Section 4.3.3.

4.3.2.1 Continuous Damage Function

The continuous damage function is the approach used by the U.S. Department of Defense Explosive Safety Board (DDESB, 2009). An example of percent damage as a function of pressure and impulse for a High Bay Metal Structure is shown in Figure 4.1. The limitations of this approach are that it does not readily allow identification of the type of damage that has occurred and which building components may be governing the percentage of damage to the structure.

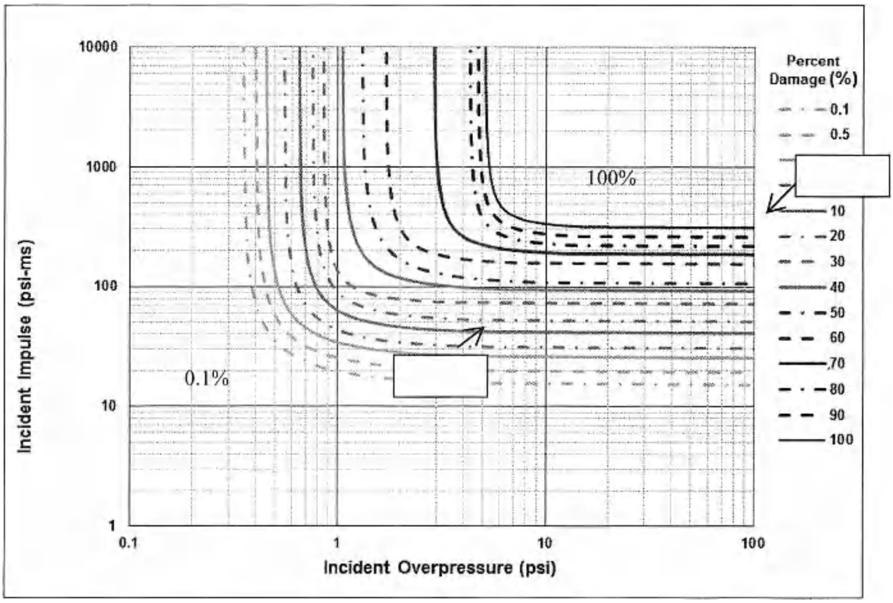

Figure 4.1. Building Damage Curves for a High Bay Metal Structure (~40,000 sq ft) (DDESB, 2009)

4.3.2.2 Discrete Building Damage Levels

Typical discrete BDLs used in the process industry are shown in Table 4.2. One advantage of this approach is that the nature of the damage is indicated by the damage description. Pressure-impulse diagrams serve to define the boundaries between the damage states when discrete BDLs are used. An illustration of the pressure-impulse curves may be presented as upper bounds on the lower damage state as shown in Figure 4.2. Illustrations of BDL 2A, 2B, and 3 for masonry and metal buildings are shown in Figure 4.3 through Figure 4.10 (courtesy of the Explosion Research Cooperative, a joint industry research program).

Table 4.2. Typical Industry Building Damage Level Descriptions (Baker, 2002)

Building Damage Level (BDL)	BDL Name	Damage Description
1	Minor	Onset of visible damage to reflected wall of building.
2A	Light	Reflected wall components sustain permanent damage requiring replacement, other walls and roof have visible damage that is generally repairable.
2B	Moderate	Reflected wall components are collapsed or very severely damaged. Other walls and roof have permanent damage requiring replacement.
3	Major	Reflected wall has collapsed. Other walls and roof have substantial plastic deformation that may be approaching incipient collapse.
4	Collapse	Complete failure of the building roof and a substantial area of walls.

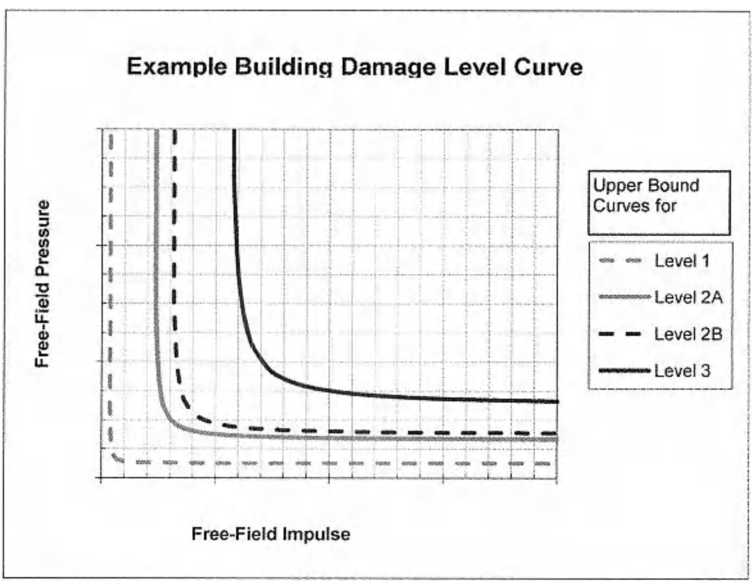

Figure 4.2. Illustration of Discrete State BDL Curves

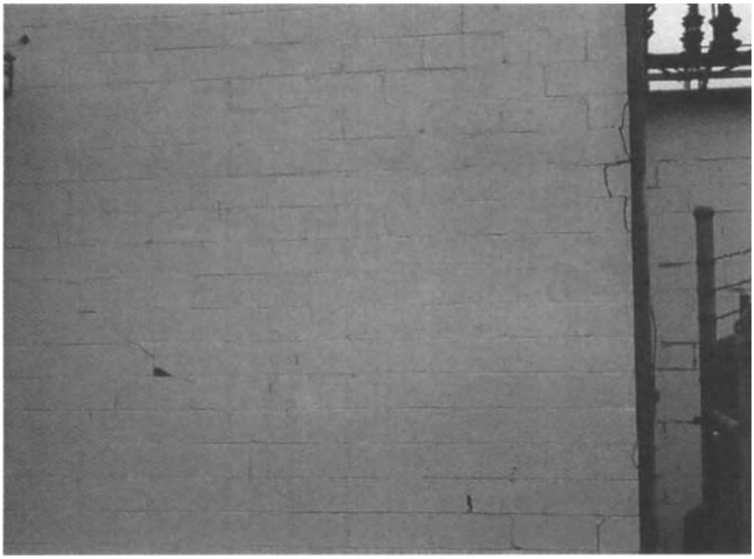

Figure 4.3. Masonry Building BDL1
(Photo Courtesy of Explosion Research Cooperative)

Figure 4.4. Pre-Engineered Metal Building BDL 1
(Photo Courtesy of Explosion Research Cooperative)

Figure 4.5. Masonry Building BDL 2A
(Photo Courtesy of Explosion Research Cooperative)

Figure 4.6. Pre-Engineered Metal Building BDL 2A
(Photo Courtesy of Explosion Research Cooperative)

Figure 4.7. Masonry Building BDL 2B
(Photo Courtesy of Explosion Research Cooperative)

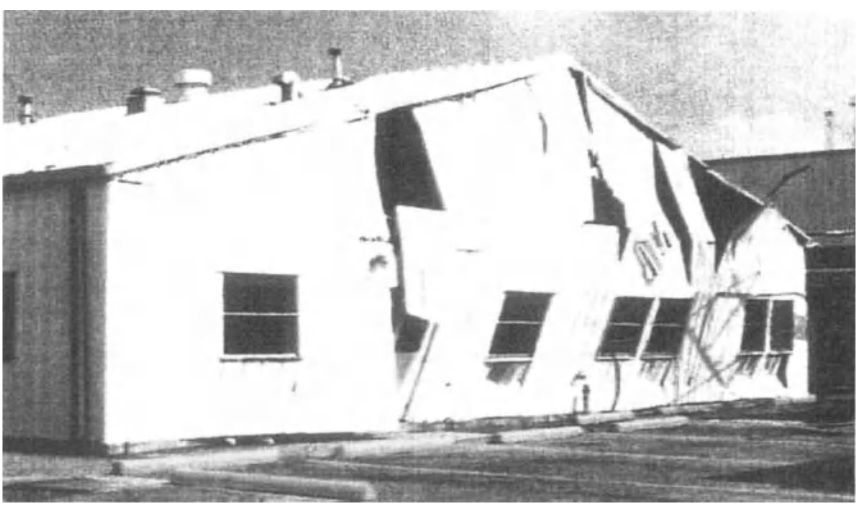

Figure 4.8. Pre-Engineered Metal Building BDL 2B
(Photo Courtesy of Explosion Research Cooperative)

Figure 4.9. Masonry Building BDL 3
(Photo Courtesy of Explosion Research Cooperative)

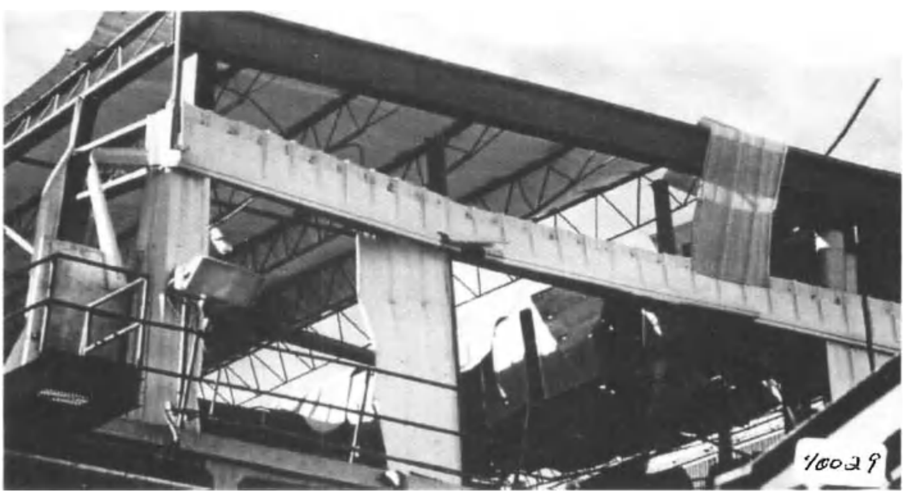

Figure 4.10. Pre-Engineered Metal Building BDL 3
(Photo Courtesy of Explosion Research Cooperative)

The U.S. Army Corps of Engineers (COE) uses a variation of discrete BDLs in which the BDL is directly tied to the level of occupant protection (U.S. Army COE, 2006). The COE BDL and protection levels are provided in Table 4.3. The COE criteria reference a damaged area rather than a damaged building. The reason for this is that the COE criteria were developed for use in assessing the vulnerability of buildings against possible terrorist bombings. A typical terrorist attack will only damage a portion of a building rather than result in a uniform damage level over an entire building. An approximate equivalency between the COE and industry criteria is shown in Table 4.4.

Table 4.3. U.S. Army COE Building Damage Levels

BDL Name	Building Level of Protection	Description
Superficial Damage	High	No permanent deformations. The facility is immediately operable.
Repairable Damage	Medium	Space in and around damaged area can be used and is functional after cleanup and repairs.
Unrepairable Damage	Low	Progressive collapse will not occur. Space in and around damaged area is unusable.
Heavy Damage	Very Low	Onset of structural collapse. Progressive collapse will not occur. Space in and around damaged area is unusable.
Severe Damage or Failure	Below acceptable DoD standards	Progressive collapse likely. Space in and around damaged area is unusable.

Table 4.4. Comparison of Industry and COE BDLs

Typical Industry Damage Level	U.S. Army COE Damage Level
1	Superficial Damage
2A	Repairable Damage
2B	Unrepairable Damage
3	Heavy Damage
4	Severe Damage or Failure

4.3.2.3 Assessment of Designed for Purpose Blast Resistant Buildings

Buildings that have been specifically designed to resist a prescribed blast load are not typically expected to suffer any structural collapse or structural component failure if subjected to the design blast loads. Such buildings may suffer plastic deformations. The approach used by the COE discussed above is well suited for estimating the response of designed for purpose blast resistant buildings when the buildings are either exposed to the design basis loads or potentially higher loads, since it provides a direct link between structural deformations, building damage, and level of protection.

4.3.2.4 Component Damage Levels

The response of critical structural components may also be used to establish siting criteria. Examples would be no permanent (inelastic) deformations of the building frame, or all cladding must remain attached to the structure. The development of component damage levels and their relationship to BDLs is discussed in detail in Chapter 5.

4.3.2.5 Correlation between Building Damage and Occupant Vulnerability

As discussed at the start of this chapter, the reason for setting occupied building criteria is to limit the hazards to which occupants are potentially exposed. When a BDL is selected, there is at least an implied estimate of the occupant vulnerability.

Among the models developed to provide a specific numerical value of the occupant vulnerability as a function of BDL is the one developed by Oswald and Baker (Oswald and Baker, 2000), and a model developed by the DDESB (DDESB, 2009). Oswald and Baker identified 10 building types as shown in Table 4.5. The occupant vulnerability for each BDL for each of the 10 types of buildings assuming typical construction and 50% of the occupants in perimeter rooms is shown in Table 4.6.

Table 4.5. Assumed Building Construction for Default Buildings (Oswald and Baker, 2000)

Building Type No.	Building Description	Roof	Frame	Walls
1	Steel frame, Steel cladding	Metal Deck	Yes	Metal Panel w/ Girts
2	Steel frame, Steel cladding, Concrete roof deck	Metal Deck with Thin Concrete Slab	Yes	Metal Panel w/ Girts
3	Steel frame, Unreinforced masonry walls	Metal Deck with Thin Concrete Slab	Yes	Unreinforced Masonry
5	Steel frame, Precast concrete cladding	Reinforced Concrete Deck	Yes	R/C Walls
7	Pre-engineered metal building	Metal Roof	Yes	Metal Panel w/ Girts
8	Steel frame, Reinforced masonry walls	Metal Deck with Thin Concrete Slab	Yes	Reinforced Masonry
9	Load bearing reinforced masonry walls	Light Metal Roof	No	Reinforced Masonry
10	Load bearing unreinforced masonry walls	Light Metal Roof	No	Unreinforced Masonry
11	Reinforced concrete frame, Reinforced masonry walls	Concrete Deck	Yes	Reinforced Masonry
12	Reinforced concrete frame, Unreinforced masonry walls	Concrete Deck	Yes	Unreinforced Masonry
Note: building types No. 4 and 6 were not used in the reference				

Table 4.6. Occupant Vulnerabilities (%) as a Function of Building Damage Level (Oswald and Baker, 2000)

Building Type No.	BDL1	BDL 2A	BDL 2B	BDL 3	BDL 4
1	0	0.01	1.7	17.1	48.8
2	0	0.01	1.7	22.1	66.8
3	0	0.01	2	28.2	78.8
5	0.005	2	8.3	32.2	98.8
7	0.002	0.008	1.7	17.1	48.8
8	0.001	0.008	2.5	28.2	78.8
9	0.001	0.008	2.5	24.7	83.8
10	0.001	0.005	2	24.7	83.8
11	0.001	0.008	2.5	32.2	98.8
12	0.001	0.005	2	32.2	98.8
Note: building types No. 4 and 6 were not used in the reference					

The DDESB approach uses a statistical distribution of the vulnerability with percent building damage for a number of predefined building types. Details on this approach are available in DDESB Technical Paper 14 (DDESB 2009).

The primary difference between the continuous and discrete occupant vulnerability models is that the continuous models (such as the DDESB) model assumes that occupant vulnerability and building damage both increases continuously with increasing load. The discrete models require the failure of an additional component before BDL and occupant vulnerability increase.

4.4 CRITERIA FOR FIRES

Fire exposure criteria may be based on spacing tables, thermal exposure level to the building of interest or vulnerability of occupants of buildings. Each approach is discussed below.

4.4.1 Spacing Table Approach

Spacing tables are widely used and acceptable under RP-752 for fire hazards. In fact, fire (specifically flammable gas cloud) hazards are one of the reasons for the use of minimum standoff distance considerations used to establish the Zone 1 boundary within the simplified approach to siting portable buildings in RP-753.

When using the spacing table approach, the requirement is that "established" tables be used for this purpose. Thus, spacing tables developed in the CCPS book "Guidelines for Facility Siting and Layout" or similar industry groups are appropriate; established index methods such as the Dow Fire and Explosion Index are also permissible. However, the user should be careful to adopt tables that are designed at least in part for building occupant protection, and not simply for equipment protection.

4.4.2 Building Exposure Criteria for Fire

Building siting evaluations are based on calculation of the potential fire exposures at the specific location of a building. if the spacing table approach is not selected. The criteria used for siting near pool or jet fire sources may include either the thermal flux, the thermal dose (combination of thermal flux and exposure time), or internal temperature. Examples of each, and the advantages and disadvantages of each, are listed below. However, alternative criteria are permitted as long as they address the fire exposure principles in the manner most appropriate to the types of exposures experienced by a company or site.

4.4.2.1 Criteria Based on Presence of a Flammable Cloud

The presence of a flammable cloud poses a hazard to building occupants due to the potential for the cloud to be drawn into the building due to natural convection and mechanical ventilation prior to ignition.

A dispersion analysis or other calculation is required to estimate the potential extent of the flammable cloud. The extent of the flammable cloud may be based on the LFL, a fraction of the LFL, or a multiple of the LFL. It should be noted that many companies apply multiple criteria depending on the building type and ventilation in the building and persistence of the cloud (i.e., time cloud is present at the building location). Multiples of LFL may be used as a criterion for short duration events. Common variables include:

- Ventilation type – natural ventilation or forced ventilation.
- Ability to quickly/automatically seal the building/shut off ventilation.
- Presence of flammable gas detectors, which may alarm and/or automatically shut off ventilation.

A company may select a higher concentration (multiple of LFL) for buildings that are relatively tight or under positive pressure and/or when the flammable gas cloud is present for a short period of time. A lower concentration (fraction of LFL) may be selected for buildings that are very open or under high mechanical (forced) ventilation rates.

4.4.2.2 Criteria Based on Presence of a Fire Near the Building

A fire in the vicinity of an occupied building could threaten the building's occupants. Criteria may be expressed in terms of this threat, as shown in Table 4.7, as applied to pool fires or jet fires. These criteria are expressed in terms that reflect the relative distance of the fire to the building.

Table 4.7. Fire Presence Criteria

Common Criteria	Principle Used	Advantages	Disadvantages
Fire flame impinges on building	If fire contacts building, this in and of itself may pose an unacceptable hazard.	Conservative	Calculation of jet fire impingement will likely utilize a model that provides a more direct measure of impact such as thermal flux.
Fire flame engulfs building	Assumes that it is possible for building occupants to escape from lesser fires.	Takes into account egress capabilities	Implies that egress is always possible if the building is not engulfed.
Fire source closer than defined separation distance	'Classic' separation distance tables used for siting buildings.	Simple approach	Does not precisely (if at all) take into account specific process conditions and inventories, and therefore is usually more conservative than necessary.

4.4.2.3 Criteria Based on Building Exposure to Thermal Flux

Thermal flux or thermal dose (combination of thermal flux and duration) at building locations may be used as a criterion to assess whether personnel can be allowed to remain in a building (or can safely escape) in case of external fires. These criteria are used to assess how long someone may be allowed to remain in a structure and are used in conjunction with emergency response planning. Some criteria used by various companies are shown in Table 4.8.

Table 4.8. Thermal Dose Criteria

Common Criteria	Principle Used	Advantages	Disadvantages
Outside of building exposed to specific thermal *flux*	1) For shelter in place for fire concept. At a given thermal flux rate, the building occupants will eventually be exposed to intolerable temperatures indoors, either because of conduction through the walls, or because the integrity of the building has been compromised (e.g. broken windows) 2) For evacuation for fire concept. At a given thermal flux rate, the building occupants will not be able to escape safely. Note that this flux level is likely to be different to 1 above.	Simple to apply, assuming release and thermal radiation models are available.	Some common thermal models (e.g. jet fires) may be overly conservative. This approach also does not take into account the duration of exposure/ or ability of building occupants to escape the building, which is a significant consideration if the shelter-in-place concept is chosen.
Outside of building exposed to a specific thermal *dose*	The rate of temperature rise within a building depends on both the thermal flux and the duration.	May be a more appropriate standard for transient fire events.	If the thermal dose is large enough, building materials could ignite, in which case, the duration of the event may not be relevant. This approach is more complicated to calculate and so is not used as often.

4.4.3 Fire Criteria Based on Occupant Vulnerability

A more direct but complicated criteria is to select either a set of building features or an exposure time that can be used to identify the actual impacts to personnel within the structure. These criteria are discussed in Table 4.9. In this case, a quantitative measure of probability of fatality is estimated, but this probability may be taken from a lookup table or calculated using mathematical models such as thermal probits.

For a case where the occupant fire exposure is only to elevated temperature inside the building (that is, the building integrity has been maintained so that there is no ingress of toxic fumes, nor is there direct thermal radiation), models have been developed that relate temperature to human impact.

Table 4.9. Occupant Thermal Vulnerability Criteria

Common Criteria	Principle Used	Advantages	Disadvantages
Occupant vulnerability (simple)	Develop an approximate measure of the probability that a building occupant will be injured or killed by a fire.	Should incorporate features of the relevant variables, but in an easy-to-use tabular form. Can be integrated into a risk assessment easily.	May not adequately address all the relevant variables for all situations.
Occupant vulnerability (complex)	Develop an explicit measure of the probability that a building occupant will be injured or killed by a fire.	Accounts for the magnitude and duration of exposure using thermal/temperature probit or similar approach. Can be integrated into a risk assessment easily.	Most difficult to calculate, and results could vary widely depending on the input assumptions made, e.g. the rate of heat transfer through a building wall, countermeasures that building occupants can take to keep cool.

4.4.4 Smoke

There are no specific criteria set for exposure to smoke as a result of a fire. However, in addition to the criteria established above for fire exposures, it is appropriate to consider the potential impact of smoke on worker vulnerability. Potential issues include:

- Obscuration – If fire criteria or mitigation are based on a presumption of worker evacuation from an exposed building, then there should be a qualitative evaluation that the escape path will not be blocked by smoke to a degree where the evacuation could not be accomplished safely.
- Carbon monoxide – The potential for the presence of high carbon monoxide in the building may need to be considered if the building is designated as Shelter-in-Place for a building that is otherwise safe from the thermal effects of a fire.
- Carbon dioxide – While the concentration of carbon dioxide produced in a fire will not typically be toxic, increased concentrations can result in more rapid breathing which, in turn, results in more rapid intake of the other combustion products that may be hazardous.
- Reduced oxygen – For both building occupants and evacuees, the potential for a reduced oxygen or particulate-containing atmosphere should be considered.

- Toxic combustion products – Some chemical fires produce combustion products that may be highly toxic. If such chemicals are present, special consideration should be given to this issue.

There is no need to consider smoke for every building, particularly when the buildings are well separated from fire sources. However, such consideration is appropriate for Shelter-in-Place when a shelter in place for fire concept is chosen. Smoke may also have to be considered for circumstances when people cannot evacuate, e.g. coker unit operators and crane operators located high in the structure; they can't evacuate down into a fire.

4.5 CRITERIA FOR TOXIC EXPOSURES

Many of the same principles used in fire exposure criteria apply for toxic exposures. As with the criteria discussed above, toxic exposure criteria may be based on either the exposure level to the building of interest, or related to impacts to the occupants of that building. Each approach is discussed below.

The definitions of the two commonly-used measures of acute toxic exposures are as follows:

Emergency Response Planning Guideline (ERPG) 3 – "the maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects." (AIHA, 2009) This level is cited in RP-753.

Immediately Dangerous to Life and Health (IDLH) – "a concentration from which a worker could escape without injury or without irreversible health effects... based on the effects that might occur as a consequence of a 30-minute exposure." (NIOSH, 1994)

The most common approaches to assessing the acceptability of a building's location and planning appropriate response to the potential exposure to toxic clouds are based on the presence of a toxic cloud at a certain concentration. This is a simplified approach similar to siting buildings based on overpressure alone for explosive hazards. Alternative approaches that address the effects of cloud duration and potential ingress will provide a more realistic assessment of potential hazards to building occupants. Examples, and the advantages and disadvantages of each, are listed below. However, alternative approaches may be used.

4.5.1 Criteria Based on Presence of a Toxic Cloud

The presence of a toxic cloud poses a hazard to building occupants due to the potential for the cloud to be drawn into the building by natural convection and mechanical ventilation. Common criteria that may be used are shown in Table 4.10. RP-753 identifies ERPG-3 as the criteria for portable buildings.

Table 4.10. Common Siting Criteria Used for Toxic Hazards

Common Criteria	Principle Used	Advantages	Disadvantages
Outside of building exposed to multiple of toxic concentrations (e.g. ERPG-3 or IDLH).	External concentration necessary to develop an internal concentration ≥ toxic threshold given assumptions of time of cloud persistence and ventilation rate in building.	Appropriate in cases where it can be assumed that building integrity is not affected by the originating event. Simple to apply.	Criteria must be set conservatively (highest ventilation rate/longest cloud persistence) to avoid missing buildings of concern. Models for this are usually based on perfect air mixing within the building, which may be non-conservative. See discussion after this table.
Outside of building exposed to a specified toxic concentration	Considers that part of the building interior could be exposed to the toxic cloud.	Simple to apply. May be more appropriate where the buildings of concern include wide-open structures like warehouses in the summer that face release sources.	May be overly conservative where buildings are 'closed', and building occupants have multiple egress options to escape, or have supplied air that can be used to shelter in place for an extended period.

As noted before for fire hazards, many owners/operators apply different concentration / persistence criteria depending on the building type and ventilation in the building. Common variables relevant to toxic events include:

- Ventilation type – natural ventilation or forced ventilation
- Ability to quickly/automatically seal the building/shut off ventilation
- Presence of gas detectors, which may alarm and/or automatically shut off ventilation
- Presence of air intake scrubbing, backup breathing air supply, or air escape packs
- Scenario considered in terms of persistence at the building location.

4.5.2 Toxic Criteria Based on Occupant Exposure

The commonly-used toxicity measures (ERPG-3 and IDLH) should not be directly equated with "fatality" except perhaps in cases where the worker is immobilized and the toxic event can persist for an extended period of time. For most chemicals (and healthy people), exposures of many hours would be required at ERPG-3 or IDLH concentrations to result in more than a marginal probability of fatality. This is not to diminish the use of ERPG-3 or IDLH in setting worker exposure criteria; it is simply a notice that a risk analyst's probit approach will normally show a large disconnect in the concentration of interest compared to an ERPG/IDLH approach. For this reason, an alternative criterion is a concentration that is probit-based by specifying an assumed duration of exposure, e.g. the concentration at which a selected probability of fatality is predicted assuming a one-hour exposure duration.

The UK Health and Safety Executive publishes values for relating toxic dosage to specific levels of impact (HSE, 2011) that incorporate this concept for a wide variety of chemicals. Approaches to setting toxic vulnerability criteria are provided in Table 4.11.

Table 4.11. Toxic Vulnerability Criteria

Common Criteria	Principle Used	Advantages	Disadvantages
Indoor concentration	Based on a calculation of the indoor concentration profile, knowing what the outdoor concentration is.	A more direct measure of impact to a person than an external concentration measure.	Results could vary depending on the input assumptions made, e.g. rate of air changes in the building.
Occupant vulnerability (simple)	Develop an approximate measure of the probability that a building occupant will be injured or killed by a toxic release.	Should incorporate features of the relevant variables, but in an easy-to-use tabular form. Can be integrated into a risk assessment easily.	May not adequately address all the relevant variables for all situations.
Occupant vulnerability (complex)	Develop an explicit measure of the probability that a building occupant will be injured or killed by a toxic release.	Accounts for the magnitude and duration of exposure using concentration/time probit or similar approach. Can be integrated into a risk assessment easily.	Results could vary depending on the input assumptions made, e.g. rate of air changes in the building. Probit equations are available for only a limited number of chemicals, and in some cases these vary significantly between sources.

A description of probit analysis is provided in CCPS books (CCPS, 2000) and Mannan (2005). Probits are frequently used in risk-based assessments to estimate the probability of fatality from a given exposure.

4.6 CRITERIA FOR BUILDING UPGRADES AND NEW BUILDINGS

Upgraded and new buildings are designed to provide protection from the potential hazards at their intended location. Conventional construction may be acceptable when a building is sited where hazards or risks are low. Specialized design may be needed when conventional construction is not adequate for the explosion, fire and toxic release hazards.

Since building upgrades and new construction involves a design process, the owner/operator give criteria to designers to achieve the desired level of performance. Blast response may include criteria related to the maximum deformation that is allowed for structural components. Fire criteria are often expressed in terms of the duration that building exterior components can survive fire exposure. Criteria for toxic protection will involve air tightness of the building and features of the air handling system (gas detection, shut down provision, etc.).

Criteria for building upgrades and new construction are described in the appropriate hazards chapters.

4.7 RISK CRITERIA

4.7.1 Use of Individual Risk Measures

When considering individual risk, there is commonly considered to be an upper bound, above which the risk is judged to be intolerable and for which action must be taken to reduce the risk.

Figure 4.11, taken from the HSE (HSE, 2001) illustrates this concept. If the risks are in the top region, the activities, as constituted, are in an unacceptable zone. Regardless of the benefits associated with the activity, risk reduction should be performed.

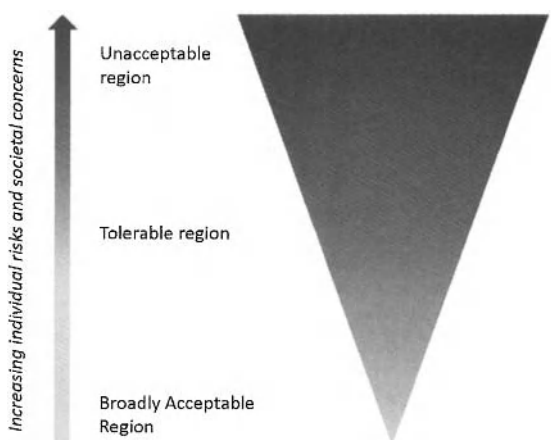

Figure 4.11. Presentation of HSE Risk Tolerance Levels (HSE, 2001)

For risks falling in the "Tolerable" region, efforts might be made to further reduce the risks so that they are as low as reasonably practicable (ALARP). In other words, activities with risks in the ALARP tolerable region are candidates for further risk reduction to the extent such risk reduction can be justified by the additional resources required to achieve it.

Figure 4.11 implies that for higher risk activities in the tolerable region (those closer to the unacceptable region), it may be appropriate to expend, proportionately, more resources for risk reduction than for those with lower risks. At some point, the risks become broadly acceptable and further risk reduction cannot be supported from a cost-benefit perspective.

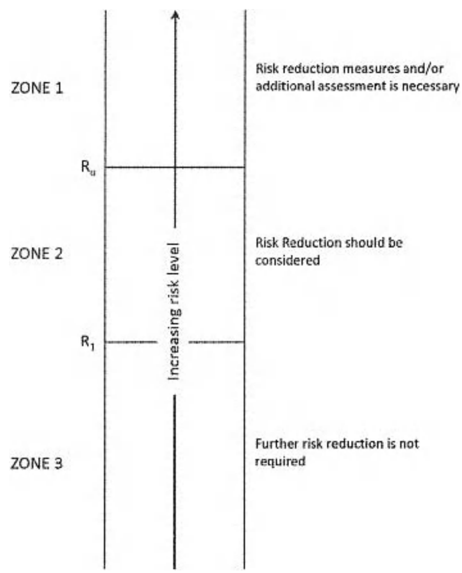

Figure 4.12. A Three-tier Framework for Risk Interpretation

Figure 4.12 presents a similar model, based upon a three-tier risk framework. Variations of a three-tier scheme have been widely adopted by governmental agencies and companies for land-use planning issues associated with major hazard sites; in some cases, "Zone 3" is being removed as a means to encourage continuous improvement (CCPS 2009b). As with Figure 4.11, Figure 4.12 shows an upper bound, *Ru*, above which risk measures and/or additional assessment is necessary. Correspondingly, there may be a lower bound below which further risk reduction is not required and where it may be impractical to continue to expend significant resources on further reducing risk that is already very low. In fact, efforts to reduce these already low risks may be counter-productive because they will divert resources from other higher risks.

