1

Introduction and Regulatory Overview

1.1 Purpose of this Book

This book provides an introduction to process safety. It is intended to be used either to accompany a stand-alone process safety course or as a resource of supplemental material for existing curricula. The book provides both text and a toolkit in the form of references, tools, lecture materials, and links to learning materials. (Refer to Online Materials Accompanying this Book.) This book is intended to familiarize the undergraduate student or early career engineer with important process safety concepts. As an overview, is not intended to provide the technical details on the topics which are available through various Center for Chemical Process Safety (CCPS) publications and other sources.

The overall learning objectives of this book are:

- State the importance of process safety as illustrated by process safety incidents,
- Use common process safety definitions and terminology,
- Summarize Risk Based Process Safety (RBPS) as defined by the CCPS,
- Participate in and contribute to basic hazard identification and risk analysis,
- Locate basic process safety information, resources, and tools,
- Apply process safety concepts to design and operation of engineered systems, and
- Contribute, in a supporting role, to the management of process safety hazards and risks.

1.2 Target Audience

The primary audience for this publication is third year to graduate level chemical engineering students and those engineers new to process safety in the workforce. This book can also be used by other engineering disciplines since process safety is important to all fields of engineering.

1.3 Process Safety – What Is It?

Process safety can be defined as follows.

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.

Note: Process safety focuses on efforts to reduce process safety risks associated with processes handling hazardous materials and energies. Process safety efforts help reduce the frequency and consequences of potential incidents. These incidents include toxic or flammable material releases (loss events), resulting in toxic effects, fires, or explosions. The incident impact includes harm to people (injuries, fatalities), harm to the

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environment, property damage, production losses, and adverse business publicity. (CCPS Glossary)

Such events happen at chemical facilities, refineries, onshore and offshore oil and gas facilities, and in other industries that handle or process flammable, combustible, toxic, or reactive materials and hazardous energies. For the rest of this book, the term “process facility” or “facility” will be used to mean the previously mentioned facilities and any other operation that handles or processes flammable, combustible, toxic, or reactive materials.

After an explosion in a BP Texas City refinery in 2005 that led to 15 fatalities and injured over 170 others, an independent commission was created to examine the process safety mindset, or culture, of BPs refinery operations, this commission came to be known as the Baker Panel. (Baker 2007) The Chemical Safety Board quoted the Baker Panel as follows.

> “Process safety hazards can give rise to major accidents involving the release of potentially dangerous materials, the release of energy (such as fires and explosions), or both. Process safety incidents can have catastrophic effects and can result in multiple injuries and fatalities, as well as substantial economic, property, and environmental damage. Process safety refinery incidents can affect workers inside the refinery and members of the public who reside nearby. Process safety in a refinery involves the prevention of leaks, spills, equipment malfunctions, over-pressures, excessive temperatures, corrosion, metal fatigue, and other similar conditions. Process safety programs focus on the design and engineering of facilities, hazard assessments, management of change, inspection, testing, and maintenance of equipment, effective alarms, effective process control, procedures, training of personnel, and human factors.” (CSB 2007)

Process safety applies to all phases of a facility life cycle. Process safety programs cover the operation of pilot facilities during the research phase. This also includes the selection of the chemistry and unit operations chosen to achieve the design intent of the process. Process safety is included in the design and engineering phase in choices about the type of unit operations and equipment items to use, the facility layout, and the equipment design. Process safety during operation includes, as was mentioned in the CSB quote, “hazard assessments, management of change, inspection, testing, and maintenance of equipment, effective alarms, effective process control, procedures, and training of personnel”. The engineering decisions made during research and development, pilot work, engineering design, and facility operations can impact process safety performance.

1.4 Process Safety, Occupational Safety, and Environmental Impact

The terms “process safety”, “occupational safety”, and “environmental impact” are different, even though they are often genericized to simply “safety”. All three deserve attention. Assuming that addressing one will manage the other is a mistake. The Baker Panel report noted that while BP had systems to support occupational safety; the company misunderstood that good occupational safety performance does not indicate good process safety performance. (Baker 2007) This concept is illustrated in this example: when choosing an airline, should you select the one that has a good record on employee slips, trips, and falls or the one that has fewer crashes?

