Chemical Process Safety

Fundamentals with Applications

Fourth Edition

Daniel A. Crowl • Joseph F. Louvar

International Series in the Physical and Chemical Engineering Sciences

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Pearson

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Library of Congress Control Number: 2019930097

Cover image: Travel Mania/Shutterstock

ISBN-13: 978-0-13-485777-0
ISBN-10: 0-13-485777-1

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Preface

We are pleased and delighted to offer the fourth edition of our textbook on chemical process safety. It is amazing to us that our original concept from the late 1980s—to produce a process safety textbook for undergraduates that reflects industrial practice—still endures and is just as valuable today as when we first envisioned this resource.

For most traditional chemical engineering courses—such as stoichiometry or thermodynamics—the technical content has been well established for many years. This is not the case for process safety, which remains a dynamically evolving field. This ever-changing nature presented an enormous challenge to us when we sought to update our text to match current technology and industrial practice.

All textbooks have several requirements. First, the content must be of value to the student or reader and must be presented in a clear and well-organized fashion. Second, the content must develop progressively, working from what the student knows to what the student doesn't know. Third, the content must be active, with lots of worked examples, figures, and tables. In our case, the textbook must also reflect industrial practice. These requirements are not easy to achieve, but we have strived to meet them in all editions of our text.

The first edition of our text was published in 1990. The main effort with the first edition was to develop a workable outline—which took a considerable effort because what we proposed had never been done before. Once the outline was developed, we then needed to collect the technical content from industry and modify and organize it for student instruction.

The second edition was published in 2002. This text was primarily an incremental edition with content additions that we realized were missing in the first edition. In particular, we added new content on flammability, primarily on the use of the flammability triangle diagrams and how they are applied to estimate target concentrations.

The third edition was published in 2011. This edition added a new chapter on chemical reactivity—which really should have been included in the first edition. The major development here was to recast the theoretical model into dimensionless form to simplify the equations for student manageability. We also continued our efforts to update the text to current industry practice.

The fourth edition was a major challenge. Process safety technology and industrial practice had changed substantially since the publication of the third edition. This resulted in a major overhaul of the entire text. Several chapters were completely rewritten, and all chapters had major modifications. We also removed some content that we deemed to be of lesser value since we wanted to reduce the page count. This removed content is still available for instructors on the Pearson Instructor Resource Center (https://www.pearson.com/us/higher-education/subject-catalog/download-instructor-resources.html).

In the first three editions, we developed new homework problems for each edition, with the result that the third edition contained more than 100 pages of homework. We decided to reduce the homework content significantly with the fourth edition, since homework appears to have less value in today's teaching environment. The 100 pages of homework from previous editions remains available for instructors on the Pearson Instructor Resource Center (https://www.pearson.com/us/higher-education/subject-catalog/download-instructor-resources.html).

Acknowledgments

We have an enormous number of people to thank for helping us with the fourth and previous editions. As the saying goes, "We stand on the shoulders of giants."

Many of the folks who assisted with previous editions have passed away, including Trevor Kletz, Gerry Boicourt, Jack Wehman, Walt Howard, Stan Grossel, Reid Welker, Charles Springer, and Ron Darby.

For this fourth edition, we thank Ray Mentzer and Ken First, who served as technical reviewers. Both Ray and Ken have both industrial and teaching experience, so their edits were very helpful, and served as a compass for our work.

We would also like to thank Ken Tague, Don Eure, Scott Tipler, Chris Devlin, Marc Levin, John Murphy, Roy Sanders, Amy Theis, Vincent Wilding, Chad Mashuga, Bob Johnson, Tom Spicer, and Ron Willey for making many content suggestions. If we missed someone, we apologize for our omission.

The Safety and Chemical Engineering Education (SACHE) faculty workshops held at a variety of chemical companies, including Dow, BASF, ADM, Cargill, Reliance, and Wacker, were instrumental in providing information and educational materials on industrial practice for this fourth edition.

The American Institute of Chemical Engineers' (AICHE) Center for Chemical Process Safety (CCPS) provided an enormous reference library and many experienced and willing industrial contacts.

Finally, we thank our wives and loved ones, who endured our emotional and physical absence during this sustained project.

We hope that this textbook continues to prevent chemical plant and academic accidents and contributes to a much safer future.

—Daniel A. Crowl
Salt Lake City, UT
—Joseph F. Louvar
Milwaukee, WI

Register your copy of *Chemical Process Safety*, *Fourth Edition,* on the InformIT site for convenient access to updates and corrections as they become available. To start the registration process, go to informit.com/register and log in or create an account. Enter the product ISBN (9780134857770) and click Submit. Look on the Registered Products tab for an Access Bonus Content link next to this product, and follow that link to access any available bonus materials. If you would like to be notified of exclusive offers on new editions and updates, please check the box to receive email from us.

About the Authors

Daniel A. Crowl retired from Michigan Technological University in 2015 and he and his wife moved to Salt Lake City, UT. He has taught the required process safety course in Chemical Engineering at the University of Utah as an Adjunct Professor since 2016. He continues to assist with AICHE sponsored faculty workshops hosted by the chemical industry.

Professor Crowl is the Past Herbert H. Dow Professor for Chemical Process Safety and an Emeritus Professor at Michigan Technological University. His research at Michigan Tech included improving the characterization methods for flammable gases and liquids. This work was coupled with BASF's Corporate Engineering and Louvar's safety program to ensure that the work was industrially relevant. This research improved the world-wide standards on flammability.

Professor Crowl received his B.S. in fuel science from Pennsylvania State University and his M.S. and Ph.D. in chemical engineering from the University of Illinois.

He began his teaching career at Wayne State University in Detroit in 1977. In 1985 he spent the summer working at BASF in Wyandotte, MI where he first learned about chemical process safety.

Professor Crowl is CCPS Certified (CCPSC) in process safety.

Professor Crowl is author/editor of several AICHE books on process safety and editor of the safety section in the seventh and eighth editions of *Perry's Chemical Engineer's Handbook*.

Professor Crowl has won numerous awards, including the Merit Award from the Mary K. O'Conner Process Safety Center at Texas A&M University, the Chemical Health and Safety Award from ACS, the Bill Doyle and Walton/Miller awards from the Safety and Health Division of AICHE, the Catalyst Award from the American Chemistry Council and the Gary Leach Award from the AICHE Board.

He is a Fellow of AICHE, ACS Safety and Health Division, and CCPS.

Joseph F. Louvar has a B.S., M.S., and Ph.D. in chemical engineering. He recently retired as a professor at Wayne State University where he taught for ten years after retiring from BASF Corporation. As a professor at Wayne State University, he taught chemical process safety, risk assessment, and process design. At BASF Corporation, he was a director of BASF's Chemical Engineering Department. His responsibilities at BASF included the production of specialty chemicals, and he managed the implementation and maintenance of five processes that handled highly hazardous chemicals covered by Process Safety Management. One of his department's responsibilities included characterizing the hazardous properties of chemicals for BASF's plants and engineering organizations. This responsibility included the management of facilities, specialized equipment, and personnel experts. His safety experts were tied into Crowl's MTU research to improve the fundamental basis. This included flammability, explosivity, and reactivity characteristics of liquids, vapors, and dusts.

Joseph F. Louvar is the author of many safety-related publications and the coauthor of two books, *Chemical Process Safety: Fundamentals with Applications* and *Health and Environmental Risk Analysis: Fundamentals with Applications*. Professor Louvar was chair of the Loss Prevention Committee of the Safety and Health Division of AICHE. He was also the CCPS staff consultant for the Undergraduate Education Committee, currently known as the Safety and Chemical Engineering Education Committee (SACHE). He was the coeditor of AICHE's journal for process safety, *Process Safety Progress.*

Nomenclature

a	velocity of sound (length/time)
A	area (length^2) or Helmholtz free energy (energy/mole); or process component availability; or arrhenius reaction rate pre-exponential constant (time^{-1})
A_t	tank cross sectional area (length^2)
ΔA	change in Helmoltz free energy (energy/mole)
AEGL	acute exposure guidance level
B	adiabatic reactor temperature increase (dimensionless)
C	mass concentration (mass/volume) or capacitance (Farads)
C_0	discharge coefficient (unitless), or concentration at the source (mass/volume)
C_1	concentration at a specified time (mass/volume)
C_p	heat capacity at constant pressure (energy/mass deg)
C_{ppm}	concentration in parts per million by volume
C_V	heat capacity at constant volume (energy/mass deg)
C_{vent}	deflagration vent constant (pressure$^{1/2}$)
C_x	concentration at location x downwind from the source (mass/volume)
$\langle C \rangle$	average or mean mass concentration (mass/volume)
d	diameter (length)
d_p	particle diameter (length)
d_f	diameter of flare stack (length)
D	diffusion coefficient (area/time), or diameter (length)
D_0	reference diffusion coefficient (area/time)

D_m	molecular diffusivity (area/time)
D_{tid}	total integrated dose due to a passing puff of vapor (mass time/volume)
E_a	activation energy (energy/mole)
ERPG	emergency response planning guideline (see Table 5-4)
EEGL	emergency exposure guidance levels (see Section 5-5)
f	Fanning friction factor (unitless) or frequency (1/time)
$f(t)$	failure density function
f_v	mass fraction of vapor (unitless)
F	frictional fluid flow loss term (energy mass) or force or environment factor
FAR	fatal accident rate (fatalities/10^8 hours)
FEV	forced expired volume (liters/sec)
FVC	forced vital capacity (liters)
g	gravitational acceleration (length/time^2)
g_c	gravitational constant (mass length/force time^2)
G	Gibbs free energy (energy/mole) or mass flux (mass/area time)
G_T	mass flux during relief (mass/area time)
ΔG	change in Gibbs free energy (energy/mole)
h	specific enthalpy (energy/mass), or height (length)
h_L	fluid level above leak in tank (length)
h_L	initial fluid level above leak in tank (length)
h_s	leak height above ground level (length)
H	enthalpy (energy/mole) or height (length)
H_f	flare height (length)
H_r	effective release height in plume model (length)
ΔH	change in enthalpy (energy/mole)
ΔH_c	heat of combustion (energy/mass)
ΔH_v	enthalpy of vaporization (energy/mass)
I	sound intensity (decibels)
ID	pipe internal diameter (length)
IDLH	immediately dangerous to life and health (see Section 5-5)
I_0	reference sound intensity (decibels)
I_s	streaming current (amps)
ISOC	in-service oxygen concentration (volume percent oxygen)
j	number of inerting purge cycles (unitless)
J	electrical work (energy)

k	non-ideal mixing factor for ventilation (unitless), or reaction rate (concentration$^{1\text{-m}}$/time)
k_1, k_2	constants in probit a equations
k_s	thermal conductivity of soil (energy/length time deg)
K	mass transfer coefficient (length/time)
K_b	backpressure correction for relief sizing (unitless)
K_f	excess head loss for fluid flow (dimensionless)
K_i, K_∞	constants in excess head loss, given by Equation 4-38
K_G	explosion constant for vapors (length pressure/time)
K_j	eddy diffusivity in x, y, or z direction (area/time)
K_P	overpressure correction for relief sizing (unitless)
K_{St}	explosion constant for dusts (length pressure/time)
K_V	viscosity correction for relief sizing (unitless)
K_0	reference mass transfer coefficient (length/time)
L	length
LEL	lower explosion limit (volume % fuel in air)
$LFL = LEL$	lower flammability limit (volume % fuel in air)
LOC	limiting oxygen concentration (volume percent oxygen)
LOL	lower flammable limit in pure oxygen (volume % fuel in oxygen)
m	mass
m_f	mass fraction
m_0	total mass contained in reactor vessel (mass)
m_{LR}	mass of limiting reactant in Equation (8-36) (mass)
m_{TNT}	mass of TNT
m_v	mass of vapor
M	molecular weight (mass/mole)
M_0	reference molecular weight (mass/mole)
Ma	Mach number (unitless)
MOC, MSOC	Minimum oxygen concentration or maximum safe oxygen concentration. See LOC
MTBC	mean time between coincidence (time)
MTBF	mean time between failure (time)
n	number of moles or reaction order
OSFC	out of service fuel concentration (volume percent fuel)
p	partial pressure (force/area)
p_d	number of dangerous process episodes
p_s	scaled overpressure for explosions (unitless)

P	total pressure or probability
P_b	backpressure for relief sizing (psig)
PEL	permissable exposure level (see Section 2-8)
PFD	probability of failure on demand
P_g	gauge pressure (force/area)
P_{max}	maximum pressure for relief sizing (psig)
P_s	set pressure for relief sizing (psig)
P^{sat}	saturation vapor pressure
q	heat (energy/mass) or heat intensity (energy/area time)
q_f	heat intensity of flare (energy/time area)
q_g	heat flux from ground (energy/area time)
q_s	specific energy release rate at set pressure during reactor relief (energy/mass)
Q	heat (energy) or electrical charge (coulombs)
Q_m	mass discharge rate (mass/time)
Q_m^*	instantaneous mass release (mass)
Q_v	ventilation rate (volume/time)
r	radius (length)
R	electrical resistance (ohms) or reliability
$\overline{R}$	Sachs scaled distance, defined by Equation 6-31 (unitless)
R_d	release duration for heavy gas releases (time)
r_f	vessel filling rate ($time^{-1}$)
R_g	ideal gas constant (pressure volume/mole deg)
Re	Reynolds number (unitless)
S	entropy (energy/mole deg) or stress (force/area)
S_m	material strength (force/area)
SPEGL	short term public exposure guideline (see Section 5-5)
t	time
t_d	positive phase duration of a blast (time)
t_e	emptying time
t_p	time to form a puff of vapor
t_v	vessel wall thickness (length)
t_w	worker shift time
Δt_v	venting time for reactor relief
T	temperature (deg)
T_i	time interval
TLV	threshold limit value (ppm or mg/m^3 by volume)

T_m	maximum temperature during reactor relief (deg)
TMEF	target mitigated event frequency (1/year)
TQ	threshold quantity (mass)
T_s	saturation temperature at set pressure during reactor relief (deg)
TWA	time weighted average (ppm or mg/m^3 by volume)
u	velocity (length/time)
u_d	dropout velocity of a particle (length/time)
$\bar{u}$	average velocity (length/time)
$\langle u \rangle$	mean or average velocity (length/time)
U	internal energy (energy/mole) or overall heat transfer coefficient (energy/area deg time) or process component unavailability
UEL	upper explosion limit (volume % fuel in air)
$UFL = UEL$	upper flammability limit (volume % fuel in air)
UOL	upper flammable limit in pure oxygen (volume % fuel in oxygen)
v	specific volume (volume/mass)
v_f	specific volume of liquid (volume/mass)
v_g	specific volume of vapor (volume/mass)
v_{fg}	specific volume change with liquid vaporization (volume/mass)
V	total volume or electrical potential (volts)
V_c	container volume
W	width (length)
W_e	expansion work (energy)
W_s	shaft work (energy)
x	mole fraction or Cartesian coordinate (length), or reactor conversion (dimensionless), or distance from the source (length)
X_f	distance from flare at grade (length)
y	mole fraction of vapor (unitless) or Cartesian coordinate (length)
Y	probit variable (unitless)
Y_G	gas expansion factor (unitless)
z	height above datum (length) or Cartesian coordinate (length) or compressibility (unitless)
z_e	scaled distance for explosions ($length/mass^{1/3}$)

Greek Letters

α	velocity correction factor (unitless) or thermal diffusivity (area/time)
β	thermal expansion coefficient (deg^{-1})
δ	double layer thickness (length)

ε	pipe roughness (length) or emissivity (unitless)
ε_r	relative dielectric constant (unitless)
ε_0	permittivity constant for free space (charge^2/force length^2)
η	explosion efficiency (unitless)
Φ	nonideal filling factor (unitless), or phi-factor for calorimeter thermal inertia (dimensionless)
γ	heat capacity ratio (unitless)
γ_c	conductivity (mho/cm)
Γ	dimensionless activation energy
χ	function defined by Equation 10-10
λ	frequency of dangerous episodes
λ_d	average frequency of dangerous episodes
μ	viscosity (mass/length/time), or mean value, or failure rate (faults/time)
μ_V	vapor viscosity (mass/length/time)
ψ	overall discharge coefficient used in Equation 10-14 (unitless)
ρ	density (mass/volume)
ρ_L	liquid density (mass/volume)
ρ_{ref}	reference density for specific gravity (mass/volume)
ρ_V	vapor density (mass/volume)
σ	standard deviation (unitless)
σ_x, σ_y, σ_z	dispersion coefficient (length)
τ	relaxation time, or dimensionless reaction time
τ_i	inspection period for unrevealed failures
τ_0	operation period for a process component
τ_r	period required to repair a component
τ_u	period of unavailability for unrevealed failures
ζ	zeta potential (volts)

Subscripts

a	ambient
ad	adiabatic
c	combustion
f	formation or liquid
g	vapor or gas
H	higher pressure
i	initiating event
j	purges
L	lower pressure
m	maximum
s	set pressure
o	initial or reference

Superscripts

°	standard
′	stochastic or random variable

Introduction

Safety is a common denominator across all aspects of life; hence knowledge should always be shared. It is not a matter for industry—it is a matter for humanity.

