

Evaluating Process Safety in the Chemical Industry

A USER'S GUIDE TO QUANTITATIVE RISK ANALYSIS



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PREFACE

Quantitative risk analysis (QRA) is a powerful analysis approach used to help manage risk and improve safety in many industries. When properly performed with appropriate respect for its theoretical and practical limitations, QRA provides a rational basis for evaluating process safety and comparing improvement alternatives. However, QRA is not a panacea that can solve all problems, make decisions for a manager, or substitute for existing safety assurance and loss prevention activities. Even when QRA is preferred, qualitative results, which always form the foundation for QRA, should be used to verify and support any conclusions drawn from QRA.

The American Chemistry Council, the Center for Chemical Process Safety, and their member companies recognize the need to provide decision makers with a guide to QRA. Chemical process industry (CPI) professionals at every level (plant managers, project managers, engineers, supervisors, etc.) need criteria for determining when risk analysis will provide information that will aid their decision making. Executives need help in understanding and evaluating QRA results that are often inscrutable to nonexperts. And all need advice concerning how detailed an analysis must be if it is to provide adequate information for a specific decision. By illustrating the judicious use of QRA, this guide will help managers use their limited resources more efficiently.

This guide summarizes some of the wisdom accumulated by CPI risk analysis practitioners and safety professionals; decision makers considering the use of QRA can benefit from this collected experience. Even though this guideline does not address every issue and circumstance concerning the use of QRA, we believe that you will be able to blend your experience with the strategies provided in this guide to make more informed decisions about using QRA.

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The American Chemistry Council, formerly the Chemical Manufacturers Association (CMA), and the American Institute of Chemical Engineers Center for Chemical Process Safety (AIChE/CCPS) have jointly published *Evaluating Process Safety in the Chemical Industry: User's Guide to Quantitative Risk Analysis*. This is a revised and updated edition of *Evaluating Process Safety in the Chemical Industry: A Manager's Guide to Quantitative Risk Analysis*, published in 1989 by CMA.

This book was written by Donald K. Lorenzo and J. Steven Arendt of EQE International, Inc. (EQE), an ABS Group Company. The technical insights, experiences, suggestions, and peer review of the CCPS Risk Analysis Subcommittee (RASC), the American Chemistry Council Process Safety Subteam (PSS), and the original (1989) CMA Process Safety Analysis Task Group (PSATG) were essential to the development of this guide.

The CCPS RASC was chaired by Dennis C. Hendershot (Rohm & Haas Company), and committee members included Daniel A. Crowl (Michigan Technological University), Scott W. Ostrowski (Exxon Mobil Chemical), Randy Freeman (Solutia, and subsequently, EQE), William Lutz (Union Carbide), Chuck Fryman (FMC Corporation), Della Wong (NOVA Chemicals), Walter Silowka (Air Products and Chemicals, Inc.), William Tilton (DuPont), Arthur Woltman (Shell), and Thomas Gibson (CCPS).

The American Chemistry Council PSS was chaired by Peter Lodal (Eastman Chemical) and included representatives from DuPont; Shell Chemical; ExxonMobil Chemical; Huntsman; Dow Chemical; Solutia; Celanese; Rohm & Haas Company; Air Products and Chemicals, Inc.; Monsanto; Union Carbide; Montell; Eastman Chemical; and Lyondell.

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EXECUTIVE SUMMARY

The art of making wise decisions is the hallmark of successful management and requires both pertinent information and good judgment. Safety-related decisions, in particular, have traditionally been based on hard-earned operating experience and intuition. As greater demand for improving the safety, health, environmental, and economic aspects of facilities is placed on companies' finite resources, the decision-making process becomes more difficult and the need for better information becomes more critical.

Company management now recognizes that simply reacting to accidents and then determining where additional safety precautions are needed is no longer acceptable — the potential effects of accidents are becoming increasingly catastrophic. Moreover, today's technical and social environment dictates that decision makers take a more proactive approach to safety-related decision making and that more thorough methods and strategies be used to gain an increased understanding of the significance of risks from their companies' operations.

Risk is defined as the combination of the expected frequency and consequence of accidents that could occur as a result of an activity. **Risk analysis** is a formal process of increasing one's understanding of the risk associated with an activity. The process of risk analysis includes answering three questions:

- What can go wrong?
- How likely is it?
- What are the impacts?

Risk assessment is the subsequent process of taking risk analysis results and answering a fourth question:

- Are the risks tolerable?

Qualitative answers to one or more of these questions are often sufficient for making good decisions about the allocation of resources for safety improvements. But, as managers seek quantitative cost/benefit information upon which to base their decisions, they increasingly turn their attention to the use of *quantitative risk analysis* (QRA).