In between these two bounds is a gray area where the decision-making process on risk reduction will be less clear, and further analysis of risk reduction should be considered.

The risk levels in this region are not high enough to necessitate risk reduction, yet they are not low enough to dismiss as insignificant. Zone 2 represents the ALARP/Tolerable region depicted in Figure 4.11. Within this zone, risk-reduction options should be implemented on the basis of practicability, risk reduction and cost. Guidance in making these kinds of decisions is covered in the CCPS book, "Tools for Making Acute Risk Decisions with Chemical Process Applications" (CCPS, 1994a).

Table 4.12 presents some published tolerance criteria from a number of countries. These proposed criteria reflect a wide variety of applications (from transport risks to new housing) and cannot necessarily be directly applied to the problem of process plant buildings. These criteria are copied from the CCPS book, "Guidelines for Developing Quantitative Safety Risk Criteria" (CCPS, 2009b), which contains many other examples of both individual and aggregate (societal) risk criteria from around the world.

Table 4.12. Comparison of Sample Individual Risk Criteria

Source of Proposal	Individual Risk Criteria	
	Format/Scope	Numerical Values (per year)
UK HSE	Upper and lower bounds for workers	$R_u = 1x10^{-3}$ $R_l = 1x10^{-6}$
State of Western Australia, Australia	Upper and lower bounds for workers	$R_u = 5x10^{-4}$ proposed for new facilities $R_l = 1x10^{-4}$ proposed for new and existing facilities
US DoD	Upper and lower bounds for workers handling explosives	$R_u = 1x10^{-4}$
IMO	Upper and lower bounds for crew members	$R_u = 1x10^{-3}$ for existing ships $R_u = 1x10^{-4}$ for new ships $R_l = 1x10^{-4}$ for new and existing ships

4.7.2 Use of Societal and Aggregate Risk Measures

Societal risk is the generic term used to describe a measure of risk which takes into account the number of people at risk. The majority of published societal risk criteria have been developed with reference to off-site populations (i.e. the public).

Aggregate risk is a specific type of societal risk measure used to express the risk to the occupants of an individual building rather than the risk from an accidental event (which may affect the occupants of multiple buildings and outdoor populations). Aggregate risk criteria for on-site building occupants are frequently set more stringently than societal risk criteria for the general public. Applying risk criteria to site personnel involves considerations that are different from those used for off-site populations. For example, on-site personnel are generally educated in the potential risks associated with their operations and have been trained in emergency response actions, including evacuation procedures. Conversely, the general public may not be aware of the risks or the appropriate emergency actions.

Figure 4.13 illustrates some societal (public) risk criteria that are in use for off-site populations in various regulated areas. But because of the important differences between worker populations and the general public, F-N criteria curves developed for risks to the general public may not be appropriate for evaluating aggregate risk to onsite building occupants. Consequently, some companies may choose to develop their own company-specific aggregate risk criteria that reflect company-specific levels of risk tolerability for on-site events that can impact occupied process plant buildings. Risk may be aggregated at the individual building level or plant-wide for all building occupants; other levels of aggregation can also be appropriate.

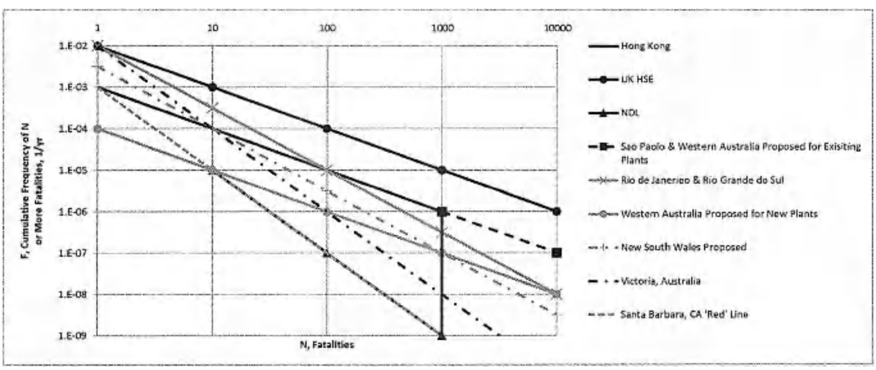

Figure 4.13. Regulated Acceptability Criteria for Societal Risk (CCPS, 2009b)

Note that the most recent HSE criterion (HSE, 2001) is a point, not a line (*"... the risk of an accident causing the death of 50 or more people in a single event should be regarded as intolerable if the frequency is estimated to be more than one in five thousand per annum."*) Note too that most societal F-N criteria curves extend out to hundreds or even thousands of fatalities, and were originally developed for offsite populations. Few buildings, if any, within process facilities have such large concentrations of people. For practical purposes, only the left side of these criteria would normally be adopted to evaluate aggregated risks in onsite occupied buildings. Criteria may also be established on an individual-building basis, in which case the criteria would normally be stricter than the criteria when aggregated across an entire site. Aggregate risk criteria should reflect the basis (e.g. site-wide or for individual buildings).

Criteria may also be established based on 'expectation values,' which are similar in concept to F-N curves. Risk matrix approaches are also permitted as long as the axes of the matrix are defined in numerical terms, and the range between adjoining levels on each axis is not overly large.

The owner/operator that needs to develop risk criteria should consider using the CCPS risk tolerance book for additional information (CCPS, 2009b).

Guidelines for Evaluating Process Plant Buildings for External Explosions, Fires, and Toxic Releases, Second Edition
by Center for Chemical Process Safety

5 EXPLOSION HAZARDS

5.1 INTRODUCTION

The presentation in this chapter discusses the approaches for evaluating explosion hazards and assumes the scenarios and criteria have been selected as discussed in previous chapters. The process developed in RP-752 is shown in Figure 5.1.

The information presented in this section is appropriate for use in consequence-based and risk-based occupied building siting studies. Hazards to occupants of buildings exposed to an external explosion stem from building debris and collapse. As a result, explosion hazard assessments involve estimating building damage and the associated occupant vulnerability.

5.2 SELECT EXPLOSION APPROACH

An owner / operator may elect to use either a consequence-based approach or a risk-based approach to assess the siting of buildings. Either approach may be used for new or existing buildings. However, when the risk based approach is used for new buildings the building designers will have to be provided a deterministic blast load and building response criteria that corresponds to the assumptions used in the quantitative risk assessment.

In a consequence-based approach, a release of a given size is assumed to occur and the blast loads are computed based on the release conditions. The direction of the release is selected such that the cloud will enter the areas of congestion and confinement that produce the maximum loads on specific buildings. An alternative consequence-based approach is to assume a "filled unit" and not address the specific release conditions.

In a risk-based siting approach, the distribution of risk has historically been based on the frequencies of releases of various sizes occurring, the probability of the vapor cloud dispersing in specified directions, and the probability the release will be ignited. The size of the flammable vapor cloud and the magnitude of the explosion are treated as a deterministic function given the release conditions and ignition. The magnitude of the building response is similarly treated deterministically based on the calculated blast loading. The development of uncertainty estimates for either the magnitude of the explosion or the level of building response to a given load is not within the scope of this book.

The potential explosion scenarios analyzed may be developed by evaluating the inherent properties of the materials being handled, in conjunction with an estimate of the quantities available, and consideration of the actual configuration and layout of the process equipment as discussed in Chapter 3. A calculation is then performed to determine potential blast effects, taking into account site-

RP-752 only requires that permanent buildings that are intended for occupancy and that are exposed to a potential explosion hazard be considered in the explosion hazards siting study. RP-753 has the same provision and allows owners to use either a simplified approach or a detailed approach in evaluating the siting of portable buildings. The approaches described in this chapter are suitable for use with RP-752 or the detailed approach in RP-753. The implementation of the RP-753 Simplified Approach is not addressed in this book since it is comprehensively addressed in the RP.

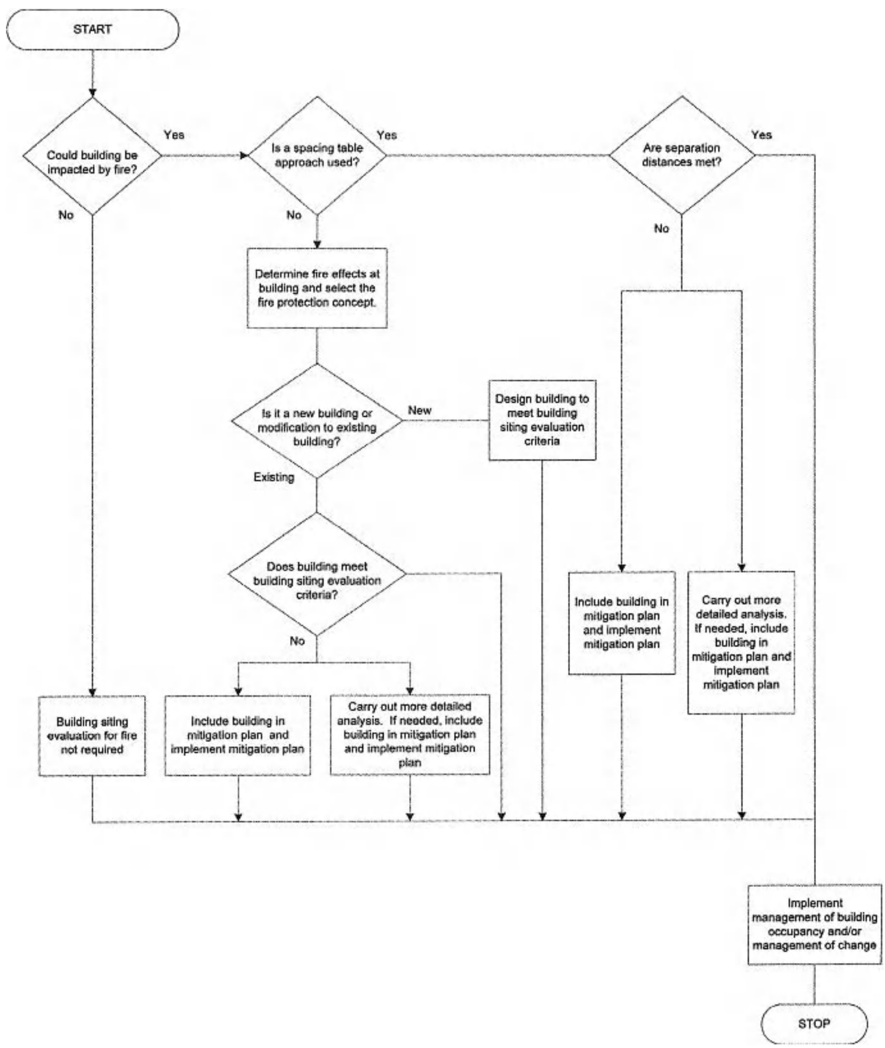

Figure 5.1. Logic Diagram for Siting Buildings with Regards to Explosion Hazards

specific factors contributing to or mitigating the potential consequences (e.g., for VCEs, degree of confinement, congestion and fuel reactivity). The resulting blast loads are then used to determine the level of building response (damage) and to determine if the response satisfies the previously established criteria as defined by the owner/operator or regulatory authority as discussed in Chapter 4.

This chapter provides a summary of pertinent information used by the analyst who is involved in evaluating behavior of buildings subjected to explosions and in the design or upgrade of buildings for explosion effects. Areas covered include a short overview of explosion parameters and the evaluation of building response to overpressure induced by potential explosions and the design and construction considerations of importance to the blast resistance of buildings.

5.2.1 Evaluation of Existing Buildings

The majority of the effort for most occupied building siting evaluations will be the assessment of existing structures. Existing structures may be assessed as a part of a plant's initial building siting evaluation or due to changes in the building's use (moving it from unoccupied to "intended for occupancy"), or a change in plant operations that has the potential to increase or decrease the blast loading on the facility. Modifications to existing buildings may also require a reassessment of the building.

When assessing an existing building an engineer will inspect the building and document the type of construction, age, and location of doors, windows, and roof mounted equipment. Where available the as-built or design drawings for the facility are obtained. Since the performance of the building can vary greatly with assumptions regarding unknown (not visible or documented) structural conditions the analyst will typically assume reasonable conditions that are consistent with the building codes and practices in effect at the estimated time of construction for the appropriate geographical region. When the design material properties have not been retained it is appropriate to assume values consistent with building practices at the time of construction. Material types and connection detailing practices have evolved over time. For example, it is reasonable to assume that a steel framed building constructed in the United States in the 1950's has steel with a static yield strength of at least 33,000 psi, but the assumption of a high value such as 50,000 psi would be difficult to justify, and the assumption of a very low value such as 26,000 psi is not warranted. The American Association of State Highway and Transportation Officials (AASHTO) published guidance on the selection of material properties based on the age of construction (AASHTO, 2010)

The construction material and source of the material used in the evaluation is documented as part of the siting study.

5.2.2 Siting and Design of New Buildings

The siting and design of new construction, whether as an addition or modification to an existing building or as an entirely new building, is handled in much the same manner as for an existing building. The blast loads at multiple potential locations on the facility may be used to compare the anticipated response of various types of construction in order to select the location and construction type. This comparison may be considered either part of the building design or siting process. The building is then designed to meet the building siting evaluation criteria.

5.3 MODELING AND QUANTIFYING AND EXPLOSION HAZARDS

The 3rd edition of RP-752 requires that explosion hazards must be quantified in terms of overpressure and impulse or overpressure and duration in order to complete a building evaluation. This is a significant change from previous editions that typically only discussed explosion hazards in terms of overpressure.

5.3.1 Vapor Cloud Explosions (VCEs)

For many sites, VCEs are the dominant explosion hazard. These explosions are caused by combustion of a dispersed cloud of vapor in a congested volume, which is a volume containing turbulence-inducing obstacles. The flame self-acceleration produces an overpressure wave that propagates into the surroundings. This overpressure can cause damage to structural and non-structural elements, leading to possible injuries or fatalities to building occupants.

VCE consequences can be predicted in a number of different ways, depending on the detail required, the specifics of the scenario, the geometry of the surroundings, and the analysis tools selected by the analyst. Some degree of simplification is used in this analysis to allow the evaluation of more scenarios than would be possible if a more resource-intensive method was used. The more detailed or complex models for VCE calculations typically provide a greater refinement of the potential blast loads.

The CCPS Guidelines for Vapor Cloud Explosion, Pressure Vessel Burst, BLEVE and Flash Fire Hazards, 2nd Edition (CCPS, 2010) provides details on how these explosion events can be calculated. The following paragraphs provide a general overview of the process of predicting vapor cloud explosions for building siting.

The models broadly fall into two categories:

- VCE Blast Curve methods
- Numerical methods

The VCE blast curve methods (i.e., Baker-Strehlow-Tang [BST], TNO Multi-energy Method [MEM], and Shell Congestion Assessment Method [CAM]) use curve lookups to determine blast load parameters. The blast curves are tailored to VCEs and predict a range of severities (CCPS, 2010). The overall process for these methods is as follows:

1. **Predict the energy of the explosion.** In this step, the mass of fuel involved in the explosion is predicted. In its most rigorous form, this prediction is based on a dispersion model and the intersection of the predicted cloud with the congested/confined volume. In simpler analyses, the cloud can be assumed to fill a congested volume. A ground reflection factor may be used, where appropriate for the blast curves selected, to account for explosions occurring close to ground level.
2. **Predict the severity of the explosion.** Using the variables allowed by the method chosen, predict the severity number (CAM and MEM) or flame speed (BST). Simplifying assumptions can be made of the severity or flame speed to conservatively overestimate the blast pressure with respect to severity.
3. **Determine blast parameters in the dimensionless curves at the building.** The blast curves use severity/flame speed and energy, and stand-off distance (distance from blast source to receptor) to determine scaled overpressure, impulse/duration, and other parameters.
4. **Un-scale the blast parameters.** The blast parameters are then converted from dimensionless to dimensional parameters using atmospheric pressure, explosion energy, and speed of sound.
5. **Apply reflection factors and other corrections.** Reflection factors and other factors to account for real-world geometry effects can be applied to the blast prediction. When blast loadings are reported to the analyst performing the structural assessment it is important to note whether the pressures and impulses are either free field (incident) or reflected (applied).

Numerical models, such as computational fluid dynamic (CFD) codes, are an alternative method to blast curve methods. Numerical modeling techniques generally try to reflect actual plant geometries, and may include refinements such as ignition location, concentration gradients, fuel reactivity, flame acceleration, etc. The high level of effort makes these analyses more suited to refinements after blast loads have been estimated with simpler methods. The resource cost for these refinements may be well justified, particularly where complex geometries may provide either blast shielding or blast focusing. Computational fluid dynamics (CFD) is particularly useful for blast load prediction inside the congested zone.

5.3.2 Pressure Vessel Burst

Pressure vessel burst (PVB), as the name implies, is a type of explosion that involves burst of a pressure vessel containing gas at elevated pressure. The term "pressure vessel" in PVB is not necessarily synonymous with the definition of pressure vessel used in ASME code; rather, any vessel or enclosure that can build significant pressure before bursting can generate a PVB. Upon burst, the sudden expansion of a compressed gas generates a blast wave that propagates outward from the source. The shell of the vessel along with attached external appurtenances is thrown, creating a fragment hazard. It is not necessary for the vessel contents to be flammable or contain reactive chemicals. PVBs occur with inert gases or mixtures as well as flammable or reactive materials.

PVBs involve only the release of energy from the compressed gas contents. Flashing of the superheated liquid upon vessel failure can also contribute to the explosion energy, but that is a separate type of explosion called a Boiling Liquid Expanding Vapor Explosion (BLEVE).

The consequence analysis process for PVBs is essentially as follows:

1. Collect data on fill level, failure pressure, fluid temperature, fluid composition, and thermodynamics.
2. Calculate the explosion energy stored in the compressed gases in the vessel.
3. Calculate the dimensionless stand-off to the receptor using the explosion energy.
4. Use the bursting vessel blast curves to determine the dimensionless blast parameters (pressure and impulse) at the receptor.
5. Un-scale the blast parameters to calculate blast loads at buildings.
6. Apply reflection factors and other factors to account for real-world effects.
7. If applicable, predict fragment throw.

Fragment throw is rarely considered as part of a building siting evaluation since most buildings at a facility have a low likelihood of being struck. Fragment throw predictions are available for circumstances where fragment impact on an occupied building may be of concern.

As with VCEs, the use of TNT equivalency models is now widely considered inappropriate for PVB prediction due to the availability of more appropriate models. The prediction process is described in more detail in Chapter 8 of the CCPS Guidelines for Vapor Cloud Explosion, Pressure Vessel Burst, BLEVE and Flash Fire Hazards, 2nd Edition (CCPS, 2010).

5.3.3 Boiling Liquid Expanding Vapor Explosions (BLEVEs)

Mitigation through evacuation is the typical approach to protect occupants from BLEVEs when there are adequate evacuation routes and time available. As an alternative, an owner may perform a building assessment if the intent is to have occupants remain in the building or if insufficient time is available for safe egress. BLEVEs occur when liquids are stored above their normal atmospheric boiling point and the storage container that they are stored in fails catastrophically. Loss of containment causes the pressure on the liquid to drop and the liquid will then boil. The pressure wave generated by the expansion of the boiling liquid and expanding vapor can propagate into the surroundings and potentially cause damage to personnel and buildings in the area. The vessel can fragment and the parts can be propelled away from the BLEVE to substantial distances. If the liquid is flammable, the flashing liquid may form a fireball, imposing a thermal pulse to personnel and buildings in the area. The prediction of BLEVEs generally follows the methodology for bursting pressure vessels with additional consideration for the contribution of the liquid energy to the explosion. The prediction process is described in more detail in Chapter 8 of the CCPS book, "Guidelines for Vapor Cloud Explosion, Pressure Vessel Burst, BLEVE and Flash Fire Hazards," 2nd Edition (CCPS, 2010).

5.3.4 Condensed Phase Explosions

Condensed phase explosions are relatively rare in refineries but may occur in chemical plants. Where a condensed phase explosion scenario is identified, the TNT equivalent explosion model is typically used, with an efficiency or yield factor being applied as appropriate, to account for the type of chemical being considered. This type of model is also used for propellants, runaway reactions, decompositions, and other very fast events. The process is as follows:

1. Estimate the energy released in the event.
2. Determine the efficiency or yield factor that is appropriate.
3. Correct the energy for the yield.
4. Use the energy to scale the stand-off (not dimensionless for high explosive blast curves).
5. Determine the blast parameters (overpressure and impulse) on the blast curves (note: no severity factor required).
6. Un-scale the blast parameters.
7. Apply reflection factors and other factors to account for real-world effects.

More details are available in the CCPS Guidelines for Vapor Cloud Explosion, Pressure Vessel Burst, BLEVE and Flash Fire Hazards, 2nd Edition (CCPS, 2010).

5.4 BUILDING RESPONSE TO EXPLOSION HAZARDS

5.4.1 General

The design of buildings to resist both accidental and intentional explosions has been proceeding on a scientific basis since the early 1800s. The distribution of the required information regarding material and approaches has accelerated since the previous edition of this book. The American Society of Civil Engineers (ASCE), the Process Industries Practices (PIP), the U.S. Department of Defense, and Norway Standards (NORSOK), and the UK Institute of Structural Civil Engineers have published guidance documents that are readily available and are listed in Table 5.1. Additional organizations active in the area of blast effects on buildings are the Explosion Research Cooperative, the Mary K. O'Connor Process Safety Institute, and the Fire and Blast Information Group (FABIG). The latter organization addresses fire and explosion issues with an emphasis on off-shore structures but has numerous technical notes and guides available that are useful in understanding technical issues.

The rest of this section provides an overview of the response of buildings to explosion hazards.

Table 5.1. Recent Publications in Blast Resistant Design

Publishing Organization	Title	Summary
U.S. Army Corps of Engineers, Protective Design Center	Single Degree of Freedom Structural Response Limits for Antiterrorism Design	Published in 2008 and includes direct correlation between building damage, component damage, and numerical limits on component response. Comprehensive in that it addressed reinforced and unreinforced masonry, steel, concrete, prestressed concrete, and wood components. No direct correlation between extent of damage and numerical values of occupant vulnerability. Building Damage is defined in discrete states as discussed in Chapter 3. (USACOE, 2006)
U.S. Department of Defense, Explosives Safety Board	**Technical Paper 14 - Approved Methods And Algorithms For DoD Risk-Based Explosives Siting, Revision 4, 21 July 2009**	Provides P-i damage curves for a number of building types and components. Provides occupant vulnerability for each building type as a function of building damage. Building damage is defined as a contiguous function as discussed in Chapter 3.(DDESB, 2009)
American Society of Civil Engineers	Design of Blast Resistant Buildings in Petrochemical Facilities	Published in 1997 and updated in 2010. Provides good overall discussion of issues including loadings and limits on component responses. Does not address building damage or occupant vulnerability per se. (ASCE, 2010)

Table 5.1, continued

Publishing Organization	Title	Summary
NORSOK	Design of Steel Structures	Published in 2004 and while intended primarily for off-shore structures, provides discussion of response limits and design charts that address the shape of the loading function as well as the presence of membrane action. Only addresses steel components.(NORSOK, 2004)
Construction Industries Institute	PIP STC 01018 Blast Resistant Building Design Criteria	Published in 2006, this document provides information on design and analysis approaches as well as numerical values limiting the deformation of structural components.
UK Institution of Structural Civil engineers	Blast Effects on Buildings, 2nd Edition	Published in 2009 and provides guidance on the design of buildings to resist both high explosive and detonations and deflagrations due to industrial, vapor cloud and dust explosions.

5.4.2 Building Damage Levels (BDLs)

The concept of BDLs has been discussed in Chapters 3 and 4. This section describes methods for computing the BDL from the response of underlying structural components. When BDLs are based on empirical fits to past incidents for specific building types, such as those listed in Table 4.5 of Chapter 4, the BDL is computed directly from pressure-impulse (P-i) curves such as the one shown in Figure 4.2 of Chapter 4. These P-i curves are typically embedded in proprietary siting software. Publicly available P-i curves are provided in Technical Paper 14 by the DDESB (DDESB, 2009).

When a BDL is constructed from the response of the building structural components, a set of combination rules is required as are definitions of the component response levels. The combination rules map the component damage levels to a building damage level. For example the collapse of the roof will typically result in a building damage level of collapse regardless of the response of the walls. Conversely non-load bearing walls may be heavily damaged but the building will remain standing. The combination rules are discussed here and the component response levels in the following section.

A complete set of rules and response limits for the approach used by the U.S. Army COE is discussed in the publication, "Single Degree of Freedom Structural Response Limits for Antiterrorism Design" (USACOE, 2006). When using the industry definitions provided in Table 4.2 of Chapter 4, a similar process is used.

For example, let us consider a company that chooses BDL 2 as its siting criterion. Recalling the definition from Chapter 3: *"Reflected wall components* *sustain permanent damage requiring replacement, other walls and roof have visible damage that is generally repairable."*

The analyst may use an SDOF approach or more sophisticated analysis of each of the wall and roof components. The reflected wall (the wall facing the explosion) may sustain damage but is not expected to collapse. If the SDOF analysis indicates failure of the reflected wall or excessive deformations of other components, the building does not meet the BDL 2A criteria and a mitigation plan or a more detailed analysis is required.

5.4.3 Component Damage Levels

5.4.3.1 Structural Components

Structural components are those components that support the building and must remain in place to resist gravity and environmental loads after the explosion. Structural components may be considered primary, secondary, or tertiary components. Primary components are framing members and components that carry the load of multiple other components. Examples would be a roof or floor girder that supports numerous joists. A secondary component would be the individual joists and the tertiary component would be the roof decking or wall cladding. Generally, primary components are limited to less deformation than are secondary components.

The loss of tertiary components is not a threat to structural collapse or integrity, but the components can become debris hazards if they are propelled into the occupied spaces by an explosion. Some guidance documents also refer to tertiary components as non-structural components.

Typical Component Damage Levels (CDLs) are defined in Table 5.2. The limits that define the CDL are expressed in terms of ductility ratio and support rotation as discussed in Section 5.4.4.1.

Table 5.2. ASCE and COE Component Damage Definitions

ASCE Response Level (ASCE, 1997)	COE Damage Level (USACOE, 2006)	COE Description
Low	Superficial Damage	Onset of visible damage; component can be repaired.
Medium	Moderate Damage	Permanent deformation of components requiring replacement.
High	Heavy Damage	Substantial plastic deformation approaching incipient collapse. Replacement is required. Component failure is possible though not probable, especially near the upper bound.
Failure	Hazardous Failure	Complete failure of component creating debris hazard. Replacement required.
	Blowout	Component is overwhelmed by the blast load causing debris with significant velocities.

5.4.3.2 Non-Structural Components

Non-structural components do not affect the stability of the building but may become a debris hazard if allowed to fail under blast loadings. Typical non-structural components include windows and doors in addition to the wall and roof cladding. Damage levels for windows and doors are summarized in Table 5.3. The calculation of the hazard rating for windows and doors may be performed dynamically using specialized software that is typically only available through government agencies in the United States. An alternative static design approach for glazing systems is available using ASTM E1300 - 09a "Standard Practice for Determining Load Resistance of Glass in Buildings," and ASTM F2248 - 09 "Standard Practice for Specifying an Equivalent 3-Second Duration Design Loading for Blast Resistant Glazing Fabricated with Laminated Glass."

Table 5.3. Window and Door Damage Levels (USACOE, 2006)

Hazard Rating	Window and Door Performance	Injury Potential
No Hazard	• Window glazing does not break. • Doors remain operable.	None or superficial injuries.
Minimal Hazard	• Glazing will fracture, remain in the frame and results in a minimal hazard consisting of glass dust and slivers. • Doors will stay in frames, but will not be reusable	Personnel in damaged area potentially suffer minor to moderate injuries, but fatalities are unlikely. Personnel in areas outside damaged areas will potentially experience superficial injuries.
Very Low Hazard Rating	• Glazing will fracture, potentially come out of the frame, but at a reduced velocity, does not present a significant injury hazard. • Doors may fail, but they will rebound out of their frames, presenting minimal hazards.	Majority of personnel in damaged area suffer minor to moderate injuries with the potential for a few serious injuries, but fatalities are unlikely. Personnel in areas outside damaged areas will potentially experience minor to moderate injuries.
Low Hazard Rating	• Glazing will fracture, come out of the frame, and is likely to be propelled into the building, with the potential to cause serious injuries. • Doors may be propelled into rooms, presenting serious hazards.	Majority of personnel in damaged area suffer serious injuries with a potential for fatalities. Personnel in areas outside damaged area will experience minor to moderate injuries.
High Hazard Rating	• Doors and glazing will fail catastrophically and result in lethal hazards.	Majority of personnel in collapse region suffer fatalities. Fatalities in areas outside of collapsed area likely.
	Note the descriptions for the COE criteria are consistent with heavy localized damage caused by terrorist weapons. The term "collapsed region" refers to local areas of wall or roof collapse and not general building collapse.	

5.4.4 Detailed Analysis

In this subsection, general treatment of the response of buildings to blast pressure loadings is described, including both simple, approximate approaches and more complex, rigorous methods. By these methods, the structural responses in terms of displacements such as deformation ratio or plastic hinge rotation are evaluated.

Estimation of building response to blast loadings is an important step in evaluating potential building damage and the probability of serious injuries or fatalities to building occupants. Conventional and blast-resistant buildings in chemical processing facilities are typically simple configurations, and blast loadings can be reasonably represented as idealized simple pulse shapes. The actual overpressure time history from a VCE will have some non-zero rise time to its peak value, followed by a non-linear decay to atmospheric pressure followed by a negative phase (when the pressure drops below atmospheric) before a return to atmospheric pressure.

The simplification of the blast loading typically used in structural analyses has an instantaneous rise to peak pressure followed by a linear decay to atmospheric. The negative phase is often ignored since the positive phase usually dictates damage level, although some companies have used a simplification of the negative phase as well. These approximate analytical techniques were developed prior to wide usage of computer methods and have been utilized for the design and evaluation of blast-resistant structures for many years. These approximate techniques are sufficiently accurate for preliminary designs in all cases, and for final designs in most cases. Many of the blast-resistant design criteria for buildings in the petrochemical industries are based on such approximate techniques. The use of approximate analytical techniques is described in the next section for simple pressure versus time loads and simple structural elements to illustrate the important principles in evaluating structural response for blast loadings. These principles are also applicable to more complex structural analysis techniques such as finite element methods, which are briefly discussed in Section 5.4.4.3.

5.4.4.1 Single Degree of Freedom (SDOF) Model

Many structural elements (walls, slabs, and beams) and structural systems (frames and shear wall structures) can be represented by a single degree of freedom (SDOF) model. The basis for the SDOF system is that there is single response parameter (the degree of freedom) that when modeled accurately will suitably predict the response of the real system. Typically the point on the member that is predicted to undergo the maximum deflection is selected as the basis for the model. However, other points of interest (such as where the deflection of a beam may hit a pipe) may also be selected for the SDOF. In such a model, the dynamic characteristics of the structure can be represented by a single mass and a single spring, as shown in Figure 5.2.

The SDOF methodology is a widely accepted approach for estimating damage to structural components subjected to time-varying blast loading and/or fragment impacts. The SDOF approach is a government and industry accepted methodology and details on its implementation are available in many guidelines (UFC, 2002; Biggs, 1964; ASCE, 1997).

