AIChE

Guidelines for Determining the Probability of Ignition of a Released Flammable Mass

Bob Stack,[a] Adrian Sepeda,[b] and Mike Moosemiller[c]

[a]Dow Chemical, 165 Uran St. Hillsdale, MI 49242

[b]CCPS Staff Consultant, PO Box 250183, Plano, TX 75025

[c]Baker Engineering and Risk Consultants, Inc., 8430 West Bryn Mawr, Suite 720, Chicago, IL 60631; mmoosemiller@BakerRisk.com (for correspondence)

Published online 11 October 2013 in Wiley Online Library (wileyonlinelibrary.com). DOI 10.1002/prs.11648

It is not difficult to find situations in which the probability of ignition for a given set of conditions varies widely from source to source. There are also some variables that are known to be important to the probability of ignition that have not yet been rigorously quantified. This results in uncertainty in risk-based studies, limiting the ability of the risk manager to justify spending for appropriate projects that would reduce the probability of ignition as a way of managing risk.

For this reason, CCPS commissioned a new book for release in 2013 that consolidates the available information on this subject and proposes ignition probability algorithms that advance the state of the art. Purchasing the book also allows access to software that codifies (and automates some of) the methods discussed in the book. The intended audiences for the book are Process Safety Subject Matter Experts (SMEs) involved in risk assessments and hazard evaluations. The timing of the new book's release is after the release of the revision to the CCPS book, "Guidelines for Evaluating Process Plant Buildings for External Fires, Explosions, and Toxic Releases," and near the release time of another CCPS book, "Guidelines for Enabling Conditions and Conditional Modifiers for Layer of Protection Analysis" in order to support the risk-based analyses described in those publications. © 2013 American Institute of Chemical Engineers Process Saf Prog 33: 19–25, 2014

Keywords: ignition; risk; risk analysis; ignition probability; LOPA

Additional Supporting Information may be found in the online version of this article.

This article was originally presented under the title "Guidelines for Evaluating the Likelihood of Ignition of Released Flammable Masses" at the 9th Global Congress on Process Safety, San Antonio, TX, 29 April to 1 May 2013.

Note: To avoid confusion, definitions of the following terms as used for the purposes of this article are provided below.

Frequency: The rate at which a certain event occurs, expressed in terms of events per unit time (e.g., "explosions per year"), Probability: The odds or expectations that a certain event will occur, given a stated starting point (e.g., the probability that I roll a "3" on a single die is 1/6). The units of probability are dimensionless, Likelihood: A term that can be used in place of either "frequency" or "probability," and generally both in the context of this paper.

INTRODUCTION

Project Concept and Status

Since the beginning of structured risk analyses, a core question in studies involving flammable releases has been, "Will the release ignite?" Technology has been developed to predict consequences of ignition with varying degrees of precision. However, the "Will it actually ignite?" question has received far less attention and technical development. We know that when a flammable material is released from process equipment, the result may be a fire, an explosion, or the release may simply dissipate with no apparent effect other than a minor environmental impact. Depending on the circumstances, the probability (likelihood) of ignition can range from 0 to 1. Most of the current methods used for estimating the probability of ignition are rather crude and in many cases are not based on actual process industry data. For anyone performing a risk-based analysis of any type (QRAs, LOPAs, risk-based facility siting studies, or even the application of a PHA risk matrix), this results in overly conservative or overly optimistic expectations of ignition. In other words, the current methods are often not much better than a guess and can be misleading, with potentially catastrophic results.

The algorithms proposed in this book represent what we believe to be the state of the art, but the reader must recognize that the "art" is still evolving. It is anticipated that software updates will occur periodically based on user feedback from the first release. A communication method will be developed and employed so that people who purchase the book, complete with the Calculation Tool, will benefit from those software updates. Therefore, the goal of this project is not only to provide a "snapshot" of the current technology in an effort to manage risk but to promote its continued improvement via user involvement and feedback.

