

# **Chemical Process Safety Fundamentals with Applications**

**Daniel A. Crowl**

**Joseph F. Louvar**

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# Preface

This textbook is designed to teach and apply the fundamentals of chemical process safety. It is appropriate for an industrial reference, a senior level undergraduate course or a graduate course in chemical process safety. It can be used by anyone interested in improving chemical process safety, including chemical and mechanical engineers and chemists. More material is presented than can be accommodated in a 3 credit semester course.

The primary objective of this textbook is to encapsulate the important technical fundamentals of chemical process safety. The emphasis on the fundamentals will hopefully help the student and practicing scientist *understand* the concepts and apply them accordingly. This application requires a significant quantity of fundamental knowledge and technology.

Since a textbook fundamentally oriented on safety has never been undertaken, we experienced several difficulties. First, an outline that presented the material in a logical and expanding fashion was very difficult to develop. Second, since chemical process safety involves a very large quantity of material, the motivation was always present to include more and more. We have tried to limit the material to those items deemed essential for industrial and university practice. Third, the fundamental basis for much of the material was long lost and had to be redeveloped.

We firmly believe that a textbook on safety could only have been possible with both industrial and academic inputs. The industrial input insured that the material was industrially relevant. The academic input insured that the material was presented on a fundamental basis to help professors and students understand the concepts.

When this textbook is completed, few universities will have required courses in chemical process safety. While the need is recognized, little flexibility is

presently available to add additional courses to the undergraduate chemical engineering curriculum. Also, faculty have little background in chemical process safety, and, finally, inadequate instructional materials are available to teach such a course. We hope this textbook solves the instructional material problem and that the remaining problems will be solved in time.

This textbook is designed for a dedicated course in chemical process safety. However, we feel that chemical process safety should be part of every undergraduate and graduate course in chemistry and chemical and mechanical engineering, just as it is a part of all the industrial experiences. This text can be used as a reference resource for these courses.

We will inevitably be criticized by some who believe our presentation is not complete or that some details are missing. The purpose of this book is not completeness but to provide a starting point for those who wish to learn about this important area.

We would like to thank Harold Fisher of Union Carbide and Joseph Leung of Fauske and Associates for reviewing the sections on two-phase flow relief and providing a number of important corrections and modifications. Edward J. Kerfoot, Michael Capraro and Jim Strickland of BASF Corporation reviewed specific chapters. Dan Goerke helped with the homework problems and solutions and suggested a number of important changes. Bruce Barna, Dave Leddy, and Nam Kim of Michigan Technological University helped develop a number of instructional modules that contributed towards the initial basis for this text. Michigan Technological University also provided a sabbatical experience to one of us (D.A.C.) which contributed to the initial textbook development. Professor Edward R. Fisher of Michigan Tech is thanked for this opportunity.

We thank our coworkers at BASF Corporation for giving us the knowledge and deep appreciation for the importance of process safety in laboratories, pilot plants and plants. This especially includes M. Capraro, J. Strickland, and K. Kilponen.

We also acknowledge and thank the members of the Curriculum Committee of the Center for Chemical Process Safety (CCPS) and the Safety and Loss Prevention Committee of the American Institute of Chemical Engineers. We are honored to be members of both committees. The members of these committees are the experts in safety; their enthusiasm and knowledge have been truly educational and a key inspiration to the development of this text.

We thank John Davenport of Industrial Risk Insurers for providing information concerning several case histories which he particularly chose because of their significant relevance to process safety. John also reviewed Chapters 6 and 7 and provided very valuable information on sprinkler system design. Walter Howard, presently a Process Safety Consultant, has given us important safety information and facts and continued encouragement to complete this project.

Finally, we acknowledge our families, who provided patience, understanding and encouragement.

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

*Detroit, Michigan*

*Daniel A. Crowl  
Joseph F. Louvar*

# Nomenclature

$a$	velocity of sound (length/time)
$A$	area (length <sup>2</sup> ) or Helmholtz free energy (energy); or process component availability
$A_t$	tank area (length <sup>2</sup> )
$\Delta A$	change in Helmholtz free energy (energy/mole)
$C$	mass concentration (mass/volume) or capacitance (Farads)
$C_0, C_1$	discharge coefficients (unitless) or concentration at a specified time (mass/volume)
$C_p$	heat capacity at constant pressure (energy/mass deg)
$C_v$	heat capacity at constant volume (energy/mass deg)
$C_{ppm}$	concentration in parts per million by volume
$C_{vent}$	deflagration vent constant (pressure <sup>1/2</sup> )
$\langle C \rangle$	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)
$D_0$	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)
$f$	Fanning friction factor (unitless)
$f(t)$	failure density function
$f_v$	mass fraction of vapor (unitless)
$F$	frictional fluid flow loss term (energy/mass)
$g$	gravitational acceleration (length/time <sup>2</sup> )
$g_c$	gravitational constant
$G$	Gibbs free energy (energy/mole) or mass flux (mass/area time)
$G_T$	mass flux during relief (mass/area time)
$\Delta G$	change in Gibbs free energy (energy/mole)
$h$	specific enthalpy (energy/mass)
$h_L$	fluid level above leak in tank (length)
$h_L^0$	initial fluid level 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)
$\Delta H$	change in enthalpy (energy/mole)
$\Delta H_c$	heat of combustion (energy/mass)
$\Delta H_v$	enthalpy of vaporization (energy/mass)
$I$	sound intensity (decibels)
$I_0$	reference sound intensity (decibels)
$I_s$	streaming current (amps)
$j$	number of inerting purge cycles (unitless)
$J$	electrical work (energy)
$k$	non-ideal mixing factor for ventilation (unitless)
$k_1, k_2$	constants in probit equations
$K$	mass transfer coefficient (length/time)
$K_b$	backpressure correction for relief sizing (unitless)
$K_g$	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)
$K^*$	constant eddy diffusivity (area/time)
$L$	length
$LEL$	lower explosion limit (volume %)
$LFL = LEL$	lower flammability limit (volume %)