In the chemical, petrochemical, and most other industries, companies are required to have an occupational safety program. This program may be required by federal or local regulations. It can apply to workers in a manufacturing plant, a research laboratory, pilot plant, and even in office locations. The focus of these programs is to prevent harm to workers from workplace accidents such as falls, cuts, sprains and strains, being struck by objects, repetitive motion injuries, and so on. These are good and very necessary programs. They typically focus on preventing harm to an individual from occupational illnesses and injuries.

They are not, however, what process safety is about. Process safety focuses on acute, though unlikely events whereas personal safety focuses on typically less acute, but more likely events.

> Process safety focuses on preventing harm from acute events that may harm multiple people (or the environment) in a single incident.

Process safety environmental impact is equally as important. Interestingly, sometimes environmental drivers can come into conflict with process safety drivers. For example, carbon canisters used to control air emissions from hydrocarbon storage tanks can catch fire if not designed, installed, and maintained properly. (Zerbonia, et al, 2001) Consider both topics and balance the risks appropriately.

Engineers will likely be faced with decisions impacting process safety and thus preventing harm to people and the environment. Although engineering is based on scientific principles, there are typically uncertainties involved in calculations and limits to any engineer's expertise. In the workplace, engineering is just one of the factors influencing business decisions. Other factors include financial resources, business goals, political constraints, organizational culture and decision-making processes. Engineering ethics is important in guiding an engineer in making decisions in the workplace.

1.5 History of Process Safety

Organizations in the process industries have a long-standing concern for process safety. (See the inset about the manufacture of nitroglycerine as an example.) Organizations originally had safety reviews for processes that relied on the experience and expertise of the people in the review. In the middle of the 20th century, more formal review techniques began to appear in the process industries. These included the Hazard and Operability Study (HAZOP), developed by ICI in the 1960s (CIA 1977), Failure Modes and Effects Analysis (FMEA), Checklist and What-If reviews. These are qualitative techniques for assessing the hazards of a process or operation.

Quantitative analysis techniques, such as Fault Tree Analysis (FTA), which had been in use by the nuclear industry, Quantitative Risk Assessment (QRA), and Layer of Protection Analysis (LOPA) also began to be used in the process industries in the 1970s, 1980s and 1990s. Modeling techniques were developed for analyzing the consequences of spills and releases, explosions, and toxic exposures. The Design Institute of Emergency Relief Systems (DIERS) was established within the American Institute of Chemical Engineers (AIChE) in 1976 to develop methods for the design of emergency relief systems to handle runaway reactions. By the mid to late 1970s, process safety was a recognized technical specialty. The American Institute of Chemical Engineers (AIChE) formed the Safety and Health Division in 1979.

In 1976, a runaway reaction occurred near Seveso, Italy that resulted in the release of 2,3,7,8-tetrachlorodibenzo-p-dioxin, commonly known as dioxin, into surrounding areas. Dioxin is a toxic chemical. Many people developed chloracne, a skin disease, and a 17 km^2 (6.6 sq. mi.) area was made uninhabitable. This incident eventually led to stricter regulations for the process industries in the European Economic Community in 1982, under what is known as the Seveso Directive (EC).

Nitroglycerine. The manufacture of nitroglycerine is an example of how process safety has evolved. Alfred Nobel began manufacturing nitroglycerine in 1864. The process was to add fuming nitric acid and sulfuric acid to glycerin while keeping the temperature at about 20-25 °C (68-77 °F). Keeping the temperature under control was critical to the safety of the process. Figure 1.1 shows a picture of an early nitroglycerine process, in which an operator is charged with observing the temperature and stopping feeds to the reactor if the temperature got too high. Note that he is sitting on a one-legged stool. The reasoning was that, if he fell asleep (watching a temperature indicator for 8 to 10 hours a day is not the most interesting thing to do), he would fall and wake up. Also, note the size of the reactor. This represents a huge amount of nitroglycerine in one place, so if it did explode, the damage would be considerable. Explosions were not uncommon. Alfred Nobel's own brother did not survive such an explosion.

Enough explosions occurred that some locations banned the use of nitroglycerine. Alfred Nobel's major breakthrough was discovering that when mixed with an inert carrier, it became safer to handle. This form of nitroglycerine is called dynamite.

The process for making nitroglycerine evolved becoming inherently safer. The large, original batch reactors were replaced with small, continuous reactors (Figure 1.2) that are a fraction of the size of the original reactors. This makes the reaction easier to control, because the heat removal capability is better (notice the cooling coils for the reactor in Figure 1.2) and the mixing intensity of the smaller reactor is higher. It also reduces the extent of the damage if an explosion did occur. Automated controls mean that no one has to stand in front of the reactor anymore.