Project Background

The hazards of flammable liquids and vapors have been known for many years, and in recent decades, have become progressively more quantitative. The Center for Chemical Process Safety (CCPS), an AIChE Technological Alliance, has addressed this issue by generating literature regarding "siting" (protection of people in buildings) and a large range of other process safety issues. The *"Guidelines for Evaluating Process Plant Buildings for External Explosions, Fires,* *and Toxic Releases, 2nd edition"* was released by CCPS in the spring of 2012. Its purpose is to provide the "how to do" for the recommendations of API 752-3rd Edition on building siting. With the technology and literature now available, industry has the tools necessary to make technologically based decisions regarding the consequences of flammable releases, and specifically regarding the consequences on building occupants should those releases ignite (or explode). This information has validated that buildings themselves are often a significant hazard should an explosion occur. Therefore, the belief that seeking refuge in a building during or immediately after an ignitable release is often exactly the wrong thing to do.

Another recently published book and a valuable resource on a related subject is the CCPS "Guidelines for Enabling Conditions and Conditional Modifiers for Layer of Protection Analysis," a follow-on to another CCPS book on the subject of Layers of Protection Analysis (LOPA).

In reality, not all releases of flammable materials ignite or explode when released to the atmosphere in an operating chemical or petrochemical facility. In most instances, it is simply a matter of the very specific circumstances and atmospheric conditions existing at that particular moment in time. This is important because industry, while charged with conducting safe and environmentally sound operations, is not able to eliminate all risk associated with manufacturing, just as an individual is not able to eliminate all risk associated with living their daily lives. Industry is, however, expected to manage the associated risk and stay within a tolerable level. That involves making risk-based decisions that are defendable and repeatable regarding siting and/or any other hazards in the workplace. Risk-based decision making involves considering, calculating, and/or determining data for the two components of risk—probability that an event will occur and the expected consequences if it does. The Risk equation is often written as:

$$\text{Risk} = \text{Frequency} \times \text{Consequence}$$

and read as "Risk is 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." (CCPS 2009).

Consequences are predictable and quantifiable if enough data exists. In the manufacturing sector that handles volatile chemicals, there is technology in place to make those calculations with acceptable precision. However, there is a large technological void when it comes to calculating the probability or likelihood that the released flammable material (gas, liquid, or vaporizing liquid) will ignite. History has shown that sometimes it does and sometime it does not.

The determination of ignition probability (of a released flammable mass) is the objective of this book. When both components of risk are able to be expressed in quantitative terms, then risk can be mathematically, and more accurately, determined and compared to other risks and/or other scenarios. The result is that this book and the technology herein, when combined with the second edition of the CCPS book "*Guidelines for Evaluating Process Plant Buildings for External Explosions, Fires, and Toxic Releases*" and/or the "*Guidelines for Enabling Conditions and Conditional Modifiers for Layer of Protection Analysis*" provides the methodology and technical basis for making risk-based siting decisions. While industry has been making risk-based decisions for many years, this is the first time that they can make these decisions with a complete set of technologies for all branches of a scenario event tree. This allows defensible, technologically based, risk-based decisions for siting—protection of people in buildings.

Additionally, the methodology and data provided by this new book will provide the platform for future risk reduction efforts and the setting of priorities involving releases. For instance, from a postevent reaction standpoint, the information gained from the risk analysis could be used to develop better and more appropriate emergency response plans—on site and off site. From a risk reduction standpoint, the analysis would identify the major contributors to the risk, allowing industry to prioritize and focus on those areas or events so that available resources are used wisely and are based on technology, rather than emotions, fear, or misconceptions.

Need for This Book

What distinguishes this effort from similar efforts in the past is recognition that the currently available data in the literature suffers from three significant shortcomings:

1. Data are limited because there is no practical means to conduct controlled experiments of many situations—we are unable to go into a variety of "live" operating units, release quantities of flammables, and record how often the clouds result in a fire, explosion, or nonignition.
2. The data that are available are either from situations that are different from a normal process plant (e.g., offshore blowouts) or are likely to be skewed (e.g., events resulting in a fire or an explosion will be in the public record much more often than releases that did not ignite, resulting in an overestimate of the probability of ignition).
3. There are variables that we can expect will be important in whether a release is ignited, or that the ignited release is a fire or an explosion, etc. but for which data do not exist or are extremely limited or biased at best. Examples include the impact of the rate of ventilation in indoor releases, the effect of different electrical classification types in the area into which the material is released or the operating conditions of the equipment relating to expected operational temperature, the innate characteristics of failure mode(s) and even simple things such as how hot pump shaft seals may get during normal operations and during failure.