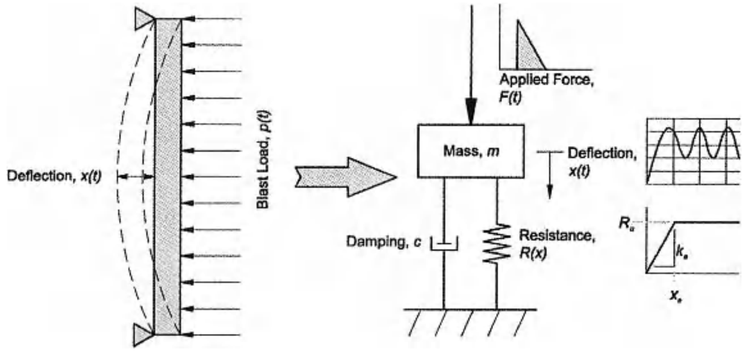

Figure 5.2. Equivalent Spring-Mass SDOF System

The resistance function of an SDOF mass-spring system is selected to replicate the load–deflection behavior of the real structure. The resistance function may be modeled as an elastic system, an elastic plastic system, a bilinear elastic-plastic system or an elastic-plastic with membrane system. An elastic-plastic system is defined by the resistance curve shown in the lower right portion of Figure 5.2. The resistance deformation functions for each of these systems are illustrated in Figure 5.3.

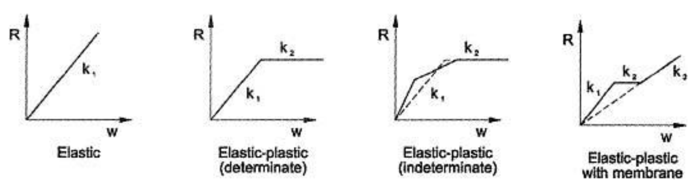

Figure 5.3. Alternative Resistance Functions

Structural components such as walls, windows, beams, doors, and panels will deform and respond dynamically when loaded with a blast pressure history *p(t)*. The SDOF model for each component (such as the column illustrated in Figure 5.2) is constructed using the component's physical structural properties (resistance function *R(x)*, damping *c*, and mass *m*) so that the model will exhibit the same displacement history *x(t)* as the point of maximum deflection in the component. The displacement history of the SDOF model is obtained with numerical integration techniques using a time-stepping computer program to solve the equation of motion of the equivalent system at discrete time steps.

For each component, an assumption must be made regarding the dominant response mode. In most instances—such as walls, beams, windows, doors—the static deflection curve (as shown in Figure 5.2) is the most appropriate to use, and provides a good approximation to the overall response, which may be a combination of several modes.

The properties of the SDOF system depend on the actual systems properties and support conditions. Once the SDOF analysis has been performed the response is compared to the component response criteria as discussed earlier. The documents cited in Table 5.1 provide numerical limits on the response.

The support reactions can be calculated from the SDOF models and compared to the connection and shear capacities of each component.

5.4.4.2 Multi-Degree of Freedom (MDOF) Systems

Theoretically, an MDOF system is any system with more than a single degree of freedom. In practice, it usually implies either a two or three degree of freedom system. The two degree of freedom (TDOF) is the most common and is discussed here.

There are many different types of TDOF systems. Unlike SDOF systems, the equations of motion for TDOF systems can have different forms depending on how the masses associated with the two degrees of freedom are supported relative to each other and how springs link the two degrees of freedom. TDOF systems consist of two structural components, where Component 1 is subject to dynamic load and is supported by Component 2. Component 2 is assumed to have rigid supports and to have no directly applied blast load. Both components must move in the same direction and must be assumed to respond primarily in the mode shape selected.

Examples of applicable TDOF systems are shown in Table 5.4. Several of these systems are illustrated in Figure 5.4 through Figure 5.7. Two examples of TDOF systems that do not meet the component support or deflection direction requirements above are shown in Table 5.5.

Table 5.4. Examples of Applicable TDOF Systems

TDOF System	Component 1	Component 2	Comments
Panel supported by beam	Panel	Beam	Panel mass is input for Component 1 and is not included in beam mass.
Roof beams supported by girder	Roof beams	Girder	Apply blast load or dynamic reaction from roof panels to beams. Include roof panel mass with beam.
Wall beams supported by column	Wall beams	Column	Apply blast load or dynamic reaction from wall panels to beams. Include wall panel mass with beam.
Blastward wall loading moment resisting frame in frame sway. Wall column is assumed rigid compared to beams.	Wall beams	Frame in sway response mode	Place blast load on beams or dynamic reaction from wall panels. Component 2 (i.e., frame sway) mass equals 100% of roof mass. Input blastward wall mass for Component 1 TDOF spreadsheet accounts for leeward wall mass equal to input blastward wall mass.

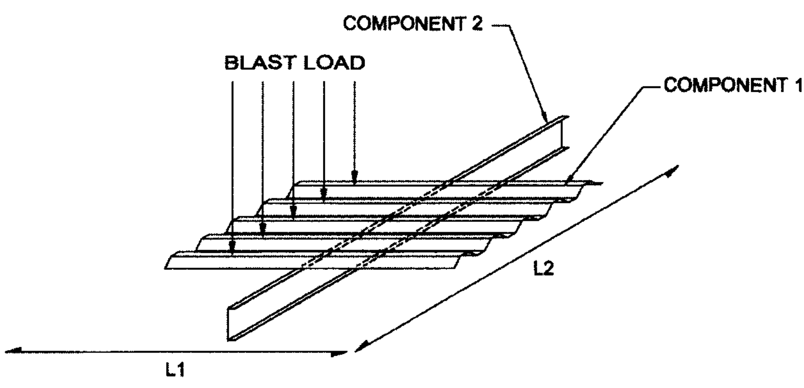

Figure 5.4. TDOF System with Panel Loading Beam

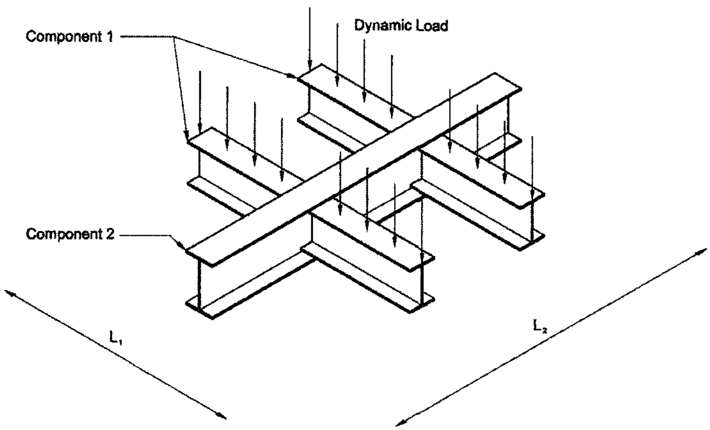

Figure 5.5. TDOF System with Two Beams Loading Girder

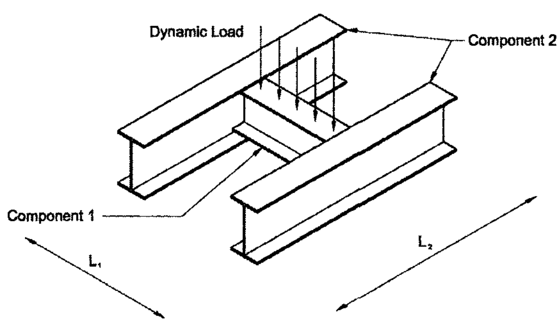

Figure 5.6. TDOF System with Beams Loading Girders at Midspan

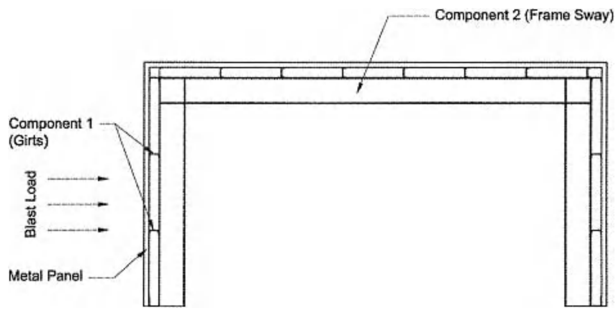

Figure 5.7. TDOF System with Girts Causing Frame Sway

Table 5.5. Examples of Non-Applicable TDOF Systems

TDOF System	Component 1	Component 2	Comments
Two story frame sway with rigid beams	First story beams and slab	Roof beams and slab	The first floor does not support the roof. The equations of motion for this system are described in Biggs (1964) on pg. 266 for a 3 story building.
Cantilever wall supported by slab	Cantilever wall	Slab	Wall and slab do not deflect in same direction. Cantilever wall moves in same direction as horizontal blast load but moment transferred from base of wall causes supporting slab to deflect in vertical direction.

The modeling of TDOF systems is discussed by Biggs (Biggs, 1964) and is typically performed using a spreadsheet or computer program.

5.4.4.3 Finite Element Analysis

The discussion provided above demonstrates the significance of the characteristics of the blast wave (peak pressure, duration) and of the structure (natural period, resistance, deformation ratio, or ductility) in evaluating the structural response to blast pressure loadings. As stated previously, these characteristics are applicable both for approximate response evaluation methods as well as for more rigorous techniques such as finite element response evaluation methods utilizing computer programs. Using the finite element method, the structural mass is typically represented as lumped concentrations at node points, with the structural stiffness or resistance represented as elements connecting the node points. Node points are assigned to locations throughout a structure where a significant change occurs in structural mass or stiffness or where deformation of the structure is to be computed. Certain node points are used to describe the boundary conditions for the structure (i.e., translation or rotation fixity in particular directions). The nodal coordinates that are free to displace each represent a degree of freedom for the structure, and an equation of motion may be developed for each degree of freedom. Types of elements include springs, beams, plates, and solids. The elements provide the resistance to relative movement between the degrees of freedom at one nodal point and those at the connected nodal point. The location of node points is determined by the analyst and is based on consideration of load distribution, real structure characteristics, and information required from the analysis.

For a finite element representation of a structure, loadings are applied at one or more degrees of freedom depending on the physical characteristics of the problem. Loadings may vary or remain constant as a function of time. For time-varying loads, the more general case solution of the equations of motion for displacements and stresses is obtained by solving the equation of motion in discrete time steps. Solutions are obtained by numerical integration in which the response from the previous time step is used as the initial condition for the time currently considered. In addition, the load function is updated at each time step. For nonlinear resistance functions, the element properties may also be modified at each time step to simulate inelastic behavior.

Two of the most widely used FEA codes for blast analysis of structures are LS-DYNA and ADINA.

LS-DYNA is a general-purpose finite element code for analyzing the large deformation dynamic response of structures, including vessels containing liquids where the liquids provide support to the vessel walls. The main solution methodology is based on explicit time integration, which is better suited for qualitative response estimates and is capable of handling less numerically stable problems. Many material models (more than 100 constitutive models and 10 equations of state) are available to represent a wide range of material behavior, including elasticity, plasticity, visco-elasticity, visco-plasticity, composites, thermal effects, and rate dependence. The code also has a host of contact algorithms.

ADINA is also used for solving a wide variety of problems in structural, thermal and fluid flow analysis. The code is capable of calculating the effects of material and response nonlinearities and is widely used within the structural community.

5.4.5 Identifying Limiting Factors

Structural components can undergo large deformations and sustain significant damage before they become debris hazards to building occupants. However, there are factors that can prevent components from reaching their full capacity, resulting in failure earlier than a ductile model will predict. Typically, the factors that limit the response of a component are:

- Shear capacity – A shear failure is a brittle failure and is thus to be avoided. The ASCE and COE references cited within this chapter have specific limitations on the use of large ductility ratios in cases where the shear capacity of a member may govern.
- Connections – Frequently, connections in existing structures are only designed to resist in-service loads. The large reaction forces generated by an explosion may overwhelm the connection or load it in a different direction.

5.5 OCCUPANT VULNERABILITY TO EXPLOSION HAZARDS

The purpose of assessing building response to potential explosion hazards is to assure the protection of the occupants. Hence, it is imperative that the analyst understand the nature of the response being calculated and the potential for injuries in light of the criteria selected. The correlation of building response and potential injuries has been highlighted through Chapters 3 and 4 of this book.

An alternative approach to estimating the potential for injuries is to explicitly calculate the injury mechanisms. These calculations require that the analyst be able to compute the response of the building, the potential for component breakup (including mass and velocity), the probability of the debris impacting an occupant, and the potential for an injury given that the impact occurs. Historically, these calculations have not been performed as part of a facility building siting evaluation. The prediction of component breakup and the subsequent debris impact on the human body is a relatively new field, and there has been significant progress recently on modeling the susceptibility of the body to blast and debris damage. Models to implement this approach may be available in the future.

5.6 ACTIONS REQUIRED AT THE COMPLETION OF THE EVALUATION

When a building siting evaluation has been completed, the next step in the siting process can occur. The next step depends on the results of the evaluation.

5.6.1 Results That Meet Criteria

When a building has been found to meet all the appropriate criteria established by the owner the analysis effort is complete. At this point the results are documented and periodically reviewed in accordance with the owner's policies to verify that there has been no change in conditions that warrant a re-evaluation. If there is a change (such as a modification to the scenarios or operating conditions) the evaluation is updated to reflect the change.

5.6.2 Results That Do Not Meet Criteria

When the results of the evaluation indicate that the building performance is unsatisfactory as compared to the pre-established criteria, the owner may either perform a refined analysis or implement mitigating actions.

5.6.2.1 Refined Analysis

Refined analysis may include either a more detailed structural assessment (potentially including a more intrusive field investigation to allow use of less restrictive assumptions) or a more detailed assessment of the potential blast loads. Simply redefining the criteria or scenarios considered is not a refined analysis. For example, performing an initial assessment with congested areas filled with a flammable mixture could be refined by conducting detailed discharge and dispersion modeling to determine flammable cloud size. However, simply deciding that a portion of the volume could be filled (with no supporting technical calculations) would not be considered a refined analysis. If the structure's performance meets the owner/operator criteria after the refined analysis, the actions discussed in Section 5.6.1 are implemented.

5.6.2.2 Mitigating Actions

Existing buildings that do not meet the owner's criteria will require a mitigation plan in accordance with RP-752. The mitigation may be the strengthening of the building, the reduction of the potential hazard, or the relocation of personnel to other buildings. Selection of the mitigation option may require an engineering study to evaluate the specific options including design and cost considerations. Mitigating actions under the consequence-based approach are limited to either making process or control changes to eliminate a governing scenario, removing the personnel from the building, or strengthening the building. Mitigation options available in the risk based approach include all of the options, the consequence-based approach as well as process or control changes that reduce the calculated frequency of occurrence of the hazard without totally eliminating it. Structural upgrades are addressed in Chapter 10.

6 FIRE HAZARDS ASSESSMENT

6.1 INTRODUCTION

When handling flammable or combustible material, the resulting consequences could involve fire. As with explosion and toxic effects, an owner/operator may choose to base a building siting evaluation using consequence-based or risk-based methods. In contrast to the other two effect types, it is also acceptable to use a look-up "spacing tables" approach for fire phenomena. Detailed assessments of the potential fire exposure and building response are typically only performed for buildings in, or very close to, process areas (where evacuation may be difficult) and buildings where the occupants may need to remain in place for an extended period of time.

It is not uncommon for explosions involving flammable or combustible materials to be followed by fire, increasing the potential effects to building occupants. If there is a significant potential for a fire to have been preceded by an explosion, the occupant vulnerability to fire should consider potential explosion damage which may compromise the building performance in protection against fire hazard.

Fire outcomes may be presented in units that describe a specific peak hazard level (e.g. thermal radiation in kW/m^2) or in units that can be related to a specific outcome of that radiation (e.g. thermal dosage translated to probability of fatality).

The building siting evaluation of fire hazards does not preclude the need to evaluate a given event for other outcomes of interest such as toxic properties, or explosion phenomena. In scenarios where multiple hazard types are present, the building siting evaluation should include the effects of each individual hazard and combinations of hazards.

A risk-based approach incorporates models that are suitable for a consequence-based approach. The spacing table approach uses established tables to determine minimum separation distances between equipment and buildings intended for occupancy.

The selection of the approach to use should be determined prior to starting the study. However, it is acceptable to perform a consequence-based or spacing table-based approach, and if the criteria are not met, to later refine the analysis with a risk-based approach.

6.1.1 Overview of Fire Phenomena and Sources of Information

In general, fires fall into the following categories:

Pool Fires. Pool fires involve flammable and combustible liquids processed at temperatures such that they remain in a liquid state with limited evaporation, and upon release will form a pool. These materials, which have the potential for pool fire upon ignition, include NFPA Class I flammable liquids such as gasoline, and NFPA Class II and Class III combustible liquids.

Jet Fires. A jet fire "is a turbulent diffusion flame resulting from the combustion of a fuel continuously released with some significant momentum in a particular direction or directions. Jet fires can arise from releases of gaseous, flashing liquid (two phase) and pure liquid inventories." [HSE, 2010a] Any flammable material and many combustible materials processed at elevated pressures may have the potential for a jet fire, depending upon the release conditions. If the processing pressures are low, and the building is sufficiently far away, little, if any, potential may exist for the building to be impacted by the jet flame.

Flash Fires. A flash fire is the combustion of a flammable gas/air mixture that produces a relatively short term thermal hazard with negligible overpressure (blast wave). In a flash fire the rate of combustion is essentially unchanged, or may increase slightly, during the event. In contrast, a VCE is distinguished by a flame front that accelerates due to the characteristics of the fuel and the turbulence that is generated as the flame front encounters obstructions.

Fireballs. A fireball results from releases that have limited mixing with air prior to ignition. The duration of the thermal exposure resulting from a fireball is significantly longer (seconds to tens of seconds) than the duration of a flash fire. Materials that can produce VCEs may also have the potential for fireballs, depending upon the release quantity and dispersion characteristics. A BLEVE involving flammable or combustible materials also produces a fireball.

The damage caused by fire may be due to direct flame contact or exposure to radiant heat. Fireballs are generally of very limited duration, and the amount of any building damage will increase with the level of heating and the duration of the exposure. The amount of damage will also depend on the building's materials of construction.

Potential fire damage to buildings can be mitigated by increasing separation distances between potential sources of hydrocarbon, applying fire proofing to the exterior of the building exposed surface, or by applying water sprays to cool exposed surfaces. Radiant heat does not have an immediate effect on most occupied buildings because they all have some fire resistance (to mitigate the effects of internal fires). Typical construction materials offering fire resistance include reinforced concrete, and reinforced or unreinforced masonry (with limited window space). Factory Mutual (1996, 2006, 2008) and Industrial Risk Insurers (IRI, 1991) provide information for fire protection and evaluation. There are limited sources of information for the purposes of building occupant protection, however. These are discussed in Section 6.3.

These are useful starting points when considering building location and protection. However, they may not be sufficient in quantifying the hazards in many situations. Methods for that purpose are described in the remainder of this chapter.

6.1.2 Overview of Assessment of Fires in a Building Siting Evaluation

The focus of this discussion will be based on the intent to protect building occupants, and not necessarily the building itself. In most process plant layouts, building occupants are exposed to a minimum of fire hazard either because the building is sited beyond the extent of fire hazards, and/or because escape is possible through an exit facing away from the hazard. However, in some cases it is possible for a building to have all its exits impaired, or there may be a requirement for staff to shelter-in-place during a fire for emergency response purposes.

An owner/operator may choose to use a spacing tables-based, consequence-based, or risk-based approach to evaluate fire issues, with the following caveats:

- If a spacing tables-based approach is used, recognized spacing tables such as those consolidated in the CCPS Guidelines for Facility Siting and Layout book are preferred.
- A consequence-based approach should be based on MCEs (Maximum Credible Event, see Chapter 3) with dispersion and thermal radiation levels quantified using rigorous mathematical approaches of the types described in various CCPS books.
- A risk-based analysis should be based on a range of scenarios with dispersion and thermal radiation levels quantified using rigorous mathematical models of the types described below.

API RP-752 provides an approach for quantifying and managing fire hazards (Figure 6.1). The steps in this figure are discussed in the following sections of this chapter.

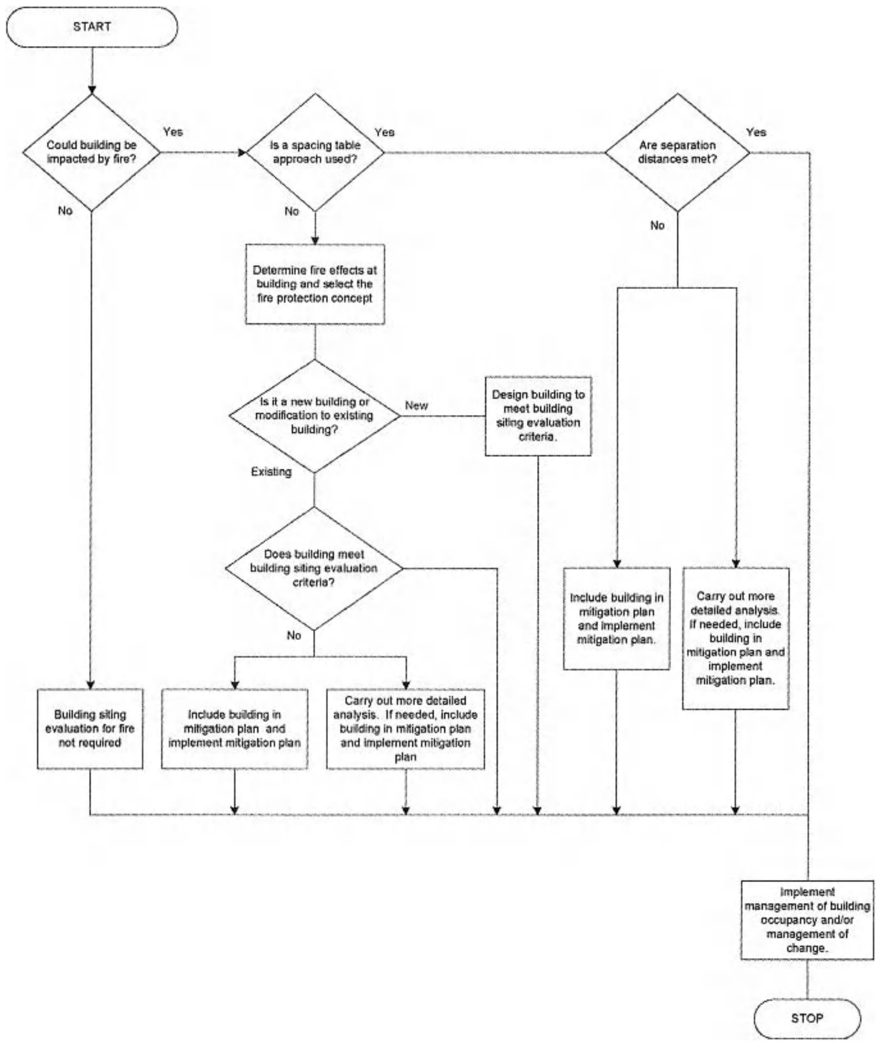

Figure 6.1. Logic Diagram for Evaluating Buildings for Fire Hazards

6.2 DETERMINING IF A FIRE HAZARD EXISTS

A building siting evaluation for fire is not necessary if it can be demonstrated that fire poses a minimal hazard to building occupants. This demonstration can be either qualitative or quantitative, but if qualitative, should explain the features that an external observer could appreciate as evidence that the fire hazard is minimal, e.g.:

- The materials at the site have minimal inherent flammability (e.g. combustible liquid handled at least 15°F below its flash point temperature, [API Publication 2218 (API, 1999)].
- The materials are present in quantities or pressures insufficient to result in a significant thermal exposure to a building.
- The material cannot be released as a flammable mist.
- The material is clearly located too far away to pose a significant exposure to a building.

Meeting these or similar criteria may not be sufficient to demonstrate a trivial fire hazard. In facilities where strong oxidizers are present (e.g. pure oxygen) normally non-flammable materials may be ignitable. The analyst should therefore not immediately dismiss fire hazards in cases where utilities or special chemical types are present that can present an unusual fire hazard. The look-up table, consequence-based and risk-based approaches are described next.

6.3 SPACING TABLE APPROACH

Spacing tables have been developed by various organizations to allow a quick review of whether fire hazards may be significant or not. A typical fire spacing table for on-site buildings is provided by CCPS in its facility siting and layout book (CCPS, 2003a), as shown on the next page. This spacing table was based on potential fire consequences, and explosion and toxic concerns may require greater spacing.

Variations in spacing may be warranted based on site-specific hazards and risks. Distances may be reduced or increased based on risk analysis or when additional layers of protection are implemented (such as: fire protection or emergency shutdown systems) based on a review of various major refining and petrochemical company spacing tables, insurance guidelines, historical spacing guidance, regulations, consensus standards and engineering experience. The intended use and limitations of the lookup table should be understood by the user of the table. For example, Table 6.1 is based on potential fire consequences in outside locations.

Table 6.1. Typical Spacing Requirements for On-Site Buildings for Fire Consequences in Horizontal Distance (ft) [CCPS 2003a]

On Site Building	Property Boundary	Utilities	Process Equipment	Main Pipe Racks	Process Unit Pipe Racks	Atmospheric & Low Pressure Flammable & Combustible Storage Tanks (up to 15 PSIG)		High Pressure Flammable Storage	Any Loading and Unloading Racks	
						<10,000 gals	>10,000 gals		Non-LPG and LFG	LPG and LFG
Office, Lab, Maintenance, Warehouse	NM	100	200	100	100	50	250	350	200	350
Fire Station, Medical Emergency Command Center	NM	100	200	100	100	100	250	350	200	350
Substation, Motor Control - Main	50	NM	200	100	100	100	250	350	200	350
Substation, Motor Control - More than one unit	50	100	50	25	25	100	250	250	200	250
Substation, Motor Control – One Unit	50	100	50	10	10	50	250	250	200	250
Control Room- Main	NM	100	200	100	100	100	250	350	200	350
Control Room - More Than One Unit	NM	100	100	30	100	100	250	350	200	350
Control Room – One Unit	NM	100	50	10	10	50	250	250	200	250
Satellite Instrument House - More Than One Unit	NM	100	100	30	100	100	250	350	200	350
Satellite Instrument House - One Unit	NM	100	50	10	10	50	250	250	200	250

1. The typical spacing distances are based on potential fire consequence (explosions, toxic, and security concerns may require greater spacing.) Variations in spacing may be warranted based on site-specific hazards and risks. Distances may be reduced or increased based on risk analysis or when additional layers of protection are implemented (such as fire protection or emergency shutdown systems.)
2. This table is not applicable to enclosed process units.

NOTES:
1. Distances are measured horizontally.
2. Typical horizontal distances between buildings, process equipment, and property lines are shown and apply to the closest edge to closest edge dimensions.
3 Where unusual conditions require closer spacing, appropriate risk reduction measures should be considered.

Sources of lookup tables or other specifications for building fire exposure include the following:

Table 6.2. Sources of Information for Protecting Buildings from Fires

Title	Comments
National Fire Protection Association. *Recommended Practice for the Protection of Buildings from Exterior Fire Exposures.* NFPA 80A. Quincy, MA, 2007.	General fire protection information for buildings.
American Institute of Chemical Engineers, *Guidelines for Facility Siting and Layout*, New York, NY.	Includes spacing tables for protection of buildings from fires.
Factory Mutual *Property Loss Prevention Data Sheets, 7-32 Flammable Liquid Operations, 2008.*	Includes spacing information for fire and explosion hazards (use of a lookup table for explosion hazards is not permitted in API RP 752).
Industrial Risk Insurers, *Engineering Standard for Layout and Spacing.*	Provides a variety of layout and spacing information, including spacing of buildings.

Some of these standards are designed to protect the building itself and only indirectly its occupants, and the level of exposure permitted for a building exterior is higher than the level to which a person inside the building would be exposed.

It is also acceptable for owner/operators to develop their own approaches. A company-specific standard may be more appropriate if unusual fire hazards (e.g. oxidizers) are present. If an owner/operator develops their own spacing table, the table should be based on existing lookup table(s) or on the quantifiable principles described later in this chapter (in which case the approach is considered to be "consequence-based").

6.4 PERFORMING A CONSEQUENCE-BASED OR RISK-BASED BUILDING SITING EVALUATION FOR FIRE

As per RP-752, any existing building intended for occupancy may be evaluated using a consequence-based or risk-based approach. To draw the distinction between consequence-based and risk-based approaches as applied to fires, consider the typical treatments of various process and environmental parameters in each type of study listed in Table 6.3.

These "typical" treatments may not always be the most appropriate. For example, if the MCE involves an abnormal reaction, the composition, pressure and temperature parameters may differ markedly from normal. Where the likely cause for a release involves abnormal conditions, it may be appropriate to consider those conditions in the analysis.

When performing a risk-based study, credit for specific elements within an existing fire hazard mitigation plan (e.g. containment systems, detectors, remotely-controlled isolation, firewalls) can be incorporated. The benefits may also be incorporated in a consequence-based approach to the extent that the mitigation measure has an inherent reliability that is equivalent to passive control (e.g. dike, firewalls) and is not vulnerable to any events that might defeat the mitigation measure. Examples of such events include as an explosion that damages the dike, a catastrophic tank failure that washes over the top of the dike, or a dike area drain valve that allows the dike contents to escape containment.

As demonstrated in Table 6.3, the additional effort required for a risk-based approach may provide tangible benefits in terms of being able to take credit for measures that cannot be as easily justified in a consequence-based study where non-passive active and procedural mitigation measures are assumed to fail.

Table 6.3. Risk-Based vs. Consequence-Based Fire Study Inputs

Process Parameter	Typical Treatment In: Consequence-Based Approach	Typical Treatment In: Risk-Based Approach
Composition	Assume typical composition, except in operations where there is a designed step in the operation in which a more severe condition is present.	Same
Pressure	Choose typical operating pressure, and assume that the pressure can be sustained after the release has begun. If it can be shown that the source pressure will drop during the event, a time-weighted average pressure may be used if thermal dose is the criterion.	Same. If it can be shown that the source pressure will drop during the event, a time-weighted average pressure may be used where thermal dose is the criterion.
Temperature	Assume typical operating condition.	Same. However, if an alternative pressure is assumed as per the row above, the temperature may need to be adjusted to reflect the depressured condition.
Available Flow / Inventory	Assume maximum normal inventory is available, and that initial release rate is sustainable. Release impact may be limited by passive measures only (e.g. limited pool size because of dikes).	Credit can be taken for systems in place for limiting the amount of a release, such as isolation valves, emergency dump systems, deluge/scrubbing, etc. In these cases, the mitigation measure is assigned a probability of failure so that generally both the failed and successful conditions are evaluated.
Event Duration	Assume the event continues indefinitely, or until the inventory is exhausted.	Event duration may be limited by isolation measures by taking into account the probability of success of the isolation and modeling the outcomes for both the successful and unsuccessful isolation cases.
Analysis Parameters		
Weather	Conservative meteorology applicable to fire type.	Probabilistic distribution of weather conditions.
Criteria	Building exposure criteria - Thermal flux - Flux and exposure time (dose) - Flammable gas concentration Consequence criteria - Occupant vulnerability	 Individual risk Aggregate risk

6.4.1 Modeling and Quantifying Fire Hazards

The scope of a building siting evaluation may include any or all of the following fire types:

- Pool fires
- Jet fires
- Flash fires and fireballs
- BLEVE (boiling liquid expanding vapor explosion) fireballs

Since the models for predicting the consequences of these fire types is discussed in detail in other references [e.g. CCPS , 2010], the analyst should refer to these other authoritative references. Following is a brief description of the key factors in analyzing each fire type, provided as an overview of the subjects and to provide guidance as to what variables fire models may incorporate.