—Doug Bourne

We believe that the traits required to achieve excellence in safety are the same as those required to achieve outstanding results in all other aspects of our business.

—Ralph Herbert, Vice President of Engineering, ExxonMobil

The learning objectives for this chapter are:

1. Understand the common definitions used for process safety.
2. Explore myths about process safety.
3. Identify components of a safety culture.
4. Discuss individual risk, societal risk, and risk populations.
5. Distinguish between voluntary risk and involuntary risk.
6. Describe safety metrics.
7. Summarize accident and loss statistics.
8. Create a risk tolerance/acceptance and risk matrix.
9. Discuss codes, standards, and regulations related to process safety.
10. Explore safeguards related to chemical process safety.
11. Explain risk-based process safety (RBPS).
12. Describe inherently safer design.
13. Describe the Bhopal, India, tragedy.

The Aluminum Company of America—otherwise known as Alcoa—was founded in 1888 by Charles Martin, who discovered an affordable way to produce aluminum via electrolysis. The company is headquartered in Pittsburgh, Pennsylvania. In 1889, Alcoa developed the first aluminum tea kettle; in 1910, it introduced aluminum foil. Today, Alcoa is the largest supplier of aluminum in the world.

In 1987, however, Alcoa was faltering. Its revenues and profits had fallen, several product lines had failed, and the company had large inventories of unsold product. Many investors considered Alcoa to be a "Rust Belt" company, associating it with the failing steel companies located in Pittsburgh and elsewhere in the United States. In addition, both the employees and unions were unhappy with the company.

As is the case with most companies facing this kind of situation, Alcoa's board of directors decided to hire a new chief executive officer (CEO). They tapped Paul O'Neill, formerly of International Paper, to lead the company.

In October 1987, O'Neill held his first press conference in a swanky hotel in Manhattan, attended by members of the media, investors, and investment managers. All attendees expected O'Neill to announce a new financial management strategy for the company. Instead, O'Neill came to the podium and said, "I want to talk to you about worker safety. I intend to make Alcoa the safest company in America. I intend to go to zero injuries." At this time, Alcoa already had an industry leading safety program.

One investment manager ran out of the press conference declaring, "The board put a crazy hippie in charge and he's going to kill the company! I called my clients and told them to sell their stock!"

But six months later, a tragedy occurred. A young employee in an Arizona plant jumped over a yellow safety wall to repair a piece of equipment and was crushed when the equipment was unexpectedly activated. O'Neill immediately called an emergency meeting of the plant's executives. He stated bluntly: "We killed this man. It's my failure of leadership. I caused his death. And it's the failure of all of you in the chain of command."

O'Neill sent a note to all workers telling them to call him at home if managers didn't follow up on safety suggestions. He received lots of calls about safety, but he also heard a lot of suggestions for other improvements—many of which would substantially reduce costs.

What were the results of O'Neill's safety leadership? In 1986, Alcoa recorded $264 million in net income on sales of $4.6 billion. When O'Neill retired at the end of 2000, Alcoa boasted record profits of $1.5 billion on sales of $22.9 billion. Alcoa's lost work days rate per 100 employees dropped from 1.86 to 0.2 by the end of O'Neill's tenure. In March 2016, that rate was a mere 0.055.

When asked later about the secret to his success, O'Neill stated, "I knew I had to transform Alcoa. But you can't order people to change. So I decided I was going to start by focusing on one thing. If I could start disrupting the habits around one thing, it would spread throughout the entire company." O'Neill's important realization was that safety performance and economic performance were, in his words, "glued together"—with outstanding safety performance resulting in outstanding economic performance. When O'Neill started at Alcoa, he wasn't sure if this approach would work perfectly, but it did.

Safety, in general, is defined as "a strategy for accident prevention." Process safety is safety applied to processes, including chemical processes. Table 1-1 provides a more complete definition of process safety, along with several important definitions provided by the American Institute for Chemical Engineers (AICHE) Center for Chemical Process Safety (CCPS).

Table 1-1 AICHE Center for Chemical Process Safety Definitions Related to Process Safety

Term	Definition	Example
Accident	An unplanned event or sequence of events that results in an undesirable consequence. The scope of the accident description is arbitrary.	A leak in a pressurized vessel containing 500 kg of ammonia.
Conditional modifier	A fractional probability that a particular event occurs.	The probability of a flammable release being ignited is 0.10.
Consequence	A measure of the expected effects of a specific incident outcome case.	A 10 kg/s ammonia leak results in a toxic cloud downwind.
Enabling condition	A fractional probability that a particular circumstance exists. It accounts for the time-at-risk.	The probability of the ambient temperature being low enough to cause a water line to freeze is 0.10.
Hazard	An inherent chemical or physical characteristic that has the potential for causing damage to people, the environment, or property.	A pressurized tank containing 500 kg of ammonia.
Hazard evaluation/ analysis	Determination of the mechanisms causing a potential incident and evaluation of the incident outcomes or consequences.	A Hazard and Operability (HAZOP) study was completed on the distillation column.
Hazard identification	Identification of material, process, and plant characteristics that can produce undesirable consequences through the occurrence of an incident.	The chemicals in the process are toxic and flammable hazards.
Impact	A measure of the ultimate loss and harm of an incident.	A 10 kg/s ammonia leak produces a downwind toxic vapor cloud resulting in local evacuations, an emergency response, plant downtime, and loss of community support.
Incident	The basic description of an event or series of events, resulting in one or more undesirable consequences, such as harm to people, damage to the environment, or asset/ business losses. In general, it is caused by loss of containment or control of material or energy. For chemicals plants, this includes fires/explosions and releases of toxic or harmful substances. Not all events propagate to an incident.	A plant incident involves a leak of 10 kg/s of ammonia producing a toxic vapor cloud.
Incident outcome	The description of the physical manifestation of the incident. This could include toxic release, fire, explosion, and so on.	A leak in an ammonia pipeline results in a toxic release.

(continues)

Table 1-1 AICHE Center for Chemical Process Safety Definitions Related to Process Safety *(continued)*

Term	Definition	Example
Incident outcome case	An incident with more than one outcome.	A chemical release results in both a toxic release and an environmental impact.
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.	The likelihood of operator burns due to a butane leak is estimated at once in 5 years.
Likelihood	A measure of the expected probability or frequency of occurrence of an event. For chemical plants, the frequency is most commonly used.	The frequency of an operator error for the process is estimated at once per month.
Process safety	A disciplined framework for managing the integrity of operating systems and processes handling hazardous substances by applying good design principles, engineering, and operating practices. It deals with the prevention and control of incidents that have the potential to release hazardous materials or energy. Such incidents can cause toxic effects, fires, or explosions, and could ultimately result in serious injuries, property damage, lost production, and environmental impact.	After the incident, the company made a considerable effort to improve corporate process safety.
Risk	A measure of human injury, environmental damage, or economic loss in terms of both the incident likelihood and the magnitude of the loss or injury.	The major risk in the process was a chemical spill into the adjacent river with environmental damage.
Risk analysis	Quantitatively combining risk estimates from a variety of scenarios using engineering evaluation and mathematical techniques to arrive at an overall risk estimate.	A detailed fault tree and event tree analysis of the process resulted in an overall risk estimate.
Risk assessment	Applying the results of a risk analysis to make decisions.	The plant added additional fire protection after completion of the risk analysis.
Risk tolerance	The maximum willingness of a company, and society as a whole, to live with a risk to secure the resulting benefits.	The plant decided after completion of the risk analysis that the risk is below their acceptable risk criteria.
Safeguard	Design features, equipment, procedures, and other resources in place to decrease the probability of an initiating cause or mitigate the severity of a loss impact.	An additional interlock was added to prevent overflow of the storage vessel.

Table 1-1 AICHE Center for Chemical Process Safety Definitions Related to Process Safety *(continued)*

Term	Definition	Example
Safety culture	The common set of values, behaviors, and norms at all levels in a facility or in the wider organization that affect process safety.	After the incident, the company decided to improve the corporate safety culture.
Scenario	A detailed description of an unplanned event or incident sequence that results in a loss event and its associated impacts. The scope of a scenario is arbitrary.	A forklift impacts an ammonia pipeline, resulting in an ammonia leak that forms a vapor cloud downwind.
Societal risk	A measure of risk to a group of people. It is most often expressed in terms of the frequency distribution of multiple casualty events.	The societal risk to the plant's adjacent community is deemed unacceptable.

Source: Adapted from AICHE/CCPS online glossary. https://www.aiche.org/ccps/resources/glossary. Accessed July 2018; and AICHE/CCPS, *Guidelines for Chemical Process Quantitative Risk Analysis*, 2nd ed. (New York, NY: American Institute for Chemical Engineers, 2000).

Another common term used in the safety realm is loss prevention, which is defined as the prevention of incidents that cause losses due to death, injury, damage to the environment, or even loss of production or inventory.

A hazard, in general, is anything that can cause an accident. Table 1-1 provides a more precise definition for a hazard that is more suitable for process safety usage. Hazards can arise due to materials, energy, physical situations, equipment design, and even procedures. In addition, hazards may be continuously present or intermittent. For instance, electricity in a room represents a continuous hazard to the room occupants. An electrical cord run across the floor of a lecture hall is also a physical tripping hazard that may not be present all the time. Note that something needs to occur for the hazard to result in an accident.

An accident is, in general, an undesirable consequence that occurs with an activity. A process safety incident has a more specific definition, being limited to an accident that occurs in a process or, more specifically, in a chemical plant. It includes undesirable outcomes, such as harm to people, damage to the environment, or asset/business losses. In general, a chemical plant incident is caused by loss of containment of chemicals or control or material or energy. An example of an incident would be a leak of ammonia from the connecting pipeline to a pressurized ammonia tank.

Typical hazards that occur in chemical plants include chemicals that are toxic, flammable, or reactive; high and low pressures and temperatures; and hazards due to the process design, maintenance, operations, control, and many other factors. An example of a hazard would be a pressurized tank containing 1000 kg of ammonia.

Hazard analysis/evaluation includes the identification of the hazard as well as the determination of how that hazard could result in a consequence. An example of a hazard analysis would be the identification of ammonia in a pressurized tank as a hazard and the identification of a leak in the connecting pipe due to corrosion as a possible incident. Estimation of the downwind airborne concentrations of ammonia would provide information on the consequences of such an incident.

The more information and knowledge one has about a process, the more thorough and valuable the hazard analysis/evaluation will be. Key process information required for chemical plant hazard analysis/evaluation includes the following items:

1. Chemical-related properties, including hazardous properties, physical properties, and more
2. Process conditions, including temperature and pressure, flow rates, concentrations, and other factors
3. Equipment design parameters, including equipment capacity, operating limits for temperature and pressure, materials of construction, and pipe wall thicknesses, among others
4. Site and plant layout, including equipment spacing, control room location, and other considerations
5. Procedures and policies, including startup, operating, shutdown, maintenance procedures, and others
6. Location and nature of adjacent communities and sensitive locations, such as schools

Other information might also be important depending on the particular process. The quality of any hazard analysis/evaluation is directly related to the quality of the information available to the analysis team.

Risk is another important definition in the process safety arena. Risk is a function of *both* likelihood and consequence, where likelihood considers either probability or frequency. It is essential to include both likelihood and consequence in the assessment of risk. As an example, consider the risk assessment for seat belt usage in automobiles. Many people argue against seat belt usage by noting that the likelihood of an accident is small—many people drive their entire lifetime without ever having an accident. However, seat belts are worn entirely to reduce the consequences of an accident and have no effect on the likelihood.

Risk analysis involves a more detailed mathematical analysis to combine the consequences and likelihood from multiple hazards. By comparison, risk assessment involves the evaluation of the risk analysis so as to make decisions—for example, decisions about which chemicals to use, the design of the plant, materials of construction, operating conditions, and so on.

1-1 Engineering Ethics

The AICHE expects all of its members, including student members, to exhibit professional conduct, as defined in its Code of Ethics for Engineers from the National Society of Professional Engineers. Every AICHE applicant must attest to knowledge of the Code of Ethics and willingness to comply with it when signing his or her membership application. As shown in Table 1-2, the

Table 1-2 American Institute of Chemical Engineers' Code of Professional Ethics

Members of the American Institute of Chemical Engineers shall uphold and advance the integrity, honor, and dignity of the engineering profession by: being honest and impartial and serving with fidelity their employers, their clients, and the public; striving to increase the competence and prestige of the engineering profession; and using their knowledge and skill for the enhancement of human welfare. To achieve these goals, members shall:

1. Hold paramount the safety, health, and welfare of the public and protect the environment in performance of their professional duties.
2. Formally advise their employers or clients (and consider further disclosure, if warranted) if they perceive that a consequence of their duties will adversely affect the present or future health or safety of their colleagues or the public.
3. Accept responsibility for their actions, seek and heed critical review of their work, and offer objective criticism of the work of others.
4. Issue statements or present information only in an objective and truthful manner.
5. Act in professional matters for each employer or client as faithful agents or trustees, avoiding conflicts of interest and never breaching confidentiality.
6. Treat all colleagues and coworkers fairly and respectfully, recognizing their unique contributions and capabilities by fostering an environment of equity, diversity, and inclusion.
7. Perform professional services only in areas of their competence.
8. Build their professional reputations on the merits of their services.
9. Continue their professional development throughout their careers, and provide opportunities for the professional development of those under their supervision.
10. Never tolerate harassment.
11. Conduct themselves in a fair, honorable, and respectful manner.

Approved by the AICHE Board in November 2015.

first item in the Code of Ethics states that the "safety, health, and welfare of the public" must be held "paramount in the performance of their professional duties." Item 2 is also related to process safety—chemical engineers have a responsibility to report activities that will "adversely affect the present and future health or safety of their colleagues and the public." Engineers have a responsibility to themselves, fellow workers, family, community, and the engineering profession.

1-2 Myths about Process Safety

A number of myths about process safety have emerged over the years. It is important to understand why these myths are false, as they can lead to disregard for key tenets of process safety.

Myth 1: Process safety costs a lot of money and has a negative impact on the company's bottom line.

The story of Alcoa presented earlier in this chapter readily dispels Myth 1. Although safety programs do cost money and there may be startup costs, the reduction in costly accidents and the improvements in all business aspects results in even greater cost savings and a net improvement in profits.

Myth 2: Process safety is the same as personal or even laboratory safety.

Figure 1-1 falsifies Myth 2 by illustrating the difference between personal and process safety. Personal safety—which includes laboratory safety—applies to accidents involving individuals, such as slips and falls, cuts, and other injuries. These events tend to have a higher frequency but lower consequences. In contrast, process safety applies to events with a lower frequency but higher consequences. The process safety and personal/lab safety domains are likely to overlap to some extent, as shown in Figure 1-1.

Myth 3: Process safety is no more than following rules and regulations.

Myth 3 is falsified by Table 1-3, which shows the hierarchy of safety programs. The hierarchy ranges from level 0 (lowest level) to level 5 (highest level). The safety program must work its way through the levels from the bottom to the top: No levels can be skipped. Thus, level 5 includes all of the levels below it:

Level 0 consists of no safety program and maybe even disdain for safety. Such a program is destined to have continuous accidents, maybe even accidents that are repeated. No improvement is ever achieved.

Level 1 is a safety program that reacts to accidents as they occur. Accidents do result in changes, but only on a reactive basis, rather than the organization taking a proactive stance. Accidents continue to occur, although specific accidents are not likely to be repeated.

Level 2 is a safety program that consists of complying with rules and regulations. Rules and regulations can never be complete, however, and can never handle all situations. Regulations have legal authority and generally set a minimum standard for industrial operations.