A defining moment in the chemical industry occurred in 1984. A release of methylisocyanate, a toxic and flammable material, occurred at a chemical plant in Bhopal, India. More than 3,000 fatalities resulted from this release. (This incident will be described in more detail in Chapter 6.) The original chemical plant design had many safeguards against this event. These safeguards were not maintained, and at the time of the incident many were not functioning. The Bhopal event drove home the point that technical expertise alone was not enough, and that hazards or risk management was as important as the technical aspect of process safety. The Bhopal incident led to the formation of the Center for Chemical Process Safety (CCPS) in 1985. The CCPS is a not-for-profit organization that is part of the U.S. based American Institute for Chemical Engineers (AIChE) with a vision to protect people, property, and the environment [by] bringing the best process safety knowledge and practices to industry, academia, the government, and the public around the world through collective wisdom, tools, training, and expertise.

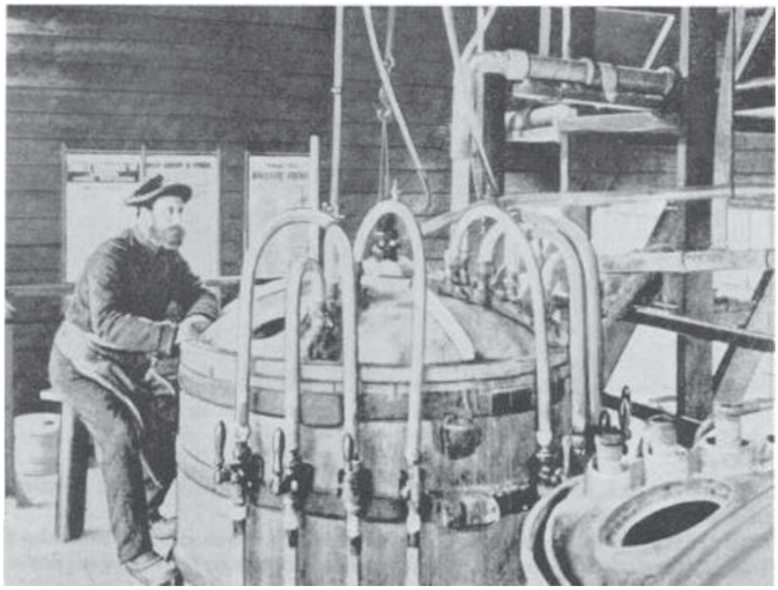

Figure 1.1. Nitroglycerine reactor in the 19th century
(Nobelprize.org)

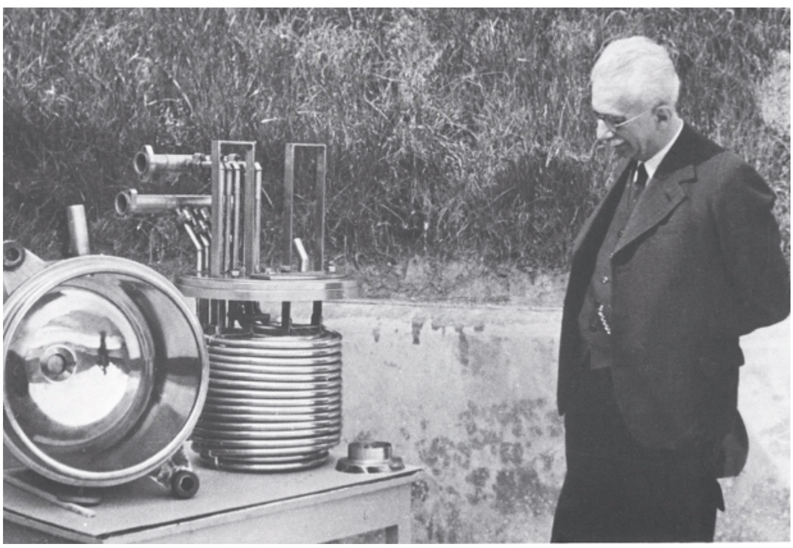

Figure 1.2. Continuous nitroglycerine reactor
(Biazzi SA)

The concept of process safety management evolved as the chemical process industries matured their focus on process safety. A management system is a formally established and documented set of activities and procedures designed to produce specific results in a consistent manner on a sustainable basis.