The net effect of these and other shortcomings is not only a lack of information. It also means that risk managers have a greatly reduced set of risk mitigation options in their toolkit. For example, if a risk manager strongly feels that prohibiting vehicular traffic near a unit will reduce the risk, his or her opinion is justifiable. However, given the available literature, there are no hard data to support this conjecture. In the absence of justification from this project, the risk manager will be unable to defend an inconvenient or costly change submitted to management. Thus, there is a very real danger that prudent risk reduction measures would not be undertaken due to a lack of data to justify the action.

Scope

The scope of this new book project was limited to the ignition of flammable liquids and vapors in external environments. It did not include ignitions for other reasons (e.g., static buildup during top tank filling), and it did not include dust ignition. Additionally, the intended application is for a land-based operation. While many of the principles developed here could be applied to operations such as offshore or shipping operations, the book and tools were not specifically designed with those applications in mind.

Approach to Project and Deliverables

The project has two primary deliverables:

- The book—which describes the approach and methodologies available for various degrees of precision;
- Software which allows users to predict ignition probabilities using their own source inputs and risk tolerance evaluation methodology.

FINDINGS OF LITERATURE DESCRIBED IN THE BOOK

The project was initiated by collecting the relevant prior work in the field, much or most of which was not cited in previous related publications. In all, useful information is provided from over 60 citations. Some reviewers of the book have commented that this is the most valuable content in the book. Following are examples of some of the information gleaned from the literature:

Factors Relevant to Ignition Probability

When developing algorithms for ignition probability prediction, it is important to make the resulting tools as effortless to use as possible; otherwise the tools will be underutilized. Therefore, it is important to capture those factors that are important, but at the same time try to distill them to the minimum number necessary to get the job done.

Factors Related to the Release Source

There are a significant number of variables that might be considered important in determining the ultimate outcome of a release of flammables. Primary variables among these are the physical and chemical properties of the materials being released, such as:

- Autoignition temperature (AIT) of the chemical
- Flash point
- Normal boiling point
- Vapor pressure
- Minimum ignition energy (MIE) of the chemical
- Flame speed
- Electrical properties of the chemical, and potential presence of contaminants

Other important factors relate to the release point itself:

- Source pressure
- Source temperature
- Release rate (function of hole size and pressure)
- Release duration
- Release location (open or congested area)
- Location of ignition sources

In at least one case (AIT), the approach would seem to be straightforward—if the material is above the AIT, it ignites; if not, ignition does not occur. Unfortunately, the real world situation is not so straightforward. The measured AIT has a number of shortcomings related to predicting the actual spontaneous ignition of a chemical, including variability in AIT test apparatuses, as well as the effects of variability in the surfaces encountered when a release occurs in a real plant environment.

Therefore, since the measured AIT is an imperfect measure of a release in the real world, it is not treated as a discrete value above which ignition is 100% certain and below which it is not. API [1] addresses this in a simple way, by assuming that autoignition occurs only when the process temperature is more than 80°F higher than the AIT. In this book, it is assumed instead that there is a range of temperatures above and below the reported AIT at which autoignition can actually occur. This and other complexities were addressed in this effort.