Level 3 introduces management systems to assess hazards and provide procedures to manage hazards. A variety of management systems can be used to achieve this level, including

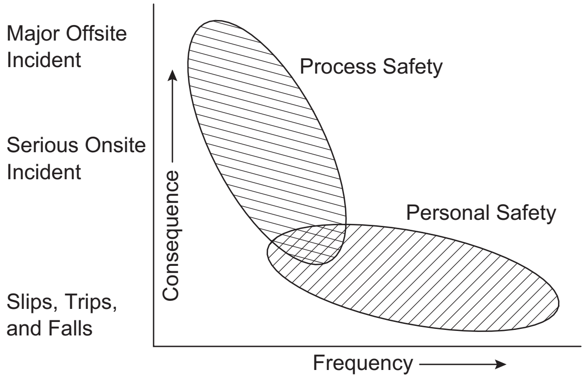

Figure 1-1 Personal safety versus process safety. Personal safety consists of more frequent, but lower consequence incidents. (Source: Dow Chemical Faculty Workshop, June 2017, AICHE.)

Table 1-3 Hierarchy of Safety Programs

Highest	5: Adapting: Safety is a core value of the organization and a primary driver for a successful enterprise.
	4: Performance: Monitoring using statistics to drive continuous improvement.
	3: Management systems: Based on job safety assessment (JSA), lock-out/tag-out (LOTO), or another approach.
	2: Complying: Focuses on adhering to rules and regulations.
	1: Reacting: To accidents as they occur.
Lowest	0: No safety—maybe even disdain for safety.

Note: The hierarchy must be worked from bottom to top without skipping any levels.

job safety assessment (JSA), lock-out/tag-out (LOTO), management of change (MOC), and other means to control hazards during operations. Written management systems provide documentation to train operators and others and to ensure consistency in operating practices.

Level 4 uses monitoring to obtain statistics on how well the safety program is performing. The performance monitoring identifies problems and corrects them. For instance, performance monitoring might indicate a large number of ladder incidents, which might be resolved by additional training in ladder safety.

Level 5 is the highest level, at which the safety program is dynamic and adapting. Safety is a core value for everything that is done and the primary driving force for a successful enterprise.

The hierarchy of safety programs shown in Table 1-3 addresses Myth 3, since rules and regulations are only at level 2. Note that the safety program developed at Alcoa was at level 5—the level that most chemical companies must achieve to have an effective safety program.

Myth 4: Process safety is a soft science—no more than hard hats or safety shoes—not engineering science.

Myth 4 is easily falsified by examining the contents of this text—notice the large number of equations. Process safety is based on engineering science and is just as fundamentally rigorous as any other academic courses in chemical engineering, relying heavily on other core concepts such as mass and energy balances, thermodynamics, fluid flow, and reaction engineering, among others.

Myth 5: Process safety applies only to the petrochemical industry.

Myth 5 is falsified by realizing that all companies require process safety, including warehouses, foundries, food processing, power plants, and so forth. For example, a leading ice cream manufacturer has a process safety vice president due to the large quantities of ammonia used in refrigeration.

Myth 6: Industry should train graduates in process safety; this topic should not be a part of the undergraduate engineering curriculum.

Myth 6, which deals with the training of professionals in safety, was debunked long ago. As early as 1918, L. DeBlois, Dupont Safety Manager, stated:

> *[S]safety engineering, with its interests in design, equipment, organization, supervision, and education … bears as well a very definite and important relation to all other branches of engineering. This relation is so close, and its need so urgent, that I am convinced that some instruction in the fundamentals of safety engineering should be given a place in the training of every young engineer. He should be taught to think in terms of safety as he now thinks in terms of efficiency. Conservation of life should surely not be rated below the conservation of energy. Yet, few of our technical schools and universities offer instruction in this subject, and the graduates go out to their profession with only vague surmises on "what all this talk on safety is about."*

Companies that hire chemical engineering graduates believe that including process safety in the undergraduate curriculum has enormous added-value, particularly in helping companies achieve level 5 in the safety hierarchy (see Table 1-3). If a graduate is hired by a smaller company, it is possible that the undergraduate curriculum is the only place where the individual will receive instruction in process safety topics. All chemical engineering undergraduates need process safety knowledge, whether they work for major chemical companies, refineries, small chemical companies, government labs and institutes, warehouses, ice cream companies, or even academia.

Myth 7: Process safety does not include product safety.

Myth 7 is falsified by realizing that all companies are responsible for their products, no matter who purchases the product and how it is used. All companies, including chemical companies, must ensure that their products are shipped safely and are used safely by whoever purchases the product.

1-3 Safety Culture

A safety culture is an essential part of any safety program, including process safety, laboratory safety, personal safety, or any safety program. Table 1-1 provides the CCPS's definition of process safety culture. Almost all accidents, whether large or small, can be attributed to a failure of safety culture, since the safety culture is such an essential and over-reaching part of any safety program.

Klein and Vaughen[1] provide a very extensive discussion of safety culture. They define safety culture as "the normal way things are done at a facility, company, or organization,

[1]James A. Klein and Bruce K. Vaughen. *Process Safety: Key Concepts and Practical Approaches.* Boca Raton, FL: CRC Press, Taylor & Francis Group, 2017.

reflecting expected organizational values, beliefs, and behaviors, that set the priority, commitment and resource levels for safety programs and performance." The same authors also provide a list of essential features for safety culture, as derived from the CCPS sources; these features are shown in Table 1-4.

Mannan et al.[2] found the following important elements of a best-in-class safety program: leadership; culture and values; goals, policies, and initiative; organization and structure; employee engagement and behaviors; resource allocation and performance management; systems, standards, and processes; metrics and reporting; continuous learning; and verification and auditing. These elements are similar to those provided in Table 1-4.

Table 1-4 Essential Features of Safety Culture

- **Establish process safety as a core value.**
  Core values are deeply held beliefs that are beyond compromise.
  Establish process safety as a core value in vision and mission statements, by clear and constant communication.
  Implement cultural activities that reinforce desired beliefs and behaviors, such as beginning all meetings with a safety moment.
- **Provide strong leadership.**
  Strong process safety leadership must be based on:
    Understanding and valuing process safety.
    Sharing personal commitment with others by displaying desired behaviors.
    Providing resources.
    Involving and supporting safety personnel.
    Consistently considering risk management in day-to-day decision making.
- **Establish and enforce high standards of performance.**
  Provide clear and consistent expectations, including in annual individual performance reviews.
  Follow safety systems and operating procedures without tolerating intentional shortcuts or other violations of requirements.
- **Document the process safety culture emphasis and approach.**
  Document safety culture core values, expectations, responsibilities, and accountabilities, including mechanisms for periodically evaluating and sustaining a strong culture.
- **Maintain a sense of vulnerability.**
  Provide systems and training to:
    Develop awareness and respect for process hazards and potential process incidents to prevent complacency.
    Ensure appropriate sensitivity to operations, including recognition of possible warning signs.
    Ensure effective incident investigations.
    Provide records of historical incidents.

(continues)

[2]M. S. Mannan, R. A. Mentzer, and J. Zhang. "Framework for Creating a Best-in-Class Safety Culture," *Journal of Loss Prevention in the Process Industries*, 26, no. 6 (2013): 1423–1432.

Table 1-4 Essential Features of Safety Culture *(continued)*

- **Empower individuals to successfully fulfill their responsibilities.**
  Ensure personnel are trained in all aspects of their roles.
  Provide personnel with appropriate resources so they can complete their work correctly and safely.
  Empower personnel to stop the work if they are concerned about safety.
- **Defer to expertise.**
  Create leadership positions where knowledgeable safety personnel have access to and credible input for decision-making processes.
  Involve other safety professionals as appropriate.
- **Ensure open and effective communications.**
  Communicate consistently and clearly on process safety goals, activities, and accomplishments.
  Provide systems for reporting of safety-related issues requiring timely response.
- **Establish a questioning/learning environment.**
  Provide risk management systems to:
    Identify process hazards and prevent process incidents.
    Include mechanisms for learning from experience.
    Ensure input from all personnel.
    Maintain critical knowledge.
- **Foster mutual trust.**
  Create an environment based on consistent management principles where personnel are comfortable:
    Participating in activities.
    Communicating with leadership and with each other honestly.
    Reporting mistakes.
    Making decisions without fear.
- **Provide timely response to process safety issues and concerns.**
  Provide systems for:
    Reporting process safety concerns.
    Following up and completing action items in a timely manner.
    Communicating action resolutions to demonstrate consistent application of process safety principles to avoid credibility problems.
- **Provide continuous monitoring of performance.**
  Develop key performance indicators for process safety and safety culture.
  Periodically review and evaluate performance indicators to identify continuous improvement opportunities.
  Share results with affected personnel.

Sources: AICHE Center for Chemical Process Safety. *Guidelines for Risk Based Process Safety* (New York, NY: Wiley/AICHE, 2007); W. L. Frank. “Process Safety Culture in the CCPS Risk Based Process Safety Model.” *Process Safety Progress*, 26 (2007): 203–208; James A. Klein and Bruce K. Vaughen. *Process Safety: Key Concepts and Practical Approaches* (Boca Raton, FL: CRC Press, Taylor & Francis Group, 2017).

In November 2010, Rex Tillerson, Chairman and CEO of ExxonMobil, testified before the National Commission on the disastrous BP Deepwater oil spill. He stated:

> *A commitment to safety therefore should not be a priority but a value—a value that shapes decision making all the time, at every level. Every company desires safe operations—but the challenge is to translate this desire into action. The answer is not*

found only in written rules, standards, and procedures. While these are important and necessary, they alone are not enough. The answer is ultimately found in a company's culture—the unwritten standards and norms that shape mindsets, attitudes, and behaviors. Companies must develop a culture in which the value of safety is embedded in every level of the workforce, reinforced at every turn, and upheld above all other considerations. … [A] culture of safety has to be born within the organization. You cannot buy culture. You have to make it yourself. … [M]ake no mistake: Creating a strong sustainable culture is a long process.

1-4 Individual Risk, Societal Risk, and Risk Populations

Risk can be addressed from many different angles. With individual risk, one person is exposed to one or more hazards, as shown in Figure 1-2. Individual risk calculations are normally performed when considering a plant employee exposed to plant hazards. In contrast, with societal risk, a group of people is exposed to one or more hazards. Societal risk calculations are normally performed when considering the risks to a community surrounding a chemical plant and exposed to multiple plant hazards. Methods to calculate and display individual and societal risk are discussed in depth in Chapter 12, "Risk Assessment."

For every accident, there are potentially many people and different populations at risk—the so-called risk populations. For an incident in a chemical plant, for example, risk populations would include the workers in the plant, workers in adjacent plants, and the people living nearby in the surrounding community since they may be seriously affected by a plant incident. The plant and community will likely also suffer physical damage, leading to a financial impact. The company's stockholders are also at risk since the company's reputation will be negatively impacted and its stock value will decline. In addition, the insurance companies for the plant and the community will suffer losses and are another risk population. The entire chemical industry, in general, will be at risk as well, since its reputation will be diminished. Other risk populations are also possible.

The primary risk population can be defined as those who suffer immediate injury or death.

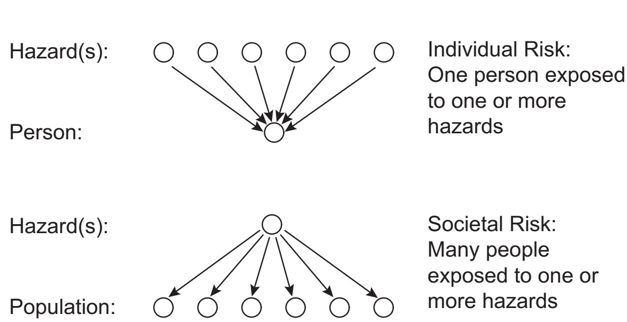

Figure 1-2 Individual versus societal risk.

1-5 Voluntary and Involuntary Risk

Chemical plant employees are aware of and trained to handle the risks that are found in their work environment—this is a legal requirement in the United States and most countries worldwide. In contrast, people in the surrounding community may not be fully aware of these risks or may not understand the risks and the associated probabilities and consequences. This difference in understanding can arise because the plant may not have properly communicated these risks to the community, new risks may have been introduced in the plant over time, or people may have moved into the community without any understanding of the risk.

People are more willing to accept risks if these are carefully explained to them—including the probabilities and potential consequences. Certainly, most car drivers understand the risks of driving a car. However, people become outraged when an industrial accident occurs that involves risks of which they were not fully aware or risks with higher actual likelihoods and/or consequences than perceived.

As an example, suppose you purchase a house for your family. Ten years later, you learn that the house was built on top of a toxic waste dump. The consequences are the adverse effects to the health of your family and a dramatic reduction in the value of your house. Certainly, you would be outraged.

A voluntary risk is "risk that is consciously tolerated by someone seeking to obtain the benefits of the activity that poses the risk."[3] An example of a voluntary risk is driving or riding in a car: Most people are aware that automobile accidents occur and accept this risk. An involuntary risk is "risk that is imposed on someone who does not directly benefit from the activity that poses the risk."[4] Examples of involuntary risk include riding an airplane, visiting a mall, and walking down the street. Living near a chemical plant or other manufacturing facility is also an involuntary risk. Individuals are typically willing to accept more voluntary risk (by a factor of 10 or more) versus involuntary risk.

A community outreach program is a very important part of any process safety program for a company and plant site. The plant officials must carefully explain the risks—including both the probabilities and the consequences—to any community that may be impacted by these risks. This effort is part of stakeholder outreach—where the set of stakeholders includes the employees, contractors, neighboring communities, neighboring companies, suppliers, customers, company stockholders, and other possible communities. The public considers chemical plants to pose a higher risk than is actually the case, so chemical plants must make a better effort to communicate these risks.

[3]AICHE/CCPS glossary, accessed December 2017.
[4]AICHE/CCPS glossary, accessed December 2017.

1-6 Safety Metrics

A very important part of any safety program is measuring the safety program effectiveness. This is done using safety metrics. Each company must identify metrics that are effective for its operations. These metrics are not universal, will change between companies and even plant sites, and will change with time.

Metrics are usually measured over a period of time and at multiple plant sites to identify any important changes or trends. Adverse changes in the metrics will trigger a management review, with resulting recommended changes for improvement.

Figure 1-3 shows the accident pyramid demonstrating the relationship between various levels of accidents based on severity. The severity level increases toward the top of the pyramid. Accidents of lower severity occur more frequently. Indeed, for every fatality, there are orders of magnitude more accidents of lesser magnitude and even more near misses. A near miss is an accident with no consequences that might have resulted in a catastrophe if conditions had been slightly different. Accidents of smaller magnitude and higher frequency, in particular near misses, provide many opportunities to recognize problems and make improvements—and, one hopes, to prevent more consequential accidents.

The problem with the accident pyramid is that the items listed are all lagging indicators. That is, the accident pyramid is based on incident outcome metrics derived *after* an accident or near miss has already occurred. It would be preferable to have leading indicators—that is, metrics that measure activities *prior to* the occurrence of an accident. Lagging metrics have historically been used more often than leading metrics because they are easier to identify and interpret, and typically must be reported to various regulators. By comparison, leading metrics are more difficult to identify and interpret.

Table 1-5 lists examples of leading and lagging metrics suitable for a chemical plant. The metrics at the top of Table 1-5 are leading indicators, while the ones at the bottom are lagging indicators. Notice that process safety culture—a leading metric—is at the very top of the table, while serious injuries and fatalities—lagging metrics—are at the bottom.

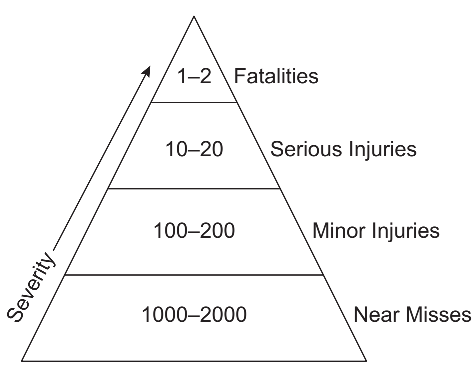

Figure 1-3 The accident pyramid showing the relationships between various levels of accidents. Metrics near the top are more leading; metrics toward the bottom are more lagging.