This guide provides information on the applicability of QRA to the chemical process industry (CPI). Although companies have many possible applications for risk analysis (e.g., determining the investment risk of a new product), this guide focuses on how risk analysis methods can be used for the improvement of process facilities. Moreover, while QRA can also be used to investigate economic, environmental, and health risks of process operations, this guide concentrates on QRA's use for estimating one particular type of risk—the risk of immediate injuries to workers or the public from single accidents involving acute exposure to energy releases or harmful substances.

Developing an appreciation of the benefits, limitations, relative costs, and complexities of using QRA is a necessity for CPI managers. To equip the potential user of QRA with this basic understanding, this guide discusses three important aspects of QRA:

- How to decide whether to use QRA
- How to set up a QRA to provide specific risk information
- How to interpret and use QRA results

This guide presents a framework to help you decide whether QRA can aid your decision making. Various factors influencing the decision to use QRA are described, and the types of information QRAs make available to managers are discussed. Managers are encouraged to first use qualitative techniques and risk screening methods as decision aids. Efficiency dictates that managers use QRA only in selected cases when decision-making information cannot be supplied by less elaborate means. But, appropriately scoped and applied, QRA can provide powerful insights for allocating finite process safety resources. This guide contains a flowchart of questions and information you can use to help determine when to use QRA.

If decision makers choose to use QRA, they must then define the analysis objectives so the results will satisfy the particular decision-making requirement. Because the cost of performing QRA is dependent

on depth and scope of study, this guide stresses the importance of defining the right problem for analysis. An overview of QRA methods is presented to help executives understand the options available when selecting QRA techniques. To help managers have realistic expectations, important limitations of QRA techniques are also discussed.

Finally, this guide presents information on interpreting and using QRA results, outlining several methods for comparing results with experience and for presenting results to enhance credibility. Because the way people view risk is an overriding concern in the use of QRA, various factors that influence risk perception are also discussed. And the guide lists some pitfalls managers should avoid in using QRA results for decision making.

When QRA is used judiciously, its advantages can outweigh the associated problems. However, companies should resist the indiscriminate use of QRA as a means to solve all problems since this strategy could be an inefficient use of finite safety improvement resources, diverting attention from other essential safety activities. Once executives can interpret and use QRA results, they will appreciate that the quality of their decisions largely rests on their ability to understand the salient analysis assumptions. Moreover, they can use QRA to determine the impacts of important assumptions, and can use these sensitivity results to better understand the limitations of QRA studies.

Quantitative risk analysis is an important tool for the CPI. But QRA must complement (and not replace) other historically successful methods for safety assurance, loss prevention, and environmental control. A new, evolving technology, and still more of an art than a science, QRA will never make a decision for you—it can only help to increase the information base you draw on when making a decision. More conventional process safety management practices, such as good design standards, proper construction, accurate procedures, thorough training, periodic safety audits, and sound management judgment, will continue to form the foundation for a safe and productive chemical industry.

ADVICE FOR THE READER

This guide is designed to equip you with a basic understanding of the benefits, limitations, and complexities of using QRA. However, this is not a “how to” manual for QRA; nor does it concentrate on how to set up a corporate QRA program. (This information can be found in the CCPS *Guidelines for Chemical Process Quantitative Risk Analysis, Second Edition*.²⁴) Instead, this guide describes the role managers and sponsors should play in ensuring the success of QRA projects. To convey this information, we use the following steps:

- Establish a basic vocabulary (Glossary). Every discipline has its own jargon, and QRA is no different
- Define a method for determining whether QRA can (or is needed to) help your decision making
- Describe what to reasonably expect from QRA
- Provide a basis for understanding QRA results, beyond the obvious statistical meanings

This guide may be read by an audience ranging from middle managers to senior executives who have different levels of knowledge about QRA. This guide may also be read by engineers and other technical staff who will be contributing to QRAs or using the results. We have, therefore, designed the chapters to allow for differences in expertise and need.

Chapter 1 defines QRA, discusses its essential elements, and dispels some misconceptions. Chapter 2 outlines considerations for deciding when to apply QRA. It presents some reasons for performing QRA and describes the types of information available from such studies. This chapter also describes practical situations in which QRA may be used successfully, as well as conditions that make QRA a less desirable choice.

Once the decision has been made to use QRA, the next step is to execute it effectively. Chapter 3 describes the process of setting up an individual QRA. This chapter discusses the importance of defining the right problem for analysis and selecting the right analysis techniques; it also provides an overview (not a how to) of the various classes of QRA techniques. Chapter 4 discusses ways to interpret and use QRA results. Conclusions about the future of QRA in the CPI are offered in Chapter 5.