It was noted earlier that one of the goals of any work such as this is to minimize user effort. This includes consolidating the number of inputs where possible. For example, if a particular chemical property can be reasonably estimated using another more widely available property, then only one entry is required instead of two. This cannot always be done—for example, in the case of AIT, one can see that there is no relationship between AIT and boiling point (Figure 1):

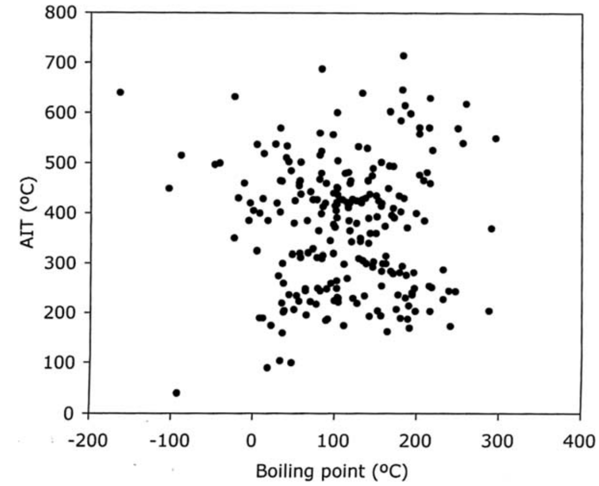

Figure 1. Non-relationship between AIT and boiling point [2].

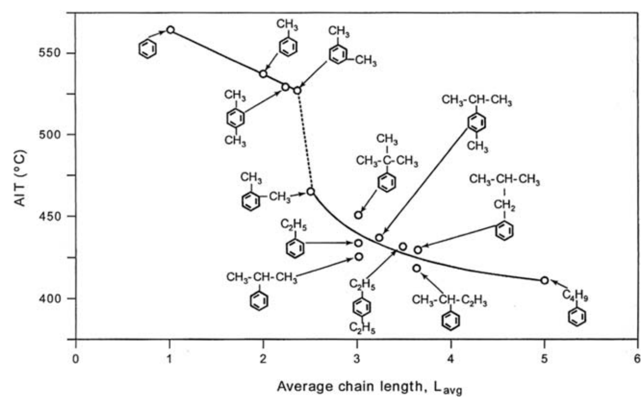

Figure 2. AIT as a function of chain length [2].

There is more of a correlation with carbon chain length (Figure 2):

However, that relationship likely cannot be extended for all flammables, and if used, there would be no net reduction in the number of inputs required.

Factors Related to the Environment into Which Material is Released

There are additional variables that can impact releases that are not ignited at the source. These include:

- Transport behavior of the released material (e.g., heavier/lighter-than-air).
- Presence of ignition sources such as running equipment, vehicles, fired heaters, hot surfaces, etc.
- Electrical classification of the area.
- (If indoors) Indoor ventilation rate.
- Area congestion.

For example, Britton [3] and Pratt [4] describe the factors that are involved in electrostatic ignition, which could occur at the source or in the open environment. Britton (Figure 3) describes the ability of some of these to ignite various chemicals:

These books provide schematic and visual representations of electrostatic phenomena, for example (Figures 4 and 5):

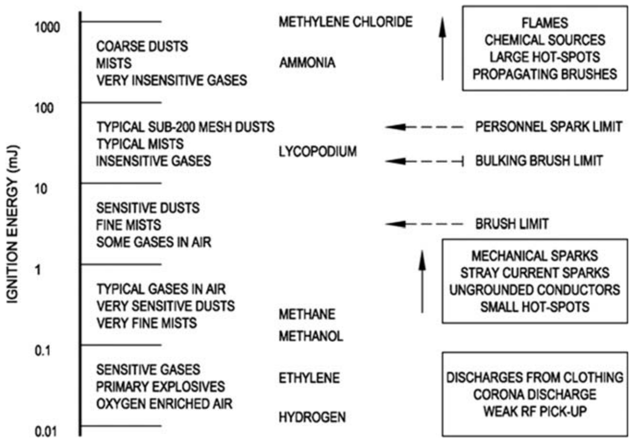

Figure 3. Ignition energies of various materials and types of ignition source that may ignite them (Updated from Ref 3]).

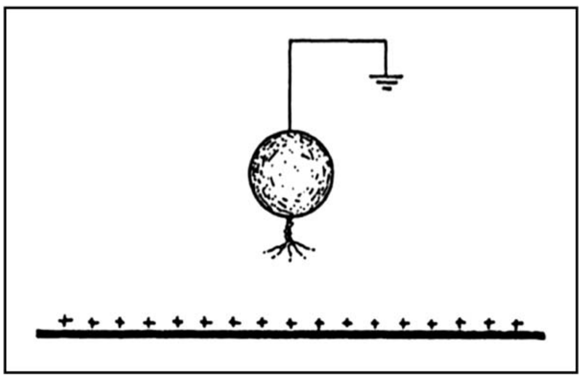

Figure 4. Brush discharge [4].