Table 1-5 Example Leading and Lagging Metrics for a Chemical Plant

Leading metrics - towards top of table

Process safety culture:
- Number of monthly process safety suggestions
- Response time for process safety suggestions to be addressed
- Number of open recommendations
- Process safety budget reduction
- Number of meetings addressing process safety
- Time to complete an incident investigation and issue a report
- Attendance at required safety meetings
- Signs of worker fatigue

Training:
- Percentage of workers who require remedial training
- Percentage of near-miss incidents with training root causes
- Change in training budget
- Number of workers with overdue training
- Training sessions canceled or postponed

Operating procedures:
- No system to gauge whether procedures have been followed
- Number of operating procedures updated per year
- Number of incident investigations that recommend changes to procedures
- Percentage of procedures that are annotated in the field
- Tolerance of failure to follow operating procedures
- Fraction of operators who believe that procedures are current and accurate
- Number of procedures that are past due for review
- Operators appear unfamiliar with procedures or how to use them

Maintenance procedures:
- Number of overdue maintenance tasks
- Number of unplanned repair work orders each month
- Work order backlog
- Change in maintenance budget
- Number of work orders that apply to equipment that no longer exists at the site
- Number of maintenance employees who hold required certification
- Number of management of change (MOC) requests
- Follow-up time on recommended actions

Inspection frequency

Safety system demands

Inspections with results outside limits

Excursions on safe operating limits

Near misses

Number of incidents

Property damage

Community response actions

Table 1-5 Example Leading and Lagging Metrics for a Chemical Plant *(continued)*

Loss of primary containment (LOPC) incidents
First aid incidents
Minor injuries
Serious injuries
Fatalities
Lagging metrics - towards bottom of table

1-7 Accident and Loss Statistics

Accident statistics are one metric to determine the effectiveness of any safety program. However, accident statistics are lagging indicators and are usually more indicative of personal safety rather than process safety.

Several methods may be used to calculate accident and loss statistics. All of these methods must be used carefully, because each method has strengths and weaknesses and no single method is capable of measuring all of the required aspects. The methods most commonly used to measure accident statistics are as follows:

- Total number of fatalities or injuries/illnesses.
- Fatality rate, or deaths per person per year
- Fatal injury rate based on total hours or total workers
- Incidence rate

All of these measures are lagging indicators, since they are tabulated after an accident has occurred.

The U.S. Occupational Safety and Health Administration (OSHA; www.osha.gov) has legal authority over U.S. workplace safety. OSHA is responsible for ensuring that U.S. workers are provided with a safe working environment. Many countries have government organizations similar to OSHA.

All U.S. workplaces are required by law to report to OSHA all occupational deaths, illnesses, and injuries. An injury includes medical treatment (other than first aid), loss of consciousness, restriction of work or motion, or injuries causing a transfer to another job. These accident statistics are tabulated by the U.S. Bureau of Labor Statistics (BLS; www.bsl.gov) and are made available to the public—albeit usually more than a year after the calendar year the data were collected. Table 1-6 provides sources for accident statistics; please refer to these sources for more updated statistics than presented here.

The total number of fatalities is most commonly used as a lagging indicator, but does not take into account the number of people working in a particular occupation. For instance, many more auto-related fatalities occur in a big state like Texas than in a small state like Vermont.

Table 1-6 Sources of Accident Statistics

United States

1. U.S. Department of Labor, Bureau of Labor Statistics (BLS), Washington, DC
   www.bls.gov/iif/
   This is an excellent, free source on occupational accident statistics in the United States.
   Data are typically two years behind.
2. National Safety Council (NSC), Itasca, IL
   www.nsc.org
   Injury Facts—an excellent source of information on work and nonwork injuries in the United States.
   The National Safety Council is a nonprofit organization dedicated to preventing accidents at work and at home.
3. *The 100 Largest Losses 1974—2015*, 24th ed., Marsh and McLennen Companies, March 2016
   This provides an excellent analysis of worldwide accidents in the hydrocarbon industry, including a brief description and financial loss for each accident.

United Kingdom

Health and Safety Executive (HSE)
www.hse.gov.uk/statistics
This is the equivalent of OSHA in the United Kingdom.

The total number of injuries/illnesses is also dependent on the number of workers. However, it has an additional problem since it requires a definition of an injury or illness.

The fatality rate, or deaths per person per year, is independent of the number of hours exposed to the hazard and reports only the fatalities expected per person per year. The exposed population may be carefully defined to ensure that it includes only those exposed to the hazard. This approach is useful for performing calculations on the general population. Fatality rate is calculated as follows:

$$\text{Fatality rate} = \frac{\text{Number of fatalities per year}}{\text{Total number of people in applicable population}} \tag{1-1}$$

The fatal injury rate is defined in two different ways. The first approach is in terms of the number of fatalities per 100,000 full-time equivalent workers employed. Thus, the worker-based fatal injury rate is calculated using the following equation:

$$\text{Worker-based fatal injury rate} = \frac{\text{Total number of fatalites during period}}{\text{Total number of employees}} \times 100{,}000 \text{ workers} \tag{1-2}$$

A similar approach can be applied to a general population. This fatal injury rate is defined in terms of 100,000 people and applied to a general, exposed population. It is calculated using the following equation:

$$\text{Deaths per 100,000 people} = \frac{\text{Total number of deaths during period}}{\text{Total people in exposed population}} \times 100{,}000 \text{ workers} \tag{1-3}$$

A work-related fatal injury rate can be defined in terms of the total hours worked by 100,000 full-time equivalent workers. For 100,000 workers working 40 hours per week and 50 weeks per year, this results in (100,000 workers × 40 hours/week × 50 weeks/year) = 200,000,000 hours. Thus, the hours-based fatal injury rate is defined by the following equation:

$$\text{Hours-based fatal injury rate} = \frac{\text{Total number of fatalities during period}}{\text{Total hours worked by all employees}} \times 200{,}000{,}000 \text{ hours} \tag{1-4}$$

Hours-based fatal injury rates (Equation 1-4) are generally considered more applicable than worker-based fatal injury rates (Equation 1-2). Hours-based rates use the total number of employees at work and the total hours each employee works. Worker-based rates will be similar for groups of workers who tend to work full time, but differences will be observed for worker groups who tend to include a high percentage of part-time workers.

The incidence rate is based on the cases per 100 workers. A worker year is assumed to contain 2000 hours (50 work weeks/year × 40 hours/week). The incidence rate, therefore, is based on 200,000 hours of worker exposure to a hazard (100 worker years × 2000 hours/year). The incidence rate is calculated from the number of incidents and the total number of hours worked during the applicable period. The following equation is used to calculate the incidence rate:

$$\text{Incidence rate} = \frac{\text{Number of incidents during period}}{\text{Total hours worked by all employees}} \times 200{,}000 \text{ hours} \tag{1-5}$$

The incidence rate is typically used for accidents involving injuries or illnesses, although it was used for fatalities in the past. The hours-based fatal injury rate is commonly used for fatalities, whereas the incidence rate is used for injuries since fatalities occur much less frequently than injuries. Using a different number of hours for these two rates brings both rates within comparable numerical values.

OSHA also uses the incidence rate for illnesses; days away from work (DAW); and days away from work, job restriction, or job transfer (DART). Table 1-7 defines these terms in relation to occupational injuries. There are many other ways to present accident statistics depending on what you wish to achieve. For instance, for airline transportation, the usual method is to report fatalities per million miles traveled.

Table 1-8 provides OSHA statistics on the total number of fatalities, the hours-based fatal injury rates, and the total recordable incidence rates for the United States in 2015, ordered from the highest number of fatalities to lowest. In 2015, a total of 4836 occupational

Table 1-7 U. S. OSHA Definitions for Occupational Injuries

Name	Definition
Fatality	Injuries or illnesses that result in death, regardless of the time between the injury and death or the length of the illness.
Injury	Any injury, such as a cut, fracture, sprain, amputation, and so forth, that results from a work-related event or from a single instantaneous exposure in the work environment.
Illness	Any abnormal condition or disorder caused by exposure to factors associated with employment, other than those resulting from an instantaneous event or exposure. This includes acute and chronic illnesses or diseases.
Days away from work (DAW)	Cases that result in days away from work (beyond the day of injury or onset of illness). The number of days away from work for these cases is determined according to the number of calendar days (not workdays) that an employee was unable to work, even if the employee was not scheduled to work those days.
Job transfer or restriction	Any case that results only in job transfer or restricted work activity. Workers who continue working after incurring an injury or illness during their regularly scheduled shift but produce fewer goods or services are not considered to be in restricted activity status.
Days away from work, job restriction, or job transfer (DART)	Any case involving days away from work (beyond the day of injury or onset of illness), or days of job restriction or days of job transfer.
Lost time injury (LTI)	The injured worker is unable to perform regular job duties, takes time off for recovery, or is assigned modified work duties while recovering.
Recordable injury	Death, days away from work, restricted work or transfer to another job, medical treatment beyond first aid, or loss of consciousness.
Other recordable cases	Injuries or illnesses that do not result in any days away from work, a job restriction, or restriction. This includes cases involving medical attention.

Source: www.osha.gov.

fatalities occurred. The peak number of fatalities was 5840 deaths recorded in 2006; the low was 4551 fatalities in 2009, primarily due to the recession of 2008—fewer workers means fewer fatalities. The total number of fatalities has been increasing slowly over the past few years (4821 in 2014) due to an increase in the number of workers, but likely at a diminished pace owing to improvements in occupational safety programs.

Several conclusions can be reached from Table 1-8. Construction (overall) has the highest number of fatalities (937), but fishing, hunting, and trapping has the highest hours-based fatal injury rate (54.8). The difference depends on the number of workers employed in each area. Construction has a larger number of workers than fishing, hunting, and trapping, resulting in the total fatalities for construction being higher and the hours-based fatal injury rate being lower. Interestingly, hospitals have the second highest total recordable incidence rate (8.1), followed by agriculture, forestry, fishing, and hunting (5.7). Table 1-8 also shows

Table 1-8 2015 U.S. Occupational Statistics for Selected Industries, Ranked from Highest to Lowest Number of Fatalities

Industry	Total fatalities	Hours-based fatal injury rate[a]	Total recordable incidence rate[b]
All Industries	**4836**	**3.4**	**3.3**
Construction (overall)	937	10.1	3.5
Transportation and warehousing	765	13.8	4.5
Agriculture, forestry, fishing, and hunting	570	22.8	5.7
Truck transportation	546	25.2	4.3
Professional and business services	477	3.0	1.4
Manufacturing	353	2.3	3.8
Government (state and local)	338	2.2	5.1
Retail trade	269	1.8	3.5
Leisure and hospitality	225	2.0	3.5
Wholesale trade	175	4.7	3.1
Government, federal	118	1.3	
Restaurants and other food services	100	1.4	3.0
Police and sheriff's patrol officers	85	11.7	5.8
Financial activities	83	0.9	1.1
Carpenters	83	6.7	
Electricians	83	10.7	2.8
Professional, scientific, and technical services	76	0.8	0.9
Roofers	75	39.7	5.6
Taxi drivers and chauffeurs	54	13.4	2.4
Information	42	1.5	1.3
Fire fighters	29	4.3	9.2
Mining (except oil and gas)	28	12.4	2.6
Chemical manufacturing	28	2.0	2.1
Fishing, hunting, and trapping	23	54.8	4.4
Utilities	22	2.2	2.2
Hospitals	21	0.4	8.1
Colleges, universities, and professional schools	17		1.8
Plastics and rubber products manufacturing	17	3.3	4.3
Oil and gas extraction	6		0.7
Chemical and allied products merchant wholesalers	3		2.2

[a]Rate per 100,000 full-time equivalent workers based on exposure hours. See Equation 1-4 and Table 1-7.
[b]Rate per 100 worker years = 200,000 hours. See Equation 1-5 and Table 1-7. This includes all recordable cases.
Source: U.S. Bureau of Labor Statistics, www.bls.gov/iif/.

that the traditional chemical engineering industries are near the bottom in terms of occupational injuries and fatalities. This group includes chemical manufacturing (28 fatalities), plastics and rubber products manufacturing (17 fatalities), oil and gas extraction (6 fatalities), and chemical and allied products merchant wholesalers (3 fatalities). The hours-based fatal injury rates and total recordable incidence rates for these industries are lower than those of many other occupational activities that are commonly considered as safer. For example, colleges, universities, and professional schools had a total of 17 fatalities in 2015. Many specific chemical companies achieve total recordable incidence rates as low as 0.2, compared to the industry average for chemical manufacturing of 2.1.

Table 1-9 provides details on the nature of the fatalities. Clearly, transportation accidents account for the largest number of fatalities in the workplace (2054 fatalities). This is followed by falls, slips, and trips (800 fatalities). With respect to the nature of the fatal injury, most of the injuries are due to multiple traumatic injuries and disorders—occupational fatalities usually involve widespread injury to many areas in the human body. With respect to the worker activity involved with the fatality, transportation accounts for the largest number of fatalities, followed by constructing, repairing, and cleaning and using or operating tools or machinery.

Table 1-9 Details on the Nature of Occupational Fatalities in 2015

Total occupational fatalities for 2015: 4836	
Event or exposure	
Transportation accidents	2054
Falls, slips, and trips	800
Contact with objects and equipment	722
Violence and other injuries by persons or animals[a]	703
Exposure to harmful substances or environments	424
Fires and explosions	121
Primary source[b]	
Vehicles	2195
Persons, plants, animals, and minerals	900
Structures and surfaces	568
Machinery	358
Chemicals and chemical products	233
Parts and materials	192
Tools, instruments, and equipment	192
Containers, furniture, and fixtures	95

Table 1-9 Details on the Nature of Occupational Fatalities in 2015 *(continued)*

Nature of fatal injury	
Multiple traumatic injuries and disorders	1855
Other traumatic injuries and disorders	1293
Intracranial injuries	803
Open wounds	558
Traumatic injuries to bones, nerves, and spinal cord	180
Burns and corrosions	78
Effects of environmental conditions	41
Traumatic injuries to muscles, tendons, ligaments, joints, etc.	18
Surface wounds and bruises	3
Worker activity	
Vehicular and transportation operations	2121
Constructing, repairing, cleaning	968
Using or operating tools or machinery	405
Other activities	374
Physical activities	308
Materials handling operations	215
Protective service operations	110

[a]Includes 417 homicides and 229 suicides.
[b]The primary source is the object, substance, person, bodily motion, or exposure that most directly led to, produced, or inflicted the injury.
Source: U.S. Bureau of Labor Statistics, www.bls.gov/iif/.

Note under the "Primary Source" heading in Table 1-9 that 233 fatalities occurred due to exposure to chemicals and chemical products. However, if you look further into the U.S. Bureau of Labor Statistics data, you find that only 5 of these deaths occurred in the chemical manufacturing industry and only 1 in operations of chemical and allied products merchant wholesalers. One can easily conclude that few fatalities in the chemical industry are due to chemical exposures; instead, most of the chemical fatalities occur in industries that are not considered chemical in nature.

Table 1-10 provides more details on fatalities in the chemical industry. Surprisingly, retail gasoline stations account for the largest number of fatalities (39 fatalities—due mostly to robberies). Within chemical manufacturing, fertilizer manufacturing (6 fatalities) and basic chemical manufacturing (5 fatalities) account for the largest number of fatalities. Petroleum refineries had 4 fatalities in 2015, while crude petroleum and natural gas extraction had 6 fatalities.

Table 1-10 2015 Fatal Occupational Injuries Related to the U.S. Chemical Industry

Chemical industry	Fatalities
Gasoline Stations (Retail)	39
Chemical Manufacturing	28
Fertilizer manufacturing	6
Basic chemical manufacturing	5
Soap, cleaning compound, and toilet prep manufacturing	4
Pharmaceutical and medicine manufacturing	3
Paint, coating, and adhesive manufacturing	2
Industrial gas manufacturing	1
All other chemical manufacturing	7
Plastics Manufacturing	13
Petroleum and Coal Products Manufacturing	12
Asphalt paving mixture and block manufacturing	5
Petroleum refineries	4
Asphalt shingle and coating materials manufacturing	3
Petroleum and Petroleum Products Merchant Wholesalers	9
Crude Petroleum and Natural Gas Extraction	6
Rubber Product Manufacturing	4
Chemical and Allied Products Merchant Wholesalers	3

Source: U.S. Bureau of Labor Statistics, www.bls.gov/iif/.

The Marsh and McLennan companies annually publish a report entitled *100 Largest Losses in the Hydrocarbon Industry.*[5] The most recent report tabulates losses from 1974 to 2015 and is based only on the property value losses from the ground up. It does not include the financial losses due to fatalities/injuries, environmental factors, lawsuits, fines, or business interruption—these additional losses could easily multiply the losses by many times. Table 1-11 shows the percentage of losses by industry sector and Table 1-12 shows the total property damage losses by event type. Reviewing these data, the first conclusion is that these losses are huge—totaling more than $33 billion, an amount that does not include losses to human life and environmental losses. Second, 87% of the losses occurred in upstream oil and gas production, refining, and petrochemicals. Finally, $25 billion in losses—75% of the total dollar losses—are from explosions and fires.