Process Safety Management (PSM) is a management system that is focused on prevention of, preparedness for, mitigation of, response to, and restoration from releases of chemicals or energy from a process associated with a facility. (CCPS Glossary)

In this book the term process safety management normally refers to the CCPS Risk Based Process Safety twenty element model. Process Safety Management, (PSM), refers to the fourteen element U.S. OSHA regulatory model. Both are described in this section.

In 1985 the Chemical Manufacturers Association (CMA), which later became the American Chemical Council (ACC) issued process safety management guidelines (CMA 1985). By 1989, the CCPS introduced a set of 12 process safety management elements (CCPS 1989). The American Petroleum Institute (API) also issued process safety management guidelines in 1990 (API RP 750). The CCPS studied the various approaches at the time and gleaned the 12 characteristics from interactions with its member companies and traditional business process consulting firms that had significant experience in evaluating management systems. Those guidelines were the first generic set of principles to be compiled for use in designing and evaluating process safety management systems.

In 1992 the U.S. Occupational Safety and Health Administration (OSHA) issued the "Process Safety Management of Highly Hazardous Chemicals" (OSHA PSM 1910.119 regulation, which had its own, although similar, set of process safety management elements. (OSHA) The U.S. Environmental Protection Agency (EPA) issued its own version in 1995 under the authority of the Clean Air Act. This regulation is commonly referred to as RMP, or Risk Management Plan, since the regulation requires the development and submittal of a risk plan based on the regulatory definitions and requirements. (EPA) Both of these regulations are described in further detail in Chapter 3.

OSHA PSM regulations cover the impacts of hazards to workers on-site; EPA RMP covers the impacts of hazards off-site. Applicability for both regulations is triggered by having more than a specified amount, commonly referred to as a Threshold Quantity (TQ), of specified chemicals, usually called Highly Hazardous Chemicals, or by more than 4,500 kilograms (10,000 pounds) of a flammable material in one location. PSM as defined by the CCPS, which does not depend on threshold quantities, is much broader than OSHA PSM and EPA RMP.

Process safety practices and formal safety management systems have been in place in some companies for many years. Process safety management is widely credited for reductions in major accident risk and in improved process safety performance in the process industry. Nevertheless, many organizations continue to be challenged by inadequate management system performance, resource pressures, and stagnant process safety results. To promote process safety excellence and continuous improvement throughout the process industries, the CCPS created risk-based process safety (RBPS) as the framework for the next generation of process safety management (CCPS 2007). RBPS has the format of a good practice and not a regulatory requirement. A comparison of CCPS RBPS elements with OSHA PSM and EPA RMP elements is provided in Figure 3.3.

1.6 Basic Process Safety Definitions

The terms “process safety” and “process safety management” have been defined previously in this section. Some other process safety terms are important to understand and use correctly. These include the following.

> A **hazard** is an operation, activity, or material with the potential to cause harm to people, property, the environment, or business; or simply, a potential source of harm. (CCPS Glossary)

Reinforcing this definition, a hazard is something with the potential to cause harm. Process safety is all about reducing the chance, the risk, that the harm will occur. A typical dictionary definition of risk, for example the Merriam-Webster online dictionary, is “the possibility of loss or injury” or “someone or something that creates or suggests a hazard”. The CCPS definition considers the hazard (what can go wrong), the magnitude (how bad can it be), and the likelihood (how often can it happen).

> **Risk** is a measure of human injury, environmental damage, or economic loss in terms of both the incident likelihood and the magnitude of the injury or loss. A simplified version of this relationship expresses risk as the product of the Frequency and the Consequence of an incident (i.e., Risk = Frequency x Consequence). (CCPS Glossary)

Although the formula for risk is simple, the concept of risk is complex. The risk level that a person is willing to tolerate is influenced by their perspective. Consider the risk of dying during a recreational activity. That is a voluntary risk: a risk that is willingly taken because the risk is outweighed by the benefit of the enjoyment. Transportation risks are also voluntary; however, the activity is seen as a necessity. Working is a voluntary risk where the risk is outweighed by the compensation received. Some non-voluntary risks include living near a chemical plant (and not being a worker at that plant). Each type of risk has different risk levels. Base jumping risk is higher risk than scuba diving. Driving is higher risk than flying. Logging is higher risk than farming. A variety of risks are illustrated in Figure 1.3 and Figure 1.4. which show fatality numbers and rate, respectively.