Figure 5. Positive brush discharge from negatively charged plastic to grounded sphere [3].

Other references discuss some of the complexities alluded to earlier. For example, multiple authors [5,6] describe how ignition by a hot surface generally occurs at a temperature substantially higher than the reported AIT. This is not only

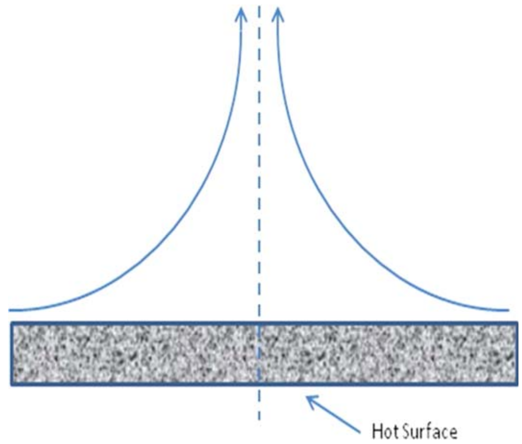

Figure 6. Flow patterns of a horizontal upward facing heated surface (adapted from Ref 6]). [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

because of the uncertainties in the laboratory value itself but also because of flow patterns around the hot surface, as depicted in the following Figure 6:

It was also recognized during the study that there are measures that may be implemented that affect these probabilities but are so situation-specific that they require the user to estimate their effectiveness in preventing ignition and/or explosion. These include gas detection systems, deluge/Halon, explosion vent panels, and the like. The software tool provided with this book will provide these input options so that the user can incorporate them into the prediction but will not provide methods to develop the input values themselves.

These and other ignition controls and phenomena are discussed in Chapter 1 of the book.

Data Sources (the basis for Chapter 3)

There are a number of investigators and regulators who have looked at the POI issue before, subject to the shortcomings of data described earlier (although generally not acknowledged). Some of this work resulted directly in algorithms for POI prediction, such as multiple studies conducted for the UK Health and Safety Executive (Table 1). These parameters are not published to our knowledge for other situations; expert judgment would be required to expand upon the lists provided in the original source documents.

In this case, the algorithms take the form of the following equation:

$$Q_A = Q_{A1} Q_{A2} \ldots Q_{A3} = \prod_{j=t}^{J} Q_{Aj}$$

$$= \prod_{j=1}^{J} \left\{ \exp\left\{ \mu_j A\left[\left(1 - a_j p_j\right)\right] e^{-\lambda_j p_j t} - 1 \right\} \right\}$$

Some other sources do not provide actual POI data, but are nonetheless useful in developing the background for ignition predictions. For example, work performed for the American Petroleum Institute (API) describes the effect of environmental conditions on ignition of various materials by a hot surface (Table 2):

Yet other sources provide historical data that can be useful in describing the relative importance of various ignition source types, for example, (Figure 7)

Table 1. Ignition source parameters for typical plant [7].