ACRONYMS

AIChE	American Institute of Chemical Engineers
API	American Petroleum Institute
CCPS	Center for Chemical Process Safety
CMA	Chemical Manufacturers Association
CPI	Chemical process industry
CPQRA	Chemical process quantitative risk analysis
ERPG	Emergency response planning guideline
FAR	Fatal accident rate
FMEA	Failure modes and effects analysis
HAZOP	Hazard and operability analysis
LOPA	Layer of protection analysis
P&ID	Piping and instrumentation diagram
PRA	Probabilistic risk analysis
QRA	Quantitative risk analysis
RASC	Risk Assessment Subcommittee
ROD	Average rate of death
STEL	Short-term exposure limit

GLOSSARY

Acceptable risk	The average rate of loss that is considered tolerable for a given activity
Accident (sequence)	A specific combination of events or circumstances that leads to an undesirable consequence
Acute hazard	The potential for injury or damage to occur as a result of an instantaneous or short duration exposure to the effects of an accident
Aggregate risk	Societal risk for onsite workers in occupied buildings (API 752)
Average aggregate risk	Average societal risk for onsite workers in occupied buildings (API 752)
Average individual risk	Average individual risks must be defined in context of the exposed population: A. <i>Average individual risk (exposed population)</i> is the individual risk averaged over the population that is exposed to risk from the facility B. <i>Average individual risk (total population)</i> is the individual risk averaged over a predetermined population, without regard to whether or not all people in that population are actually exposed to the risk C. <i>Average individual risk (exposed hours/worked hours)</i> for an activity may be calculated for the duration of the activity or may be averaged over the working day
Average rate of death (ROD)	The average number of fatalities that might be expected per unit time from all possible incidents
Chronic hazard	The potential for injury or damage to occur as a result of prolonged or repeated exposure to an undesirable condition
Consequence	The direct, undesirable result of an accident, usually measured in health/safety effects, environmental damage, loss of property, or business costs

CPQRA	The acronym for chemical process quantitative risk analysis. It is the process of hazard identification followed by numerical evaluation of incident consequences and frequencies, and their combination into an overall measure of risk when applied to the chemical process industry. It is particularly applied to episodic events. It differs from, but is related to, a probabilistic risk analysis (PRA), a quantitative tool used in the nuclear industry
Dispersion model	A mathematical model describing how material is transported and dispersed from a release
Emergency response planning guideline (ERPG)	A system of guidelines for air concentrations of toxic materials prepared by the American Industrial Hygiene Association. An ERPG is the maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 hour with the following results: • ERPG-1: Nothing other than mild transient adverse health effects or perception of a clearly defined objectionable odor • ERPG-2: No irreversible or other serious health effects or symptoms that could impair an individual's ability to take protective action • ERPG-3: No life-threatening health effects
Episodic event	A release of limited duration, usually associated with an accident
Event tree (analysis)	A logic model that graphically portrays the range of outcomes from the combinations of events and circumstances in an accident sequence. For example, a flammable vapor release may result in a fire, an explosion, or in no consequence depending on meteorological conditions, the degree of confinement, the presence of ignition sources, etc. These trees are often shown with the probability of each outcome at each branch of the pathway
Expected value	The statistical average of a variable described by a probability distribution
Failure modes and effects analysis (FMEA)	A hazard identification technique in which all known failure modes of components or features of a system are considered in turn, and undesired outcomes are noted
Fatal accident rate (FAR)	The average number of fatalities expected in a particular worker population of interest over a period of 10 ⁸ worker-hours (roughly 1,000 employee working lifetimes)
Fault tree (analysis)	A logic model that graphically portrays the combinations of failures that can lead to a particular main failure (TOP event) or accident of interest. Given appropriate data, fault tree models can be quantitatively solved for an array of system performance characteristics (mean time between failures, probability of failure on demand, etc.)

GLOSSARY

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F-N curve	A graphical illustration of the cumulative frequency (F) of accidents resulting in a consequence of greater than or equal to N impacts. A way of illustrating societal risk
Frequency	Number of occurrences of an event per unit of time
Hazard	A chemical or physical condition that has the potential for causing damage to people, property, or the environment
Hazard and operability (HAZOP) analysis	A technique to identify process hazards and potential operating problems using a series of guide words to study process deviations
Importance	The probability a specific component (or collection of components) is contributing to a system failure, given that the system is failed
Incident	An unplanned release of hazardous chemicals or energy
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
Layer of protection analysis (LOPA)	A simplified form of event tree analysis using selected accident scenarios and order-of-magnitude estimates to determine whether additional protection is needed
Likelihood	A measure of the expected probability or frequency of occurrence of an event
Probability	The expression for the likelihood of occurrence of an event or an event sequence during an interval of time or the likelihood of the success or failure of an event on test or on demand. By definition, probability must be expressed as a number ranging from 0 to 1
Process safety management	A program or activity involving the application of management principles and analytical techniques to ensure the safety of chemical process facilities
Quantitative risk analysis (QRA)	The systematic development of numerical estimates of the expected frequency and/or consequence of potential accidents associated with a facility or operation
Rare event	An event or accident whose expected frequency is very small. The event is not expected to occur during the normal life of a facility or operation
Risk	A measure of human injury, environmental damage, or economic loss in terms of both the incident likelihood and the magnitude of the loss or injury