Table 1-13 is a list of non-occupational fatalities in the United States for the year 2014 ranked from the highest number of fatalities to lowest. Also shown is the deaths per 100,000 people, as defined by Equation 1-3. In 2014, there were 136,053 non-occupational fatalities due to unintended injuries—compared to 4836 occupational fatalities. Poisoning accounted for the

[5]*100 Largest Losses in the Hydrocarbon Industry* (New York, NY: Marsh and McLennan Companies, 2015).

Table 1-11 Percentage of Property Damage by Industry Sector

Industry sector	Percentage of total losses
Upstream production of oil and gas	33%
Refining	29%
Petrochemicals	25%
Gas processing	8%
Terminals and distribution	5%

Source: *The 100 Largest Losses 1974–2015*, 24th ed. (New York, NY: Marsh and McLennan Companies, March 2016), p. 10.

Table 1-12 Property Damage Values Based on Event Type

Event type	Property damage ($U.S. billions, adjusted to December 2015 $)
Explosion	$21.19
Fire	$4.36
Blowout	$2.54
Storm	$2.00
Collision	$1.32
Earthquake	$1.23
Sinking	$0.61
Release	$0.23
Mechanical damage	$0.27
Total	**$33.75**

Source: *The 100 Largest Losses 1974–2015*, 24th ed. (New York, NY: Marsh and McLennan Companies, March 2016), p. 10.

highest number of fatalities, although this includes 38,718 poisoning deaths by drug overdose. This alarmingly large number of fatalities is dramatically increasing each year. Motor vehicle deaths numbered 35,398—a total that has been increasing slowly for the past few years. In 1972, the number of motor vehicle fatalities reached a peak of 56,278. In 2014, 58 people died from electrocution by exposure to electric transmission lines, while 25 died from lightning.

Comparing Table 1-13 with Table 1-8 shows that the total number of fatalities in the workplace is much lower than the non-occupational fatalities in the general population: The number of workplace fatalities is comparable to the number of deaths by choking. Choking, falls, motor vehicle deaths, and poisonings all exceed the total number of workplace fatalities by a large margin. Also note that the general population is much larger than the total number of workers in the general population. Nevertheless, this comparison does provide an indication of the magnitude of workplace deaths compared to non-occupational deaths.

Table 1-13 Non-Occupational Fatalities in the United States Due to Unintentional Injuries, 2014

Injury class	Total fatalities	Deaths per 100,000 people
All deaths (occupational and non-occupational)	136,053[a]	42.7
Poisoning	42,032[a]	13.2
Motor vehicle	35,398	11.2
Falls	31,959	10.0
Choking	4816	1.5
Drowning	3406	1.1
Fires, flames, and smoke	2701	0.4
Exposure to excessive natural cold	930	
Firearm discharge	270	0.2
Exposure to excessive natural heat	244	
Exposure to electric transmission lines	58	
Lightning	25	
Flood	8	

[a]Includes 38,718 fatalities due to drug overdose.
Source: *Injury Facts* (Itasca, IL: National Safety Council, Itasca, IL, 2015), www.nsc.org.

In summary, accident statistics show that:

- The chemical industry has much lower fatalities and hours-based fatal injury rates than many other occupational activities that are commonly considered to be safer.
- The numbers of transportation and motor vehicle fatalities are high in both occupational and non-occupational environments.
- Chemical industry incidents, although infrequent, can result in huge property losses.

The chemical industry includes chemical plants, refineries, and other industrial sites using chemicals. Despite the relatively small number of fatalities that occur in the chemical industry, the potential always exists for a major incident—though such an event remains unlikely. Clearly, no unintended injury or fatality is acceptable in the workplace or elsewhere. All safety programs must drive toward zero injuries.

Example 1-1

A company employs 1000 full-time employees. If the company has one fatality over a one-year time period, calculate (a) the worker-based fatal injury rate and (b) the hours-based fatal injury rate. If the company has one recordable injury rate in that same year, calculate (c) the total recordable incidence rate. Compare the answers for parts (b) and (c) to the numbers for chemical manufacturing in Table 1-8.

Solution

a. From Equation 1-2:

$$\text{Worker-based fatal injury rate} = \frac{\text{Total number of fatalities during period}}{\text{Total number of employees}} \times 100{,}000 \text{ workers}$$
$$= \frac{1}{1000 \text{ workers}} \times 100{,}000 \text{ workers}$$
$$= 100$$

b. From Equation 1-4:

$$\text{Hours-based fatal injury rate} = \frac{\text{Total number of fatalities during period}}{\text{Total hours worked by all employees}} \times 200{,}000{,}000 \text{ hours}$$
$$= \frac{1 \text{ fatality}}{(1000 \text{ employees})(50 \text{ weeks/yr})(40 \text{ hours/wk})} \times 200{,}000{,}000 \text{ hours}$$
$$= \frac{200{,}000{,}000 \text{ hours}}{2{,}000{,}000 \text{ hours}}$$
$$= 100$$

c. From Equation 1-5:

$$\text{Recordable incidence rate} = \frac{\text{Number of incidents during period}}{\text{Total hours worked by all employees}} \times 200{,}000 \text{ hours}$$
$$= \frac{1 \text{ recordable incident}}{2{,}000{,}000 \text{ hours}} \times 200{,}000 \text{ hours}$$
$$= 0.10$$

The part (b) answer compares to a chemical manufacturing value of 2.0 and the part (c) answer compares to a chemical manufacturing value of 2.1. The part (b) answer is well above the chemical industry value while the part (c) answer is well below it.

1-8 Risk Perception

People perceive risks in different ways, though their perceptions might not always be supported by the actual statistics. The actual risk associated with the chemical industry is generally much less than that perceived by the public. Thus, the chemical industry is held to a higher safety standard than other industries. This requires continuous improvement in chemical industry safety programs to achieve the necessary public trust, credibility, and license to operate.

1-9 Risk Tolerance/Acceptance and Risk Matrix

Risk tolerance or acceptance is defined as "the maximum level of risk of a particular technical process or activity that an individual or organization accepts to acquire the benefits of the process or activity."[6] We cannot eliminate risk entirely—all activities inevitably involve risk. Indeed, people accept risks many times during their daily activities. For instance, simply crossing the

[6]AICHE/CCPS Glossary, accessed September 2017.

street involves a risk assessment as to where and when to cross. People accept risks based on their perceived risk—which may or may not be the actual risk. The risk accepted is voluntary based on the perceived risk, while any additional actual risk not perceived will be involuntary.

Engineers must make every effort to minimize risks within reasonable constraints. No engineer should ever design a process that he or she knows will result in certain human loss or injury. For a chemical plant, at some point in the design stage or at every point in the operation of the plant, the corporation (this decision involves both the workers and management) must determine whether the risks are acceptable. The risk acceptance must be based on more than just perceived risks.

Risk tolerance may also change with time as society, regulatory agencies, and individuals come to expect more from the chemical industry. As a consequence, a risk that was considered tolerable years ago may now be deemed unacceptable.

A risk matrix is a semi-quantitative method to represent risk and to help companies make risk acceptance decisions. A typical risk matrix is shown in Table 1-14. The consequence or severity of the incident is found in columns 1, 2, and 3, and the likelihood of that incident occurring appears in columns 4 through 7. The incident severity is used to estimate the severity category and the safety severity level. The likelihood level is selected based on the frequency of the incident, as shown in columns 4 through 7. The combination of the severity category row and the likelihood column is used to determine the risk level, A through D.

The severity levels are listed under columns 1, 2, and 3 in Table 1-14. They include human health impacts; direct costs of fire and explosion in dollars; and chemical impacts. The chemical impact is based on a chemical release quantity called a threshold quantity (TQ). Table 1-15 lists TQs for a number of common chemicals.

The target mitigated event frequency (TMEF) listed with the safety severity level is the minimum frequency level desired for this level of severity. It defines the frequency for acceptable risk.

Some risk matrixes include a severity column based on environmental impacts. However, the environmental impact is implicitly related to the quantity of chemical released: The greater the chemical release, the greater the environmental impact. Thus, environmental impact is implicit in this risk matrix.

The procedure for using the risk matrix of Table 1-14 is as follows:

1. Select the severity levels from columns 1, 2, and 3 and select the highest level from any of these columns.
2. Read the Risk Category and Safety Severity Level from the highest row.
3. Select the likelihood from columns 4 through 7.
4. Read the risk level from the intersection of the Safety Severity Level row and the Likelihood column.

The risk levels are identified just below the table and define the risk and the required response. The Safety Severity Level contains the TMEF. The TMEF will be useful for the layer of protection analysis (LOPA) method presented in Chapter 11.

Table 1-14 Risk Matrix for Semi-Quantitative Classification of Incidents

Risk Matrix

1. Select the severity from the highest box in either of columns 1, 2, or 3. Read the Category and Safety Severity Level from the same row.
2. Select the likelihood from columns 4 through 7.
3. Read the Risk Level from the intersection of the severity row and the likelihood column.

TMEF: Target mitigated event frequency (yr^{-1}).
TQ: Threshold quantity—see Table 1-15.

						Likelihood			
						4 LIKELY Expected to happen several times over the life of the plant	**5 UNLIKELY** Expected to happen possibly once over the life of the plant	**6 IMPROBABLE** Expected to happen possibly once in the division over the life of the plant	**7 IMPROBABLE, BUT NOT IMPOSSIBLE** Not expected to happen anywhere in the division over the life of the plant
Severity	**1 Human health impact**	**2 Fire, explosion direct cost ($)**	**3 Chemical impact**	**Severity category**	**Safety severity level**	0–9 years	10–99 years	≥ 100 years	> 1000 years
	Public fatality possible, employee fatalities likely	Greater than $10 million	≥ 20 × TQ	Catastrophic	**4** TMEF = 1×10^{-6}	Risk level A	Risk level A	Risk level B	Risk level C
	Employee fatality possible, major injury likely	$1 million to < $10 million	9 × to < 20 × TQ	Very serious	**3** TMEF = 1×10^{-5}	Risk level A	Risk level B	Risk level C	Risk level D
	Lost time injury (LTI) likely[a]	$100,000 to < $1 million	3 × to < 9 × TQ	Serious	**2** TMEF = 1×10^{-4}	Risk level B	Risk level C	Risk level D	Negligible risk
	Recordable injury[b]	$25,000 to < $100,000	1 × to < 3 × TQ	Minor	**1** TMEF = 1×10^{-3}	Risk level C	Risk level D	Negligible risk	Negligible risk

Risk level A: Unacceptable risk; additional safeguards must be implemented immediately.
Risk level B: Undesirable risk; additional safeguards must be implemented within 3 months.
Risk level C: Acceptable risk, but only if existing safeguards reduces the risk to as low as reasonably practicable (ALARP) levels.
Risk level D: Acceptable risk, no additional safeguards required.

[a]Lost time injury (LTI): The injured worker is unable to perform regular job duties, takes time off for recovery, or is assigned modified work duties while recovering.
[b]Recordable injury: Death, days away from work (DAW), restricted work or transfer to another job, medical treatment beyond first aid, or loss of consciousness.

Table 1-15 Threshold Quantities (TQ) for a Variety of Chemicals

2000 kg = 4400 lb$_m$	**1000 kg = 2200 lb$_m$**	**500 kg = 1100 lb$_m$**
Acrylamide	Acetic anhydride	Acetaldehyde
Ammonium nitrate fertilizer	Acetone	Acrylonitrile
Amyl acetate	Acetonitrile	Calcium cyanide
Amyl nitrate	Aldol	Carbon disulfide
Bromobenzene	Ammonium perchlorate	Cyclobutane
Calcium oxide	Aniline	Diethyl ether or ethyl ether
Carbon dioxide	Arsenic	Ethane
Carbon, activated	Barium	Ethylamine
Chloroform	Benzene	Ethylene
Copper chloride	Benzidine	Furan
Kerosene	Butyraldehyde	Hydrazine, anhydrous
Maleic anhydride	Carbon tetrachloride	Hydrogen, compressed
n-Decane	Copper chlorate	Lithium
Nitroethane	Copper cyanide	Methylamine, anhydrous
Nitrogen, compressed	Cycloheptane	Potassium
Nitrous oxide	Cycloheptene	Potassium cyanide
Nonanes	Cyclohexene	Propylene oxide
Oxygen, compressed	Dioxane	Silane
Paraldehyde	Epichlorohydrin	Sodium
Phosphoric acid	Ethyl acetate	Sodium cyanide
Potassium fluoride	Ethyl benzene	Sodium peroxide
Potassium nitrate	Ethylenediamine	Trichlorosilane
Sulfur	Formic acid	
Tetrachloroethylene	Heptane	**100 kg = 220 lb$_m$**
Undecane	Hexane	Hydrogen bromide, anhydrous
	Methacrylic acid	Hydrogen chloride, anhydrous
200 kg = 440 lb$_m$	Methyl acetate	Hydrogen fluoride, anhydrous
Ammonia, anhydrous	*n*-Heptene	Methyl bromide
Carbon monoxide	Nitrobenzene	Methyl mercaptan
	Nitromethane	Sulfur dioxide
5 kg = 11 lb$_m$	Octanes	
Acrolein	Phenol, molten or solid	**25 kg = 55 lb$_m$**
Arsine	Propylamine	Chlorine
Diborane	Pyridine	Cyanogen
Dinitrogen tetroxide	Silver nitrate	Germane
Methyl isocyanate	Sodium permanganate	Hydrogen sulfide
Nitric oxide, compressed	Tetrahydrofuran	Nitric acid, red fuming
Nitrogen trioxide	Toluene	Sulfuric acid, fuming
Phosgene	Triethylamine	
Phosphine	Vinyl acetate	
Stibine	Zinc peroxide	

Source: AICHE/CCPS. Details on how to compute the TQ are available from *AICHE/CCPS Process Safety Metrics: Guide for Selecting Leading and Lagging Indicator* (New York, NY: American Institute of Chemical Engineers, 2018).

Example 1-2

A risk analysis is performed on an incident involving a hole in a storage vessel containing a specific chemical. The chemical has a TQ of 5 lb_m. Calculations for this hole release estimate a total release of 50 lb_m of chemical. An employee fatality is possible with such a release, and the fire and explosion direct cost is estimated at $150,000. This incident is expected to occur once over the life of the plant. Use the risk matrix in Table 1-14 to determine the risk category, safety severity level, TMEF, and risk level.

Solution

Using Table 1-14, the following severity levels are selected under columns 1, 2, and 3:

Human Health Impact: Employee fatality possible

Fire, Explosion Direct Cost: $100,000 to < $1 million.

Chemical Impact: 9× to < 20× TQ

Selecting these three levels under columns 1, 2, and 3, respectively, results in the highest severity category of "Very serious," with a safety severity level of 3 and a TMEF of 1×10^{-5}. The likelihood is selected from column 5, since this is expected once over the lifetime of the plant.

Combining the Severity Category row of "Very serious" with Likelihood column 5 gives a risk level of B. Risk level B is defined as an "Undesirable risk; additional safeguards must be implemented within 3 months."

Note that if we could drop the severity level or decrease the likelihood, we can reduce the risk level. The LOPA method presented in Chapter 11 is a formalized method to add more safeguards to reduce the risk level to the TMEF.

The risk matrix provided in Table 1-14 is one specific example; that is, most companies customize the risk matrix to work for their particular situation. Additional methods for determining risk are presented in Chapter 12 on risk assessment.

1-10 Codes, Standards, and Regulations

Codes, standards, and regulations are an important part of chemical process safety.

- A *code* is a set of recommendations developed by a team of knowledgeable people, who are most likely to be associated with an industrial professional organization. Codes do not have legal authority, but governments might adopt one by turning it into law.
- A *standard* is more elaborate, explaining in a lot more detail how to meet the code. That is, codes tell you what you need to do, and standards tell you how to do it. Standards do not carry the weight of legal authority, but governments might adopt them by turning them into laws.
- A *regulation* is developed by a government and has legal authority. It may be based on a code or standard. Violations of regulations could result in fines and/or jail time.

Table 1-16 lists a number of regulations, codes, and standards important to process safety in the United States.