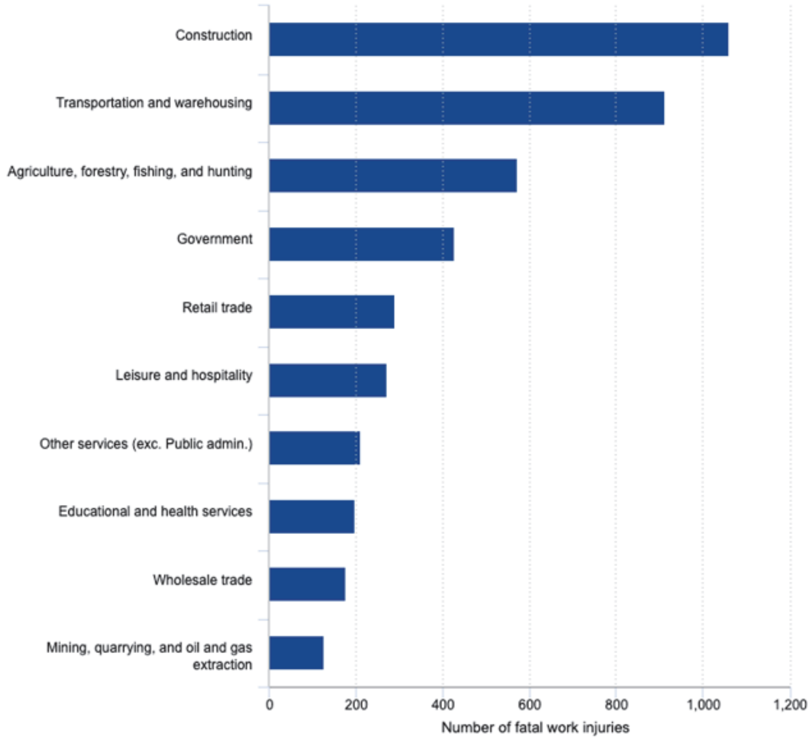

Figure 1.3. Number of fatal work injuries, by industry sector, 2019
(BLS 2019)

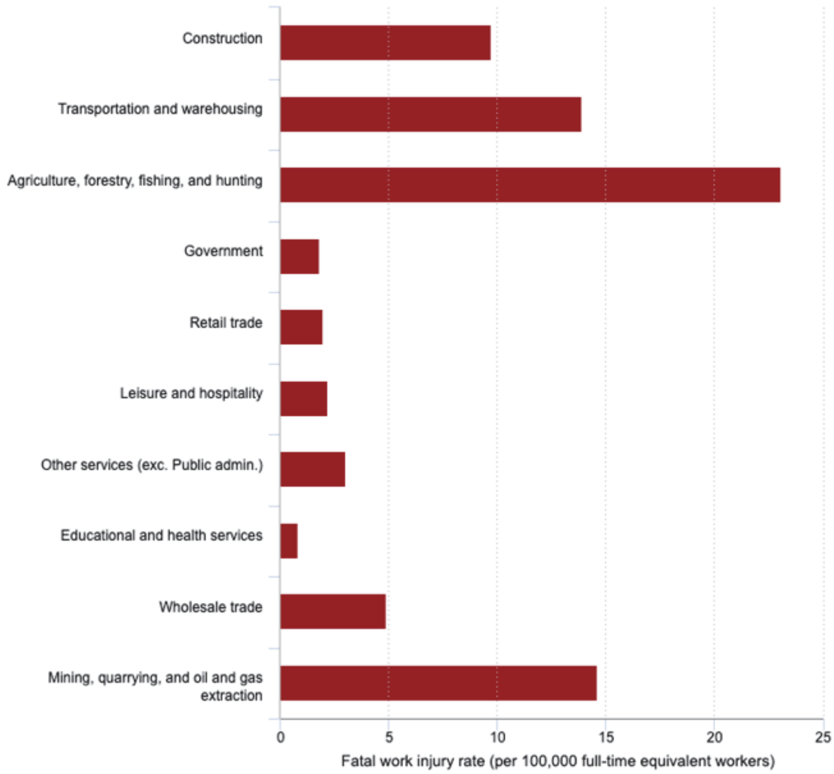

Figure 1.4. Fatal work injury rate by industry sector, 2019
(BLS 2019)

It is important in industry to manage risk at a level that the company decides it can tolerate. Individuals all have a different perception of tolerable risk; companies need to define a risk tolerance level understood by all. As employees make decisions on how to conduct work, the implicit risk level should be consistent such that a single employee's decisions do not increase risks level beyond tolerability and thus, potentially impact all employees by degrading the company's performance.