6.4.1.1 Pool Fires

The thermal dosage (radiant energy absorbed over time) emitted from a pool fire on a specific target is primarily dependent on the following factors:

- Pool surface area
- View factor or proximity to target
- Duration that the pool fire is sustained
- The propensity of the fuel to produce a 'clean' vs. 'smoky' flame

Other factors (e.g. weather conditions) may also play a role.

Pool fires often take time to develop, allowing alarms and notifications for personnel evacuation in emergency response situations.

6.4.1.2 Jet Fires

The thermal dosage emitted from a jet fire on a specific target is primarily dependent on the following factors:

- Release rate of fuel
- View factor and proximity to target
- Duration that the fire is sustained
- The propensity of the fuel to produce a 'clean' vs. 'smoky' flame

There are some significant limitations to common fire models which the analyst should appreciate when determining the applicability of a particular model to a specific building siting situation. These include the following:

Flame Lift - Jet fire modeling is imperfect, with the models generally underpredicting observed flame lift after the point of origin. In this respect, the predicted heat flux and flame length will be conservative in situations where the jet is initially pointed directly at a building.

Flame Impingement/Engulfment Potential - Flame impingement is not treated in the standard jet fire models, and these models may significantly underpredict the thermal load on a building in the event of impingement [Cowley (a), (b), (c)].

6.4.1.3 Flash Fires

Since flash fires are transitory in nature they are generally neglected in evaluating hazards to building occupants. However, Ashe and Rew, 2003 have investigated the issue of flash fires and note the following potential effects of a flash fire that could pose hazards to building occupants:

- *Minor blast damage from the weak deflagrative effects of flash fires (window breakage etc.);*
- *Flame penetration into buildings (through open windows or doors, or those damaged by heat or blast effects)*
- *Gas ingress to buildings (particularly well-ventilated parts of buildings) producing internal explosions*
- *Radiative heat transfer to occupants through windows*

6.4.1.4 BLEVEs

The blast effects from a BLEVE were considered in Chapter 5; the thermal radiation effects are the scope of this discussion. Simple correlations exist for predicting BLEVE magnitudes [CCPS 2010, TNO 2005]. The level of radiation that is imparted to a building follows the same methods described for other fire types. Since the duration of BLEVEs is limited, fire impact may be limited.

6.4.1.5 Toxic Combustion Products

In addition to the thermal and radiation effects of a fire, toxic combustion products may be formed. The owner/operator may assess whether this is a significant additional hazard on a case-by-case basis.

6.4.2 Building Response to Fire Hazards

The effects of fire on people may be direct (thermal radiation) or indirect (building set on fire, building collapse). Discussed next is the effect of fires on buildings.

6.4.2.1 Effect of Fire on Buildings

The effects of fires on buildings are reported in various publications. Structural steel is said to lose half of its tensile strength at 500 °C, and steel will transmit heat from the building exterior to the interior quickly compared to other materials. Wood can ignite at temperatures as low as 150 °C for prolonged exposures, or at thermal radiation load of 5 kW/m^2 if pilot ignition is present. Glass softening and cracking can occur as well. Concrete/masonry fails due to spalling as opposed to softening, but the relationship with temperature is similar to that for steel.

Most of these effects are expressed in terms of temperature, whereas most models predict effects in terms of thermal radiation level. Converting thermal radiation to temperature for a typical multi-component structure is problematic because of the many variables at play, although TNO (1992) provides a basic heat balance approach for poorly-conductive materials such as wood and glass.

If the expected radiant heat load exceeds the capacity of the building materials to resist it, further evaluation may be appropriate. However, in most cases it is expected that by the time a building starts to fail due to thermal ignition or fatigue, the building occupants have already evacuated or have been exposed to unacceptable thermal exposure.

Another issue is the use of blast resistant modules (BRMs) to mitigate explosion hazards, generally for the purpose of allowing staff to remain close to or inside a unit with a significant blast hazard. While protecting against explosions, locating BRMs inside operating units exposes the occupants to fire hazards, perhaps more so than before BRMs were widely used.

6.4.3 Calculation of Internal Temperature Risk

6.4.3.1 Energy Absorption by the Building

Because of complexities that are typically encountered, the heat transfer from the exterior to the interior of the building is usually not modeled rigorously. Rather, estimates are based on general characteristics of the fire and the occupied building.

To estimate how the interior temperature in a building increases with time, where valid, it can be assumed that there is no break in the building's integrity, either through broken windows, open ventilation, building catching on fire, etc. In this case, all thermal hazards to building occupants result from energy absorption by the exterior of the building, which is then transmitted to the air within the building. Even this is usually a complicated situation to model, since energy absorption through structural support members may be different than through walls. However, simple heat transfer methods may provide sufficient rigor to perform this calculation in some situations.

6.4.3.2 Occupant Vulnerability to Fire

Occupant vulnerabilities to fires are usually tabulated and, as with other hazard vulnerabilities, is expressed as a probability of between 0 (no vulnerability) to 1 (certain impact). Table 6.4 and Table 6.5 are examples of occupant vulnerability tables for fires. Table 6.4 describes the cases where there is an extended exposure (e.g. pool or jet fire), and presumes the ability to estimate the thermal load. Table 6.5 simply describes a fire exposure in terms of the potential presence or absence of a flammable gas cloud. Note that these tables are provided only as examples to illustrate the form and possible values associated with such tables. Each situation is different and will likely require different forms/values.

Table 6.4. Example Building Occupant Vulnerability (OV) from Radiant Heat Levels on Building Exterior from Pool and Jet Fires

Building Type	Thermal Radiation Level 1	Thermal Radiation Level 2	Thermal Radiation Level 3
Conventional Building Construction	OV = 0, for maximum thermal radiation load (TRL) < "X" BTU/hr-ft^2	OV = f(TRL), for maximum thermal radiation load of "X"-"Y" BTU/hr-ft^2	OV = 1, for maximum thermal radiation load > "Z" BTU/hr-ft^2
Fire-Resistant Building Construction	OV = 0, for maximum thermal radiation load < "X1" BTU/hr-ft^2	OV = f(TRL), for maximum thermal radiation load of "X1"-"Y1" BTU/hr-ft^2	OV = 1, for maximum thermal radiation load > "Y1" BTU/hr-ft^2

Table 6.5. Example Occupant Vulnerabilities Inside Buildings for Ignition Outside Buildings

Concentration at Building Perimeter	Occupant Vulnerability	
	"Normal Building Construction"	Building with Gas Detection/Shutdown Features
> LFL	1.0	0.1[(a)]
< LFL	0	0

(a) Assumes gas detection, etc. designed to Safety Integrity Level (SIL) 1 equivalent.

More detailed versions of Table 6.5 may be appropriate for other situations: for example, (a) warehouse buildings with many openings, (b) buildings with/without gas detection and manual HVAC shutdown, (c) short-term vs. long-duration gas clouds.

Criteria such as those in Tables 6.4 and 6.5 imply a certain limit to the duration of the radiation. The algorithms described in these tables will not be appropriate for all situations. BLEVEs will, by definition, have a limited duration; pool and jet fires may continue for some minutes or even hours.

If the temperature inside the building can be modeled, the resolution of the predictions can be improved, since correlations exist for the effect of elevated temperatures on people (TNO Green Book, 1992). Building temperature vs. time predictions can also be based on wall heat transfer models assuming perfect mixing of the interior air, or using computational fluid dynamics models.

6.4.3.3 Potential for Direct Fire Ingress to a Building

Not accounted for in simple models is the potential for the building integrity to be compromised. Direct entry of thermal radiation and combustion products may occur through any of the following means:

- "Designed" openings: e.g. open warehouse doors
- Forced draft: e.g. HVAC
- Natural draft: normal 'breathing' through walls, cracks, seals
- Penetrations
- Incident-induced cracks: e.g. cracks in masonry due to thermal expansion of steel support beams

It is probably not practical to try to model all these situations. However, their potential should be considered as part of a building siting evaluation and a building design program.

6.5 OCCUPANT RESPONSE TO FIRE HAZARDS

If process plant buildings are constructed of fire-resistant material, there is generally time for occupants to evacuate if escape routes are available. One important consideration in fire evaluation is the fact that fire has the potential to impact building occupants through products of combustion such as smoke and carbon monoxide. Properly designed ventilation systems may prevent smoke or products of combustion from entering the building. For further guidance, the reader is referred to various NFPA and SFPE publications. This topic is discussed further in Chapter 7.

It is generally assumed that building occupants will evacuate in response to a threatening fire condition, assuming there is a safe means of egress from the building. Experience shows this is not necessarily the case. In addition, some emergency plans call for some staff to remain in the building to prevent escalation of the emergency, if there is assurance that continued occupancy is safe. These issues are discussed next.

Many studies have been performed on human response to fires; however the vast majority of these studies are with respect to fires inside the building, not external fires. Since the latter situation is of interest here, there is limited work upon which to draw conclusions.

One can expect that occupants of a PSM-covered facility would be more knowledgeable about fire hazards, have had fire/emergency drills, etc. resulting in behavior better than the cited cases. Nonetheless there is some probability of a building occupant not following the prescribed protocols.

6.5.1 Relevance of Training and Drills – Human Reactions

The response of people to a potential escape situation has probably been quantified most often in offshore oil and gas production facility risk assessments. Behaviors in these facilities are consistent with assumptions about the benefit of training and drills in reinforcing "familiarity" with an escape plan. They also suggest that there is a potential for people to escape via a more "familiar" route, even if there is a hazard present along that route. This implies the need to either be certain that the escape plan uses a route that is always safe, or (a) emphasizes the need to assess the escape route hazards prior to escaping and (b) provides for alternatives.

DiMattia (2005) worked on this question for offshore facilities. This study relies on expert opinion and general human error protocols, much more so than actual incident data (thankfully, such data are rare). The SFPE Handbook of Fire Protection Engineering (SFPE 2008) also provides useful guidance on this subject.

6.6 DEFINING THE FIRE PROTECTION CONCEPT

Before performing assessments or new building design, the intended strategy for building occupancy should be defined. RP-752 lists two options:

- Shelter-in-place for fire
- Evacuation for fire

The choice will be reflected in the site emergency response plan, new/revamp building design and escape plan. It may also be incorporated in the consequence and impact modeling discussed earlier.

6.6.1 Evacuation Considerations

The most obvious considerations for evacuation from an occupied building that is exposed to a fire are the following:

- Ability to quickly and safely exit the building
- Ability to quickly and safely move from the building area to an area that is not exposed to the fire

A building siting evaluation study may make reasonable assumptions about the ability of people to escape from a building exposed to fire based on the building escape paths, plant layout and the apparent potential sources of fires in the proximity of the building. These assumptions should be verified with the local operating staff and emergency planning personnel to ensure they are valid.

Table 6.6 and Table 6.7 describe some thermal radiation exposure limits that appear in two standards that can be considered when evaluating a fire evacuation path. Note that there are notes associated with the original version of Table 6.7 that should be reviewed from the source document.

Table 6.6. Recommended Design Total Radiation (from API RP 521)

Permissible Design Level (K)		Conditions
British Thermal Units per Hour per Square Foot	Kilowatts per Square Meter	
5000	15.77	Heat intensity on structures and in areas where operators are not likely to be performing duties and where shelter from radiant heat is available (for example, behind equipment)
3000	9.46	Value of K at design flare release at any location to which people have access (for example, at grade below the flare or a service platform of a nearby tower); exposure should be limited to a few seconds, sufficient for escape only
2000	6.31	Heat intensity in areas where emergency actions lasting up to 1 minute may be required by personnel without shielding but with appropriate clothing
1500	4.73	Heat intensity in areas where emergency actions lasting several minutes may be required by personnel without shielding but with appropriate clothing
500	1.58	Value of K at any location where personnel with appropriate clothing may be continuously exposed

Notes:

1. On towers or other elevated structures where rapid escape is not possible, ladders must be provided on the side away from the flare, so the structure can provide some shielding when K is greater than 2000 British thermal units per hour per square foot (6.31 kilowatts per square meter).
2. Solar radiation contribution varies by geographical location and is generally in the range of 250 to 330 BTU/hr/ft^2 (0.79 to 1.04 kW/m^2)

Table 6.7. Allowable Thermal Radiation Flux, Excluding Solar (from EN 1473)

Equipment Inside Boundary	Maximum Thermal Radiation Flux (kW/m^2)
Concrete outer surface of adjacent storage tanks [a]	32
Metal outer surface of adjacent storage tanks	15
The outer surfaces of adjacent pressure storage vessels and process facilities	15
Control rooms, maintenance workshops, laboratories, warehouses, etc.	8
Administrative buildings	5

[a] For pre-stressed concrete tanks, maximum radiation fluxes may be determined by alternative methods.

The heat flux level can be reduced to the required limit by means of separation distance, water sprays, fireproofing, radiation screens or similar systems.

6.6.2 Impact to Operations

In siting a new building, or in evaluating the siting of an existing building, it is relevant to note the exposures to which a building may be subjected, and whether any people in the building are expected to or would feel compelled to stay in place during a fire in order to protect the plant operations. This question leads to two outcomes:

- If a building occupant is expected to stay in place, the building should be designed to handle all the credible exposures including provision of clean air to occupants – both with respect to protecting the occupants and with respect to continuing to perform the process or emergency functions controlled from the building if they are critical.
- If a building occupant is expected to evacuate in a fire emergency, the building should either be designed to allow safe operation during the emergency period, or to allow an automated, orderly shutdown. Ideally, the building also has systems in place to prevent major damage in the absence of staff.

A building siting evaluation should describe the policies with regards to evacuation vs. sheltering in place for buildings that are routinely occupied. These policies should be reviewed with the actual building occupants to verify that they are credible.

7 TOXIC HAZARDS ASSESSMENT

7.1 INTRODUCTION

In this chapter, the impacts of acute toxic releases on building occupants are considered. These impacts may be described in terms of a specific concentration of interest (e.g. ERPG-3) or in terms of a specific outcome (e.g. probability of fatality). RP-752 provides a logic flow path for quantifying and managing toxic hazards with buildings (Figure 7.1). The steps in this figure are discussed in the following sections of this chapter.

This chapter is not exclusive of the requirements in the other chapters. There are a number of chemicals materials that are both toxic and flammable, and on occasion a flammable event may result in toxic combustion products that have a greater impact than the fire that generates them. In cases where multiple hazards are present, all hazards should be considered unless it can be shown that they have minor effects.

A consequence-based or risk-based approach can be used for building siting evaluation for toxic material release. A risk-based approach should utilize models suitable for a consequence-based study.

7.2 DETERMINING IF A TOXIC HAZARD EXISTS

If it can be demonstrated that a significant toxic hazard does not exist to building occupants, a building siting evaluation for toxics is not required. This demonstration can be qualitative, and can include an explanation of the following features that an external observer could appreciate as demonstrating no significant toxic hazard:

- The materials at the site have minimal inherent toxicity (e.g. NFPA health hazard rating of 0, 1 or 2)
- The material is incapable of forming a hazardous toxic vapor concentration upon release.
- The materials are present in small quantities that cannot present a toxic vapor hazard at occupied buildings (either due to low concentrations or limited amount of time that the concentration is present).

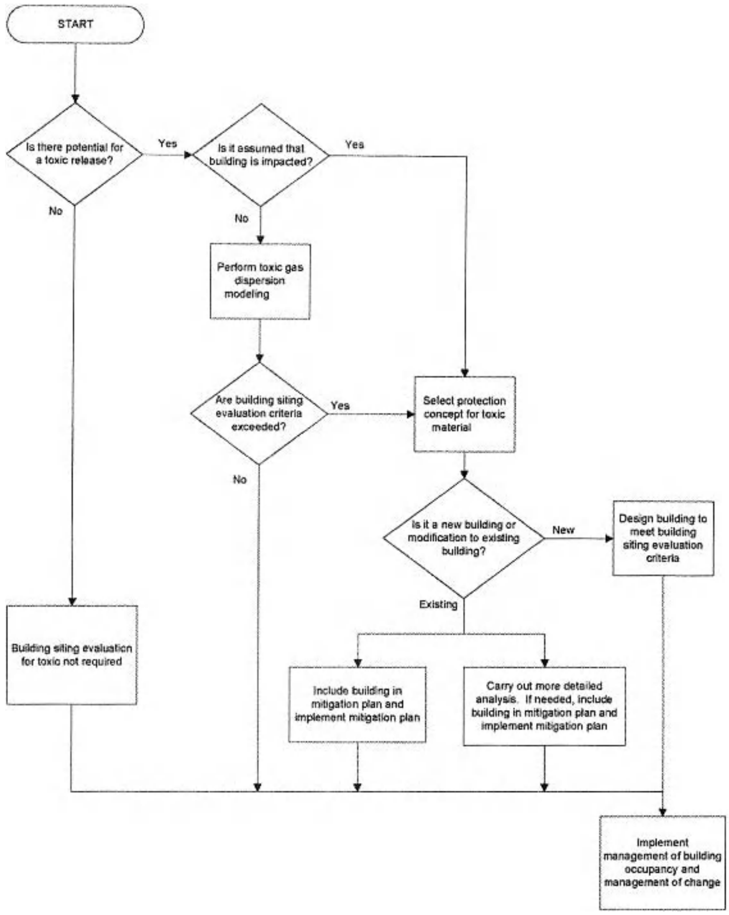

Figure 7.1. Logic Flowpath for Evaluating Toxic Risk to Occupied Buildings

The owner/operator may consider whether there are any non-toxic materials on the site that could generate hazardous amounts of toxic products in the event of a fire or other chemical reaction. Generally these issues will not be addressed within the building siting evaluation since:

(a) The toxic exposure from fire will generally be less than the fire exposure for building occupants

(b) Mixing of incompatible chemicals is managed by means other than building siting (e.g. administrative rules regarding separation between incompatibles)

If a toxic hazard is present, but is believed not to be significant, the absence of a significant hazard to building occupants can be demonstrated through use of a dispersion model. References for appropriate dispersion models are discussed later in this chapter.

The threshold for determining "significance" of an impact at a given building can be based either on an external concentration of interest that could impair escape (e.g. IDLH or ERPG-3), or toxic concentrations inside the building if it is planned that the building occupants will shelter in place.

To document that there is no significant toxic impact, the scenario basis (e.g. MCE), model name or description, input assumptions (release temperature, pressure, etc.) and the results of the dispersion modeling should be included in the building siting evaluation.

7.3 BUILDING SITING EVALUATION FOR TOXICS

As per RP-752, any existing buildings intended for occupancy and having a toxic exposure that exceeds the criteria set by the owner/operator should be included in the building siting evaluation for toxic material release, and a mitigation plan should be developed to address the issue.

To draw the distinction between consequence-based and risk-based approaches as applied to toxic material releases, consider the typical treatments of various process and environmental parameters in each type of study as shown in Table 7.1.

Table 7.1. Risk-Based vs. Consequence-Based Toxic Study Inputs

Process Parameter	Typical Treatment in:	
	Consequence-Based Study	Risk-Based Study
Composition	Assume typical composition, except in operations where there is a designed step in the operation in which a more severe condition is present.	Same
Pressure	Choose typical operating pressure, and assume that the pressure can be sustained after the release has begun. However, if it can be shown that the source pressure will drop during the event, a time-weighted average pressure may be used if the inventory is limited.	Same. However, if it can be shown that the source pressure will drop during the event, a time-weighted average pressure may be used.

Table 7.1, continued

Process Parameter	Typical Treatment in: Consequence-Based Study	Typical Treatment in: Risk-Based Study
Temperature	Assume typical operating condition.	Same. However the temperature may need to be adjusted if there is a depressured condition, as per above.
Available Flow / Inventory	Assume maximum normal inventory is available, and that initial release rate is sustainable. Release impact may be limited by passive measures only (e.g. limited pool size because of dikes).	Credit can be taken for measures for limiting the amount of a release, such as isolation valves, emergency dump systems, deluge/scrubbing, etc. The control is assigned a probability of failure, and both the failed and successful conditions are evaluated.
Event Duration	Assume the event continues indefinitely, or until the inventory is exhausted.	Event duration may be limited by isolation measures, similarly to the entry in the previous row.
Analysis Parameters		
Endpoint for Analysis	Concentration-based endpoint representing a significant exposure (e.g. ERPG-3, IDLH), not taking into account the event duration.	Not applicable. The 'threshold' is the lower limit of the impact of interest (e.g. 1% probability of fatality).
Weather	Conservative meteorology. Select windspeed, direction temperature, humidity, stability and ground roughness factor resulting in maximum dispersion range (e.g. Pasquill Stability F, 1.5 m/sec wind speed).	Probabilistic distribution of weather conditions.
Criteria	Building exposure criteria - Toxic concentration - Toxic concentration and time (dose) Consequence criteria - Occupant vulnerability	Individual risk Aggregate risk

Credit for specific elements of the facility's toxic hazard control and mitigation systems (e.g. containment systems, detectors, remotely-controlled isolation, deluge/dilution systems, siting buildings based on prevailing wind data) can be incorporated in a risk-based toxic approach. The mitigation measures may also be incorporated in a consequence-based approach, to the extent that the mitigation has an inherent reliability that is equivalent to passive control (e.g. dike for reducing vaporization of a liquid toxic material) or passive mitigation (e.g. tightly sealed building to minimize toxic material ingress) and is not vulnerable to any events that might precipitate the toxic release (e.g. an explosion).

The additional effort required for a risk-based study approach may provide tangible benefits in terms of being able to take credit for measures that cannot be as easily justified in a consequence-based study where active and procedural mitigation protection measures are assumed to fail. Also, an owner/operator may utilize a toxic impact (probability of fatality) output for their consequence-based criteria, thus incorporating the event duration. This needs to be done with care, since in the case of toxics the impact is not necessarily greatest for the largest-sized releases (for a given inventory), since the event duration is less. A consequence-based study should select the release conditions that result in the highest impact – which, again, may be different than the release conditions resulting in the highest concentration.

Once the approach has been selected, it remains to perform the building siting evaluation for toxic material release in a defensible manner. This is the subject of most of the remainder of this chapter.

If there is a reasonable belief that the amount of toxic material(s) onsite could impact all buildings to the owner/operator's threshold of interest, then modeling is not necessary. For example, the consequences of a MCE involving release from a chlorine rail car likely does not need to be modeled to determine the impact, since it is likely to exceed any consequence-based criteria. In such a case the owner/operator can simply acknowledge this and move forward to hazard management without performing consequence modeling. Subsequent modeling may or may not be appropriate to validate the effectiveness of the hazard management strategy that is chosen.

The "typical" treatments described in Table 7.1 may not always be the most appropriate. For example, if the MCE involves an abnormal reaction, the composition, pressure and temperature parameters may differ markedly from normal. Where the likely cause of a release involves abnormal conditions, it may be appropriate to consider those conditions in the analysis.

7.3.1 Modeling and Quantifying Toxic Hazards

For both the consequence-based and risk-based approaches it is necessary to select an appropriate consequence model that can estimate the release source term and appropriate dispersion (Gaussian, Heavy-gas, etc.) phenomena to the desired end-point. Criteria for selecting and utilizing consequence models are described next.

7.3.1.1 Selection of Consequence-Based Models

There are a large number of models or combinations of models that can be used for a building siting evaluation of toxic material release [CCPS 2000, Taylor 1994, TNO Purple Book, 2005]. In order to satisfy the requirements of RP-752, the following attributes are desirable:

- Use of a model that incorporates variables that are recognized by experts in the field as being important such as release temperature, hole size and meteorological conditions. It is not necessary for the model to be based directly on fundamental principles – a correlation-based approach is also permissible. However, where a 'non-fundamental' approach is used, it ideally either: (a) incorporates directly or indirectly the relevant variables, or (b) makes conservative assumptions about variables that are not explicitly mentioned in the model.
- The model selected is appropriate for the material type and release conditions. For example a heavy gas dispersion model is not appropriate to calculate dispersion distances for pressurized lighter-than-air releases at elevated height and ambient temperatures.

The details of discharge and dispersion models are amply described in the references cited in this chapter and are not repeated here. These models apply equally for both toxic and flammable cloud dispersions.

7.3.1.2 Process Limitations

In some cases the initial release rate from a loss of containment event can be sustained indefinitely. In other situations, the rate at which material can be released through a hole may be limited after a (possibly short) time by the surrounding process. Examples include:

- Inventory – If the available material is exhausted after some period of time, this should be taken into account in the model. This is particularly true for toxic events, since their impacts are directly related to the duration of the exposure.
- Pump/compressor capacity – Frequently a leak will be fed by an upstream pump or compressor. If the initial predicted leak rate is greater than the capacity of the pump/compressor, the line may quickly depressure until it reaches a steady-state condition where the release rate equals the pump/compressor capacity at that reduced pressure. The analyst should consider whether the initial rate or the steady-state rate is the more appropriate basis for modeling.
- Flow control valves – If a leak occurs downstream of a flow control valve, the valve should automatically act to limit the release if the instrument driving the valve is located upstream of the release.
- Pressure drop in piping – For larger releases such as pipe ruptures, the release rate may be limited by the pressure drop in the line.
- Emergency isolation devices or de-inventory systems – Such systems can be used to dramatically limit the duration of an event in some cases.

There is a distinction between the consequence-based and risk-based studies approaches in taking credit for the limits described in the bullets above, however. In general, a consequence-based approach (Maximum Credible Event) will assume that active and procedural control measures will fail, whereas a risk-based study approach can take credit for such measures. Exceptions may be present for consequence-based toxic material releases if it can be shown that the release is immediately constrained by physical limits (e.g. (a) line blowdown; (b) maximum flow point on a pump curve, where flow backwards from downstream of the leak source is negligible).

Other Limits

The magnitude of an event outcome may be limited by other infrastructure containment systems such as a dike or drainage to a sump. A dike is useful in constraining the location of a release; it is also likely to reduce a toxic (or flammable) cloud size by limiting the surface area over which a volatile chemical can vaporize. Dikes are high-integrity safeguards, and in most cases can be assumed to function without fail. However, it should be pointed out that in the most catastrophic events (instantaneous tank rupture) a dike may fail to contain the material released either partially (e.g. due to either overwashing of waves) or completely (i.e. or due to hydraulic forces), even if the dike containment volume is sufficient to contain the entire tank contents.

7.3.1.3 Measures of Toxic Exposure

It is recognized that the impacts of a toxic material exposure on an individual depend on both the concentration of the chemical and the duration of the exposure. This time-dependence is sometimes ambiguous, as in the following definitions of measures commonly used to express toxic hazard effects:

Immediately Dangerous to Life and Health (IDLH) – "An atmospheric concentration of any toxic, corrosive or asphyxiant substance that poses an immediate threat to life or would cause irreversible or delayed adverse health effects or would interfere with an individual's ability to escape from a dangerous atmosphere."

Emergency Response Planning Guidelines, Level 3 (ERPG-3) – "the maximum concentration in air below which it is believed nearly all individuals could be exposed for up to one hour without experiencing or developing life-threatening health effects."

Of course, definitions of terms such as "life threatening" are subjective and ambiguous as well. For many chemicals, an exposure of several hours at IDLH or ERPG-3 concentrations is required for a healthy individual to become a fatality. Therefore the analyst is cautioned not to "compare apples and oranges" when assessing the relative hazards of toxic and fire or explosion outcomes at a site. That is, an explosion may result in building damage that can be correlated to a probability of fatality, whereas ERPG and IDLH cannot.

Probits

In a risk-based approach the predictions for toxic gas dispersion *impacts* are generally based on a more rigorous principle using probits. In this approach, biological response to toxic gases is described by a normal distribution, indicating different susceptibility of individuals. This distribution is transformed to a linear form by a "probit" equation, typically of the following form:

$$Y = a + b \times ln(C^n t)$$ **Eqn 7-1**

Where Y is the probit value, *a*, *b*, and *n* are constants, *C* is the concentration of the chemical (in molar ppm or mg/m^3), and *t* is the time of exposure (in minutes). The coefficient *n* is related to the mechanism of toxicity on the body organs affected by a given chemical. The normal distribution is adjusted in the probit form to a midpoint of Y = 5 corresponding to a 50% probability. Values of Y of interest are 2 and higher, corresponding to a probability of fatality on the order of 1% or more.

7.3.1.4 Sources of Toxicology Data

Probit Constants

CCPS and TNO (CCPS 2000, TNO 1992) publish some widely-used probit constants for some of the more common toxic chemicals. The value of the probit equation can be converted to a probability of fatality using a standard table provided in these references.

HSE

Probit equations are only available for a limited set of the most commonly-used toxic chemicals. A much more extensive list of toxic chemical characteristics has been prepared by the Health and Safety Executive (HSE, 2011) in the UK. The HSE uses two levels of impact, "SLOT" and "SLOD". These terms have several definitions, most notably:

SLOT (Specified Level of Toxicity) – "Highly susceptible people possibly being killed"

SLOD (Significant Likelihood of Death) – "50% mortality in exposed population"

There is no direct comparison between the HSE data and the other approaches, but the results seem consistent. The HSE values can be used as a basis for estimating probabilities of fatality for the broader range of chemicals in the HSE list.

There is no specified method for converting a SLOT/SLOD form into a probit form in order to facilitate interpolation or extrapolation from the SLOT/SLOD values to other impact magnitudes. Therefore, if SLOT/SLOD data are used for impact levels other than those SLOT/SLOD definitions, the basis for doing so should be described by the analyst.

Department of Homeland Security

The U.S. Department of Homeland Security is investigating the area of toxic dosage/impact relationships and has released quantitative values for a limited number of chemicals [Famini et al. 2009].

7.3.1.5 Lookup Table Format

A simpler alternative is to use a lookup table. Use of such a lookup table should be based on a combination of research-based principles (e.g. probits) and expert judgment (to assess the reliability of the safety systems in place, and presumed behavior by the people being exposed). An example is the EPA's Risk Management Program consequence modeling guidance document.

Lookup tables are appropriate for use in risk-based studies if they incorporate the benefits of non-passive protections. Therefore, it is preferable for sites to develop their own tables based on their specific circumstances, given that the table:

- Does not take credit for non-passive protection measures (for consequence-based studies)
- Is based on dosage principles – that is, takes into account both concentration and duration of exposure (for risk-based studies)
- Takes into account the rate of air changes in a building through mathematical methods. However, for consequence-based studies, a worst-case ventilation assumption (e.g. assume maximum air changes during the release) should be made unless it can be demonstrated that there is a very high probability that the ventilation will be adjusted as desired during the event.
- Gives results that err on the conservative side.

7.3.2 Building Design for Occupant Protection from Toxics

7.3.2.1 Toxic Ingress to a Building

Estimating the Concentration/Time Profile

As a toxic cloud envelops a building, the concentration of the chemical inside the building will start rising from zero, reach some maximum, and then drop as the cloud passes. Since the impact of the exposure depends on the concentration/time relationship, it is important to have a reasonable estimate of what this relationship is.

All buildings are somewhat porous; air intrudes through open windows, cracks around doors and windows, and through the HVAC (heating, ventilating, and air conditioning) system. The ventilation rate is defined in terms of the number of air changes per hour (ACH). The minimum value of the ventilation rate with the HVAC turned off varies with wind speed, typically between 0.1 and 2 ACH as measured by Wilson, (1996). However buildings with open doors, such as many warehouses, may have on the order of 6 ACH. Additional forced ventilation may be provided for process areas with possible toxic gas leaks.

A building with good mixing has a time-dependent indoor concentration, $C_{in}(t)$ forced by the time-varying external concentration, C_{ext} (t) as illustrated in Figure 7.2 for 2.0 ACH. The response to an outdoor concentration idealized as a square wave is a first-order decay (exponential) increase, followed by a decrease.