Table 1-16 Selected Regulations, Codes, and Standards That Apply to the Chemical Industry

Regulations

U.S. Occupational Safety and Health Administration (OSHA), www.osha.gov

29 CFR[a] 1910.119 Process Safety Management of Highly Hazardous Materials

This applies to manufacturing sites when on-site inventories of chemicals exceed the threshold values provided in the regulation. A prevention program involving 14 elements must be maintained.

U.S. Environmental Protection Agency (EPA), www.epa.gov

40 CFR 68 Risk Management Programs (RMP)

This applies to releases of toxic or flammable materials that could have off-site impacts. If chemicals exceed threshold quantities, a consequence analysis must be completed to estimate off-site impacts. A prevention program involving 11 elements must be maintained.

U.S. Department of Homeland Security (DHS), www.dhs.gov

6 CFR 27 Chemical Facility Anti-Terrorism Standards (CFATS)

This establishes risk-based performance standards for the security of chemical facilities. An online Chemical Security Assessment Tool must be completed to identify the company's security tier. Each tier has chemical security requirements.

Codes

National Fire Protection Association (NFPA), www.nfpa.org

NFPA 70: National Electrical Code (NEC)

NFPA 101: Life Safety Code

American Society of Mechanical Engineers (ASME), www.asme.org

ASME Boiler and Pressure Vessel Code

Standards

National Fire Protection Association (NFPA), www.nfpa.org

NFPA 45: Standard on Fire Protection for Laboratories Using Chemicals

NFPA 68: Standard on Explosion Venting by Deflagration Venting

NFPA 69: Standard on Explosion Prevention Systems

NFPA 652: Standard on the Fundamentals of Dust Explosions

American Society for Testing and Materials (ASTM), www.astm.org

ASTM D93: Standard Test Methods for Flash Point by Pensky-Martens Closed Cup Tester

ASTM E681-09 Standard Test Method for Concentration Limits of Flammability of Chemicals (Gases and Vapors)

American Petroleum Institute (API), www.api.org

API Recommended Practice 521: Selection and Installation of Pressure Relieving Devices in Refineries

API Recommended Practice 754: Process Safety Performance Indicators for the Refining and Petrochemical Industries

International Electrochemical Commission (IEC), www.iec.ch

IEC 61511: Safety Instrumented Systems for the Process Industry Sector

[a] *Code of Federal Regulations.*

Codes, standards, and regulations vary considerably between countries around the world. This creates challenges for engineers in one country who are designing a plant to operate in another country, or even for shipping chemicals from one country to another. Codes, standards, and regulations also change with time.

In the United States, OSHA and EPA use the codes and standards as a basis for Recognized and Generally Accepted Good Engineering Practices (RAGAGEP). RAGAGEP means that each plant site must keep its facility up to date with respect to codes and standards that apply to that plant, even though these codes and standards do not have regulatory authority. RAGAGEP is a complex regulatory and legal issue, well beyond the scope of this book.

1-11 Safeguards

Figure 1-4 shows the sequence of events in an incident. The hazard is shown on the left side of the figure, and the consequences are shown on the right side. The initiating event, or cause, may be "a device failure, system failure, external event, or improper human inaction that begins a sequence of events leading to one or more undesirable outcomes."[7] It is usually caused by internal plant events such as operational problems, equipment failures, human error, and design deficiencies, to name a few possibilities. The initiating event may also be caused by events external to the plant, including natural phenomena such as lightning strikes, floods, tornadoes, or other influences outside the plant boundaries.

The enabling conditions are "operating conditions necessary for an initiating cause to propagate into a hazardous event. Enabling conditions do not independently cause the incident, but must be present or active for it to proceed."[8] An enabling condition makes the beginning of the scenario possible. Such conditions are represented as probabilities—for example, the probability of a unit being in a particular state of operation (e.g., recycle mode, startup), the probability that a particular raw material or catalyst is in the process, or the probability that the temperature or pressure is within high or low values.

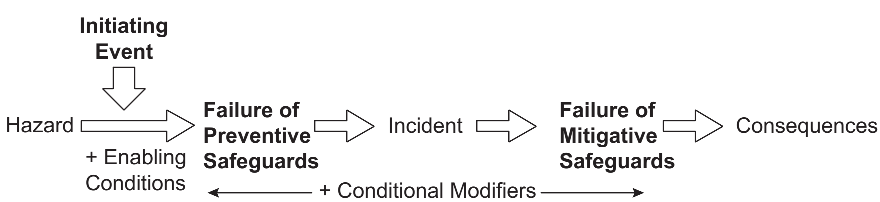

Figure 1-4 The sequence of events causing a hazard to result in an incident with consequences.

[7]Center for Chemical Process Safety, *Guidelines for Initiating Events and Independent Protection Layers in Layer of Protection Analysis* (New York, NY: Wiley, 2015).

[8]Ibid.

Conditional modifiers are conditions that occur after initiation and impact a step in the sequence either before or after the incident has occurred. They could include weather conditions (wind direction and speed), presence of people, and probability of ignition, among other factors.

Chemical plants use several types of safeguards to prevent incidents or to reduce the impact of an incident. Once an initiating event has occurred, safeguards come into play, as shown in Figure 1-4. A safeguard is a design feature, equipment, procedure, or even software that is in place to prevent or mitigate the consequences of an initiating event. Two types of safeguards are distinguished: preventive and mitigative. A preventive safeguard (also called a protection layer) intervenes after the initiating event to stop the event from developing further into an incident. A mitigative safeguard is a safeguard that reduces the consequences after an incident has occurred. Thus, preventive safeguards *stop* the propagation of the initiating event to an incident while mitigative safeguards *reduce* the consequences after an incident has occurred. Table 1-17 lists a variety of common preventive and mitigative safeguards used in the chemical industry.

In reality, not all safeguards are 100% effective or are working all the time. Figure 1-5 shows these safeguards as slices of Swiss cheese, where the holes represent defects in the safeguards. These kinds of defects in safeguards are dynamic and can come and go—that is, the "hole" size can change with time and even move around on the Swiss cheese. Only a few Swiss cheese safeguards are shown in Figure 1-5 to simplify the figure—the actual number of safeguards depends on the magnitude of the hazard.

Table 1-17 Common Preventive and Mitigative Safeguards Used in the Chemical Industry

Preventive Safeguards: Prevents an initiating event from proceeding to a defined, undesirable incident; also called a protection layer.

- Basic process control system (BPCS)
- Safety instrumented functions (SIF)
- Safety instrumented systems (SIS)
- Alarm systems
- Operator response to an alarm or process conditions
- Pressure relief system with containment (may also be considered mitigative)
- Procedures
- Maintenance
- Interlocks
- Emergency shutoff valves
- Flame/detonation arresters
- Inhibitor addition to reactor
- Emergency cooling systems
- Vapor inerting and purging to prevent flammable mixtures
- Grounding and bonding to prevent static accumulation
- Normal testing and inspection

Table 1-17 Common Preventive and Mitigative Safeguards Used in the Chemical Industry *(continued)*

Mitigative Safeguards: Reduce the consequences after an incident has occurred.
- Active fire protection, including sprinklers, sprays, foams, and deluges
- Emergency fire water system
- Passive fire protection including insulation
- Flammable vapor detectors
- Emergency response, including on-site and off-site
- Plant and equipment layout and spacing
- Diking around storage areas/processes
- Emergency power
- Blast walls
- Water curtains to disperse vapors
- Blast resistant control rooms
- Explosion blow-out panels on process vessels

Source: *Guidelines for Risk Based Process Safety,* AICHE Center for Chemical Process Safety (Wiley, NY), 2007.

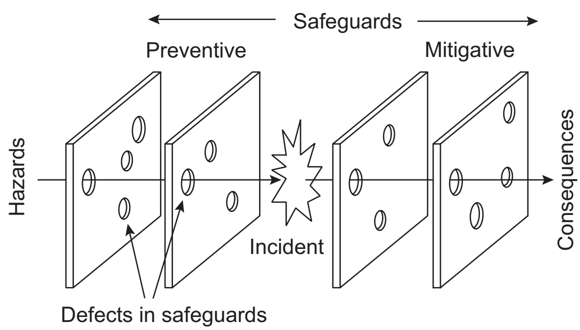

Figure 1-5 Swiss cheese model showing defects in the safeguards. If the defects line up, an incident will occur with resulting consequences.

Preventive maintenance of equipment at specified frequencies is designed to ensure that safeguards work properly, even as equipment ages. Only one preventive safeguard must work successfully for the incident to be stopped. Since multiple safeguards are present, if one safeguard has a defect, the initiating event will propagate through the defective safeguard but will be stopped by another safeguard. If the defects or "holes" in all the preventive safeguards line up, however, then the initiating event will propagate to an incident. Many well-known catastrophic incidents have occurred with many safeguards in place.

Once an incident has occurred, consequences are expected, although they might be minimal at this point. If mitigative safeguards are lacking, it is possible that the incident could expand in scope. For instance, the incident might be the leak of a flammable liquid from the process to the surroundings. If the flammable liquid ignites, then a fire or explosion might occur, greatly expanding the consequences. Thus, the mitigative safeguards, in this case, are intended to prevent the ignition of the released flammable liquid and the expansion of the consequences. In this example, the mitigative safeguards might be foam, water sprays, or other fire protection methods to prevent ignition.

It is possible that the mitigative safeguards could completely contain the incident and prevent it from increasing in scope and consequences. However, if some of the mitigative safeguards are not working or not effective, then additional consequences are expected.

Mitigative safeguards may be effective for only a specific incident outcome. For instance, safeguards designed to reduce the probability of ignition of a flammable material may not be effective in reducing the toxicity of the vapor if it does not ignite.

To see how preventive and mitigative safeguards work together, consider the following example: A chemical reactor vessel can be damaged by the effects of high pressure, maybe even resulting in the destructive bursting of the reactor vessel. The basic process control system (BPCS) controls the operation of the reactor to prevent high pressure. However, high pressure can arise from many sources—almost too numerous to completely prevent using the BPCS. Thus, reactor vessels are also equipped with relief devices in the form of spring-operated valves that open with high pressure, discharging the reactor contents to reduce the pressure. The BPCS is a preventive safeguard since it prevents the buildup of pressure in the reactor—but it cannot be expected to work all the time or to handle all possible situations. The relief device is a mitigative safeguard since it operates after the high-pressure incident has occurred and reduces the consequences of the incident. As a result of the relief device's actions, the consequences of the high pressure incident are loss of product from the reactor and a clean-up of the relief discharge. Without the relief device, the consequences of the high-pressure incident might be permanent pressure damage to the reactor vessel or maybe even destructive bursting of the vessel, leading to substantial damage to the surrounding equipment and workers. Since there are many ways for high pressure to build up in a reactor vessel, many preventive and mitigative safeguards are usually present.

1-12 The CCPS 20 Elements of Risk-Based Process Safety

In 2007, the AICHE Center for Chemical Process Safety published *Guidelines for Risk Based Process Safety.*[9] The risk-based process safety (RBPS) approach

> *recognizes that all hazards and risks in an operation or facility are not equal; consequently, apportioning resources in a manner that focuses effort on greater hazards and higher hazards is appropriate. … The RBPS system may encompass all process safety issues for all operations involving the manufacture, use, storage, or handling of hazardous substances or energy. However, each organization must determine which physical areas and phases of the process life cycle should be included in its formal management systems, based on its own*

[9]Center for Chemical Process Safety, *Guidelines for Risk Based Process Safety* (New York, NY: Wiley, 2007).

risk tolerance considerations, available resources, and process safety culture. … The RBPS elements are meant to apply for the entire process life cycle.

The 20 elements of RBPS are listed in Table 1-18. These elements are organized in four major foundational blocks: (1) commit to process safety, (2) understand hazards and risks, (3) manage risk, and (4) learn from experience.

OSHA has a similar set of 14 elements that are included as part of 29 CFR 1910.119 on process safety management.[10] The OSHA elements of this regulation are (1) employee participation, (2) process safety information, (3) process hazards analysis, (4) operating procedures, (5) training, (6) contractors, (7) pre-startup safety review, (8) mechanical integrity, (9) hot work permits, (10) management of change, (11) incident investigation, (12) emergency planning and response, (13) audits, and (14) trade secrets. While these 14 elements are contained within the CCPS 20 elements, the OSHA regulation has legal authority.

Table 1-18 The 20 Elements of Risk-Based Process Safety

Foundational Block: Commit to Process Safety
1. Process safety culture
2. Compliance with standards
3. Process safety competency
4. Workforce involvement
5. Stakeholder outreach
Foundational Block: Understand Hazards and Risks
1. Process knowledge management
2. Hazard identification and risk analysis (HIRA)
Foundational Block: Manage Risk
1. Operating procedures
2. Safe work practices
3. Asset integrity and reliability
4. Contractor management
5. Training and performance assurance
6. Management of change
7. Operational readiness
8. Conduct of operations
9. Emergency management
Foundational Block: Learn from Experience
1. Incident investigation
2. Measurements and metrics
3. Auditing
4. Management review and continuous improvement

Source: AICHE Center for Chemical Process Safety, *Guidelines for Risk Based Process Safety* (Hoboken, NJ: Wiley Interscience, 2007).

[10]OSHA 1919.119, *Process Safety Management* (1992). www.osha.gov.

The 20 CCPS RBPS elements are described here:[11]

Element 1—Process Safety Culture: A positive environment in which employees at all levels are committed to process safety. This starts at the highest levels of the organization and is shared by all. Process safety leaders nurture this process. (See Section 1-3, “Safety Culture.”)

Element 2—Compliance with Standards: Applicable regulations, standards, codes, and other requirements issued by national, state/provincial, and local governments; consensus standards organizations; and the company itself. Interpretation and implementation of these requirements. Includes development activities for corporate, consensus, and governmental standards. (See Section 1-10, “Codes, Standards, and Regulations.”)

Element 3—Process Safety Competency: Skills and resources that the company needs to have in the right places to manage its process hazards. Verification that the company collectively has these skills and resources. Application of this information in succession planning and management of organizational change.

Element 4—Workforce Involvement: Broad involvement of operating and maintenance personnel in process safety activities, to make sure that lessons learned by the people closest to the process are considered and addressed.

Element 5—Stakeholder Outreach: A process for identifying, engaging, and maintaining good relationships with appropriate external stakeholder groups. This would include the surrounding community, suppliers of raw materials, customers, government agencies and regulators, professional societies, contractors, and more.

Element 6—Process Knowledge Management: The assembly and management of all information needed to perform process safety activities. Verification of the accuracy of this information. Confirmation that this information is correct and up-to-date. This information must be readily available to those who need it to safely perform their jobs.

Element 7—Hazard Identification and Risk Analysis: Identification of process safety hazards and their potential consequences. Definition of the risks posed by these hazard scenarios. Recommendations to reduce or eliminate hazards, reduce potential consequences, and reduce frequency of occurrence. Analysis may be qualitative or quantitative, depending on the level of risk.

Element 8—Operating Procedures: Written instructions for a manufacturing operation that describes how the operation is to be carried out safely, explaining the consequences of deviation from procedures, describing key safeguards, and addressing special situations and emergencies.

Element 9—Safe Work Practices: Procedures to safely maintain and repair equipment, such as permits to work, line breaking, and hot work permits. This applies to nonroutine operations.

Element 10—Asset Integrity and Reliability: Activities to ensure that important equipment remains suitable for its intended purpose throughout its service. Includes proper selection of materials of construction; inspection, testing, and preventive maintenance; and design for maintainability.

[11]AICHE/CCPS online glossary, www.aiche.org, accessed October 27, 2017.

Element 11—Contractor Management: Practices to ensure that contract workers can perform their jobs safely, and that contracted services do not add to or increase facility operational risks.

Element 12—Training and Performance Assurance: Practical instruction in job and task requirements and methods for operation and maintenance workers, supervisors, engineers, leaders, and process safety professionals. Verification that the trained skills are being practiced proficiently.

Element 13—Management of Change: Process of reviewing and authorizing proposed changes to facility design, operations, organization, or activities prior to implementing them, and ensuring that the process safety information is updated accordingly.

Element 14—Operational Readiness: Evaluation of the process before startup or restart to ensure the process can be safely started. Applies to restart of facilities after being shut down or idled as well as after process changes and maintenance. Also applies to startup of new facilities.

Element 15—Conduct of Operations: Means by which the management and operational tasks required for process safety are carried out in a deliberate, faithful, and structured manner. Managers ensure workers carry out the required tasks and prevent deviations from expected performance.