$m$	mass
$m_0$	total mass contained in reactor vessel (mass)
$m_{\text{TNT}}$	mass of TNT
$m_v$	mass of vapor
$M$	molecular weight (mass/mole)
$M_0$	reference molecular weight (mass/mole)
$Ma$	Mach number (unitless)
MTBC	mean time between coincidence (time)
MTBF	mean time between failure (time)
$n$	number of moles
$p$	partial pressure (force/area)
$p_d$	number of dangerous process episodes
$P$	total pressure or probability
$P_b$	backpressure for relief sizing (psig)
$P_g$	gauge pressure (force/area)
$P_{\text{max}}$	maximum pressure for relief sizing (psig)
$P_s$	set pressure for relief sizing (psig)
$P^{\text{sat}}$	saturation vapor pressure
$q$	heat (energy/mass)
$q_f$	heat intensity of flare (energy/time area)
$q_s$	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
RHI	reaction hazard index defined by Equation 13-1
$r_f$	vessel filling rate (time <sup>-1</sup> )
$R_g$	ideal gas constant (pressure volume/mole deg)
Re	Reynolds number (unitless)
$S$	entropy (energy/mole deg)
$S_m$	material strength (force/area)
$t$	time
$t_c$	emptying time
$t_p$	time to form a puff of vapor
$t_v$	vessel wall thickness (length)
$t_w$	worker shift time

$\Delta t_v$	venting time for reactor relief
$T$	temperature (deg)
$T_d$	material decomposition temperature (deg)
$T_i$	time interval
$T_m$	maximum temperature during reactor relief (deg)
$T_s$	saturation temperature at set pressure during reactor relief (deg)
$u$	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 time) or process component unavailability
$UEL$	upper explosion limit (volume %)
$UFL = UEL$	upper flammability limit (volume %)
$v$	specific volume (volume/mass)
$v_l$	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 coordinant (length)
$X_f$	distance from flare at grade (length)
$y$	mole fraction of vapor (unitless) or Cartesian coordinate (length)
$Y$	probit variable (unitless)
$z$	height above datum (length) or Cartesian coordinate (length) or compressibility (unitless)
$z_c$	scaled distance for explosions (length/mass <sup>1/3</sup> )

## GREEK LETTERS

$\alpha$	velocity correction factor (unitless)
$\beta$	thermal expansion coefficient (deg <sup>-1</sup> )
$\delta$	double layer thickness (length)
$\epsilon$	pipe roughness (length) or emissivity (unitless)

$\epsilon_r$	relative dielectric constant (unitless)
$\epsilon_0$	permittivity constant for free space (charge <sup>2</sup> /force length <sup>2</sup> )
$\Phi$	nonideal filling factor (unitless)
$\gamma$	heat capacity ratio (unitless)
$\gamma_c$	conductivity (mho/cm)
$\chi$	function defined by Equation 9-6
$\lambda$	frequency of dangerous episodes
$\lambda_d$	average frequency of dangerous episodes
$\mu$	viscosity (mass/length/time) or mean value or failure rate (faults/time)
$\mu_v$	vapor viscosity (mass/length/time)
$\Psi$	overall discharge coefficient used in Equation 9-14 (unitless)
$\rho$	density (mass/volume)
$\rho_L$	liquid density (mass/volume)
$\rho_{ref}$	reference density for specific gravity (mass/volume)
$\rho_v$	vapor density (mass/volume)
$\sigma$	standard deviation (unitless)
$\sigma_x, \sigma_y, \sigma_z$	dispersion coefficient (length)
$\tau$	relaxation time
$\tau_i$	inspection period for unrevealed failures
$\tau_0$	operation period for a process component
$\tau_r$	period required to repair a component
$\tau_u$	period of unavailability for unrevealed failures
$\zeta$	zeta potential (volts)

**SUBSCRIPTS****SUPERSCRIPTS**

c	combustion	°	standard
f	formation or liquid	'	stochastic or random variable
g	vapor or gas		
m	maximum		
s	set pressure		
o	initial or reference		

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