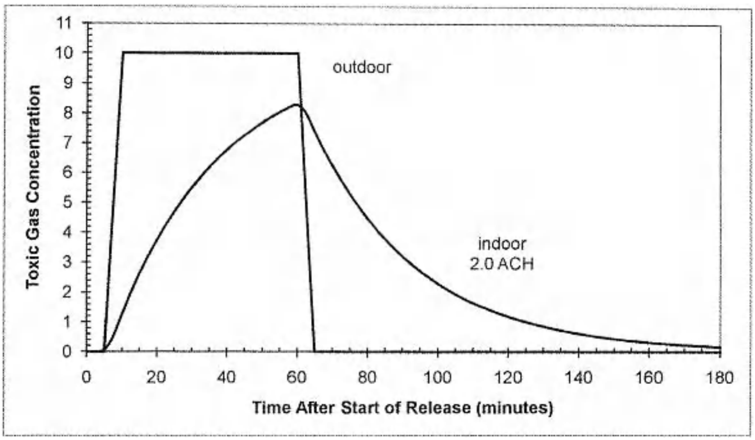

Figure 7.2. Indoor and outdoor mean concentration for a very leaky building with 2.0 air changes per hour during a 66 minute outdoor release event (Wilson, 1996)

If needed, more sophisticated models that take into account air intake locations, air flow patterns within the building, etc. can give more precise exposure predictions to individuals at specific locations within a building. Often this level of precision is not necessary, since the error in assuming a perfect mixing condition may not be that much different than the level of precision in the probit equation for a given chemical.

Event Progression and Aftermath

For hazard management as well as dosage calculation, it is important to know when the exterior toxic cloud has passed. Once the cloud has passed, the concentration in the building will start to drop, but the rate at which it drops depends on the actions of the building occupants. If the building's HVAC is shut off in the toxic event response, the concentration buildup during the exposure to the cloud is lower. However, if the cloud has passed and the HVAC is still shut off, the toxic concentrations within the building will persist much longer than if the HVAC is restarted and fresh air is forced through the building. For this reason it is important that there be some mechanism by which the building occupants learn when a toxic cloud has passed.

Modeling Implications for Linear Dosage

Figure 7.2 represents the usual approach to modeling indoor concentration. Note that Figure 7.3 illustrates that in the long run the integrated total linear dosage (the area under the curves) may be equal for indoor exposure and outdoor exposure. In this case a leaky indoor shelter is only advantageous if people move outside, or if they open windows and doors after the toxic cloud has passed.

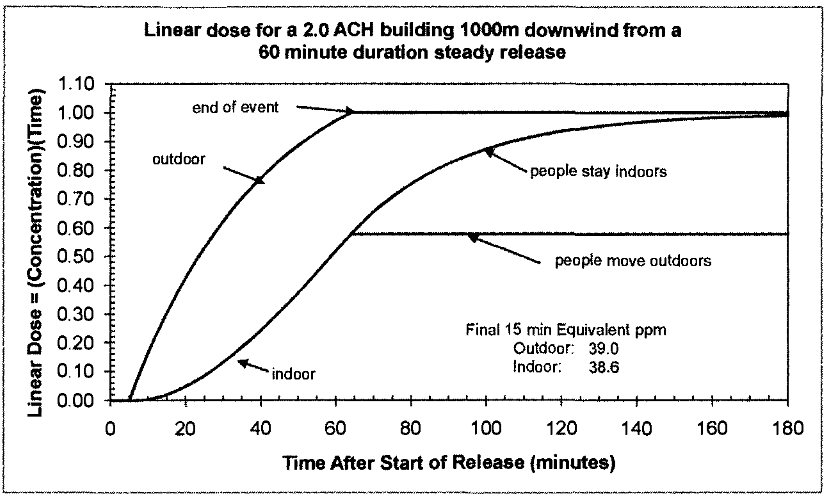

Figure 7.3. Comparison of linear dosage for three sheltering policies (Wilson and Zelt, 1990)

Figure 7.3 also shows that moving outside after 66 minutes would result in about half the dose that people would get if they were outdoors for the entire event. But, since people outdoors would almost certainly complete an evacuation to safety in less than 30 minutes, sheltering-in-place does not seem to be the best alternative for this situation.

The implications of these plots for emergency response (e.g. providing building occupants with the information they need to know when the toxic cloud has passed) are apparent. There are other complications to this mathematical treatment, also discussed in Wilson and Zelt. The National Institute for Chemical

Studies have documented a number of case studies demonstrating the value of sheltering in place [www.nicsinfo.org/index.asp].

7.4 DEFINING THE TOXIC PROTECTION CONCEPT

7.4.1 Strategy for Building Design and Occupancy

The intended strategy for building occupancy during an emergency is defined. The owner/operator selects one of the two following options:

- Shelter-in-place for toxic material release
- Evacuation for toxic material release

The choice will be reflected in the site emergency response plan, new/upgraded building design and escape plan. It may also be incorporated in the toxic gas dispersion and occupant vulnerability modeling discussed in the next sections.

7.4.2 Selection of Strategy to Implement

Selecting between shelter-in-place and evacuation involves estimates of how quickly a release can be detected and personnel notified and actions taken. In general, not all buildings need to be designed for or designated as toxic shelters. However, consideration needs to be given to the amount of time it will take to detect a release and notify affected staff, and for the staff to take the appropriate action of moving to a safe location. Thus toxic management includes not only elements of building design, but also leak detection, emergency warning system and training.

7.5 EVACUATION VS. SHELTERING-IN-PLACE

7.5.1 Attributes of Shelter-in-Place Strategy

The principles for evacuation/shelter-in-place are similar to those described for fires with respect to the relevance of training, understanding human behavior and the potential impact to operations. Of course, toxic events are qualitatively different in several respects as well. The following are important considerations, excerpted from RP-752:

"Shelter-in-Place for Toxic Materials Release

When the "shelter-in-place for toxic materials release" concept is chosen, owners/operators should consider providing the following features for each building intended for occupancy:

- *HVAC systems capable of shutdown of the system or placement in recirculation mode, whichever is more appropriate;*

- *systems to notify occupants of external material release;*
- *emergency communications equipment (telephones are acceptable);*
- *PPE as necessary;*
- *seals for windows, doors, and penetrations.*

The performance requirements for these features may be designed/assessed based on:

- *length of time personnel are required to remain in the building;*
- *length of time that the toxic material impedes escape from the building; or*
- *appropriate industry standards, guidelines and practices.*

Some materials are both toxic and flammable. A toxic exposure could precede or follow a fire or explosion. The building siting evaluation should consider potential explosion damage, which may compromise their performance as a shelter-in-place for toxic material release."

Consideration needs to be given to the amount of time it will take to detect a release and notify affected staff, and for the staff to take the appropriate action of moving to the shelter and ensuring it is secured (e.g., shutdown of HVAC system, closing/sealing doors and windows). Note that the people to be notified may be outdoors, occupants of another building, or occupants of another part of the same building. Thus protection of personnel from toxic material release includes not only elements of building design, but also leak detection, emergency warning system and training.

Whether an existing building can be designated for shelter in place for toxic material release is largely determined by the air tightness of the building. Testing for the air changes per hour with the HVAC turned off can be done by releasing a tracer gas such as sulfur hexafluoride inside a closed building and monitoring the decay of the tracer gas concentration. Performing this test over a range of external wind speeds is preferred.

Note too that an entire building does not need to be shelter-qualified. In fact, there are several advantages to having a specified "shelter within a building", including:

- Economics of designing a smaller space for high integrity.
- Protection from other aspects of the event, such as a precursor explosion, that could compromise the integrity of the main building.
- Ease of accounting for personnel.
- Centralized communications with the rest of the plant.

Other features are also likely to be beneficial. These include the ability to monitor toxic concentrations in the HVAC inlet or inside the building, providing air bottles to maintain positive pressure while the HVAC is shut down and more. Note that credit for these measures can be taken as part of a risk-based assessment, but not for consequence-based studies except to the extent that they are passive measures with no significant probability of failure, including the probability of failure as a result of the event or precursor event (e.g. explosion damage).

There are occasions when a building may be exposed to a toxic hazard after some precursor event that has compromised the building's integrity. Perhaps the most common example of this is exposure to toxic combustion products from a fire that follows an initial explosion that damages the building. More serious variations involve knock-on (domino) effects from an explosion resulting in a loss of containment of a toxic inventory. In such a case, the original basis for the shelter-in-place strategy (that the building has a certain level of 'tightness' or air change rate) may not be valid, since the event that led to the toxic release could also result in loss of building integrity.

7.5.2 Attributes of Evacuation Strategy

RP-752 also addresses some basic features of an evacuation strategy:

"Evacuation for Toxic Material Release

When the "evacuation for toxic material release" concept is chosen, owners/operators shall provide the following emergency response features for each building intended for occupancy:

- *emergency action procedures and training that will facilitate evacuation;*
- *emergency exits and safe evacuation routes;*
- *evacuation plan that directs personnel to a designated "shelter-in-place" or specified assembly area;*
- *means to warn building occupants to the presence of a toxic material release;*
- *plan to account for occupants;*
- *PPE as necessary for scenario potential exposure."*

Another factor that owner/operators may wish to consider qualitatively is that during evacuation there is an increase in inhalation rate and physical activity. Values tabulated by Withers and Lees (1985) show that people who attempt to walk out of a plume have two to three times the inhalation rate of people at rest.

7.5.3 Strategy for Leak Detection

Unlike fire and explosion consequences, there may be no obvious indications that a toxic release has taken place. For this reason it is important for the analyst and the risk management manager to evaluate thoughtfully how, and how quickly, a toxic release will be detected.

Some materials have an odor threshold, well below toxic or flammable concentrations of concern. In those cases, odor may be the most reliable way to detect releases. Automated detectors have improved over the years, but many automated detectors will register more than one material. This can result in repeated false alarms when trying to detect low level concentrations. Some ethylene oxide sensors, for example, also detect carbon dioxide. When a low level of ethylene oxide detection is attempted, numerous false alarms can result in an industrial setting.

In some cases, detection near the potential release source may be more reliable than detection at the building air inlet because detectors near the source can be set to alarm at a more reliable (higher) concentration level. Also, detectors have varying levels of reliability which can be taken into account in determining whether, or how much, credit should be given for them.

A strategy for leak detection may or may not be sophisticated, depending on the chemicals to be detected, unit layout, personnel location and more, and may include a combination of point vs. perimeter detectors. A useful reference on this subject is the CCPS book on Continuous Monitoring for Hazardous Material Releases (CCPS, 2009a).

For existing buildings, the emergency response plan may be to adopt the shelter in place concept for a set of scenarios (e.g. where a toxic release occurs and there is no damage to the building) and the evacuate concept for another set of scenarios (e.g. where the building integrity is compromised). For a new building it may be possible to design the building such that its integrity for use as shelter-in-place is not compromised by (for example) VCEs with the potential to cause toxic material release.

Guidelines for Evaluating Process Plant Buildings for External Explosions, Fires, and Toxic Releases, Second Edition
by Center for Chemical Process Safety

8 FREQUENCY AND PROBABILITY ASSESSMENT

8.1 INTRODUCTION

The previous five chapters of this book explained how to determine the scope of a building siting evaluation, the process for selecting criteria, and the methods available for determining the potential consequences associated with explosive, fire, or toxic hazards. For owners/operators who elect to use a consequence-based approach, those chapters provide the technical basis for completing the building siting evaluation. However, for owners/operators that choose to undertake a risk-based approach, another piece of information is required, and that is the frequency at which the explosion, fire, or toxic release scenarios may occur.

For risk-based building siting evaluations, the frequency of each modeled scenario may consider factors such as:

- Frequency of initial release
- Probability distribution of the quantity and location of the release
- Probability of ignition (for explosion and fire hazards)
- Probability of atmospheric parameters (wind direction, atmospheric stability)
- Probability of failure/success of each layer of protection passive, active and procedural mitigation measures.
- Probability of a specific outcome

The terms "frequency" and "probability" are defined in the glossary. The essential distinction is that frequency is reported on a "per unit time" basis whereas probability is dimensionless. And hence "Risk" is a combination of consequence and *frequency* rather than consequence and *probability*.

The application of these factors is illustrated in Table 8.1 for two explosion scenarios: (1) a VCE and (2) a level control valve failure that allows gas blow-by from a high pressure system to a low pressure system. For a VCE to develop, the fuel must be released and form a flammable cloud. The frequency of the release may be calculated by assigning frequencies to the various failure causes identified in Table 8.1 or estimated from data that integrates all sources. The size of the cloud is determined by the process release conditions (e.g. temperature, pressure, and available inventory or maximum flow capacity) and whether or not there are active systems present (such as shut off valves) that may limit the size of the release. The development of the frequencies is discussed in Section 8.3. As the cloud is formed, the wind and inertial forces carry it either toward or away from a specific building and into or away from areas of congestion and confinement. The weather conditions and potential for ignition are frequently modeled probabilistically, but once the direction is selected and ignition occurs, the resulting energy and severity of the explosion, building damage, and occupant vulnerability are calculated deterministically as described in Chapter 5.

For the gas blow-by case, the entry of high pressure gas into a low pressure system may result from a single failure (level control valve stuck open). If there is not enough capacity in the low pressure system to absorb the high pressure gas flow, then the only other failure required may be the failure (or undersizing) of the relief valves in the low pressure system. Once the event (the bursting vessel) occurs, all the downstream consequences are modeled deterministically using the methodologies identified in Chapter 5.

Table 8.1. Simple Illustration of Factors Used to Determine Explosion Frequencies

A Few Examples of Initiating Events	Size of Release	Probability of Ignition	Factors Affecting Severity of Explosion	Type of Hazard
Pipe leak • Pipe struck by equipment • Corrosion failure • Material incompatibility • Vibration Valve Leak Valve left open (human error)	Hole size Line Size Upstream Pressure Liquid (that flashes) versus vapor flow Isolation equipment does or does not operate Rate of depressurization Temperature	Presence of competent ignition sources • No ignition (no fire or explosion) • Immediate ignition (fire only) • Delayed ignition (Potential VCE)	Presence of congestion and/or confinement	VCE
Gas blow-by/ vessel burst	Not applicable	None required	Determined by the vapor space and burst pressure of the vessel that fails.	Vessel burst

The situations can be more complex. In the case of a runaway chemical reaction, it may not be practical to provide the theoretical relief capacity required for the runaway condition, in which case high integrity process controls are generally in place. The failure of these controls may result in either a vessel burst and/or a VCE from the released reactor contents.

This approach describes the typical process for quantifying frequencies of outcomes of individual release scenarios, which are then aggregated with all other release scenarios to determine overall outcome frequencies. It is also possible to utilize historical incident data at the unit level using company or industry data for similar units for this purpose, and some operators take this approach. This is discussed further in Section 8.2.2.

8.2 DEVELOPING A SCENARIO LIST

8.2.1 Individual Source Based Approach

The first step in determining the frequency of various types of scenario outcomes is to determine what initiating failures can contribute to such outcomes. Initiating events can be described either generically (i.e. a failure occurs, but its causes are not identified), or by situational analysis (i.e. an event occurs because of a specific failure or combination of circumstances; failure occurs due to a specific failure mechanism). Either approach can be appropriate, assuming that frequency data exists or can be developed to support the analysis. Regardless, the analysis must explicitly (situational analysis) or implicitly (generic analysis) consider the range of events that could result in the negative outcomes. Following is a list (which is not exhaustive) of possible scenarios for chemical processing facilities:

Typical initiating events included in generic data

- Overpressure of a process or storage vessel caused by loss of control of reactive materials or external heat input
- Release due to corrosion
- Opening of a maintenance connection during operation
- Pump seal failure, valve stem packing leak, flange gasket leaks, etc.
- Stress corrosion fracture of a process vessel, causing release of contents

Typical initiating events which may require situational derivation of the frequency

- Overpressure of a process or storage vessel caused by loss of control of reactive materials or external heat input
- Opening of a maintenance connection during operation
- Excess vapor flow into a vent or vapor disposal system
- Breaking off of a small-bore pipe such as an instrument connection due to dropped object
- Drain or vent valve inadvertently left open

Appendix A of the CCPS CPQRA book, Guidelines for Chemical Process Quantitative Risk Analysis (CCPS, 2000) presents other potential scenarios. The frequency of each of these events may be difficult to quantify individually, particularly since they may be manifested across a wide range of hole sizes. This complexity is the reason risk analysts often use databases which present failure frequencies for release of a range of hole sizes from various types of piping and equipment due to unspecified (generic) failures (e.g. ¼-inch hole, 2-inch hole, line rupture).

The use of generic failure data is perfectly acceptable as long as the analyst is confident that:

- there are no unusual sources of failure that would result in a frequency higher than a generic failure rate would suggest;
- the source of generic failure data incorporates all the relevant failure causes (there are some databases that specifically exclude some failure causes such as operator error);
- the frequencies that are available are appropriate to the range of piping and equipment, and range of failure sizes, that need to be considered for the hazard being evaluated;
- the database is the most relevant available (e.g. nuclear-based data vs. process industry data).

8.2.2 Scenario Outcome Based Approach

In a scenario outcome based approach, it is assumed that an event takes place, without identifying the source events that contribute to that outcome. An approach in this case, using a VCE example, is to assume that all the congested volume of a process unit can be filled with flammable gas and then ignited.

The combination of unit-level consequences and unit-level frequencies may result in very conservative risk values since the outcome (e.g. "worst case" explosion) is typically paired with a frequency that includes scenarios that are less severe than the "worst case." However the method does provide a risk result with somewhat less effort than that required for the individual source approach.

When performing a study using the scenario outcome based approach it is important to be sure that risks are not underestimated by neglecting smaller scenarios than what the assumed "worst case" considers. This is particularly true for toxic releases – since the impact of a toxic discharge is dependent on the duration of the release, smaller releases may pose more hazard/risk than what an observer might assume to be the "worst case." This caveat also applies to flammable releases, since the (usually) greater frequency of smaller scenarios may offset the high impact of larger scenarios when performing the risk calculation. For this reason, analysts will often pair a "high magnitude" scenario with a smaller one (e.g. Considine and Hall, 2009).

8.3 CALCULATION OF FREQUENCY OF INITIATING EVENT OR ACCIDENT

Several methods may be used to estimate the frequency of an initiating event or accident, including:

1. use of historical data available from inside the company or site,
2. use of historical data available from outside the company,
3. prediction by calculating the frequency of a combination of contributing causes,

or some combination thereof, each of which is discussed next. A key message is that the dataset used, wherever it comes from, needs to be understood so that it is not misapplied. Significant errors can be introduced into the risk assessment if the analyst does not understand the basis of the source frequencies, and can be the biggest error that can be made in risk assessments.

8.3.1 Use of Company Historical Data

In this method, the site or company has collected information regarding the history of failures of a certain equipment type and/or the history of incidents on its process units, and applies that knowledge to developing the frequency estimate. This type of data reflects the standards of design, maintenance, and operations that are specific to the site or company, and so in that respect is the most desirable data possible. Unfortunately, use of site/company data alone is often not sufficient for the purposes of a risk assessment for the following reasons:

- There may not be enough data available from a single site or company. This is generally a function of whether enough operating-years of experience and incidents have taken place. For high leak frequency items there may be sufficient site/company data, but major failures are rare.
- The data is incomplete (not all incidents have been reliably recorded, or have not been recorded using a consistent set of definitions).
- The equipment/process units to which the data is to be applied may be qualitatively different in service type to the equipment on which the data was collected.

It is possible to overcome each of these objections.

In the first case, limited but quality plant data can be combined with more statistically-significant general industry data using statistical methods such as Bayesian mathematics (e.g. CCPS, 2000; Gelman, 2004, TNO, 1997) to develop an event frequency estimate that incorporates plant history and is still statistically significant.

The second case requires developing a rigorous plant/company data collection process. The methods for developing such data have been previously described in the CCPS book "Guidelines for Improving Plant Reliability through Data

Collection and Analysis" (CCPS, 1998) that is the basis for an ongoing data collection committee within the American Institute of Chemical Engineers (the Process Equipment Reliability Database [PERD]). Less rigorous but acceptable data collection methods and taxonomies can be adopted from reliability data sources such as OREDA (2002).

The last bulleted case on the previous page is a difficulty shared by almost all data sources – finding a statistically significant failure frequency for equipment that may be designed, installed, maintained, and almost inevitably has an operating history different from any other equipment item in the world. Perhaps the most widely-used method for accounting for all these variables is via the risk-based inspection (RBI) methodology developed by the American Petroleum Institute (API 2000, 2002) and several commercial firms. However, the output of RBI is not precisely in the form desired for a risk-based facility siting assessment, so use of RBI for this purpose is discouraged except by subject matter experts in both RBI and quantitative risk assessment (QRA).

8.3.2 Use of Historical Industry (Generic) Data

Because of the limitations described in the previous section, initiating event/accident data will usually be adopted from one of the many failure rate/accident databases in the public and private domains, some of which are listed in Table 8.2.

These data sources can have their shortcomings, typically including:

- The data is not site-specific, company-specific, or in some cases even process industry-specific.
- The sources have ill-defined or inconsistent definitions of a leak.
- The data is "generic" in the sense that the failures are not described in terms of particular causative mechanisms. Thus the source database may include failures that do not apply to the situation at hand, or conversely may undercount events resulting from a failure mechanism that is important to the equipment at hand.
- Incident descriptions are often misleading (e.g., fires are often incorrectly described as explosions).

For these reasons it is best not to depend on a single source of data, but rather to assemble the available data sources and select some combination of them that are most applicable to the site's operations. Where available, it is also advisable to examine raw data rather than an analysis of the data.

Table 8.2. Some Commonly-Used Equipment Failure Rate Databases

Subject Type	Reference	Comments
General sources:	[These should be consulted for all equipment types]	
General	Rasmussen, 1975	30+year-old data used for assessing nuclear plants. But still a cited, seminal work.
General	Lees (Mannan, 2005)	The process risk analysis "bible." Relatively up-to-date, but still cites much older material by necessity.
General	CCPS, 1989b	An initial effort at a chemical process industry database. Unfortunately it was not progressed, and has limited data as a result.
General	IEEE, 1983	Contains data on a variety of systems, for a variety of failure modes; but nuclear-based.
General	OREDA, 2002	Covers equipment types of interest, offshore industry based.
General	E&P Forum, 1996	A compendium of onshore, offshore, shipping and other failure rates.
General	TNO Red Book, 1997	A widely cited source, although superseded by the next source.
General	RIVM Bevi dataset	Recommended failure frequencies for use in safety reports in the Netherlands. Reference Manual Bevi Risk Assessments version 3.1 - Introduction 01-01-2009. This document (http://www.rivm.nl/milieuportaal/images/Reference-Manual-Bevi-Risk-Assessments-version-3-2.pdf) is an update to the TNO Purple Book. RIVM is the research institute supporting VROM – the Dutch Regulator for external safety.
General	Flemish Govt. Handbook, Failure Frequencies for Drawing up a safety report, 2009	Recent publication that includes several equipment types not covered in other databases. This dataset is mandated for use in Seveso case risk assessments in Belgium.
General	HSE (FRED), 2010b	Publicly-available information has been recently updated
General	HCRD, 2009	UK HCRD dataset for UK North Sea process facilities. UK HCRD has 4000 fully documented leak incidents from a known population of facilities. High quality data, but includes some incidents that are normally not considered in risk-based studies (e.g. small spills from properly isolated equipment during maintenance).

Table 8.2, continued

Subject Type	Reference	Comments
Additional equipment-specific sources:		
Pressure vessels	Smith and Warwick, 1981	A widely-quoted source. Unfortunately, the data is limited, and include pressure vessel applications that may or may not be of interest to general process industry analysts.
Storage tanks	OGP, 2010	Recently released directory of storage incident frequencies from the International Association of Oil & Gas Producers.
Compressors	Bloch and Geitner, 1994	Includes a number of reliability modifiers that can be used to customize an analysis. Emphasis is on on-stream reliability, as opposed to leaks.
Cross-country pipelines	DOT (Keifner, 1996)	Largest database of US pipeline data
General	Office of California State Fire Marshal, 1993	Provides detailed analysis of variables affecting leak rates
Pipeline	Muhlbauer, 1999	Not data, but a useful reference work describing the many factors that can influence pipeline leak rates.
Pipeline	CONCAWE (Lyons, 1998)	European pipeline data source
Pipeline	EGIG, 2008	European gas pipeline data source
Truck/Rail transporters	U.S. DOT Traffic Safety Facts, 2002	Information is available on the web from the U.S. Department of Transportation statistics.
Shipping	FEMA, 1989	Provides a risk assessment protocol, with numbers, for shipping hazardous materials.
	CCPS, 1995a	Methods and data for conducting transportation risk assessments.
Human error	NUREG (Swain, 1983 and Embrey, 1984)	The primary works in this area, but focused on the nuclear industry.
	SPAR-H NUREG/CR-6883 (Gertman, 2005)	The SPAR-H human reliability analysis method. NUREG/CR-6883. Idaho National Laboratory, prepared for U. S. Nuclear Regulatory Commission.
	CCPS, 1994b	Good subject overview.
Accident Data		
	Marsh (2009)	Provides accident data. Population data can be obtained from other sources (e.g. Oil and Gas Journal for number of operating refinery process unit)
	Gertman, 2005	Overall loss prevention source that includes an appendix containing summaries of many major incidents that have taken place worldwide.
	Mannan (2005); CSB (2002)	A mainly statistical review of past reactive chemical incidents.

The data is generally provided on a 'per item' basis (e.g. per vessel-year, per foot of pipe per year), and so the raw frequencies are multiplied by the item inventory that is exposed to the particular scenario being modeled.

8.3.3 Prediction by Quantifying Contributing Causes

Fault Tree Analysis (FTA)

The earlier approaches are usually applied to "generic" loss of containment events whose cause is not considered or reported in the data. However in some cases a "generic" approach is not appropriate, for reasons including the following:

- The controlling failure cause is not a "common" (e.g. corrosion) failure mechanism, but rather is specific to the process being studied. An example is a vessel burst due to a runaway reaction or release from a specific operation e.g. breaking containment operations such as filter removal, sampling, draining loading/unloading road tankers etc.
- The event is a "planned" failure. An example is lifting a relief valve or rupture disk that discharges directly to the atmosphere.

In both of these there are multiple contributors to the failure – for example, a cooling water pump to a reactor jacket fails, the backup pump fails to auto start, and the emergency reaction 'kill' chemical fails to be added in time, resulting in a runaway reactor condition.

Unless the event occurs regularly enough for statistically-significant amounts of data to have been collected (one hopes not), an approach such as fault tree analysis can be useful in developing a reasonable estimate of the frequency. Fault tree methodology and nomenclature are described in many sources [e.g. NUREG-0492 (U.S. Nuclear Regulatory Commission, 1981) and Guidelines for Chemical Process QRA (CCPS, 2000)]; an example from the latter is shown in Figure 8.1.

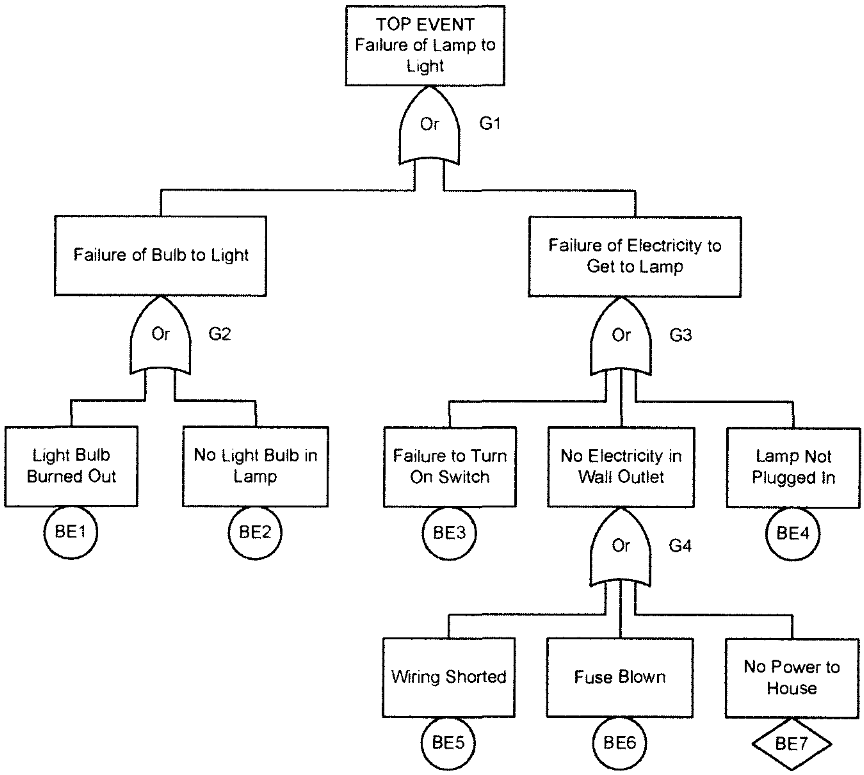

Figure 8.1. Fault Tree Example

In principle, it should be possible to quantify each branch of the fault tree using a combination of public data sources, plant history and expert judgment. It is likely that a crude estimate of the frequency has been determined by a Process Hazards Analysis (PHA) team, in which case the team's estimate should be compared with any calculated value as a 'reality check.'

Fault trees can be valuable for reasons beyond the building siting evaluation application; traditionally they are used to highlight the most important contributors to a potential failure and hence, identify those components in the fault tree that are most worthy of attention (maintenance, testing). In recent years, there has been a renaissance of fault tree work in the process industry as a result of Safety Instrumented System evaluations.

In any case, when employing the fault tree methodology it is important to have some means of calibrating the accuracy of the tree. This is because each input to the tree presents some level of uncertainty, which in the aggregate can result in significant deviations from reality. Often there are one or more "top events" that have happened at a site or in industry that can be used as a point(s) of reference for a quantified fault tree, after taking into account any differences between the design and operation. It is noteworthy that the "top events" themselves are typically uncommon enough that they are not statistically significant as "data" for that event, but yet have great value in validating fault trees.

Failure Modes and Effects Analysis (FMEA)

FMEA, and the closely-related Failure Modes, Effects and Criticality Analysis (FMECA) are methods that are typically used to evaluate the reliability of specific components of a system such as a compressor. The goal in this example is to construct a failure frequency from the bottom up, by scrutinizing all the ways in which the compressor could fail (e.g. seal or bearing failure) and quantifying the failure frequency of each of these components.

The origins of this approach include the U.S. military, which is described in military documents (USDOD, 1974), or, more readily, in public sources such as Wikipedia.

A partial example of FMECA output is provided in Figure 8.2; the form shown here is just one of many layouts commonly used for these studies.

Layers of Protection Analysis (LOPA) and Safety Integrity Level (SIL) Analyses

This approach, described in detail in the CCPS LOPA book (CCPS, 2001) may be applied either to estimating the frequency of an initiating event and/or to the frequency of the outcome, depending on whether the protective measures that are in place apply to preventing the cause or to control or mitigate its consequences.

In the most common forms of this method, a given protection layer is assigned an order-of-magnitude estimate of its probability of success in preventing the undesired outcome. Thus a "SIL 1" protection has at least as reliable as probability of failure on demand (PFD) = 10^{-1}, and "SIL 2" has PFD $\leq 10^{-2}$ per demand. An example of LOPA/SIL study output from the CCPS LOPA book (CCPS, 2001) is provided in Figure 8.3.

Since the estimates are often only order-of-magnitude in precision, their main utility in the context of a risk-based facility siting study is that they are values for typical protective measures that are widely accepted and in the public domain.