Process safety is about managing risks.

Fundamentally, process safety is about answering these questions.

1. What can go wrong? (human injury, environmental damage, or business economic loss).
2. How bad could it be? (magnitude of the loss or injury).
3. How often might it happen? (likelihood of the loss or injury).
4. How can the risk be prevented, or its impact minimized?

Not all processes and operations have the same amount of risk. Understanding risk helps a company decide how to prioritize its efforts to manage process safety. Resources, that is, money and people, are finite. When designing, operating, and maintaining a facility, the engineer has a wide range of options of which process safety management activities to implement at the facility (with the minimum requirement being complying with local and federal regulations). Process safety should be risk-based; a process with low risk does not warrant the same amount of resources as one with high risk.

1.7 Organization of the Book

This book moves from understanding and identifying hazards to analyzing and managing risk and concludes with a brief discussion on systems used to manage process safety.

Chapters 1, 2, and 3 answer the question ***what is process safety and why should I care about it?*** This includes defining basic terms, describing CCPS Risk Based Process Safety, and identifying prevalent process safety regulations, codes, and standards.

Chapters 4 through 9 answer the question ***what are the hazards?*** Basic concepts of fire, explosion, toxics, reactive chemicals, and other hazards are described along with where to find data on hazardous properties of materials and metrics used to classify incidents involving those materials.

Chapters 10 through 15 answer the question ***how do I address the hazards in my design?*** This is aligned with the three questions noted in the previous section: *what can go wrong, how bad can it be, and how often might it happen?* These chapters go through the basics of incorporating process safety in design and identifying what can go wrong in terms of equipment failure. Consequence analysis and risk assessment concepts are introduced along with methods to mitigate risk.

Chapters 16 through 20 answer the question ***how do I manage risk in operations?*** The topics of human factors, operational readiness, management of change, operating procedures, conduct of operations, safe work practices, and emergency management are addressed.

Chapters 21 through 23 answer the question ***how do I sustain the focus on process safety?*** These chapters address the RBPS elements that focus on the management of process safety and how all the aspects come together to support process safety culture.

The chapters begin with a seminal process safety incident. Many of the incident investigations revealed that deficiencies in multiple process safety topics contributed to the incidents. This book highlights the key points in each incident that are relevant to that chapter. Most of the process safety incidents cited in this book come from these sources.

Incidents that Define Process Safety (CCPS 2008)
More Incidents that Define Process Safety (CCPS 2019)
U.S. Chemical Safety Board Investigations and videos (CSB)

A list of CSB investigations and videos, organized by chapters in this book, is provided in Appendix G. Additionally, refer to Appendix H for a table listing root causes for selected major process safety incidents.

Most chapters conclude with:

- Problem sets,
- Other relevant incidents,
- What a new engineer might do, and
- References

The following symbols are used to bring attention to important points in the text.

Tools and references

Definitions

Key points

1.8 Use of this Book in University Courses

This book is intended to support both the teaching of an introductory level process safety course and also as a reference for the inclusion of process safety topics in typical engineering courses. To support the latter, a matrix relating the chapters in this book with typical engineering courses is included in Appendix B.

This book focuses on general process safety concepts while the textbook by Crowl and Louvar, *Chemical Process Safety, Fundamentals with Applications, 4th Edition* (Crowl 2019), provides a more fundamental engineering approach to process safety. These books can be used in combination.

1.9 Exercises

1. Describe the differences in focus between process safety and occupational safety.
2. Name two major incidents and the process safety regulations that were prompted by the incidents.
3. Explain the relationship between “hazard” and “risk”.
4. Figure 1.4. lists risks associated with various industries. Select 5 of these industries and identify what hazards may be inherent in that industry.
5. Identify 3 risks you take routinely. For each,
    a) Identify if it is voluntary or non-voluntary.
    b) Identify what can go wrong.
    c) Identify how bad it could be.
    d) Identify how often the bad outcome might happen.

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