		Base Case, or "Typical", Ignition Source Parameters						
Land-Use Type	Ignition Sources	p	ta	ti	a	λ	μ	Loc.
1. Car park	"Rush hour" vehicles	0.2	6	474	0.0125	0.0021	160	Out.
	"Other" vehicles	0.2	6	54	0.1	0.0167	3	Out.
	Smoking	1	10	470	0.021	0.0021	8	Out.
2. Road area	"Rush hour" vehicles	0.1	6	474	0.0125	0.0021	160	Out.
	"Other" vehicles	0.1	6	54	0.1	0.0167	3	Out.
	Delivery vehicles	0.1	6	24	0.2	0.0333	20	Out.
	Traffic control	1	0	15	0	0.0667	20	Out.
3. Controlled roads	Delivery vehicles	0.2	6	24	0.2	0.0333	20	Out.
4. Waste ground	None	0	–		0	0	0	Out.
5. Boiler house	Boiler	1	120	360	0.25	0.0021	200	In.
6–11 Flames	Continuous (indoors)	1		0	1	0	200	In.
	Continuous (outdoors)	1	–	0	1	0	200	Out.
	Infrequent (indoors)	1	60	420	0.125	0.0021	200	In.
	Infrequent (outdoors)	1	60	420	0.125	0.0021	200	Out.
	Intermittent (indoors)	1	5	55	0.0833	0.0167	200	In.
	Intermittent (outdoors)	1	5	55	0.0833	0.0167	200	Out.
12. Kitchen facilities	Smoking	1	5	115	0.042	0.0083	200	In.
	Cooking equipment	0.25	5	25	0.167	0.0333	100	In.
13–15. Process areas	"Heavy" equipment levels	0.5	–		1	0.028	50	In.
	"Medium" equipment	0.25	–		1	0.035	50	In.
	"Light" equipment levels	0.1	–		1	0.056	50	In.
16. Classified	None	0	–		0	0	0	In.
17. Classified (Ex.)	Material handling	0.05	5	25	0.167	0.0333	10	Out.
18. Storage (Ex.)	Material handling	0.1	10	20	0.333	0.0333	10	Out.
19. Office	"Light" equipment levels	0.05	–		1	0.056	20	In.

Table 2. Open air auto-ignition tests under normal wind and convection current conditions [5].

	Published Ignition Temperatures (Approximate at Time of Test)		Hot Surface Temperature Without Ignition Occurring	
Hydrocarbon	°C	°F	°C	°F
Gasoline	280−425	540−800	540−725	1000−1335
Turbine oil	370	700	650	1200
Light naphtha	330	625	650	1200
Ethyl ether	160	320	565	1050

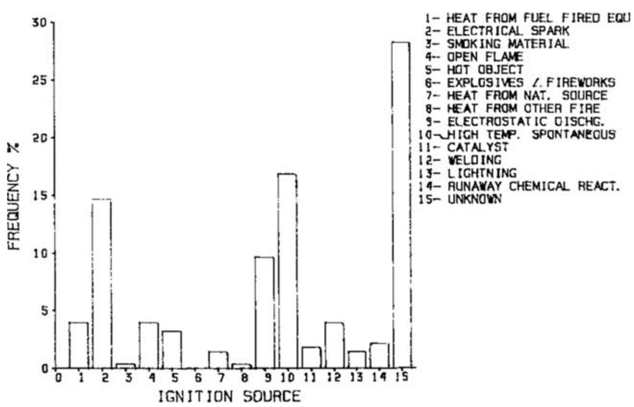

Figure 7. Hydrogen incident statistics—1961 to 1977—distribution by ignition source [8].

Some references help describe other useful properties such as potential mixing rules for multicomponent flammable streams (Figure 8):

These references and many others were considered in the development of the algorithms used for predicting ignition and explosion probabilities.

Subject Matter Expert Survey

A survey of subject matter experts was taken to assess their opinions on the probability of ignition/explosion in a variety of situations. The survey included consideration of a range of scenarios with hundreds of combinations of variables that had previously been determined to be significant. Interestingly, the survey results revealed many of the same inconsistencies (differences in experiences) that were the reason for the project in the first place, and "validated" the variance in experimental and field test results for hydrogen.

PROJECT DELIVERABLES

Overview

The book and algorithms were released earlier this year. The algorithms take the following forms, in their most complex manifestation:

- Probability of Immediate Ignition = f (AIT versus release temperature, release pressure, chemical MIE, etc.)
- Probability of Delayed Ignition = f (temperature, release pressure, MIE, etc.)