System: Truck loading flexible hose connection

Component	Potential Failure Mode	Potential Effects	Potential Causes/Mechanisms	Current/Planned Controls	Severity	Likelihood	Notes
Fittings (fixed)	Leak/rupture	Release to atmosphere (same for all events except as noted)	Degradation (corrosion, etc.)	Leaks are visible. Failure mode is not likely to be rupture. Deluge exists for small leaks.	A	4	
	Leak/rupture		Replacement with incorrect part	Expectation is that only the hose itself will be replaced with regularity, and parts as needed.	A	3	Assumption about controls may not be true if proposed idea of welding all connections is adopted.
	Leak		Fitting not tightened properly		C	3	Possible to use torque wrench to ensure consistent tightening?
Check valve	Fails to seat on demand	Large release from truck would continue unabated.	Collection of deposits and liquid acid has been observed in this service in other facilities.		A	3	Consider performing functional testing of check valves at some interval. Determine response if check valve fails.
Hose connection to truck	Leak/rupture		Hose not tightened properly, in worst case not tightened at all because of distraction during activity.	Two people are present to check connections are made properly. System is pressure tested with nitrogen prior to opening to process.	A	3	Possible to use torque wrench to ensure consistent tightening?
	Pinhole leak		Reused old O-ring to make connection.	Plentiful supply of O-rings to be made available.	D	2	
	Modest / moderate leak		Connection made with no O-ring in place.	This should be obvious during pre-load pressure test.	C	3	

Figure 8.2. Failure Modes, Effects and Criticality Assessment Example

Scenario Number 2a	**Equipment Number**	**Scenario Title:** Hexane Storage Tank Overflow. Spill not contained by the dike.	
Date:	**Description**	**Probability**	**Frequency (per Year)**
Consequence Description / Category	Release of hexane outside the dike due to tank overflow and failure of dike		
Risk tolerance Criteria (Category or Frequency)	Action Required Tolerable		$>1 \times 10^{-3}$ $<1 \times 10^{-5}$
Initiating Event (typically a frequency)	Loop failure of BPCS LIC.		1×10^{-1}
Enabling Event or Condition		N/A	
Conditional Modifiers (if applicable)			
	Probability of Ignition	N/A	
	Probability of personnel in affected area	N/A	
	Probability of fatal injury	N/A	
	Others	N/A	
Frequency of Unmitigated Consequence			1×10^{-1}
Independent Protection Layers			
	Dike (existing)	1×10^{-2}	
	SIF (to be added – see Actions)	1×10^{-2}	
Safeguards (non-IPLs)	Human action not an IPL as it depends upon BPCS generated alarms. Cannot be used as BPCS failure is initiating event (Approach A)		
Total PFD for all IPLs		1×10^{-4}	
Frequency of Mitigated Consequence			1×10^{-5}
Risk Tolerance Criteria Met? (Yes/No): Yes, with added SIF.			
Actions Required to Meet Risk Tolerance Criteria	Add SIF with PFD of 1×10^{-2} Responsible Group/Person: Plant Technical / J. Doe June 2002 Maintain dike as an IPL (Inspection, maintenance, etc.)		
Notes	Add action items to action tracking database.		
References (links to originating hazard review, PFD, P&ID, etc.):			
LOPA analyst (and team members, if applicable):			

Figure 8.3. LOPA Example

8.3.4 Factors that May Indicate Failure Rates Different than Standard Values

One of the shortcomings of using "generic" failure rate data is that such data is not application-specific. This can be frustrating to the owner/operator because mathematically-speaking, there is no incentive to provide improved designs, maintenance/inspection or other programs that would lower the risk because it cannot be demonstrated that the frequency has, in fact, been lowered through, for example, increasing the frequency of inspections or improved training. The risk assessment may need to be refined provide this justification, where an objective basis for the adjusting the frequency can be obtained or derived.

The following factors may be considered when determining failure frequency. This list does not presume to be exhaustive:

History of previous incidents. Frequent near misses may indicate breakdowns in process safety management systems. They may also indicate that the facility is more likely to continue to have additional near misses (which may eventually result in a serious incident), unless changes are made to prevent recurrence.

In evaluating failure frequency, past incidents or inspections can provide invaluable guidance. For example, if there is history of corrosion in a given service it may be possible to project the frequency of a failure in the future using actual failures or a technology such as risk-based inspection. Naturally, one would expect that a known, repeated failure cause would be addressed through proactive measures to reduce its failure rate in the future, and so using plant data as a basis for predicting the future may be conservative in this respect.

Process operating conditions. Some process conditions that may increase the frequency of a scenario include high temperatures or pressures, or unusually low temperatures; highly exothermic reactions; processes that handle highly corrosive, erosive, or unstable materials; or processes subject to frequent pressure or temperature cycling.

Conversely, processes that are not corrosive or operate at moderate pressures and temperatures may be less likely to have an event as a result of corrosion or a process-induced failure.

Design allowance or design integrity. Although processing facilities are designed and built to appropriate codes and standards, many process mechanical designs have additional conservatism built into them. This can take the form of extra wall thickness for piping, upgraded metallurgy, or even additional processing capacity such as dual trains to allow for more frequent maintenance. Any of these factors might decrease the frequency of a scenario of concern.

Operating complexity. Complex operations may introduce the potential for overlooking safety-related issues in the design phase and may also present challenges for operators to accurately and quickly assess plant upsets and respond with appropriate action.

Human factors. Frequent manual operations may increase the potential for an event to occur. Human error rates can increase due to factors such as distractions, fatigue, time pressure or increasing task complexity. An example is an operation requiring the repeated draining of water from a vessel containing hydrocarbon. If the drain time is of sufficient duration that the operator is tempted to leave the drain valve open while attending to other duties, the operator could forget to return and close the valve, leading to a hydrocarbon release.

The design of the unit can also increase the potential for an event to occur. Unit designs that do not take into account the movement and actions of an operator are more likely to result in misoperation which can lead to an incident, or escalation of an event as the operator needs longer response times to understand and attempt to mitigate a developing event.

Age of facility. Older equipment, particularly equipment subject to frequent thermal or mechanical cycling, may have a higher frequency of failure. Additionally, newer equipment may incorporate improvements designed to reduce the potential for equipment failure. This consideration can be applied not only to individual pieces of equipment, but to entire process units.

Brand new equipment may fail if it is not designed correctly, the wrong material is used in construction, or the actual operating conditions at start up exceed the design safe operation envelope. Equipment age is discussed further in the next section.

Overall effectiveness of protective systems and emergency controls. Protective systems, such as alarms, shutdown systems, and emergency controls are often the keys to incident prevention and timely operator response. Protective systems that are properly designed, tested, and well maintained can reduce the frequency. Conversely, systems that are not tested and maintained may result in a high frequency.

Positive management controls. It is important to note that many of the considerations discussed earlier, if managed properly, could decrease scenario frequency.

- The age of the facility does not necessarily increase the frequency of equipment failure. Properly designed, inspected, and maintained equipment may in fact have a low frequency of failure. Years of operating experience may provide valuable information such as the locations of high-corrosion rates in piping and may also bring about repeated design improvements.
- Operations at cold temperature may decrease the risk of external corrosion because any water that reaches the equipment freezes.
- Frequent manual operations may increase the operators' familiarity with the equipment and force hands-on observations that could prevent failures.

8.3.5 Data Modification Methods

There are some approaches used to modify generic failure frequencies that have been described in the literature. The benefits and shortcomings of some example approaches are discussed next. The analyst must be careful to ensure that no bias is introduced as a result of using these methods; see also Section 8.3.8.

Modifications to frequencies are permissible because the modifications are generally linear and are easily traceable. This contrasts with the 'consequence' side of the risk equation, since any modifications to consequence models would be expected to be non-linear and much less easily traced and validated.

Thomas Model

The Thomas Model (Thomas, 1981) is based on data analyzed by H.M. Thomas in 1981. It proposes using equipment age, thickness, and diameter (for piping) as parameters that can be used to adjust generic equipment failure rates, as follows.

Age - To adjust for the age of the equipment, he uses a single figure (Figure 8.4). Note that the factor in Figure 8.4 represents the cumulative probability of leakage failure up to that age.

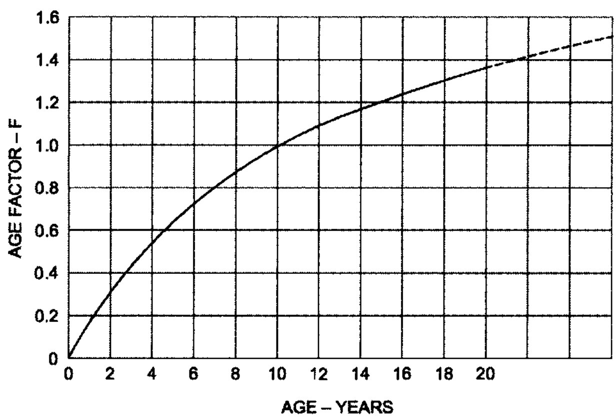

Figure 8.4. Modifying Piping Leak Failure Rates to Account for Aging (Thomas, 1981)

More sophisticated approaches (e.g. RBI) now exist for handling the age effect, but in the absence of the detailed information required for an RBI analysis, the Thomas approach may be suitable. However, it is suggested that it only be used for the initial portion of equipment life, as the Thomas analysis describes 'infant mortality' but not 'wear out' phenomena.

Thickness - Thomas provides data that suggest that *all else being equal*, failure rates are inversely proportional to the square of the thickness of the equipment – that is, a pipe that is twice as thick as a reference pipe has ¼ the failure rate of the reference. However, the analysis must be sure to give credit where credit is due. If a plant has thicker piping because the service is extremely high pressure, or extremely corrosive, the net effect of the increased thickness may simply be to compensate for this severe service. In this case the increased thickness may only serve to bring the failure frequency back to something close to generic.

For the purposes of adjusting failure frequencies, and in the absence of high severity service, it may be appropriate to use the "standard" piping schedules as the baseline (generic) line thickness, and to adjust to higher schedules as per the Thomas approach.

Diameter - Thomas proposes that the total leak failure rate from a pipe will be directly proportional to the pipe diameter, as the surface area available for leakage increases proportionately with the diameter. At first glance this conjecture appears to be inconsistent with other sources of data, which suggest that failure rates are roughly inversely proportional to diameter. However, process pipe thickness typically increases significantly with increasing pipe diameter as shown in Figure 8.5, and so this needs to be accounted for to make apples-to-apples comparisons.

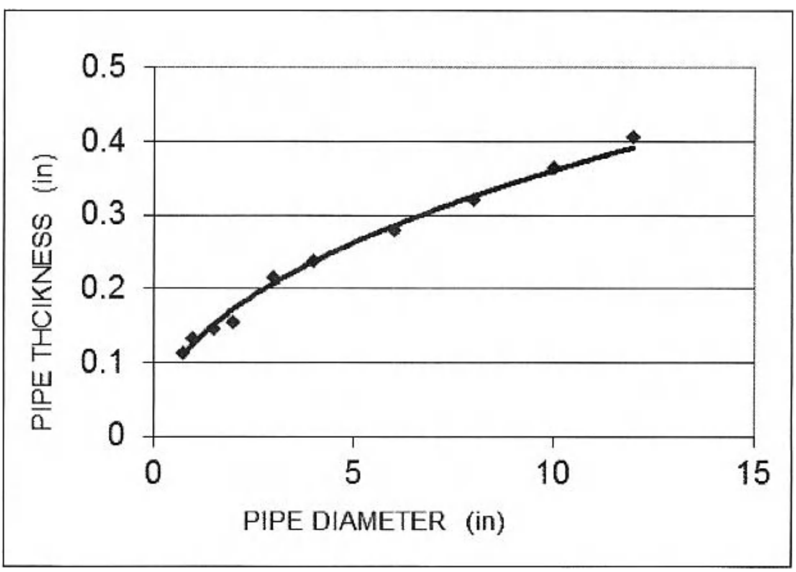

Figure 8.5. Typical Variation in Wall Thickness with Pipe Diameter (ASME, 2004)

Safety Management Effectiveness

Equipment in the same service may perform significantly better at one site compared to another site. This is typically ascribed to better mechanical integrity programs, more or less conservative design standards, better operator training and more. These factors are addressed through a facility's process safety management systems. The CCPS Guidelines for Technical Management of Chemical Process Safety, Guidelines for implementing Process Safety management Systems, and Plant Guidelines for Technical Management of Chemical Process Safety describe the essential areas of management activity necessary for reducing the frequency of explosions, fires and toxic events.

Over the years, various investigators (e.g. API, 2000; Pitblado, 1990) have attempted to quantify the benefits (or demerits) that process safety management has on the frequency of equipment failure by asking a series of questions that address various aspects of process safety, many of which are similar to what might be encountered during a Process Safety Management (PSM) audit. The benefits of incorporating this approach are two-fold: (1) developing more accurate (in principle) failure frequencies, and (2) providing an incentive for sites to improve their PSM systems.

This approach may be effectively applied; however, two caveats are worth noting:

- There is a significant potential for subjectivity variances in scoring the effectiveness of a PSM program, which can lead to inconsistent results depending on who is doing the auditing.
- In practice, well-run plants that are most representative of the industry generally score within a relatively narrow band (~ between a 0.5 and 2 multiplier to generic failure rates). This error band is not dissimilar to other sources of error in generic data.

More recent industry initiatives can provide a basis for quantification of the effect of PSM. Two of these are described in CCPS Process Safety Metrics book (CCPS 2008a) and API RP 754 (API 2010). Also, Pitblado et al. (2010) compares 4 methods for modifying generic frequencies and concludes that a safety barrier approach is the soundest modification approach. This assesses the quantity and quality of safety barriers deployed against a whole range of leak causes and benchmarks this against the generic data source (in the example case comparing typical refineries to the UK HCRD). This modification factor is applied to all generic data used in a QRA study.

The dynamic nature of process safety management systems requires management to continually monitor the effectiveness of these systems to ensure that plant risks are controlled to tolerably low levels. The effects of the flux of management, personnel equipment, ownership of the site, life cycle planning, and economic cycles also dictates that facility siting studies be revalidated periodically to revisit assumptions made originally as part of a continuous improvement cycle to assure that process safety integrity is maintained.

8.3.6 Risk-Based Inspection

The RBI technology provides the potential for adjusting generic failure frequencies to values that are more application-specific and therefore, more accurate. However, this approach must be used with caution because of the different goals of RBI vs. risk-based facility building siting evaluation. Most significant of these is a need to recognize that not all sources of risk are amenable to inspection alone; see also Section 8.3.8.

8.3.7 Elimination of Failure Classes

Companies and their insurers often analyze failure data to determine the major sources of failures and, ideally, devote resources to address those that are most important. An example of such a breakdown is shown in Figure 8.6:

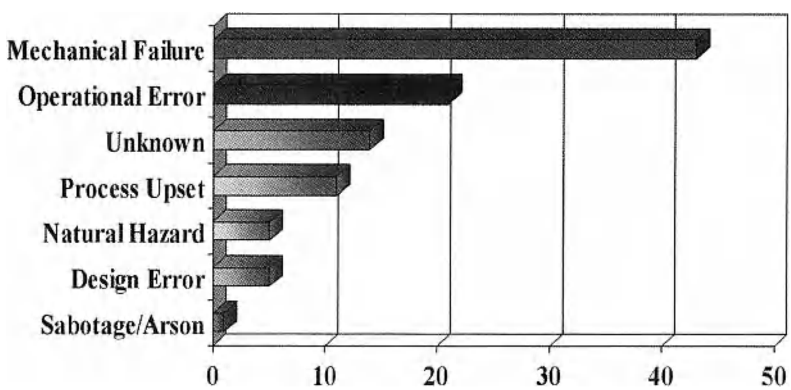

Figure 8.6. Loss Cause in the Petrochemical Industry (percentage of losses) (Marsh, 1999)

In principle, it should be possible to take credit if a particular class of causes can be eliminated – for example, if a site is in a location that is less prone to natural hazards. In practice, it is difficult to defend this approach, since:

- Hazards that are felt to be trivial may not be, they just may not have been observed recently.
- The benefits in frequency reduction are usually minor compared to other uncertainties in the analysis.

Therefore, in many cases this approach may not yield useful or defensible quantification of failure rates, although it may still be appropriate to address such general classes of failure causes. Note that technologies exist to address some types of 'general hazards' – for example, risk-based inspection (RBI) to address "mechanical failures." Often, methods such as RBI will be performed independently from a risk-based building siting analysis; however in some cases it may be possible to incorporate methods like RBI into the siting study.

8.3.8 Interference Between Frequency Modification Methods

Each of the methods described earlier can be appropriate and defensible when applied individually in the right circumstances. However, applying more than one of these methods to a particular equipment item introduces a significant potential for double-counting of benefits. For example, if one takes credit for thicker piping using the Thomas method, it is inappropriate to take credit for the same measure using an RBI approach, or to also take credit for having high design/PSM standards. Therefore it is strongly urged that if any of these methods are used, only one be used for any given potential release source unless it can be verified that there is no double-counting, or the modification is made in a more fundamental approach such as fault tree in which modifications can be applied to specific branches of the tree.

In general, the approaches described offer the benefit of improved failure frequency estimates, but likely at the expense of reproducibility between different analysts assessing the same situation. These methods should therefore be used with discretion, and using a protocol that can be shown to be consistently applied from one practitioner to the next and from one facility to the next.

8.4 PROBABILITY AND FREQUENCY OF FINAL OUTCOMES

8.4.1 Event Trees

In most cases, a given initiating event can have a number of outcomes depending on the circumstances present at the time of the event. The event tree method is a common approach to quantifying the frequency of each outcome. An event tree can be thought as a mirror image of a fault tree – in this case, starting with the fault tree "top event" which is the event tree "initiating event" and progressing to a multiplicity of outcomes rather than starting with a multiplicity of basic events and progressing to the top event.[1] An event tree of a form that would be typically used in a risk assessment is provided in Figure 8.7.

[1] In fact, in recent years it has become popular to marry simplified versions of a fault tree to an event tree in a technique known as a "Bow Tie" because of its shape.

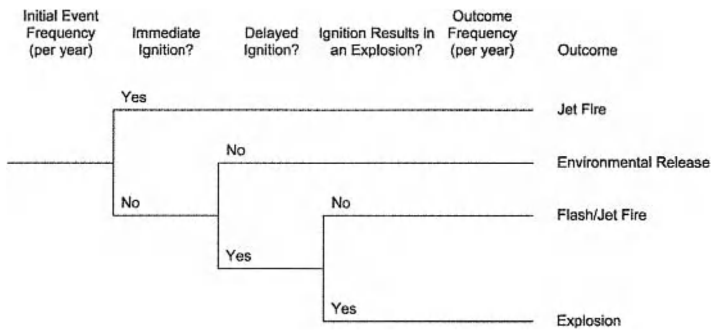

Figure 8.7. Event Tree for Calculating Loss of Containment Outcome Frequencies

It may be necessary to insert additional branches into the event tree – for example, to account for wind direction since ignition sources, areas of congestion/confinement and/or receptor buildings may not exist in some directions away from the source, or to account for active protection systems working or failing. But this is a useful, basic form of an event tree that can be modified as needed to accommodate other relevant parameters.

8.4.2 Quantification of an Event Tree

The next task is to quantify the event tree. It is important to keep the mathematics of the event tree straight to avoid generating nonsensical results. The units necessary are the following:

- *Initial Release* – This is a frequency, expressed in "occurrences per year" or other time-based measure.
- *Conditional Events* (e.g. immediate ignition, wind direction/speed, atmospheric stability, delayed ignition, explosion/given delayed ignition, occupancy levels). These are probabilities, and are dimensionless.
- *Outcomes* – These are frequencies, expressed in "occurrences per year" or other time-based measure.

A particular outcome frequency is then the product of the initial event frequency and the conditional probabilities that lead to that outcome.

The initial event frequency is determined using the methods described previously. Conditional probabilities are calculated by various means, described next.

Probability of Immediate Ignition

There are several published sources of data or methods (e.g. API, 2000 and Cox, 1990) that have been proposed to develop the probability that a release of a flammable material will ignite immediately.[2] Many of these sources use broad-based probabilities, e.g. probability of immediate ignition (POII) of a propane release = 0.1, or probabilities that are based on applications that may not be reflective of process plant operations (e.g. offshore). The analyst must not adopt such values blindly since the actual POII can vary widely (for example, if the material is released above its autoignition temperature, or adjacent to a fired heater). Other investigators [Spencer and Rew 1997, TNO 2005, UKOOA 2006, CCPS 2012] have considered additional variables that are known to affect this probability.

Probability of Meteorology

At most airport locations, meteorological data is collected hourly and consists of: wind speed, wind direction, cloud height and total cloud cover data, and consists of the number of occurrences within each of 6 wind speeds, 16 wind directions, and 6 stability categories). Typically for risk analysis, three years of data are collected and used to calculate wind speed/stability class probabilities as well as wind direction probabilities. The user should make reasonable accommodations to the available data if, for example, the topography surrounding the site is dramatically different than that at the weather station. Some sites also may have their own weather stations, and data from these stations may also be used in the risk analysis study.

Even with the ever-increasing capacity of computers, it is not practical to incorporate all combinations of wind direction and atmospheric stability into risk tools. For this reason, the wind rose data is usually consolidated into 2 to 6 representative climatic conditions. Similarly, it is not feasible to model all possible combinations of ambient temperature and humidity. Generally a conservative approach is to take the maximum monthly average temperature and average annual humidity. Chemicals that tend to dominate risk assessments also tend to have boiling points under this temperature, such that in the aggregate this approach should be conservative. However, where the boiling point of the material of interest is near the assumed ambient condition, it may be appropriate to select a higher "common conservative case" temperature to ensure that no significant non-conservatisms are introduced.

Probability of Delayed Ignition

In the mathematics of the event tree, this is the probability of a "delayed ignition", where we would expect to include ignitions due to the released material contacting an external ignition source such as rotating equipment, fired heaters, passing vehicles, hot work/surface, etc.

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[2] "Immediately" in this context means an ignition that occurs before a flammable cloud sufficient to result in an explosion can develop.

This number is dependent on a wide variety of release and environmental conditions, and ideally these factors should be at least considered in lieu of using a fixed, 'all purpose' value.

The CCPS book on ignition probabilities (CCPS, 2012) provides algorithms for evaluating ignition probabilities based on key variables such as the following:

- The material being released. [Some materials are easier to ignite than others; the Minimum Ignition Energy is one measure of this propensity]. Some materials will readily form a vapor cloud while others will typically form liquid pools with some vaporization. In addition, some releases may reach an ignition source due to having a wide flammable range (e.g. acetylene) compared to other chemicals whose range is narrower.
- The magnitude of the release. The larger the release, the more likely it is to find an ignition source because of larger cloud size. Sometimes, larger releases persist for a longer time, increasing the chance that low energy ignition sources could cause ignition.
- The duration of the release and the numbers/density and 'strength' of ignition sources [the longer the cloud is present, and the greater the number of ignition sources, the more likely the chances of ignition; 'hard' ignition sources such as open flames will be more likely to ignite a cloud than 'soft' sources such as hot surfaces or power lines]
- Indoors vs. outdoors operation, indoor ventilation rates [all else being equal, an interior space with limited ventilation can contain a flammable cloud more than open spaces]
- Whether the areas into which the cloud drifts are classified or not [this is related to the third bullet, but may be applied across a given area as opposed to a specific point ignition source]

The same references that addressed immediate ignition probabilities can also provide guidance on values and algorithms that can take these variables into account. Note that it is not the intent of this guidance to *prescribe* the use of the more detailed approaches; in many cases a 'generic' value may be sufficient. However, the analyst should at least *consider* the significance of these variables for their specific facility.

Related to the question of 'generic' vs. detailed ignition probability models is the following fact: The existing probability models are based as much on expert opinion as hard data. Unlike tests of consequence models, it is problematic to develop controlled experiments to determine the probability that a given release will result in a fire or explosion that would be applicable to the broad spectrum of situations encountered in the process industry. And whereas there are records of most of the major loss incidents, there is little information available about releases that did <u>not</u> result in a large loss. So with respect to fire and explosion frequencies/probabilities, it may be possible to describe the numerator but not the denominator of this relationship.

The CCPS book on ignition probabilities (CCPS, 2012) is intended to address this concern by introducing algorithms that include variables not previously addressed.

Probability of Ignition Resulting in Explosion

At this point in the event tree it is assumed that a delayed ignition has occurred, and it just remains to determine whether the ignition results in a fire or VCE. As for the earlier conditional probabilities, it is common for analysts to apply a standard value for this probability. However, this probability is known to depend on some variables including the magnitude of a release (Cox, 1990 and others). This may be a result of a larger release having a larger area of coverage for the flammable vapor cloud and therefore a higher probability of the flammable cloud encountering potential explosion sites (e.g. congested spaces). Models that describe the potential for a VCE are described in other texts including one by CCPS (CCPS, 2010).

Outcome Frequencies

The frequency of each of the outcomes described in the event tree in Figure 8.7 (which does not take into account additional complexities such as meteorology) is then:

Frequency of Explosion = Initial release frequency × (1 – Probability of immediate ignition) × (Probability of delayed ignition) × (Probability that delayed ignition results in an explosion)

Frequency of Fire (but no explosion) = Initial release frequency × [Probability of immediate ignition + (Probability of Delayed Ignition) × (1 - Probability that delayed ignition results in an explosion)]

Frequency of Unignited Discharge = Initial release frequency × (1 – Probability of immediate ignition) × (1 - Probability of delayed ignition)

These are illustrated with the simple event tree example in Figure 8.8.

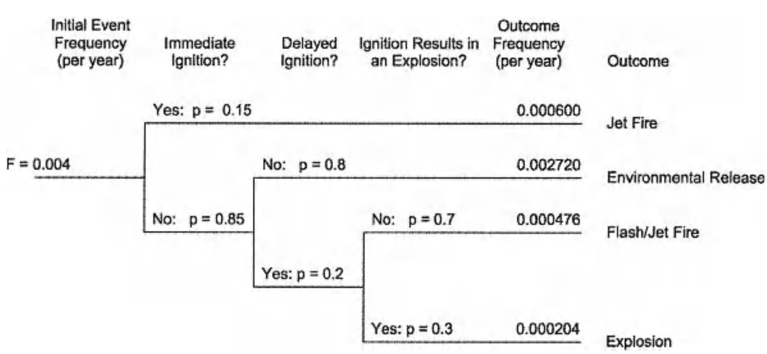

Figure 8.8. Basic Quantified Event Tree Example

Note that a fire is likely to occur subsequent to an explosion, and this may be accounted for separately.

8.5 UNIT-BASED OUTCOME FREQUENCIES

Some operators develop outcome (e.g. explosion) frequencies on a unit-level rather than on an aggregated scenario-by-scenario basis. There are advantages and disadvantages to this approach, some of which are listed here:

Advantages –

- The analysis is greatly simplified
- For common unit types, there is information publically available on the expected frequency of certain types of incidents such as explosions (e.g. API 2003).

Disadvantages –

- In many cases the outcome definitions are not precise. For example, in the case of an explosion frequency for unit type "Y," it is often not known how large the explosion, fire or unignited release was. Because of this, the user is generally obliged to assume the worst about the incident to avoid having a non-conservative result.
- There is an implicit assumption that the unit being reviewed is similar in design, layout, and operation to the 'typical' unit that comprises the failure frequency database. Thus there is a need to be able to defend this assumption.
- There is no ability to account for process (differences in inventory process conditions, mitigation systems, etc.), or geographical improvements (e.g. reduction in confinement and/or congestion through equipment layout, spacing relative to other process units, etc.) that would reduce the frequency of explosion.

The steps in developing the unit-level outcome frequency are simply these:

- Find a source of unit-based frequency data that is representative of your operations.
- Make any appropriate adjustments based on your specific operations vs. a 'typical' unit of that type [see Moosemiller, 2010 for an example].
- Couple this frequency with an outcome severity that can be shown to err on the side of conservatism.

It is permissible to use multiple levels in the analysis. A unit explosion frequency might be used as a first-pass check, for example. More detailed risk-based tools could then be applied based upon the results of the high-level assessment.

Since there is no specific initiating event for which the frequency can be quantified, the user of this approach relies on unit level outcome frequencies. Examples of these were provided in the original version of API RP 752 for refinery process units (1995), and expanded upon later by Moosemiller (2010).

9 RISK ASSESSMENT

9.1 INTRODUCTION

The methods for quantitative risk assessment are well described in the CCPS book, *Guidelines for Chemical Process Quantitative Risk Analysis*, [CCPS, 2000] and elsewhere (e.g. TNO Purple Book, 2005; Taylor, 1994). Therefore this text will only provide an overview of the key elements of risk assessment in the context of building occupants.

Risk is a complex topic that involves company-specific information and sometimes regulator-specific information, in which case both need to be sufficiently addressed. For instance in some parts of the world (Section 9.4), a tolerable level of risk is defined by a regulatory agency for everyone operating within that jurisdiction, while in other parts of the world (such as the USA) the acceptable limits of risk are less clearly defined. For a company with global operations, this can make it challenging to manage risk consistently across the various regimes. To the user who is establishing an approach within their organization for assessing and addressing risks from VCEs and toxics, it is strongly recommended that they involve their company's legal experts to assure that the approach they develop is consistent with the company's operations.

9.1.1 Scope of Risk in This Book

It is important to set the boundaries of what is to be included in a risk-based building siting evaluation for the purposes of conforming with API RP-752. People are subjected to a variety of risks in the workplace or from day-to-day living. Some of these are relevant to managing the hazards resulting from building location, some are not. This book focuses on "managing the risk from explosions, fires and toxic vapor releases to on-site personnel located in new and existing buildings intended for occupancy," as per RP-752.

Risk analysis considers the consequences of explosion, fire and toxic release scenarios on building occupants as well as the frequency with which the scenarios might occur. In general, the occupants of buildings should not be placed at a level of risk that exceeds criteria established by the owner operator because of their work location. The building, by its existence, may increase the risk to the occupants due to building debris hazards from an explosion. In evaluating the overall risk to an individual, the building may represent one factor among many factors contributing to that risk within the process plant. In some cases, the building may represent a significant contribution to a building occupant's risk, warranting efforts to mitigate the risk. In other cases, the risk to building occupants may be sufficiently low and no action is required.

Many other risks are considered to be outside the scope of this book, including but not limited to:

- Risks due to presence of utility gas piping inside a building, when the gas is used solely for heating/cooking purposes.
- Risks due to use of nitrogen backup for instrument air in control room instrumentation, with potential asphyxiation within the building.
- Risks from sabotage or terrorism.
- Internal fires (e.g. electrical fires, garbage fires).

9.1.2 Definition of Risk in This Book

Risk is a measure of human injury in terms of both scenario likelihood (frequency) and the magnitude of the loss or injury (consequences). Similarly, "risk" is defined by CCPS as:

"A measure of potential injury, environmental damage, or economic loss in terms of both the incident likelihood and the magnitude of the injury, damage, or loss."

Thus, "risk" is not associated solely with the consequences of a scenario, but also with the frequency at which those consequences are expected to be realized. In the context of occupied buildings, "risk" can be presented from various perspectives, including but not limited to the following:

- Risk to any occupant of a building (a form of "individual risk," which in this case is sometimes referred to as "geographic risk")
- Risk to a specific occupant of the building (a form of "individual risk," which in this case is sometimes referred to as "personal risk")
- Risk to a group of people within the building ("aggregate risk," sometimes referred to as "societal risk")
- Risk to the building itself (a type of "individual risk" or "geographic risk")

The use of risk in a building siting evaluation is usually the risk of fatality for an individual or group of individuals, although other risk types can be considered *in addition to* fatality risk. The risk of fatality for explosion hazards includes life-threatening injuries simply because the models have been developed on that basis. Inclusion of life-threatening injury in explosion evaluations is due to the potential that they may become a fatality without prompt rescue and medical assistance. Fire and toxic fatalities tend to occur more slowly than explosion-related fatalities, and so the proximity of medical assistance is usually not the limited factor in determining whether an exposure results in a fatality. For the sake of brevity, the term "fatality" as used in risk calculations will refer to the level of injury consistent with the occupant vulnerability model used for each hazard.