Element 16—Emergency Management: Plans for possible emergencies that define actions in an emergency; resources to execute those actions; practice drills; continuous improvement; training or informing employees, contractors, neighbors, and local authorities; and communications with stakeholders in the event that an incident does occur.

Element 17—Incident Investigation: Process of reporting, tracking, and investigating incidents and near misses to identify root causes; taking corrective actions; evaluating incident trends; and communicating lessons learned.

Element 18—Measurement and Metrics: Leading and lagging indicators of process safety performance, including incident and near-miss rates as well as metrics that show how well key process safety elements are being performed. This information is used to drive improvement in process safety. (See Section 1-6, "Safety Metrics.")

Element 19—Auditing: Periodic critical review of process safety management system performance by auditors not assigned to the site to identify gaps in performance and identify improvement opportunities, and track closure of these gaps to completion.

Element 20—Management Review and Continuous Improvement: The practice of managers at all levels of setting process safety expectations and goals with their staff and reviewing performance and progress toward those goals. May take place in a staff or "leadership team" meeting or on a one-on-one basis. May be facilitated by process safety leader but is owned by the line manager.

Table 1-19 presents common chemical plant activities associated with each of the 20 elements. When a chemical plant incident occurs, the incident investigation usually finds deficiencies in many of the elements. The 20 elements provide a comprehensive management system to handle risks in chemical plants and other facilities. All of the elements are important, and all must be given adequate consideration. Chemical engineers are involved in all aspects of the 20 elements.

Table 1-19 Typical Activities Associated with the 20 Risk Based Process Safety (RBPS) Elements

1. **Process safety culture**
   Develop or deploy corporate process safety culture programs.
   Identify process safety culture issues and influence corporate changes.
   Maintain a strong process safety culture among team members.
   Conduct formal assessments to identify gaps and recommend improvements in the process safety culture.
2. **Compliance with standards**
   Interpret or apply standards for internal use.
   Participate in standards development.
   Develop a system to identify standards and uniformly administer and maintain the information.
3. **Process safety competency**
   Develop a training program to increase workers' level of competency.
   Develop competency profiles for critical process safety positions.
   Evaluate a unit to determine gaps in competency.
4. **Workforce involvement**
   Develop, lead, or participate in organizing workforce involvement efforts at the corporate, business, plant, or unit level.
   As a supervisor, regularly lead discussions around process safety concerns or issues with operating personnel.
   As a worker, provide constructive feedback aimed at improving process safety and track feedback to resolution.
5. **Stakeholder outreach**
   Lead community action panel (CAP) meetings.
   Work with the local community to create an area CAP and facilitate meetings.
   Develop site or corporate practices or standards to coordinate and manage major off-site accident risks, to include communications with stakeholders.
   Coordinate an emergency response simulation or drill in the community.
6. **Process knowledge management**
   Validate existing Process and Instrument Diagrams (P&IDs) with actual plant configuration.
   Develop safe operating limits and consequences of deviations for a process unit.
   Update process safety knowledge following management of change (MOC).
   Write internal standards for the company.
   Develop a database of relief devices.
7. **Hazard identification and risk analysis**
   Develop and/or implement corporate methods and procedures for hazards analysis and risk assessment.
   Develop consequence assessment simulations.
   Lead or participate in process hazards analysis (PHA).
8. **Operating procedures**
   Write or revise operating procedures to make them clearer and more usable.
   Review and update operational procedures for a site.
   Identify safe operating limits for a process.

Table 1-19 Typical Activities Associated with the 20 Risk Based Process Safety (RBPS) Elements *(continued)*

9. **Safe work practices**
   Participate in confined-space operations.
   Certify confined-space operations attendants.
   Participate in or develop and audit line breaking and/or lock-out/tag-out (LOTO) procedures.
   Develop a corporate work permit policy.
   Audit and/or improve safe work practices.
10. **Asset integrity and reliability**
    Review and assess data from inspections; draw conclusions and make recommendations.
    Develop or implement practices, procedures, and strategies to manage the integrity in a facility, site, or company.
    Research published corrosion rates to provide general guidance for developing specifications.
11. **Contractor management**
    Audit contractors for safety.
    Develop recommendations and actions to improve contractor performance.
    Develop process safety requirements for hiring new site contractors.
12. **Training and performance assurance**
    Develop process safety training programs.
    Provide oversight of corporate or site process safety training program.
    Give or receive process safety training.
13. **Management of change (MOC)**
    Develop corporate procedures for change management.
    Participate in management of change reviews.
    Author MOC documentation.
    Identify a site MOC coordinator.
14. **Operational readiness**
    Lead and/or participate in pre-startup safety reviews (PSSR).
    Develop commissioning and startup plans.
    Identify critical process safety information (PSI) required to operate safely.
    Start up a process that is ready to operate.
15. **Conduct of operations**
    Implement practices intended to maintain the operational discipline at a facility.
    As a front-line worker, cooperate with peers to ensure that performed tasks are done exactly as prescribed over a long period of time.
    Actively monitor and make corrective action plans related to the performance of process safety operating tasks.
16. **Emergency management**
    Set up or participate in emergency response drills with community responders.
    Work with corporate officials to perform emergency drills or table-top drills.
    Participate in planning and addressing potential plant emergencies.
17. **Incident investigation**
    Participate in an accident investigation.
    Manage accident investigation action items.
    Develop and implement corporate procedures for incident investigation.

(continues)

Table 1-19 Typical Activities Associated with the 20 Risk Based Process Safety (RBPS) Elements *(continued)*

18. **Measurements and metrics**
    Act as the site lead for or participate in collecting and reporting metrics.
    Prepare reports on process safety metrics.
    Develop and implement site or company metrics.
19. **Auditing**
    Participate in process safety audits, either as an auditor or an audited party.
    Develop process safety audit methods.
    Manage audit recommendations to ensure they are implemented.
20. **Management review and continuous improvement**
    Participate in management reviews.
    Evaluate results from management reviews and proposed/reviewed recommendations for improvement.
    Engage management to follow up and close out actions derived from management reviews.

Example 1-3

A valve in a chemical plant is replaced by a valve from the warehouse. Unfortunately, the warehouse valve was not constructed of the same material as the original and within a few months corrosion caused the valve to leak, causing a release of toxic material. Which element of RBPS applies to this scenario?

Solution

The element most directly impacted is Element 13, management of change. Whenever equipment is replaced, steps must be taken to ensure that the replacement part has the identical function as the original part. Other elements that might also be involved are Element 1, process safety culture; Element 3, process safety competency; Element 6, process knowledge management; Element 9, safe work practices; Element 10, asset integrity and reliability; Element 12, training and performance assurance; and Element 15, conduct of operations. Can you identify how all of these other elements are involved? This type of incident would likely invoke a management review (Element 20) to identify the cause and take corrective action to prevent this type of incident from occurring again.

1-13 Inherently Safer Design

Section 1-11, "Protecting Against Hazards: Safeguards," described how hazards are protected with safeguards to prevent initiating events from propagating into more serious incidents with consequences. These safeguards add considerable cost to the process and also require testing and maintenance—and even with these actions, the safeguards can still fail.

If we could design a process with fewer hazards, then the process would be simplified, and the safeguards reduced. This is the essence of inherently safer design—to eliminate hazards rather than to provide complex safeguard hierarchies around the hazards. An inherently safer plant uses the elimination of hazards to prevent accidents rather than depending on control systems, interlocks, redundancy, special management systems, complex operating instructions, or elaborate procedures. Inherently safer plants are tolerant of errors; are generally cost-effective; and are simpler, easier to operate, and more reliable.

Table 1-20 provides examples of the four inherently safer design strategies: minimize, substitute, moderate, and simplify. Other references[12] provide more detailed strategies, but many of these additional strategies can be included in the four shown in the table. The four strategies listed in Table 1-20 are the traditional strategies, though they might go by other names (shown in parentheses in the table).

Table 1-20 Inherently Safer Design Strategies

Type	Example applications
Minimize (intensification)	Replace a large batch reactor with a smaller continuous reactor. Reduce storage inventory of raw materials. Improve management and control to reduce inventory of hazardous intermediate chemicals. Reduce process hold-up.
Substitute (substitution)	Use mechanical pump seals instead of packing. Use a welded pipe rather than a flanged pipe. Use solvents that are less hazardous. Use chemicals with higher flash point temperatures, boiling points, and other less hazardous properties. Use water as a heat transfer fluid instead of hot oil.
Moderate (attenuation and limitation of effects)	Reduce process temperatures and pressure. Use a vacuum to reduce the boiling-point temperature. Refrigerate storage vessels to reduce the vapor pressure of liquids. Dissolve hazardous material in a nonhazardous solvent. Operate at conditions where reactor runaway is not possible. Locate control rooms remotely from the process to reduce impacts of accidents. Provide adequate separation distance from process units to reduce impacts of accidents. Provide barriers to reduce impacts of explosions. Provide water curtains to reduce downwind concentrations.
Simplify (simplification and error tolerance)	Reduce piping lengths, valves, and fittings. Simplify piping systems and improve ability to follow the pipes within them. Design equipment layout for easy and safe operation and maintenance. Select equipment that requires less maintenance. Select equipment with higher reliability. Label process equipment—including pipelines—for easy identification and understanding. Design control panels and displays that are easy to comprehend. Design alarm systems to provide the operators with critical information.

[12]Trevor Kletz and Paul Amyotte. *Process Plants: A Handbook for Inherently Safer Design,* 2nd ed. (Boca Raton, FL: CRC Press, 2010).

The *minimize* strategy entails reducing the hazards by using smaller quantities of hazardous materials in the process. When possible, hazardous materials should be produced and consumed on site—this minimizes the storage and transportation of hazardous raw materials and intermediates.

The *substitute* strategy entails replacing hazardous materials with less hazardous materials. For example, a nonflammable solvent could replace a flammable solvent.

The *moderate* strategy entails using hazardous materials under less hazardous conditions. This includes using these materials at lower temperatures and pressures. Other approaches include (1) refrigeration to lower vapor pressures, (2) diluting solutions to a lower concentration, and (3) using larger particle-sized solids to reduce dust explosions, to name a few.

The *simplify* strategy is based on the fact that simpler plants are friendlier than complex plants, because they provide fewer opportunities for error and because they contain less equipment that can cause problems. Often, the complexity in a process is driven by the need to add equipment and automation to control the hazards. Simplification reduces the opportunities for errors and mis-operation.

In the strictest sense, inherently safer design applies only to the elimination of hazards. Some of the inherently safer design strategies shown in Table 1-20 treat hazards by making the hazard less intense or less likely to occur. For instance, simplifying a complex piping system reduces the frequency of leaks and operator error, but does not completely eliminate the hazard—the remaining pipes and valves can still leak. The inherently safer design strategies that eliminate the hazard are called first-order strategies, whereas strategies that make the hazard less intense or less likely to occur are called second-order strategies.

Although inherently safer design should be applied at every point in a process life cycle, the potential for major improvements is the greatest at the earliest stages of process development. At these early stages, process engineers and chemists have the maximum degree of freedom in the selection of the reaction, chemicals, process technology, and plant design and process specifications.

Inherently safer design can significantly reduce the hazards in a process, but it can go only so far. Many chemicals and products are used precisely because of their hazardous properties. For instance, if gasoline is the product, then flammability is the necessary hazardous property for this product—this hazard cannot be eliminated.

After we have applied inherently safer design as much as possible, we can use a hierarchy of management systems to control the remaining hazards, as shown in Table 1-21. Inherently safer design appears at the top of the hierarchy and should be the first approach, followed by passive, active, and procedural strategies. The strategies closer to the top of Table 1-21 are more robust than the lower strategies and should be preferred.

Active safeguards require the physical motion or activity in the performance of the equipment's function; a valve opening or closing is an example. A passive safeguard is hardware that is not physically actuated to perform its function; dikes around storage vessels are an example. Procedural safeguards, often called administrative safeguards, are administrative or management safeguards that do not directly involve hardware; an operating procedure is an example.

Table 1-21 Hierarchy of Process Risk Management Strategies. The strategies at the top of the table are more robust

Strategy	Emphasis	Examples
Inherent	See Table 1-20.	Minimize (intensification). Substitute (substitution). Moderate (attenuation and limitation of effects). Simplify (simplification and error tolerance).
Passive	Minimizes the hazard through process and equipment design features that reduce either the frequency or the consequence without the active functioning of any device.	Using equipment with a higher pressure rating than the maximum possible pressure. Blast walls around process equipment to reduce blast overpressures. Dikes around storage vessels to contain spills. Separation of equipment from occupied buildings and other locations where personnel may be present.
Active	Requires an active response. These systems are commonly referred to as engineering controls, although human intervention is also included.	Alarms, with operator response. Process control system, including basic process control systems, safety instrumented systems, and safety instrumented functions. Sprinklers and water deluge systems. Pressure relief devices. Inerting and purging systems. Water curtains to knock down gas releases. Flares.
Procedural	Based on an established or official way of doing something. These are commonly referred to as administrative controls.	Policies. Operating procedures. Safe work practices, such as lock-out/tag-out, vessel entry, and hot work. Emergency response procedures. Training.

One potential problem with inherently safer design is risk shifting. That is, application of inherently safer design strategies might shift the risk from one population to another. For example, one company used a highly toxic chemical as a catalyst in a process. The chemical was highly effective and was recycled with little make-up. The company decided to replace the highly toxic catalyst with one that was considerably less toxic—an inherently safer approach by substitution. The less toxic catalyst required a substantial amount of make-up, necessitating regular and substantial truck shipments. While the risk to the company's employees was reduced, the risk to the community was increased due to the truck shipments along municipal roads.

Environmental impacts should also be considered in inherently safer designs. A classic example of this is refrigeration systems. In the very early days of refrigeration, ammonia was used as a refrigerant. Ammonia is toxic, and leaks of this gas can affect both employees and the surrounding communities. Later, chlorofluorocarbons (CFCs) were developed to replace ammonia. Since these refrigerants are not toxic, CFCs were inherently safer than ammonia. However, in the 1970s, CFCs were found to deplete the ozone layer. Hydrochlorofluorocarbons (HCFCs) were used for a short period since these had less impact on the environment. More recently, many refrigeration systems have returned to ammonia as a preferred refrigerant primarily to reduce environmental impacts.

Example 1-4

Carbon tetrachloride was originally used as a dry-cleaning fluid and was very effective. In the 1950s, carbon tetrachloride was phased out and replaced by perchloroethylene (PERC). Today, other alternatives, such as carbon dioxide, are being considered. Why?

Solution

Carbon tetrachloride worked very well as a dry-cleaning fluid. However, it has high toxicity and can damage the liver, kidneys, and central nervous system. It is a possible carcinogen, and repeated exposure to the vapors by the dry-cleaning workers and customers resulted in adverse health effects.

PERC is also a possible carcinogen and can affect the liver and kidneys. It can result in adverse health effects, albeit not as severe as the effects associated with carbon tetrachloride.

Other dry-cleaning alternatives, such as carbon dioxide, silicones, and propylene glycol ethers, are possible replacements, but they have higher costs. Their use demonstrates inherently safer design by substitution of a hazardous material with one less hazardous.

1-14 The Worst Chemical Plant Tragedy: Bhopal, India, 1984[13]

The Bhopal, India, tragedy occurred on December 3, 1984, in a pesticide plant jointly owned by Union Carbide (USA) and its affiliate Union Carbide India Limited (UCIL). More than 2500 lives were lost due to inhalation and exposure to methyl isocyanate (MIC) vapor released from the plant. Another 200,000 people suffered various levels of exposure, with the adverse effects ranging from blindness to nausea. Many people who survived the incident suffered from severe health effects for the rest of their lives.

MIC was used as an intermediate chemical in pesticide production and was stored on-site. This compound is reactive, toxic, volatile, and flammable. The maximum exposure concentration of MIC for workers over an 8-hour period is 0.02 ppm (parts per million). Individuals exposed to concentrations greater than 21 ppm experience severe irritation of the nose and throat. Death at larger concentrations of MIC vapor is due to respiratory distress.

[13]John F. Murphy, Dennis Hendershot, Scott Berger, Angela E. Summers, and Ronald J. Willey. "Bhopal Revisited." *Process Safety Progress*, 33, no. 4 (2014): 310–313.

MIC demonstrates a number of other hazardous physical properties. Its boiling point at atmospheric conditions is 39.1°C, and its vapor pressure is 348 mm Hg at 20°C. The vapor is about twice as heavy as air, meaning that the vapors stay close to the ground once released. In addition, MIC reacts exothermically with water. Although the reaction rate is slow, with inadequate cooling the temperature will increase and the MIC will begin to boil. MIC storage tanks are typically refrigerated to prevent this.