Risk analysis	The development of a quantitative estimate of risk based on engineering evaluation and mathematical techniques for combining estimates of incident consequences and frequencies
Risk assessment	The process by which the results of a risk analysis (i.e., risk estimates) are used to make decisions, either through relative ranking of risk-reduction strategies or through comparison with risk targets
Risk contour	Lines that connect points of equal risk around the facility ("iso-risk" lines)
Risk estimation	Combining the estimated consequences and likelihood of all incident outcomes from all selected incidents to provide a measure of risk
Risk management	The systematic application of management policies, procedures, and practices to the tasks of analyzing, assessing, and controlling risk in order to protect employees, the general public, and the environment, as well as company assets, while avoiding business interruptions
Risk measures	Ways of combining information on likelihood with the magnitude of loss or injury (e.g., risk indices, individual risk measures, and societal risk measures)
Risk targets	Objective-based risk criteria established as goals or guidelines for performance
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
Uncertainty	A measure, often quantitative, of the degree of doubt or lack of certainty associated with an estimate of the true value of a parameter

1

INTRODUCTION

*What the decision maker
wants is access to hope.*

G.L.S. SHACKLE

1.1. BACKGROUND

Successfully managing industrial facilities requires pertinent information and good judgment. When you must make a decision affecting the level of safety of your organization's various enterprises, you need information about the risks posed by the activities of interest. Once in possession of these risk insights, you can be more effective in making risk management decisions. If information concerning the risk impact of possible choices is not available, then you are less likely to make an optimal decision.

Historically, managers in the chemical process industry (CPI) have relied upon industry experience when judging the risks associated with their facilities and activities.^{1,2} The CPI has been successful in maintaining an excellent safety record compared to industry overall. But as new process technologies are developed and deployed, less of the historical experience base remains pertinent to safety assurance. Other potentially hazardous industries—such as nuclear power, aerospace, and defense—have lacked the prior experience necessary to assess the safety aspects of the advanced technology of new designs.^{3,4} The absence of relevant historical data in these industries led to the development of techniques for predicting risks, including many of these now used to perform quantitative risk analysis (QRA).⁵ The CPI has adapted many of these techniques and has developed new methods to deal with the diverse hazards of chemical process facilities.

QRA is fundamentally different from many other chemical engineering activities (e.g., chemistry, heat transfer, reaction kinetics) whose basic property data are theoretically deterministic. For example, the physical properties of a substance for a specific application can often be established experimentally. But some of the basic “property data” used to calculate risk estimates are probabilistic variables with no fixed values. Some of the key elements of risk, such as the statistically expected frequency of an accident and the statistically expected consequences of exposure to a toxic gas, must be determined using these probabilistic variables. QRA is an approach for estimating the risk of chemical operations using the probabilistic information. And it is a fundamentally different approach from those used in many other engineering activities because interpreting the results of a QRA requires an increased sensitivity to uncertainties that arise primarily from the probabilistic character of the data.

Estimating the frequencies and consequences of rare accidents is a synthesis process that provides a basis for understanding risk. (Throughout the published literature, the terms risk assessment and risk analysis are used interchangeably in reference to this process.) Using this synthesis process, you can develop risk estimates for hypothetical accidents based upon your experience with the individual basic events that combine to cause the accident. (Basic events typically include process component failures, human errors, and changes in the process environment, and more information is usually known about these basic events than is known about accidents.) System logic models are used to couple the basic events together, thus defining the ways the accident can occur.

With the advent of this new safety analysis technology, and the need for providing better input to risk management and safety improvement decisions, many CPI safety professionals are calling for increased use of QRA. And, given the contemporary technical and social environment, *it is imperative that management personnel understand the strengths and weaknesses of QRA technology.*

1.2. THE PROCESS OF RISK ANALYSIS

Risk analysis is the process of gathering data and synthesizing information to develop an understanding of the risk of a particular enterprise. Risk analysis usually involves several of the five risk management activities shown in Figure 1. CPI companies have many possible applications



FIGURE 1. Elements of risk management.