9.1.3 Qualitative Versus Quantitative Risk Assessment

Over the years, many process industry qualitative risk assessment techniques have been developed. These include risk matrices commonly used to rank scenarios in Process Hazards Analyses. These qualitative approaches have merit in the proper application. For example, a *PHA Risk Matrix* incorporates the knowledge of the people closest to the operation – those who are in a good position to assess unit-specific standards of design, operation and maintenance, as well as the potential for upset conditions.

In some respects these approaches can be advantageous. For example, use of these techniques may be helpful in their ability to identify non-standard scenarios (ones that require fault tree analysis or FMEA to evaluate properly). Where practical and defensible, the knowledge from qualitative approaches can be incorporated into a consequence-based or risk-based building siting evaluation. However, such approaches are generally inadequate for the detailed consequence and risk analyses required by RP-752 for explosion and toxic risks for various reasons, including:

- Qualitative approaches typically employ crude approximations (at best) of chemical discharge and dispersion models.
- The VCE models used within these qualitative approaches for vapor clouds usually do not adequately account for cloud interactions with volumes of congestion/confinement, and the inherent tendency of chemicals to reach explosive flame speeds (or not).
- Qualitative approaches may not consider structural strength of occupied buildings, or may consider structural strength in a superficial manner.
- For risk-based studies of the toxic releases, the approaches do not adequately address the concentration-duration (dosage) relationship.

In short, qualitative and semi-quantitative approaches do not address the complexities of the many variables that are critical to an accurate building siting evaluation. Because of these issues, qualitative and semi-quantitative risk approaches should not be used in building siting evaluations except if developed based on rigorous consequence models that are conservative for all scenarios that might be encountered.

It is not the intent of this book to eliminate or discourage the use of the qualitative and semi-quantitative techniques mentioned above in contexts other than building siting evaluation, and some components may be usable as frequency modifiers if they have a defensible basis. As noted, there are elements of these methods that are useful to hazard and risk analysis. To the extent that these methods provide credits for good process safety practices, they provide incentives to facilities to incorporate good practices that might not be otherwise rewarded and so should not be discouraged.

For this reason, these tools may be appropriate for:

- internal company process safety auditing purposes;
- deciding the *order* in which more detailed facility siting studies are performed; or
- deciding the order in which hazard/risk mitigation measures are instituted.

9.2 RISK MEASURE TYPES

9.2.1 Common Risk Measures

CCPS's *Guidelines for Chemical Process Quantitative Risk Analysis* (CCPS 2000) identifies three main categories of risk measure: Individual Risk, Societal Risk (aka "Aggregate Risk" when applied to the occupants of a building in this book), and Risk Index. RP-752 requires consideration of both individual risk and aggregate risk, but not risk index. Each is described next.

Individual Risk expresses the risk to the occupant of a building that is exposed to a hazard. It is normally calculated as the frequency of serious or fatal injuries per year (fatalities/year). Three of the more common individual risk measurements are:

- *Building Geographic Risk* - defined here as the risk to a person who occupies a specific building 24 hours/day, 365 days/year. Of course such a person does not exist in a facility but can be represented by a building that is occupied by an individual continuously; e.g. a control room. Building geographic risk for an individual is a simplified approach that eliminates complicating variables that require assumption of presence factors, etc. Furthermore this definition provides the frequency of a potential fatality being observed for a given building and it is similar to the traditional definition of "individual risk" as described in the CPQRA book for a person outdoors 24 hours/day, 365 days/year.
- *Maximum Individual Risk* is defined as the risk to the most exposed individual in an exposed population. In the case of personnel in process plant buildings, this is the person who spends the most time in the building under study. The risk to this most exposed individual is calculated by multiplying the expected frequency of each specific scenario by the occupant vulnerability, and then multiplying this value by the person's fractional occupancy (i.e., fraction of time spent in the building). The total risk to this most exposed individual is the sum of the risks calculated for all specific scenarios. It should be noted that this risk measure is a subset of the building geographic risk measure and can be arrived at by multiplying the building geographic risk by the fraction of time that the most exposed individual spends in a building. While this

measure provides important information to the user, it does not represent the risk of having a fatality in a building that is continuously occupied.

- *Average Individual Risk* is defined as the individual risk averaged over the entire population that is exposed to the risk (e.g., all the building occupants at a large plant). This is a useful risk measure if the risk is reasonably uniform over the population being measured.

Aggregate Risk measures the potential for scenarios to affect many people within a building or buildings. Aggregate risk is often presented as a frequency distribution of multiple-casualty scenarios, called an F-N curve, showing the frequency of scenarios (F) leading to N or more fatalities. A typical F-N curve is illustrated in Figure 9.1.

While aggregate risk has historically been applied to scenarios that can impact the public, major accidents in chemical processing plants may also have the potential to affect large numbers of people on site since they are closer to the source. In particular, a single major scenario could affect multiple buildings and many individuals inside each building. Thus, the concept of aggregate risk can be applied to on-site risk evaluations as well as off-site evaluations.

Published data are available on the application of aggregate risk measures, including the development of risk tolerability limits for F-N curves. However, most of this guidance has been developed for characterizing risks to the general public (and referred to as "societal risk" in that context) and would not normally be considered as a basis for assessing risks to on-site personnel. It is appropriate, therefore, to suggest the "aggregate risk" measure, similar in concept to the 'classic' use of "societal risk," for on-site applications to process plant buildings.

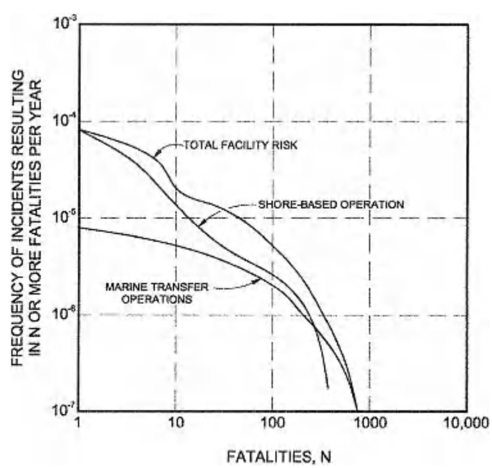

Figure 9.1. Example of Aggregate (Societal) Risk (F-N) Curve (CCPS, 2000)

Aggregate risk is used to measure the collective risk to people in a facility that could be exposed to a scenario or scenarios. It indicates the frequency that a specified number of people will suffer a specific level of harm (e.g., death).

In general, consideration of individual risk reflects the need to ensure that each building occupant is not exposed to inordinate risk. Aggregate risk addresses those situations where, because of a single scenario, many building occupants could be at risk, or the business as a whole may be exposed to an inordinate risk. Both individual and aggregate risk should be considered when decisions concerning building occupants are to be made.

Another measure of aggregate risk combines the consequence/frequency pairs for all scenario outcomes at a site and expresses them as a single number such as "X" fatalities per year. This "risk index" approach (the term used in the CCPS CPQRA book) is reported in various forms and under various names such as "societal risk index" (SRI), "risk expectation value," and "potential loss of life" (PLL). It is uncommon for risk tolerance criteria to be established for this risk measure. However, it is frequently used as the basis for decision-making regarding risk mitigation measures, e.g.:

- Prioritizing risk reduction measures – implementing risk reduction measures that have the greatest ratio of risk reduction to cost first.
- Determining the extent of risk mitigation – determining when the cost of a risk mitigation measure provides substantial risk reduction, and also when little risk reduction is provided for the cost of the mitigation measure.

Index approaches are permitted under RP-752.

9.2.2 Alternative Risk Types

Although the methods described in the previous section are the ones most commonly applied historically, some companies have determined that related but different risk measures are more meaningful for their operations. Some of these alternative measures include:

"Personal Risk" – The risk to a specific individual (e.g. John Smith) or job function such as "Unit A Field Operator." The benefits of this approach are that it allows the computation of risk to take into account: (a) that an individual is on the job only part of the day (in the same way as *maximum individual risk*), and (b) that an operator moves from location to location during the course of a work shift. In contrast, risk to an individual in a single geographic location such as a building ("individual risk" – still the most widely used basis for risk criteria) assumes a 24 hour/day presence at that location.

Calculating personal risk depends on having an accurate accounting of the fraction of time, or "presence factor" that people spend in specific locations. The risks at each individual location are then prorated by the presence factor and aggregated to calculate the overall risk for an individual.

Note that for an individual who is located in a building for 100% of time on site the value of *personal risk* will be the same as *maximum individual risk* for that building.

"Building Risk" – The risk that a building meets a specified damage level (e.g. irreparable damage). This level of damage can often be translated into a probability of fatality for building occupants and therefore, into other human health risk measures. Thus this risk measure is generally calculated as a bridge to a human risk calculation.

There are variations of these themes that can also be a valid basis for setting risk management criteria.

9.2.3 Summary of Risk Types

Each risk measure described here has its advantages and its limitations. These are summarized in Table 9.1.

Table 9.1. Summary of Some Major Types of Risk Measures

Risk Measure	Advantages	Limitations
Building Geographic Risk (IR)	Measures the risk at a building, such that the risk cannot be artificially subdivided by moving people around. Is more easily compared to external reference risks (e.g. risk of smoking, vehicle accidents)	Does not account for the number of people exposed. Assumes 24 hours/day presence, and so reflects some multiple of the risk to a specific person.
Maximum IR	Identifies the risk level to the most exposed person in a building.	By itself, it does not account for people other than the maximum exposed person.
Average IR	Provides an overall measure of risk at a site that can be easily compared to other sites.	May not be meaningful if there is wide variability in exposure to different people at the site.
Aggregate Risk	Accounts for the number of people exposed.	Depending on the type of measure used, it may not provide an obvious indication of the risks to individuals.

In cases where there are limited personnel present at a site (e.g. pump station), individual risk may be a more meaningful risk measure than aggregate risk. On the opposite extreme, a site that has a large office building located near a process area would want to evaluate aggregate risk. For these reasons, evaluating both individual and aggregate risk is necessary.

The intended strategy for mitigating risk will also drive which risk measures are used. If a cost/benefit approach is used, then a risk index form of aggregate risk is beneficial. In any case, owner/operators will frequently use more than one risk measure type in order to capture the benefits of each.

9.3 CALCULATING RISK

The risk of a given outcome of a specific hazard scenario is the product of the occupant vulnerability and the frequency at which that impact is realized (usually expressed on a "per year" basis). Depending on the type of risk being calculated, other factors such as "presence factor" (the fraction of time an individual is exposed), and the level of occupancy may also enter the calculation. That is,

Risk = Frequency (/yr) × Occupant Vulnerability × [other factors]

The total risk of a given hazard scenario is the sum of the risks of the individual outcomes that can result from that hazard, and the total risk of an operating unit or a facility is the sum of the risks of the individual hazard scenarios.

Whether calculating individual risk (in its various manifestations) or aggregate risk the inputs are initially the same; it is only the manner in which the inputs are combined that is different. Again, the core input is a series of outcome/frequency pairs from the range of scenarios being considered.

Examples of some risk calculations follow. Other examples of risk types and how to calculate them are provided in Chapter 4 of the CCPS book, *Guidelines for Chemical Process Quantitative Risk Analysis*, [CCPS, 2000]. There are many possible ways of calculating risk, any of which may be appropriate for the application. The examples that follow are not intended as an endorsement of a particular method of calculating risk for a specific situation, nor are they intended as an exhaustive list of options.

9.3.1 Overview

If a scenario-by-scenario approach is selected, then the risk assessment process begins by identifying specific scenarios that apply to the facility under review. The analyst should:

- Identify the inventories of toxic, flammable and combustible materials within the process plant and the physical conditions under which they are contained. Similarly, identify other materials or process conditions that can result in explosions, including condensed-phase explosions, physical explosions, or uncontrolled chemical reactions.
- Identify credible initiating events for accidents involving toxic material releases, explosions, or fires.
- Identify intermediate events that either propagate or mitigate the developing accident scenario.

- For each initiating event, determine the various accident pathways defined by the credible combinations of intermediate events.
- Identify the range of possible scenario outcomes affecting process plant buildings and their occupants, including explosions and fires that can result from the various accident pathways.
- Estimate the frequency of the initiating events and apply appropriate conditional probabilities to the various intermediate events that may occur (Chapter 8).

If a unit-based approach is selected, then there is a similar pairing of scenario consequence with scenario frequency. In this case, however, the scenario is something that happens at the unit level (e.g. ignition of gas cloud that covers the unit) paired with the historical frequency of similar scenarios.

9.3.2 Calculating Individual Risk

Calculation of individual risk for a building occupant requires combining scenario outcome frequency, occupant vulnerability and, for some individual risk calculations such as "personal risk", the presence factor for the most exposed individual. The result is risk expressed as the expected frequency of the outcome consequence (e.g. serious or fatal injuries).

Table 9.2 presents a calculation table, which demonstrates an approach for determining risk to multiple process plant buildings at a facility.

$$R_{1,1} = I_1 \, V_{1,1} \, T_1$$ **Eqn 9-1**

Where:

I_1 = Incident frequency

$V_{1,1}$ = Occupant vulnerability

T_1 = Fractional time of attendance calculated as hours per week/168 that the most exposed individual is in building B_1

In this case, the frequency is derived from the combination of factors described in Section 8.1 and repeated here:

- Frequency of initial release
- Probability distribution of the quantity and location of the release
- Probability of ignition (for explosion and fire hazards)

- Probability of atmospheric parameters (wind direction, atmospheric stability)
- Probability of failure/success of each layer of protection
- Probability of a specific outcome

The total risk to the most exposed individual in a particular building is the sum of the component risk to the building from each process unit. For example:

$$R(1) = R_{1,1} + R_{2,1} \qquad \textbf{Eqn 9-2}$$

Where:

$R(1)$ = Individual risk to the most exposed individual in Building B_1

$R_{1,1}$ = Component risk from process unit U_1

$R_{2,1}$ = Component risk from process unit U_2

Table 9.2. Calculation of Individual Risk

Process Unit	Building No.	Incident Frequency	Occupant Vulnerability	Fractional Time of Attendance	Individual Risk
U_1	B_1	f_1	$V_{1,1}$	T_i	$R_{1,1}$
U_1	B_2	f_1	$V_{1,2}$	T_2	$R_{1,2}$
U_1	B_3	f_1	$V_{1,3}$	T_3	$R_{1,3}$
U_2	B_1	f_2	$V_{2,1}$	T_1	$R_{2,1}$
U_2	B_2	f_2	$V_{2,2}$	T_2	$R_{2,2}$
U_2	B_3	f_2	$V_{2,3}$	T_3	$R_{2,3}$

U = Unit; B= Building; f= Frequency; V= Vulnerability; T= Time; R = Risk

While this example is provided to show how maximum individual risk is calculated, the individual risk for a continuously occupied building would be the same computation with the fractional time of attendance set to “1”.

9.3.3 Calculating Aggregate Risk

In individual risk, the outcome of interest is simply the occupant vulnerability. In aggregate risk the outcome of interest is the occupant vulnerability multiplied by the number of occupants, which results in an expected number of people that experience the outcome of interest. The number of occupants or occupancy level is typically not constant so a fraction of time is often utilized to address different occupancy levels for a given building. Typically, occupancy levels are established for different situations (e.g. day vs. night, by shifts, or normal vs. peak occupancy).

Table 9.3 presents a calculation table for aggregate risk. The aggregate risk is expressed as the number of scenarios resulting in *N* serious or fatal injuries per year.

The frequency $f_{i,j,k}$ at which scenario *i* might affect building *j* during time fraction *k* can be calculated as follows:

$$f_{i,j,k} = I_i \, x_{j,k} \qquad \textbf{Eqn 9-3}$$

$N_{i,j,k}$, the number of fatalities (or other specified outcome) in building j caused by scenario i during time fraction k, can be calculated as follows:

$$N_{i,j,k} = p_{i,j} \, M_{j,k} \qquad \textbf{Eqn 9-4}$$

Where:

I_i = Incident frequency

$p_{i,j}$ = vulnerability of building occupant

$M_{j,k}$ = occupancy of building

$x_{j,k}$ = fraction of time *Mj,k* occupancy exists

i = scenario designator

j = building designator

k = occupancy case designator

Table 9.3. Calculation of Aggregate Risk

Process Unit	Building No.	Incident Frequency	Occupant Vulnerability	Building Occupancy	Fraction of All Time This Occupancy Level Exists	Outcome Frequency	No. of Serious or Fatal Injuries (Outcome)
U_1	B_1	I_1	V_{11}	M_{11}	X_{11}	f_{111}	N_{111}
				•	•	•	•
				•	•	•	•
				•	•	•	•
				M_{1n}	X_{1n}	f_{11n}	N_{11n}
U_1	B_2	I_1	V_{12}	M_{21}	X_{21}	f_{121}	N_{121}
				•	•	•	•
				•	•	•	•
				•	•	•	•
				M_{2n}	X_{2n}	f_{12n}	N_{12n}
U_1	B_3	I_1	V_{13}	M_{31}	X_{31}	f_{131}	N_{131}
				•	•	•	•
				•	•	•	•
				•	•	•	•
				M_{3n}	X_{3n}	f_{13n}	N_{13n}
U_2	B_1	I_2	V_{21}	M_{11}	X_{11}	f_{211}	N_{211}
				•	•	•	•
				•	•	•	•
				•	•	•	•
				M_{1n}	X_{1n}	f_{21n}	N_{21n}
U_2	B_2	I_2	V_{22}	M_{21}	X_{21}	f_{221}	N_{221}
				•	•	•	•
				•	•	•	•
				•	•	•	•
				M_{2n}	X_{2n}	f_{22n}	N_{22n}
U_2	B_3	I_2	V_{23}	M_{31}	X_{31}	f_{231}	N_{231}
				•	•	•	•
				•	•	•	•
				•	•	•	•
				M_{3n}	X_{3n}	f_{23n}	N_{23n}

The frequency and consequence /outcome pairs (the risk of a specific outcome of a specific event) generated in Table 9.3 are sorted by decreasing risk outcome, with the top scenario being the one that resulted in the highest number of fatal injuries. An F-N curve can be generated by plotting these pairs. The outcome frequencies are successively added in descending order, so that for each N a cumulative outcome frequency F is generated equal to the sum of all the outcome frequencies with N or more fatal injuries (or other selected injury threshold used as the basis for criteria by the owner/operator). The cumulative frequency/outcome data points are then plotted using logarithmic scales to create F-N curves for occupants of each building.

The total aggregate risk for a building can be determined by generating an F-N curve using frequency and outcome data for scenarios in each unit potentially impacting that building.

The value of this risk measure is that it provides a frequency of different levels of impacts, including potential for multiple impacts.

The same information utilized to generate the F-N curve can be used calculate the "index" types of measures. For example, next is a calculation for the aggregate risk index (aka potential loss of life):

$$ARI = f_{i,j,k} \times N_{i,j,k} \quad \textbf{Eqn 9-5}$$

EXAMPLE

Background

A large processing facility has a centrally located cafeteria constructed of unreinforced masonry. This cafeteria is open for breakfast and lunch, Monday through Friday. The following table represents the occupancy profile for this building. Included in these figures are three food service personnel present from 6:00 a.m. to 3:00 p.m.

Time	Average Occupancy	Time Fraction
6:00 a.m. - 7:00 a.m.	5	0.030
7:00 a.m. - 9:00 a.m.	45	0.060
9:00 a.m. - 11:00 a.m.	10	0.060
11:00 a.m. - 1:00 p.m.	100	0.060
1:00 p.m. - 5:00 p.m.	7	0.118
5:00 p.m. – 6:00 a.m.	0	0.386
Weekends	0	0.286

Based on a 52-week year (8,736 hours)

The cafeteria can be impacted by explosions from three different process units. An independent industry research project estimated the frequency of explosion for process units similar to those in the facility as 2.3×10^{-4}, 3.2×10^{-4}, and 9.1×10^{-4} per year, respectively.

Approach

First, the blast parameters at the cafeteria from the nearby process units are calculated. Peak side-on overpressures are determined as approximately 1.3 psi (0.087 bar), 1.5 psi (0.10 bar), and 1.0 psi (0.069 bar) from Units 1, 2, and 3, respectively. The resulting occupant vulnerabilities have been determined through knowledge of the expected building damage and the historical record of occupant vulnerability for buildings of design having that level of damage. The duration of each scenario is sufficiently long such that the peak overpressure is the controlling determinant of building damage.

The next step is to determine the building damage and estimate the occupant vulnerability. These are estimated from the methods described in Sections 4 and 5.

Calculating Maximum Individual Risk

Since generic data are available on the frequency of explosions in similar units, the last piece of information that is still needed to calculate maximum individual risk is the fractional time of attendance for the most exposed individuals. These are the food service personnel, who are present 9 hours a day, five days a week, for a fractional attendance within any given week of (9 × 5)/168 = 0.268 hrs present/hrs in a week.

All of this information can be summarized in a table similar to Table 9.4. It can be seen that the individual risk (last column) is the product of the preceding three columns.

Table 9.4. Summary of Individual Risk Inputs

Process Unit	Building	Incident Frequency (occurrences/yr)	Occupant Vulnerability	Fractional Time of Attendance	Individual Risk (/yr)
1	Cafeteria	2.3×10^{-4}	0.3	0.268	1.8×10^{-5}
2	Cafeteria	3.2×10^{-4}	0.6	0.268	5.1×10^{-5}
3	Cafeteria	9.1×10^{-4}	0.1	0.268	2.4×10^{-5}

The maximum individual risk from the three process units is the sum of the contributing risk from each unit:

Maximum individual risk = $(1.8 + 5.1 + 2.4) \times 10^{-5} = 9.3 \times 10^{-5}$ /yr

This represents the combined individual risk from multiple scenarios. The company has adopted an upper bound of 1.0×10^{-4} /yr for individual risk. Thus the cafeteria, based on individual risk, meets the company criteria, though marginally. In addition to individual risk, the company needs to consider aggregate risk. The cafeteria may or may not meet the company aggregate risk criteria.

Aggregate Risk

The information needed to calculate aggregate risk can be tabulated as follows (Table 9.5). In this case, the "Incident Frequency" and "Occupancy Time Fraction" columns are multiplied to get the "Outcome Frequency" column, and the "Occupancy Vulnerability" and "Number of Building Occupants" columns are multiplied to get the "No. of Affected People" column.

Table 9.5. Inputs for Aggregate Risk Calculation

Unit	Incident Frequency (/yr)	Occupant Vulnerability	Number of Building Occupants	Occupancy Time Fraction	"f" Outcome Frequency (/yr)	"N" No. of Affected People
	2.3×10^{-4}	0.3	5	0.030	6.9×10^{-6}	1.5
	2.3×10^{-4}	0.3	45	0.060	1.4×10^{-5}	14
1	2.3×10^{-4}	0.3	10	0.060	1.4×10^{-5}	3.0
	2.3×10^{-4}	0.3	100	0.060	1.4×10^{-5}	30
	2.3×10^{-4}	0.3	7	0.118	2.7×10^{-5}	2.1
	3.2×10^{-4}	0.6	5	0.030	9.5×10^{-6}	3.0
	3.2×10^{-4}	0.6	45	0.060	1.9×10^{-5}	27
2	3.2×10^{-4}	0.6	10	0.060	1.9×10^{-5}	6.0
	3.2×10^{-4}	0.6	100	0.060	1.9×10^{-5}	60
	3.2×10^{-4}	0.6	7	0.118	3.7×10^{-5}	4.2
	9.1×10^{-4}	0.1	5	0.030	2.7×10^{-5}	0.5
	9.1×10^{-4}	0.1	45	0.060	5.7×10^{-5}	4.5
3	9.1×10^{-4}	0.1	10	0.060	5.5×10^{5}	1.0
	9.1×10^{-4}	0.1	100	0.060	5.5×10^{-5}	10
	9.1×10^{-4}	0.1	7	0.118	1.1×10^{-4}	0.7

Using the scenario frequency and number of serious/fatal injuries calculated from Table 9.5, an F-N curve can be generated to present the results.

The frequency/impact pairs generated in Table 9.5 are sorted by decreasing outcome, with the top scenario being the one that results in the highest number of serious injuries or fatalities. The outcome frequencies are then successively added in descending order, so that for each N, a cumulative outcome frequency F is generated equal to the sum of all the outcome frequencies with N or more fatalities. The cumulative frequency/outcome data points can now be plotted using logarithmic scales to create F-N curves for building occupants.

The total aggregate risk for a building can be determined by generating an F-N curve using frequency and outcome data for all process units and all scenarios in each unit potentially impacting that building.

Table 9.6 was prepared using the outcome frequency and number of serious/fatal injuries, and arranging them in order of decreasing numbers of impacts:

Table 9.6. FN Curve Input Data

N (No. of Affected People)	f (Outcome Frequency) (occurrences/year)	F (Cumulative Outcome Frequency) (occurrences/year)
60	1.9×10^{-5}	1.9×10^{-5}
30	1.4×10^{-5}	3.3×10^{-5}
27	1.9×10^{-5}	5.2×10^{-5}
14	1.4×10^{-5}	6.6×10^{-5}
10	5.5×10^{-5}	1.2×10^{-4}
6.0	1.9×10^{-5}	1.4×10^{-4}
4.5	5.5×10^{-5}	1.9×10^{-4}
4.2	3.7×10^{-5}	2.3×10^{-4}
3.0	$(.95+1.4) \times 10^{-5}$	2.5×10^{-4}
2.1	2.7×10^{-5}	2.8×10^{-4}
1.5	6.9×10^{-6}	2.9×10^{-4}
1.0	5.5×10^{-5}	3.4×10^{-4}

Plotting the cumulative outcome frequency against the number of serious/fatal injuries yields the F-N curve shown in Figure 9.2.

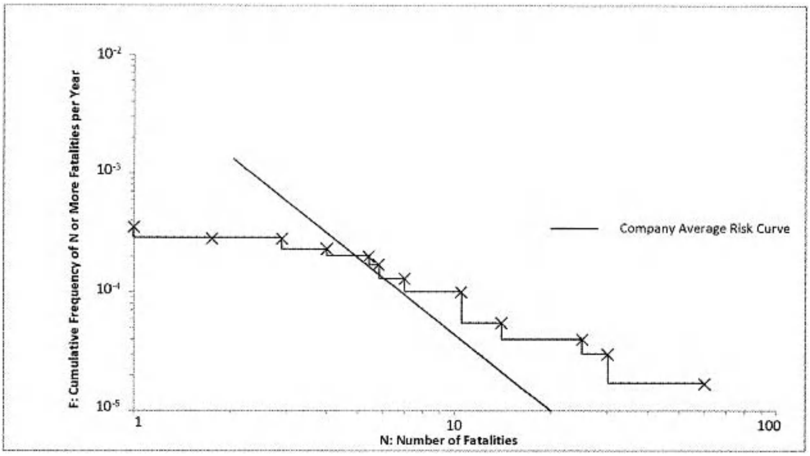

Figure 9.2. Calculated F-N Curve from Example

The company has developed internal aggregate risk criteria. A comparison of these criteria with the calculated risk for personnel occupying the cafeteria shown in Figure 9.2 indicates the calculated risk curve is above the upper limit of tolerability for high values of N.

On simple inspection, it appears that the risk presented by the cafeteria exceeds the company criteria. Further analysis may be conducted (if allowed by the company's evaluation criteria) to determine what is driving the risk values prior to instituting mitigation measures.

Exceedance Curves

An approach closely mathematically related to F-N curves is the "exceedance curve" approach. Some people refer to an F-N curve as an "exceedance curve," but the definition of exceedance curves here is when the outcome ("N") is measured in terms of a physical impact (e.g. overpressure at a building location) to the plant infrastructure rather than to the number of personnel affected. The methodology is based on achieving a level of individual risk within the broadly acceptable region (as defined by the UK HSE, 1989). However there are some significant pitfalls which are described in CIA 2010. For further details of this methodology see Bakke and Hanson, 2003; Chamberlain 2004; and CIA 2010.

For the purposes of RP 752 compliance, it is possible to set criteria based on the exceedance, assuming that the exceedance is consistently translatable to an occupant vulnerability.

Risk Index

A risk index can be calculated for this example by multiplying each scenario frequency by the expected number of serious injuries or fatalities. This results in a parameter known as the aggregate risk index or PLL (or Potential Loss of Life) as shown in Table 9.7.

Table 9.7. Risk Index (Aggregate Risk) Calculation

Unit	Incident Frequency (/yr)	Occupant Vulnerability	Building Occupancy	Occupancy Time Fraction	Outcome Frequency Occurrences /Year	No. of Serious/Fatal Injuries	Fatalities /Year
	$2.3x10^{-4}$	0.3	5	0.030	$6.9x10^{-6}$	1.5	$1.0x10^{-5}$
	$2.3x10^{-4}$	0.3	45	0.060	$1.4x10^{-5}$	14	$1.9x10^{-4}$
1	$2.3x10^{-4}$	0.3	10	0.060	$1.4x10^{-5}$	3.0	$4.1x10^{-5}$
	$2.3x10^{-4}$	0.3	100	0.060	$1.4x10^{-5}$	30	$4.1x10^{-4}$
	$2.3x10^{-4}$	0.3	7	0.118	$2.7x10^{-5}$	2.1	$5.7x10^{-5}$
	$3.2x10^{-4}$	0.6	5	0.030	9.5 x10	3.0	$2.8x10^{-5}$
	$3.2x10^{-4}$	0.6	45	0.060	$1.9x10^{-5}$	27	$5.1x10^{-4}$
2	$3.2x10^{-4}$	0.6	10	0.060	$1.9x10^{-5}$	6.0	$1.1x10^{-4}$
	$3.2x10^{-4}$	0.6	100	0.060	$1.9x10^{-5}$	60	$1.1x10^{-3}$
	$3.2x10^{-4}$	0.6	7	0.118	$3.7x10^{-5}$	4.2	$1.6x10r^{4}$
	$9.1x10^{-4}$	0.1	5	0.030	$2.7x10^{-5}$	0.5	$1.4x10^{-5}$
	$9.1x10^{-4}$	0.1	45	0.060	$5.5x10^{-5}$	4.5	$2.5x10^{-4}$
3	$9.1x10^{-4}$	0.1	10	0.060	$5.5x10^{-5}$	1.0	$5.5x10^{-5}$
	$9.1x10^{-4}$	0.1	100	0.060	$5.5x10^{-5}$	10	$5.5x10^{-4}$
	$9.1x10^{-4}$	0.1	7	0.118	$1.1x10^{-4}$	0.7	$7.5x10^{-5}$
PLL = $6.5 x10^{-3}$ fatalities per year							

Summing the expected fatalities results in a PLL of 6.5×10^{-3} expected fatalities per year for the occupants of the cafeteria. Most owner/operators do not use PLL or other risk index measures unless the calculations are the basis for determining the cost-effectiveness of risk mitigation measures.

9.4 INTERPRETATION AND USE OF RISK MEASURES

This Guideline discusses risk in the context of whether or not the perceived level of risk is tolerable. As noted by the United Kingdom (U.K.) Health and Safety Executive (HSE, 1992):

"Tolerability does not mean acceptability. It refers to a willingness to live with a risk so as to secure certain benefits and in the confidence that it is being properly controlled. To tolerate a risk means that we do not regard it as negligible or something that we might ignore, but rather as something we need to keep under review and reduce still further if and as we can."

Recommending risk tolerance criteria is beyond the scope of this book. Further, risk tolerance is company-specific and each company should consider establishing criteria that reflect company goals and objectives as well as any applicable regulations. Concepts and examples for developing criteria are described in the CCPS book, "Guidelines for Developing Quantitative Safety Risk Criteria" [CCPS, 2009b].