At the time of the MIC release, the Bhopal plant was under extreme financial pressure. It was able to sell only about one-third of its design capacity on the Indian market. In June 1984, the plant's managers decided to turn off the refrigeration system on the 15,000-gallon liquid MIC storage tank in an effort to reduce costs. A flare system was also present to burn any MIC vapors from the storage tank, but the flare was taken out of service several weeks prior to the incident due to a corroded pipeline. A sodium hydroxide (NaOH) scrubber system was also present to handle small releases, but it had been taken out of service for cost savings. With the shutdown of the refrigeration system, flare, and scrubber, no mitigative safeguards remained between the MIC storage tank and the external environment.

The area around the plant was zoned for industrial use. However, the siting of a major chemical manufacturing plant at the city's edge created a large opportunity for employment. Several shanty towns were built immediately adjacent to the plant and were inhabited by more than 30,000 people. Zoning laws were in place to prevent the establishment of such shanty towns, but local politicians looked the other way regarding the enforcement of the zoning laws.

The incident was initiated by water contamination of the 15,000-gallon liquid MIC storage tank. Many theories have been proposed to explain how this happened, but there is no publicly available evidence confirming any of these theories. The water caused the MIC to heat up and boil. The pressure in the storage tank increased until the relief system opened, discharging the MIC vapors directly into the air. The temperature of the MIC in the vessel was reported to reach 100°C—well above its boiling point. An estimated 25 tons of toxic MIC vapor was released. The incident occurred during the night when most residents in the adjacent shanty towns were asleep. The toxic cloud dispersed into the shanty town areas, with tragic consequences: The residents of the shanty towns suffered many of the deaths and the severest of injuries during the MIC release.

Prior to the incident, Union Carbide was viewed as a large, well-respected, high-tech American company. In 1980, its annual sales totaled $9 billion. The company had 116,000 employees at 500 sites. It had successfully operated the Oak Ridge National Lab for 40 years—a very important facility for the U.S. nuclear program. Union Carbide produced many well-recognized consumer products, including Eveready batteries, Prestone antifreeze, and Linde gases. Graduating chemical engineers considered Union Carbide a "must interview" company and a very desirable employer.

Before the incident, Union Carbide stock traded for a price between $50 and $58. In early 1985, after the Bhopal incident, the stock price dropped to $32 to $40. Union Carbide also became the target of a hostile takeover by GAF Corporation. To repel this takeover, Union

Carbide was forced to sell its consumer products division—its most profitable division. In 1986, the company sold assets worth $3.3 billion to repurchase 38.3 million shares of stock in an effort to protect the company from further takeovers. It was able to retain its commodity chemicals division.

In February 1989, the Supreme Court of India mediated payment of $470 million from Union Carbide and Union Carbide India. Union Carbide paid the settlement within 10 days of the order.

The downward spiral of Union Carbide continued until the remaining assets were purchased by Dow Chemical in 1999. The Bhopal incident was the beginning of the end for Union Carbide.

In March 1985, the AICHE, responding to industry concerns about the Bhopal incident and chemical plant safety, established the Center for Chemical Process Safety. According to the Center, CCPS is "dedicated to improving the ability of engineers to deal with process hazards." Today, CCPS is a world leader in chemical process safety.

The Bhopal incident also resulted in a considerable number of industry initiatives and government regulations related to process safety. Clearly, incidents have a lasting impact on the reputation of the chemical industry and can change the practice of chemical engineering forever.

Root causes are defined as "failures … that lead to an unsafe act or condition resulting in [an] accident."[14] For any accident, there are typically multiple root causes. If any of those root causes did not occur, then the accident would not have occurred. For the Bhopal incident, the immediate root cause of the incident was the presence of water in the MIC storage tank. Several other root causes occurred, including turning off the refrigeration system, the flare, and the NaOH scrubber system. If a detailed incident report were publicly available, other root causes would likely be identified. Although no official, publicly available, and detailed report of the Bhopal incident was ever published, publicly available information suggests almost all of the 20 elements of RBPS, as shown in Table 1-18, were involved.

Example 1-5

For the Bhopal incident, identify the hazard(s), the initiating event, enabling conditions, conditional modifiers, and safeguards. Also determine whether the safeguards were preventive or mitigative.

Solution

The hazard of the Bhopal incident was the large quantity of toxic MIC present in the storage vessel. The initiating event for the incident was the introduction of water into the MIC storage tank, which caused the temperature of the MIC to increase to its boiling point. The enabling condition was the large quantity of MIC in the storage vessel.

There were many conditional modifiers, including the presence of the shanty town around the plant and its large population. Also, the incident occurred at night when everyone was asleep, and the weather conditions were such that there was little wind to rapidly transport and disperse the vapors.

[14]AICHE/CCPS glossary, accessed November 27, 2017.

Emergency response was nonexistent, including emergency response in the community. These conditional modifiers did not directly cause the incident, but they resulted in increased consequences of the incident.

The safeguards were the refrigeration unit, flare, and scrubber. None of these were functioning at the time of the incident. The refrigeration unit was designed to keep the MIC cool and below its normal boiling point under normal storage conditions. It is not known if it had adequate capacity to handle the exothermic reaction due to the presence of water. Under normal circumstances, the refrigeration unit was preventive. The flare was designed to handle the vapors from the storage vessel; it was mitigative. It is not clear if it could handle the full vapors from the boiling MIC. The NaOH scrubber was designed only for routine releases from the storage vessel—most likely due to filling of the vessel and thermal expansion of the liquid. It was probably mitigative.

1-15 Overview of Chemical Process Safety

Process safety includes hazard identification and evaluation, as well as risk analysis. It can be simplified to the following questions:

1. What are the hazards?
2. What can go wrong and how?
3. How bad can it be?
4. How often can it happen?
5. What is the risk?
6. How do we control and manage this?

Question 1 is discussed in Chapter 2, Toxicology; Chapter 3, Industrial Hygiene; Chapter 6, Fires and Explosions; Chapter 8, Chemical Reactivity; and Chapter 11, Hazards Identification. Questions 2 and 3 are discussed in Chapter 4, Source Models; Chapter 5, Toxic Release and Dispersion Models; Chapter 6, Fires and Explosions; and Chapter 12, Risk Assessment. Questions 4, 5, 6, and 7 are discussed in Chapter 12, Risk Assessment.

Chapters 7, 9, 10, and 13 focus on systems designed to prevent specific types of incidents. Chapter 7, Concepts to Prevent Fires and Explosions, discusses common fire and explosion prevention methods. Chapter 9, Introduction to Reliefs, and Chapter 10, Relief Sizing, discuss the primary method to protect process systems from the damaging effects of high pressure. Chapter 13, Safety Procedures and Designs, presents incident prevention systems in general.

Suggested Reading

General Aspects of Chemical Process Safety

S. Mannan, ed. *Lees' Loss Prevention in the Process Industries*, 4th ed. (London, UK: Butterworth-Heinemann, 2012).

S. Mannan, ed. *Lees' Process Safety Essentials* (London, UK: Butterworth-Heinemann, 2013).

D. W. Green and M. Z. Southard, eds. *Perry's Chemical Engineers Handbook*, 8th and 9th eds., Section 23: Process Safety (New York, NY: McGraw-Hill, 2008 and 2019).
J. A. Klein and B. K. Vaughen. *Process Safety: Key Concepts and Practical Approaches* (Boca Raton, FL: CRC Press, 2017).

Accident Statistics

U.S. Bureau of Labor Statistics, www.bls.gov
Marsh and McLennan Companies, *The 100 Largest Losses, Large Property Damage Losses in the Hydrocarbon Industry.* Search the web for "100 largest losses."

AICHE/CCPS 20 Elements of Risk-Based Process Safety

Center for Chemical Process Safety. *Guidelines for Risk Based Process Safety* (New York, NY: American Institute of Chemical Engineers, 2007).
Center for Chemical Process Safety. *Introduction to Process Safety for Undergraduates and Engineers* (Hoboken, NJ: Wiley, 2016).

Inherently Safer Design

Center for Chemical Process Safety. *Inherently Safer Chemical Processes: A Life Cycle Approach*, 2nd ed. (Hoboken, NJ: Wiley, 2009).
T. Kletz and P. Amyotte. *Process Plants: A Handbook for Inherently Safer Design*, 2nd ed. (Boca Raton, FL: CRC Press, 2010).

Bhopal Incident

Chemical and Engineering News (February 11, 1985), p. 14.
John F. Murphy, Dennis Hendershot, Scott Berger, Angela E. Summers, and Ronald J. Willey. "Bhopal Revisited." *Process Safety Progress*, 33, no. 4 (2014): 310–313.

Case Histories

U.S. Chemical Safety and Hazard Investigation Board, www.csb.gov.
CCPS Process Safety Beacon, electronically published monthly by email subscription and available at no charge in many languages. https://www.aiche.org/ccps/resources/process-safety-beacon

Problems

1-1. Engineering ethics: Write an essay on why you think safety (and process safety) is an important part of any engineering ethics statement.

1-2. Classify the following from 0 to 5 based on the hierarchy of safety programs provided in Table 1-3. Explain why.

  a. The company and plant executive teams are very receptive to any safety suggestions and the suggestions are reviewed and implemented on a timely basis.

b. A change is made in a laboratory apparatus after a valve has leaked.
c. A change is made in a laboratory apparatus after a JSA review is completed.
d. The faculty member in charge of a laboratory has very little knowledge about safety.
e. The faculty member in charge of a laboratory states that "Safety is very important!" but does nothing after a small accident.
f. The company uses several leading safety metrics to assess its safety program.
g. The laboratory meets all the rules in the safety manual.
h. The faculty member in charge of a laboratory states that the safety program is interfering with the research efforts.
i. The laboratory is a mess.

1-3. Safety culture: Classify the following activities as either strengthening or weakening process safety culture. Explain why.
a. The plant manager schedules an important safety meeting that everyone must attend. At the meeting, the plant manager introduces a person from corporate safety and then excuses himself, stating that he has a more important meeting to attend elsewhere.
b. The faculty member in charge of a research lab states that not everyone in the laboratory needs to wear safety glasses—only people who are doing hazardous operations. Visitors also do not need to wear safety glasses.
c. The faculty member in charge of a research laboratory states that "No work is ever done in a clean lab!"
d. The faculty member in charge of a research laboratory states that his students—not him—are in charge of the safety program and does little else.
e. The plant manager institutes a suggestion box for safety ideas, and these ideas are discussed and resolved at the required safety meeting.
f. A suggestion box for safety ideas is implemented, but it takes the plant management many months to respond to the suggestions.
g. A research laboratory requires safety glasses, but the workers in the lab must purchase their own safety glasses.
h. A research laboratory requires safety glasses. The safety glasses are provided but are available only in a room down the hallway.
i. The laboratory safety manual has not been reviewed or updated in many years.
j. The faculty member in charge of a teaching lab tells the students that they have primary responsibility for safety, and the faculty member provides the training, resources, management and continuous auditing to ensure that the students are successful.

1-4. Individual and societal risk: For the following cases, identify the primary risk population, classify the case as involving individual risk and/or societal risk, and identify the risk as voluntary or involuntary.
a. A worker does not wear the required personal protective equipment for the chemicals being used.
b. A large butane storage facility is built next to a congested neighborhood.
c. A person drives a car from New York to Los Angeles.

d. A person drives a car without wearing the seat belt.
e. A person drives a car while intoxicated.
f. An airplane is produced with a manufacturing defect.
g. A tank truck containing gasoline is driven from the refinery to the gas station for unloading.
h. An underground pipeline is routed through a residential area.
i. A person climbs a cliff face solo.

1-5. Safety metrics: Classify the following as either leading or lagging safety metrics. Explain why.
a. Number of reports of unsafe activities in a plant
b. Number of near-miss incidents
c. Money spent on insurance claims
d. Number of visits to the plant first aid facility
e. Number of process alarms that were managed without incident
f. Time duration to complete maintenance

1-6. Accident and loss statistics: Return to Example 1-1. For parts (b) and (c), the length of time for both the hours-based fatal injury rate and the recordable incidence rate was 1 year. What time period is required for the hours-based fatal injury rate and the recordable incidence rate to be equal to the chemical manufacturing rates?

1-7. Accident and loss statistics: If the U.S. population in 2014 was 325 million people, calculate the deaths per 100,000 people from lightning strikes using the total fatalities from lightning in Table 1-13. Also calculate the fatality rate.

1-8. Use the risk matrix in Table 1-14 to determine the risk level for the Bhopal incident. Estimate the severity category, the safety severity level, the likelihood, and the risk level.

1-9. Codes, standards, and regulations: Go to the www.osha.gov web site and look up the OSHA regulation CFR 1910.119: Process Safety Management of Highly Hazardous Chemicals. Use Appendix A to determine the threshold quantities for the following chemicals. If your plant site exceeds this threshold quantity, then this standard applies.
a. Ammonia, anhydrous
b. Chlorine
c. Hydrogen fluoride
d. Propylene oxide

1-10. Safeguards: Classify the following safeguards as either preventive or mitigative.
a. A safety instrumented system to shut down a process if an unsafe operating condition occurs.
b. A foam system to reduce evaporation from a pool of leaked hydrocarbon.
c. A dike around a storage vessel.
d. A flow limiter is installed on a feed line to a chemical reactor to ensure that the reaction rate does not exceed a maximum value.
e. Covers are placed over pipe flanges to prevent liquid spraying.
f. A containment pond is built to collect any liquid runoff from a plant.

g. A relief device is installed on a chemical reactor to protect the reactor vessel from the damaging effects of high pressure.
h. A containment system is installed to collect the effluent from a relief device.
i. The basic process control system.
j. An emergency alarm system.
k. An alarm system to notify the operator of out-of-limits process conditions.
l. A gas chromatograph is installed to confirm chemical concentrations in a process.
m. All plant operations personnel are given yearly emergency response training.

1-11. CCPS elements: Classify the following activities as being most directly related to one of the 20 elements of RBPS. Although many elements may be involved, list only the single most applicable element. An element may be used more than once.
a. The plant has an open house for the local community.
b. A plant-wide emergency response drill is completed once each quarter.
c. A wide selection of courses on process safety are made available to the employees, and they are given the time and the motivation to enroll and complete the courses.
d. The plant manager demonstrates a shared responsibility for the plant safety.
e. All contractors on site are required to watch a video with an overview of the plant process safety and may be required to complete additional safety training depending on the type of work.
f. Participation in monthly safety meetings is required of all workers.
g. A small incident is investigated by the safety committee, with a final report being issued with recommendations and follow-through.
h. A permit system is developed to ensure that no welding or open flames are present when flammable liquids are handled.
i. Critical safety instrumentation is calibrated on a regular basis by the instrumentation personnel.
j. The plant site is audited on a regular basis by the corporate safety personnel.
k. Plant operating procedures are reviewed and updated to ensure that they conform to actual practice.
l. A management system is developed to ensure that all replacement equipment is identical in function to the original equipment.
m. When the electrical code changes, the plant staff reviews the changes to ensure that the plant meets the revised codes.
n. A hazard identification procedure is implemented for all existing processes.
o. Technical documents, engineering drawings and calculations, and equipment specifications are placed online for all workers to use.
p. A shutdown process is verified to be in a safe condition for restart.
q. A documented operations program is established to maintain reliable worker performance.
r. Leading and lagging metrics are established to gauge process safety performance.

s. An annual evaluation is developed to determine if management systems are performing as intended.

t. Appropriate information is made available to people who need it.

1-12. Inherently safer design: Which inherently safer design strategy applies to each of the following?

a. A flammable solvent is used to control the temperature in a reactor. The solvent is replaced by a nonflammable solvent.

b. A valve that requires 10 turns to close is replaced by a quarter-turn valve.

c. The equipment in a process can withstand 10 bar gauge (barg) of pressure even though the actual process operates normally at 5 barg. The pressure relief valve opening pressure is reduced from 10 barg to 8 barg.

d. A plant stores a large quantity of a hazardous intermediate chemical to keep the plant operating during upsets in the upstream process. The intermediate storage is eliminated and the process reliability is improved to prevent upsets and downtime.

e. An alternative reaction pathway is used that involves less hazardous raw materials.

f. The trays on a distillation column are replaced by structured packing, which operates over a wider range of operating conditions.

Additional homework problems are available in the Pearson Instructor Resource Center.

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