There is also an appendix discussion of explosion probability. It was originally intended that this discussion would

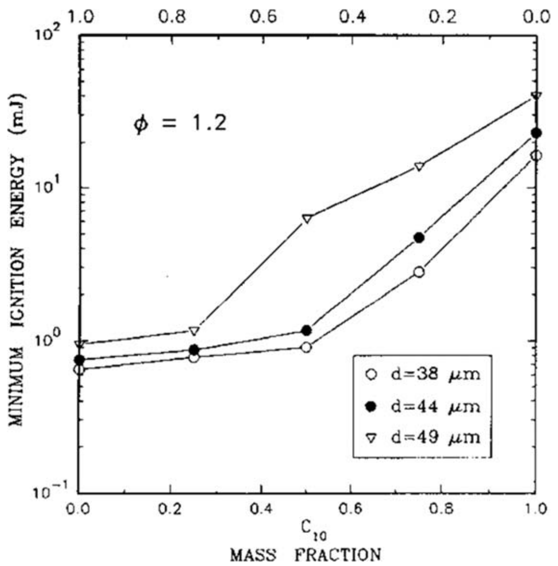

Figure 8. Minimum ignition energies versus component mass fraction for bicomponent fuel sprays [9].

be in the main part of the book but it was recognized that it should be treated differently because there are key variables (e.g., congestion and confinement of the space in which the ignition takes place) that are outside the scope of this effort. For this reason, the explosion discussion is framed in terms of the probability of explosion *given the requisite environmental conditions necessary for an explosion to take place.*

Probability of Explosion = *f* (chemical, degree of congestion/confinement in release area, presence/effective of explosion prevention measures, etc.)

Simpler versions requiring lesser degrees of input effort are also provided for applications such as PHA team risk matrix use and LOPAs. However, chemical properties for over 200 chemicals are built into the software (and book), reducing the level of effort required from the user.

Some of the more interesting or novel relationships adopted or developed include the following:

$$\text{Probability of Immediate Ignition} = \text{POII}_{\text{ai}} + \text{POII}_{\text{static}},$$

where $\text{POII}_{\text{ai}} = f$ (T and AIT) and $\text{POII}_{\text{static}}\ \alpha \text{P}^{1/3}$ and $\text{MIE}^{-0.6}$

$$\text{Probability of Delayed Ignition} = \text{PODI}_{\text{S/D}} \times M_{\text{MAG}} \times M_{\text{MAT}},$$

where $\text{PODI}_{\text{S/D}} = f$ (ignition source strength and duration of exposure), $M_{\text{MAG}} = f$ (hole size$^{\text{const.}}$) and $M_{\text{MAT}} = f$ (log (MIE))

Other relationships are being developed to account for the special issues associated with indoor releases. The Level 3 analyses will also provide modifications based on refinements to some of the inputs (e.g., MIE as $f(T)$ and MIE as f (droplet size)).

Book Contents

The next step was to compile and analyze the information from the literature and convert it into book form. The contents of the book include the following:

Chapter 1: Introduction—This chapter provides an overview of the reasons for the book, its scope, and an overview of ignition concepts.

Chapter 2: Estimation Methods—This chapter shows the development and result of the ignition probability algorithms. An illustration of the method is also provided.

Chapter 3: Technical Background and Data Sources—This chapter compiles the available literature (discovered during the research and developmental phases of the complete project) on ignition probabilities and illustrates the highlights of that data.

Chapter 4: Additional Examples—This chapter discusses the limitations of ignition likelihood models and other important conceptual information. Twenty case studies that illustrate the algorithms in both typical, atypical, and "out of scope" situations are included in this chapter. It also shows how the methods can be used for risk mitigation.

Chapter 5: Software Illustration—This chapter gives step-by-step instructions, with software screen captures to help the user navigate the software and use it effectively and efficiently.

Software

The development of ignition probability algorithms took place in parallel with the development of Chapters 2, 4, and 5 of the book. The book and software provide ignition probability algorithms at three levels of detail:

Basic Level—Default values for probability of immediate ignition (POII), probability of delayed ignition (PODI), and probability of explosion given delayed ignition (POE). These are independent of process or environmental variables, and so are primarily intended for screening-level purposes only.

Second Level—Algorithms for POII, PODI, and POE that incorporate the widely accepted variables affecting these probabilities, and for which published information exists (e.g., chemical type, release temperature versus autoignition temperature, release rate, "strength" of ignition sources and duration of exposure).