In performing any risk analysis, it should be remembered that risk measures, at best, are only estimates of possible scenario frequency and consequences. All risk measurements have uncertainties. In some situations, the uncertainties can be significant. The fact that risk measurement is imprecise should be a consideration in any risk-based decision-making process. Section 4.5 of the CCPS book, *Guidelines for Chemical Process Quantitative Risk Analysis*, [CCPS, 2000] provides further discussion of uncertainty in risk decision making.

Risk analysis is most effectively used to compare alternatives. With comparative studies, utilizing the same methodologies and assumptions, the uncertainties in the risk analysis tend to become less important. Risk analysis studies that are not being used to compare alternatives can benefit by the development of criteria or methodologies against which the estimated risk levels can be judged.

See Section 4.6 for guidance on how to put risk measures in perspective, to determine the "tolerability" of a risk.

10 MITIGATION PLANS AND ONGOING RISK MANAGEMENT

If the company's building siting evaluation criteria (whether consequence-based, risk-based or spacing table-based) have not been met following the siting evaluations for permanent buildings, then a mitigation plan that includes the planned actions and a schedule for completing them is developed in accordance with RP-752. If portable buildings do not meet the company's criteria, the buildings may be moved in lieu of other mitigation actions.

10.1 DEVELOPMENT OF MITIGATION PLANS

API RP-752 recommends that a mitigation plan include the mitigation measures and the schedule for implementation, and both the mitigation measures and schedule should be documented. Such plans may include all of the buildings that did not meet the owner/operator's criteria for explosion, fire, and toxic release, or separate plans for each building may be developed. RP-752 also provides hierarchy of mitigation measures, which follows inherently safer design principles.

10.1.1 Selection of Mitigation Measures

If the company's building siting evaluation criteria (whether consequence-based, risk-based or spacing table-based) have not been met following the siting evaluations, the owner/operator may select the mitigation approach and may choose to:

- Eliminate the hazard.
- Move the building (if portable).
- De-occupy the building and relocate personnel into buildings that meet the criteria.
- Select and implement passive mitigation measures such as:
  - Reducing the quantity of material that can contribute to the hazard, or
  - Strengthening or otherwise modifying the building in question.
- Select and implement active mitigation measures such as:
  - Installation of additional shut-off valves or alarm systems
  - Install HVAC isolation systems.

Passive mitigation measures should, if properly designed, have a higher success probability and require less ongoing maintenance than other approaches. RP-752 provides the hierarchy of mitigation measures shown in Table 10.1. All mitigation measures that are effective in bringing the building siting to within the owner's acceptance criteria are allowable.

Additional information on passive, active, and procedural mitigation measures is provided in Table 10.1, Table 10.2, Table 10.3, and Table 10.4.

Note that these measures are considered suggestions and not requirements, since the most effective approaches to take will vary for each site. Also, this list should not be considered limiting; it is quite possible that measures other than those listed would be effective in a given situation. Some release mitigation strategies are described in great detail in the literature (CCPS 1997, Fthenakis 1993).

Table 10.1. Hierarchy of Mitigation Measures (RP-API, 2009)

		Example Measure
Passive	Eliminate hazard	Substitute with nonhazardous material/process conditions
	Prevent release (i.e., reduce frequency of scenario)	Upgrade metallurgy or design of equipment Reduce leak sources (eliminate flanges, drains, small bore piping, etc.) Rate equipment for maximum upset pressure
	Control size of scenario	Minimize confinement Minimize congestion Utilize spill control dikes, curbs, etc. to limit extent of pool fires and limit vapor dispersion from pools of flashing liquids Minimize release rate – provide process flow restrictions (either limiting pipe size of adding restricting orifices) to reduce the potential severity of a release from downstream equipment Reduce inventory of hazardous material (can reduce duration of fire and gas release scenarios)
	Mitigate effect to building occupants	Relocate personnel (especially personnel that are not essential) Design or upgrade existing building to protect occupants from explosion, fire or toxics Tightly seal windows and tight double doors (airlocks) to minimize toxic/flammable gas and smoke ingress
Active	Prevent release (i.e. reduce frequency of scenario)	Safety instrumented systems
	Control size of scenario	Fire and gas/emergency shutdown systems (reducing quantity released) Fixed/automatic active fire fighting systems
	Mitigate effect to building occupants	Issue occupants with personal protective equipment (PPE) for hazards HVAC air intake shut down on detection of flammable/toxic gas
Procedural	Prevent release (i.e. reduce frequency of scenario)	Mechanical integrity inspection Permits for hot work, lockout/tagout, line breaking, lifting, etc. Sampling to prevent contamination of reactive materials
	Control size of scenario	Manual active fire fighting systems
	Mitigate effect to building occupants	Emergency response plan including, as appropriate: evacuation, escape routes, shelter-in-place, etc. Evacuate building occupants during start-up and planned shutdowns

Table 10.2. Passive Mitigation Measures

Type	RP-752 Examples	Discussion
Eliminate hazard	• Substitute with non-hazardous material/process conditions	Where economically feasible, this should almost always result in a lower-risk condition. Exceptions might involve the introduction of new risks (hazards). (The MoC connected to a change such as this would likely consider the hazards associated with introduction of a new chemical, new reactions, new hazards, etc.)
Prevent release	• Upgrade metallurgy or design of equipment • Reduce leak sources (eliminate flanges, drains, small bore piping, etc.) • Rate equipment for maximum upset pressure • Use of double-walled piping.	It should be possible to quantify the first of these using RBI or similar technology. The second option is generally desirable, but may be constrained by operating/maintenance requirements. If the third option is considered, the true maximum upset condition should be carefully thought through, since providing equipment with a higher pressure rating poses the potential of creating a higher stored-energy source if that pressure can be exceeded. Double-walled piping and similar strategies may be defeated by some failure causes (e.g. external contact)
Control size of scenario	• Minimize confinement • Minimize congestion • Utilize spill control dikes, curbs, etc. • Minimize release rate – provide flow restrictions • Reduce inventory of hazardous material	The first two bullets have the effect of reducing the magnitude of a potential explosion (as well as providing better emergency access/egress). Thus, all else being equal, there would be a preference for wider spacing between equipment,* use of grated decks vs. solid decks, etc. It should be recognized that dikes and curbs are not necessarily foolproof. It is possible for large releases to wash over (or through) a dike; more commonly, a rainwater drain valve from a diked area is left open, or the capacity of drainage from a curbed area is inadequate.
Mitigate effect to building occupants	• Relocate personnel • Design or upgrade building to meet potential MCEs • Tightly seal windows and doors to prevent gas and smoke ingress	It is possible under some risk criteria to reduce risk by simply dividing a person's time between different buildings, each of which may pose the same or even higher risk than the current location. Such a "strategy" is not permissible.

*Albeit at some additional cost. An increase in piping lengths could translate to greater leak frequency.

Table 10.3. Active Mitigation Measures

Type	RP-752 Examples	Discussion
Prevent release	• Safety instrumented systems	A subject matter expert should determine the frequency reduction credit. Frequency reduction credits for an SIS system are based upon enforcement of a prescribed maintenance/testing program.
Control size of scenario	• Fire and gas/emergency shutdown systems • Fixed/automatic active fire fighting systems	The reliability levels for these systems depend upon enforcement of prescribed test/inspection programs. These systems should be designed to resist the event of interest – e.g. a fire should not be able to damage or prevent access to equipment intended to fight the fire. The design and activation of the system should be carefully thought out. A balance should be drawn against competing risk factors, e.g.: • Automated vs. manual activation of emergency system – Automated activation may result in spurious trips that could cause a hazard or process upset; manual activation may not occur quickly enough to defeat the hazard. • Response time – A realistic assessment of operator behavior should be conducted. Despite instructions, if activation of an emergency system causes other problems (e.g. drenching of an operator in the deluge area) an operator may take seconds or minutes to get field confirmation of the hazard before activating the response. Also, it may take time for the system itself to control, e.g. an automatic HF mitigation system can take up to 5 minutes before water can effectively control the release.
Mitigate effect to building occupants	• Issue occupants with personal protective equipment (PPE) for hazards • HVAC air intake shut down on detection of flammable/toxic gas	In the first case, the PPE inventory and drill/testing program should be rigorously controlled. In the second case it is useful to have detection that can also sense when the vapor cloud has passed. During the exposure, the building will likely have 'breathed' in some of the gas. The sooner the 'all clear' condition is known, the sooner clean air can be reintroduced to the building to purge any hazardous vapors inside.

Table 10.4 Procedural Mitigation Measures

Type	RP-752 Examples	Discussion
Prevent release	• Mechanical integrity inspection • Permits for hot work, lockout/tagout, line breaking, lifting, etc. • Sampling to prevent contamination of reactive material	The benefits of inspection can be quantified using RBI or related approaches. The work permit system should be routinely monitored and audited.
Control size of scenario	• Manual active fire fighting systems • Restricting traffic flow near process areas to prevent unnecessary ignition sources or accidental impacts on equipment.	The reliability levels for firefighting systems depend upon enforcement of prescribed test/inspection programs.
Mitigate effect to building occupants	• Emergency response plan including, as appropriate: evacuation, escape routes, shelter-in-place, etc. • Evacuate nonessential personnel during start-up and planned shutdowns.	The first case requires periodic training/testing, posted maps, etc. The second case is a recognition that a disproportionate number of incidents occur during transient conditions such as startups and shutdowns.

10.1.2 Mitigation Schedule

RP-752 does not prescribe a time frame for completing implementation of the mitigation strategy. The owner/operator develops a timeline for implementation of mitigation measures. Companies then track the implementation of the mitigation plan in a manner similar to that used for PHAs. Some mitigation measures may take several years to completely implement. There is an expectation that the program be developed and implemented "promptly" like other Process Hazard Analysis (PHA) recommendations.

Although not required, it may be possible to integrate the follow-up measures from a building siting evaluation into other risk management program activities such as the systems commonly used to track recommendations from PHAs, compliance audits, or incident investigations. Integration into existing programs may assure that building risk mitigation strategies are treated with the same level of attention as other conditions posing similar risks.

The building siting evaluation action items should be continually tracked, and their resolution incorporated in subsequent updates to the building siting evaluation.

10.1.3 Interim Measures

A risk analysis of the interim period (the time until the final mitigation measures are implemented) may indicate that the risks are significant but can be tolerated temporarily. Like a temporary MOC, the interim measures are put into place for a specified period of time.

Table 10.5. Examples of Situations in Which Interim Risk Management Measures May be Necessary

Situation	Long-Term Solution	Potential Interim Measure(s)
Existing control room cannot withstand projected blast load.	Move control functions to centralized remote control building (implementation period ~ 3 years).	1) Remove non-essential personnel during startups and shutdowns. 2) Close up windows with reinforced masonry. 3) Move scheduled inspection program for unit from 2nd upcoming turnaround to the next turnaround.
Contractor meeting/break rooms are too close to process units (explosion and toxic issue)	Convert unused remote warehouse to house contractors (implementation ~ 4 months for HVAC and communications upgrades).	1) Provide tent facilities for interim period. Locate in remote area and provide communication link between Control Room and tent area to warn of any releases. 2) Develop emergency weather evacuation plan for tornadoes, etc.
Warehouse building provides too many openings to prevent toxic cloud ingress.	Install rapid closing doors; provide additional toxic gas detectors between sources of potential hazard and drum handling unit with audible alarms. (implementation period ~ 8 months) Provide a room which can be used for shelter-in-place for toxic material release with escape route away from source of toxic material.	1) Institute policy to keep doors and windows closed during specified unit startups and shutdowns, while providing additional fans, etc. for operator comfort. 2) For large openings such as truck access bays, install vertical plastic strips to minimize air flow. 3) Utilize rear-facing truck bays when possible, and keep unused bay doors closed.
Vehicular traffic too great near a process unit (potential ignition sources) and impact hazard.	Develop traffic plan; acquire bus service to route people through site, and prohibit personal vehicle traffic.	1) Prohibit personal vehicle traffic, and allow only equipment traffic and traffic by foot. 2) Provide for exceptions due to health or extreme weather conditions.
Insulator's shop too close to tank farm (pool fire hazard).	Move insulators to a new location (~ 12 months to implement)	1) Provide vehicle parking and building entrance on the side of the building facing away from the tank farm. 2) Where practical, move inventories to a more remote tank.

10.2 BUILDING MODIFICATIONS

10.2.1 Structural Strengthening to Increase Protection from Explosion Hazards

Many buildings can be hardened or upgraded to increase their blast resistance. Such upgrades are usually engineered to add a specified level of blast resistance. Options for upgrading blast resistance of an existing building may include the strengthening of the existing deficient structural members to provide additional members to add resistance to the blast loading. Steel members may be strengthened by securing additional steel to the flanges or chords (in case of flexural deficiencies) or the web (for shear deficiencies). Concrete structures may be strengthened with fiber overwraps or with additional concrete cast or pneumatically placed and tied to the existing element. Other upgrade measures might include adding supporting members to increase resistance and reduce unsupported spans, strong-backing walls for increased resistance, through-bolting of walls to roofs, floors, and intersecting walls to improve overall structural integrity, and replacing or reinforcing doors and windows with blast-resistant elements.

The Federal Emergency Management Agency has published FEMA 426, "*Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings*" (FEMA 2003), and FEMA 453, "*Safe Rooms and Shelters - Protecting People Against Terrorist Attacks*" (FEMA 2006). While both of these documents are intended for antiterrorism projects, many of the techniques and approaches presented are directly applicable to protecting building occupants from industrial hazards.

One method for improving protection of existing buildings from certain types of explosions is to provide a wall or barrier between the explosion source and the building. A barricade wall is most useful for bursting pressure vessels, BLEVEs, and condensed phase reactions since its main advantage is to provide fragment protection to a building. To be most effective, a barricade wall must be located close to the explosion source so as to intercept fragments early in their trajectory. Blast walls, which are intended to protect the building against the explosion overpressure, must be near the protected building to be effective. With increasing distance from the blast wall, the pressure and impulse defract around or over the wall and return to levels that would occur without the blast wall, or in some geometries exceed the blast load without the blast wall. In many situations, the installation of blast walls is very expensive and impractical.

Another approach for providing blast protection for an existing building, particularly if it is small, is to enclose it in an independently constructed blast-resistant enclosing structure. Such a structure could be designed for large deformations for evaluation-case explosion scenarios, provided enough clearance exists to avoid collateral damage to the protected building.

Masonry walls may be reinforced by the addition of steel tubes that span from the floor slab to the roof diaphragm. This upgrade allows the posts to carry the load vertically and the masonry only needs to span horizontally between the posts. The upgrade requires careful consideration of the post and wall response as well as the attachment between the posts and the wall. An implementation of this upgrade is shown in Figure 10.1. Additional reinforcing may be required to secure door or window frames to the walls as shown in Figure 10.2 and Figure 10.3.

Figure 10.1. Steel Posts Added to Exterior of Masonry Wall

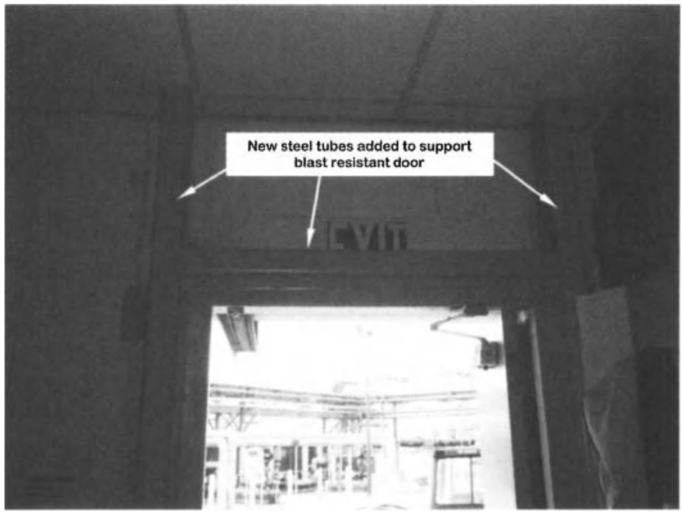

Figure 10.2. Additional Steel Framing Inside of Upgraded Door

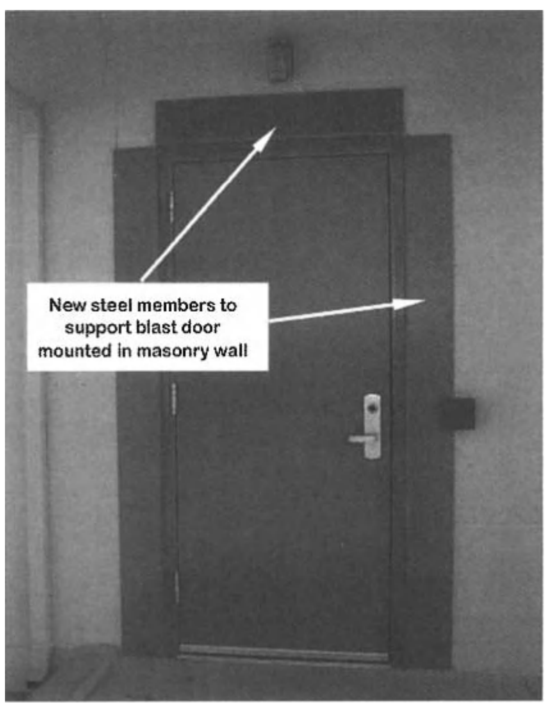

Figure 10.3. Steel Framing around Door to Secure to Masonry Wall

Pre-engineered metal buildings can be upgraded with addition of new wall girts and the strengthening of framing members as shown in Figure 10.4. Similarly, new roof purlins may be installed as required as shown in Figure 10.5. The addition of new girts and purlins serves to strengthen the wall panels by decreasing their span and reduces the load on the existing girts and purlins by reducing the contributory area (spacing) for each member.

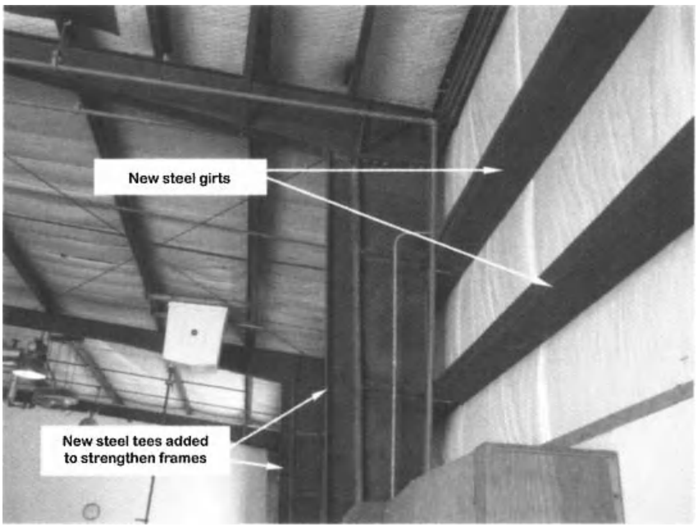

Figure 10.4. New Girts and Framing Members in Pre-Engineered Metal Building

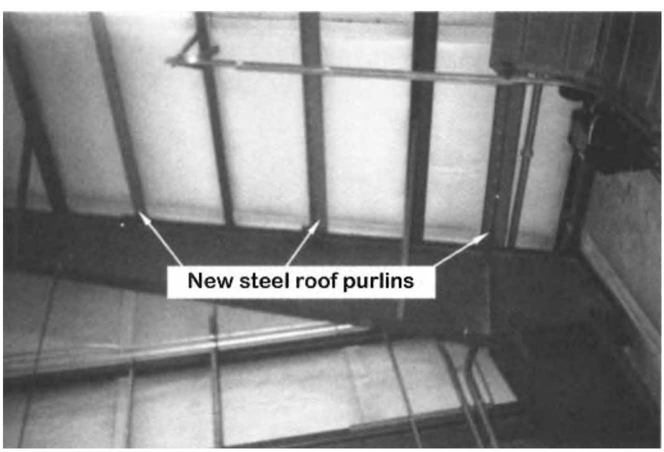

Figure 10.5. New Roof Purlins Installed Between Existing Purlins

10.2.2 Structural Modifications to Mitigate Fire Hazards

A building that fails to meet the owner's acceptance criteria for fire may fail for one or more of several reasons. Some examples of the potential to fail to meet criteria and candidate structural modifications are:

- If the predicted temperature within a building rises above the owner-selected criteria, additional coatings or insulation materials may be applied, or water spray added to reduce the temperature increase. Note this situation is only likely to occur within a metal building such as a blast-resistant module (BRM).
- If jet fire impinges on a building, a barricade could be installed to prevent the jet from reaching the building, or additional insulation added to mitigate the thermal load on the building.
- Providing additional protected egress routes.

Where the fire hazard (or risk) does not meet owner/operator criteria, other measures may be warranted. The Chemical Industries Association in the U.K. has published a useful guide (CIA, 2010) to building design in process plants. Among the many considerations they discuss are the following suggestions for mitigating fire hazards:

- *"Reduce the pool size by curbing, so keeping the fire small.*
- *Increase separation distance between the building and the hazard.*
- *Providing thermal protection to the building by thermal shielding.*
- *Elimination of windows, or fitting of heat resistant windows; permanently closing any opening windows facing sources of fire.*
- *Cladding building walls to increase fire resistance.*
- *Smoke seals can be fitted to doors and emergency doors can be made automatic self closing."*

10.2.3 Structural Modifications to Mitigate Toxic Hazards

A building that fails to meet the owner's acceptance criteria for toxics may be modified using the following:

- Installation of windows and doors with lower infiltration rates, or the addition of double entry plenums at entrances. A double entry plenum is one in which the air pressure is higher in the plenum than the outside air, but lower than the pressure in the building. Thus when an individual opens the outer door, the air in the plenum pushes potential toxics to the exterior. Once this door is closed and the door from the interior of the building to the plenum is opened, the clean air flows from the building into the plenum.

- Provision of an elevated air intake.
- Provision of a filtered or scrubbed air intake.
- Interior modifications to the building to allow that portion of the structure to be used as a Shelter-in-Place (use of an isolatable "safe space).

Chapter 3 of the Federal Emergency Management Agency's publication FEMA 453 (FEMA, 2006) provides guidance on the design and management of "safe rooms" that can be applied to toxic risk mitigation for building occupants. While the features mentioned by FEMA are developed for a somewhat different purpose, and are not required to satisfy RP 752, there are many useful ideas in this source that can be adopted or adapted for use for toxic hazard/risk management for facilities covered by RP 752.

The Chemical Industries Association in the U.K. has also published a useful guide (CIA, 2010) to building design for toxic hazards in process plants. Among the many considerations they discuss are the following that they consider to be "essential" for toxic design:

- *"Doors and windows must close properly with adequate seal.*
- *Doors must be self closing and with non-shrink seals [material does not shrink and create gaps] on all four edges.*
- *Frames of doors and windows must be of non-shrink type under normal use and have non-hardening mastic sealant applied to all four edges.*
- *Doors and windows must resist any overpressure that might accompany or precede the release of toxic gas from a pressurised source if the toxic risk resulting for a catastrophic failure is judged to be unacceptable.*
- *Penetrations for cables and ducts must be sealed.*
- *Service (e.g. water, gas, electricity) trenches, cellars or ventilated voids/cable ducts must be sealed.*
- *Air bricks, and other ventilation penetrations (e.g. those to limit condensation) which cannot be effectively sealed in an incident, must be avoided.*
- *Gas leakage routes at the wall to ceiling joint of the toxic gas refuge must be eliminated. Special attention needs to be taken if the toxic gas refuge has a false or suspended ceiling.*
- *Openings between the toxic refuge and the roof space must be sealed.*
- *The floor construction must be sealed against ingress of toxic gas (especially in temporary buildings).*
- *All mortar joints must be tight, especially around the lintels and where there is through-the-wall flashing.*

- *Joints between or associated with profiled cladding/inner wall and ceiling must be sealed with non-hardening mastic compound or stitch fixings."*

Several other "desirable" features are also provided in the CIA guide (CIA, 2010), along with guidance on providing sufficient space and breathable air for each person in a shelter (approximately 0.06 m^3 per person per minute of occupation).

Guidelines for Evaluating Process Plant Buildings for External Explosions, Fires, and Toxic Releases, Second Edition
by Center for Chemical Process Safety

11 MANAGING THE BUILDING SITING PROCESS

11.1 MANAGEMENT OF CHANGE

Systems should be in place to review and update building siting evaluations to ensure that risk continues to meet owner/operator criteria. Changes related to the explosion, fire and toxic release hazards, the protection offered by a building, and the occupancy of a building may trigger a management of change (MOC) evaluation. The change may be permanent or temporary, which affects the actions taken in the MOC. Such situations may include, but are not limited to:

- Changes to plant operations, processes or equipment (including decommissions or additions) that cause a change in potential for, or severity of, explosion, fire, or toxic impacts at the building location;
- A new building intended for occupancy is added to the facility;
- A modification or addition to an existing building occurs that could cause a change in the potential for, or severity of, explosion, fire, or toxic material release impacts;
- The building's occupancy status changes from "not intended for occupancy" to "intended for occupancy";
- The number of personnel or time spent inside the building increases either permanently or for a defined period of time.

When the change that triggered the MOC is permanent, a revision of the building siting evaluation may be necessary. For change that is for a defined period of time, interim risk mitigation measures may be appropriate.

A robust MOC process applied to facility siting will result in documentation that is kept up to date. This documentation will assist in periodic revalidation of the facility siting program, such as is required for Process Hazards Analyses in the U.S. PSM regulation.

11.1.1 Managing the Occupancy of the Building

Common building occupancy issues that owner/operators have dealt with are described in Table 11.1.

Table 11.1. Examples of Unintentional Risk Increases

Situation	Potential Problem	Potential Solution
Staff hiring or relocation (increased risk)	Staff moved from lower (or no) risk to higher risk location without informing risk managers	Institute policy treating people relocations within the Management of Change process
Facility siting study prepared that only incorporates currently-occupied buildings	Unoccupied buildings do not appear on an action list. They may therefore be perceived as being "safe" and occupied at a later date	Same as above Include all structures, even unoccupied structures, in the facility siting analysis
Facility siting study only considered hazards in the vicinity of existing structures	Hazards in more remote location (e.g. tank farms) may exist, but someone locating a building may review the report and conclude that the area is a safe zone	Same as top item Include all hazards, even remote hazards, in the facility siting analysis
Contractor trailer is sited near a process area for an upcoming turnaround in conformance with RP-753	Contractor personnel occupy the building prior to the process unit being shut down, resulting in higher risk than owner/operator criteria allows	Disallow occupancy of the trailer except under previously identified safe situations
Decision is made to (re)locate an operator's shelter far away from the process	Immediate risks due to process events may be reduced, but other risks may be introduced: Risk of injury while walking from shelter to the process area (vehicular or other) Risk of event escalation due to delayed response time	Conduct analysis (qualitative or quantitative) to determine optimal shelter location. Identify key emergency scenarios requiring field operator intervention Evaluate emergency response times vs. likely process hazard escalation for these cases. Balance with expected building damage level at optional locations for the MCEs assessed in the siting study

11.2 DOCUMENTATION REQUIREMENTS

11.2.1 Building Siting Procedure

The overall building siting evaluation process provides a framework that is a useful structure for documentation. The major steps in the process and potential documentation for each step are identified in API RP-752. They include:

- Building siting evaluation procedure – describe the overall procedure followed to accomplish the building siting evaluation.
- The assessment approach – identify whether a consequence or risk-based approach was used, or if the spacing tables approach was used. RP-752 does not give preference to either the consequence- or risk-based approaches, so the documentation does not need to justify the approach but needs to clearly state the approach used. The use of the spacing table approach is applicable only for fire hazards.
- Scenario selection basis – identify how scenarios were selected, and how past industry experience was considered. This is an appropriate place to identify the basis for selecting the MCE if a consequence-based approach is used.
- Analysis methodologies – identify the analysis methods used for the fire, explosion, and toxic hazards present.
- Applicability of analysis methodologies – a statement that sets forth why the selected methods are appropriate for the scenarios the methods are applied to.
- Data sources used in the analysis – the appropriate source of the information is identified. While not stated in RP-752, the intent is to ensure that the evaluation is applicable to the existing or planned future conditions on the site at the time the evaluation was performed.
- Applicability of data sources – if data such as operating temperatures or failure rates are used, state why the data are applicable to the scenarios considered if this is not apparent.
- Building siting evaluation criteria – identify the criteria selected by the owner/operator.
- Results of the analysis – identify which buildings meet the selected siting evaluation criteria and which do not. The mitigation plans for buildings that do not meet owner/operator requirements may be a separate document.

11.2.2 Mitigation Plan

The development of mitigation plans is discussed in Chapter 10. Mitigation plans may take time to develop. There are often multiple options to consider, and evaluation of the options may require some engineering analysis. For example, an owner/operator may wish to evaluate upgrading an existing building to improve blast resistance versus the cost of constructing a new building. Implementation of mitigation measures may require an extended period of time, such as a capital project. In circumstances where an engineering analysis is needed to evaluate mitigation options, the engineering study can be a scheduled task in the mitigation plan with a specified schedule. The selected mitigation option may change the mitigation plan tasks and schedule, in which case the plan can be updated and the reason for the plan changes documented.

11.3 DOCUMENTATION OF MITIGATION SYSTEMS CRITERIA AND PERFORMANCE

Building design criteria as they apply to each hazard type are part of the building siting evaluation documentation. The criteria may be further developed into specifications for the building structure and equipment that are used to procure mitigation systems. For example, the criteria for protection from toxic material ingress may be a limitation on air changes per hour, which may be implemented with specifications on seals at joints, penetrations, doors and windows.

Active protection systems have additional documentation of the performance. Active systems have maintenance and monitoring throughout the life cycle of the system to ensure that the protection level is maintained at the intended level. Examples of active systems include HVAC, gas detection, and safety instrumented systems. The documentation includes verification that the protection system was implemented, effective, and is in continuous use over the life cycle of the building.

Similar to the standards for testing, inspecting, and monitoring changes to process equipment, building design features should be subject to regular inspection, testing, and management of change.

11.3.1 Documentation of Mitigation Actions

Mitigation actions are performed after the building siting evaluation has been concluded. As a result, the mitigation actions are often not mentioned in the building siting evaluation documentation. Documentation of the mitigation action creates a record of the action adopted and demonstrates that the risk has been mitigated. The documentation also provides a basis for owner/operators to continue to monitor the mitigation measure to ensure that it is appropriately maintained and implemented as long as it is needed.

Documentation of mitigation actions may include:

- Mitigation options considered;
- Rationale for selecting the final mitigation option;
- Mitigation system performance criteria;
- Maintenance requirements;
- Verification that the mitigation system was implemented properly;
- Ongoing system performance monitoring to verify that the mitigation system continues to perform as intended.

11.4 MAINTAINING DOCUMENTATION "EVERGREEN"

If all the buildings evaluated meet the owners' criteria, no additional documentation is required beyond that listed in the bullets. However, ongoing follow-up and maintenance activities are always required as discussed in Chapter 10, including managing occupancy and Management of Change. Examples of follow-up and maintenance activity documentation may include:

- Record of periodic inspection of buildings designated not intended for occupancy to ensure they have not become occupied.
- Proper installation of building features specifically included for risk mitigation, such as an air filtration system or blast door.
- Maintenance records for HVAC controls and sensors needed for control of toxic vapor infiltration.
- MOC documentation for an increase in occupancy of building housing essential personnel near a process unit.
- Siting evaluation for expansion of an occupied building.
- Temporary MOC for a motor control center (MCC) project requiring contractors to work in the MCC for several weeks modifying electrical equipment.
- Periodic evaluation of administrative controls that are part of the risk mitigation plan to demonstrate that the controls are in place, training in the procedures is current, and the administrative controls are effective. An evacuation plan is an example of an administrative control for toxic and fire hazards.

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