Third Level—Algorithms for POII, PODI, and POE that incorporate additional variables that are considered or assumed to be important, but for which data is extremely limited or nonexistent. We expect up to five such additional variables to be included. Examples include: (1) electrical classification area type, (2) indoor versus outdoor operation, (3) indoor ventilation rates, (4) administrative controls (e.g., prohibitions to vehicular traffic), and (5) physical controls (e.g., deluge systems). Note that by definition, these algorithms will be expert-based as opposed to data-based. As such, straightforward models will be developed that will be acknowledged as being "prototypes" for each variable.

WORKED EXAMPLE

It is not possible to fully explain the basis of the technology in this short article, but the appendix to this article provides an example from Chapter 4 of the book that illustrates the workings of the technology. When reading through the example, note that simply adding in a factor for the wind rose-based probability that the wind would blow the vapor cloud toward the truck (probability that the vapor cloud reaches the ignition source) would lead to close agreement between the Level 1 and Level 2 results.

SUMMARY

CCPS published the findings of this ignition probability review and analysis in book and software form. The timing of the book/software was intended to complement the release of two other CCPS books: *"Guidelines for Evaluating Process Plant Buildings for External Fires, Explosions, and Toxic Releases"* (second edition) and *"Guidelines for Enabling Conditions and Conditional Modifiers for Layer of Protection Analysis"* (expected to be released in late 2013). The new book supports risk-based analyses that are described in those references. However, the potential uses of this information are much wider, and will likely include LOPA, QRA, event tree, PHA risk matrix applications, and more. The result will be a series of algorithms organized across three levels of sophistication (and input requirements) that allow the effort put into the analysis to be commensurate with the level of refinement needed by the user.

In contrast to previous efforts to predict ignition probabilities, this effort focuses more effort on the physical and chemical properties of the material being released and the immediate release environment. It also considers relevant variables not quantified in previous efforts. The result is an approach which incorporates more variables than previous efforts. The corollary benefit to risk managers is that the treatment of the added variables will provide a basis for quantifying the benefits of risk reduction measures that were heretofore not quantified in publically-available references. Thus, the toolkit of the risk manager will be significantly broadened, and more realistic risk estimations can be made.

As-is, it may not be the complete “missing link,” but with your help and feedback we can over time enhance its precision, reliability, and scope. With that thought in mind, CCPS will develop and maintain a website for users to give feedback, suggestions, etc. all in the effort to enhance the value of this new tool and, ultimately, better understand and manage risk.

LITERATURE CITED

1. API, Risk-Based Inspection Base Resource Document, API Publication, Washington, D.C., 581, 1st Ed., 2000.
2. V. Babrauskas, Ignition Handbook, Fire Science Publishers/SFPE, Issaquah, Washington, 2003.
3. L.G. Britton, Avoiding Static Ignition Hazards in Chemical Operations, Center for Chemical Process Safety, American Institute of Chemical Engineers, New York, NY, 1999.
4. T.H. Pratt, Electrostatic Ignitions of Fires and Explosions, Center for Chemical Process Safety, American Institute of Chemical Engineers, New York, NY, 2000.
5. API, Ignition Risk of Hydrocarbon Liquids and Vapors by Hot Surfaces in the Open Air, API Recommended Practice, Washington, D.C., 2216, 3rd Ed., 2003.
6. D. Duarte, J. Rohalgi, and R. Judice, The influence of the geometry of the hot surfaces on the autoignition of vapor/air mixtures: some experimental and theoretical results, Process Saf Prog 17 (1998), 68–73.
7. J.H. Daycock, and P.J. Rew, Development of a method for the determination of on-site ignition probabilities, Health & Safety Executive Research Report 226, 2004.
8. R. Zalosh, T. Short, P. Marlin, and D. Coughlin, Comparative Analysis of Hydrogen Fire and Explosion Incidents, Progress Report No. 3,” for Division of Operational and Environmental Safety, United States Department of Energy, Contract No. EE-77-C-02–4442, July 1978.
9. K.-P. Lee, S.-H. Wang, and S.-C. Wong, Spark ignition characteristics of monodisperse multicomponent fuel sprays, Combust Sci Technol 113 (1996), 493–502.