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Risk-Based Approach – Damage Criteria

A State-of-the-Art Review of Damage Criteria for People and Structures

An ioMosaic White Paper

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Abstract

This manuscript is divided in three sections. The first and second sections address human vulnerability and structural damage due to explosions and fires, respectively. For explosions, overpressure, impulse and probit analysis are the parameters of interest; while for fires, thermal flux, thermal dose and probit analysis are the pertinent parameters. The third section addresses dispersions, and focuses only on human vulnerability due to toxicity. It is important to note that flammable dispersions are not addressed as they are inherently considered as part of the fires damage criteria (e.g., flash fires). Finally, for explosions, fires and toxic dispersions, generic available criteria in the related literature has been reviewed and compiled and internationally recognized sources of input data have been presented.

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Manuscript Scope of Work

This paper compiles human vulnerability and structural damage criteria from well-known literature references for explosions, fires and dispersion analysis.

In the first section, the manuscript addresses human vulnerability from explosions. Based on the contents described below, three parameters should be considered when evaluating human vulnerability due to overpressure: (1) overpressure, (2) impulse and (3) probit analysis. However, it is important to mention that dedicated criteria for human vulnerability based on the Department of Defense (DoD) is addressed in the following reference: **[1]** "Facility Siting Addressing Explosions Impacting Process Plant Permanent and Portable Buildings, Combining Exceedance Curves, Structural Response and Human Vulnerability Criteria," After addressing human vulnerability the following section presents several well-known overpressure thresholds for domino effect and escalation analysis. It is important to note that even though the impulse has a potential effect on escalation triggered by explosions, it is normal to only use overpressure. Additionally, the following two references address the domino effect and escalation triggered by explosions phenomena, based on only thresholds and based on the Single Degree of Freedom (SDOF) approach: **[2]** "Domino Effect and Escalation Triggered by Explosions – Combining Exceedance Curves and Overpressure Threshold Criteria;" and **[3]** "Domino Effect and Escalation Triggered by Explosions – Combining Exceedance Curves, Single Degree of Freedom and Pressure-Impulse Diagrams."

The second section addresses the human vulnerability, domino effect and escalation from fires. With regards to human vulnerability, three parameters need to be considered: (1) thermal flux, (2) thermal dose and (3) probit analysis. The following reference is developed with the aim to address building occupant human vulnerability through a detailed risk-based approach using Heat Flux Exceedance Curves (HFECs) as addressed in reference **[4]** "Facility Siting Addressing Fires Impacting Process Plant Permanent and Portable Buildings, Combining Exceedance Curves and Human Vulnerability Criteria."

Similarly to explosions, domino effect and escalation triggered by fires is also briefly explained in this manuscript. The following references further address this phenomenon and include a case study based on well-known thresholds approach and the Dynamic Thermal Stress Analysis (DTSA) approach: **[5]** "Domino Effect and Escalation Triggered by Fires – Combining Exceedance Curves and Time to Failure Simplified Methodologies;" and **[6]** "Domino Effect and Escalation Triggered by Fires – Combining Dynamic Thermal Stress Analysis and Wall Segmentation Approach."

Finally, in the third section only human vulnerability due to toxic dispersions is addressed; i.e., there is no potential for domino effect triggered by toxic clouds. When addressing human vulnerability due to toxic dispersions, the damage criteria is based on: (1) probit analysis and (2) exposure thresholds limits or doses. When it is desired to evaluate flammable dispersions, the vulnerability is based only on exposure thresholds as illustrated in the fires damage criteria. Similar to explosions and fires, a dedicated reference is developed to specifically address facility siting for toxic dispersions: **[7]** “Facility Siting Addressing Hazardous Vapor Cloud Dispersions Impacting Process Plant Permanent and Portable Buildings, Combining Exceedance Curves and Human Vulnerability Criteria.”

As a summary, the present manuscript collects several criteria, well-known thresholds and data for addressing human vulnerability regarding the three hazards used in a risk-based approach assessment or Quantitative Risk Assessment (QRA): overpressure, thermal radiation and toxicity. Furthermore, for both explosions and fires, domino effect and escalation phenomena are addressed.

Explosions

Introduction

The main intention of this section is to present the human vulnerability and domino effect and escalation due to explosions. The first part focuses on fatality criteria based on risk-based quantitative assessments. Additionally, injury thresholds are also presented where appropriate. Note that the human vulnerability criteria and guidance are applicable to personnel working within the considered facility and the public located beyond the installation fence line. Thus, it can be used for risk-based quantitative assessments addressing onsite and offsite risks. The second part addresses domino effect and escalation due to explosions. Three concepts should be clearly understood when assessing a domino accident: (1) primary event, (2) secondary target and (3) secondary scenario. A primary event is defined as the accident scenario of concern and its final outcomes are expressed in terms of physical effects such as thermal radiation or overpressure. Secondary targets are equipment that may be damaged by the primary event and, if damaged, the associated secondary scenarios that have the potential to cause final outcomes escalating the primary event.

Three different approaches can be used for defining damage criteria of explosions: (1) overpressure, (2) impulse and (3) Probit analysis:

The **overpressure** is defined as the pressure caused by a blast wave over and above normal atmospheric pressure.

The **impulse** is the parameter that accounts for the area under the explosion overpressure history, which accounts for the explosion phase duration; i.e., positive impulse.

Probit functions are based on a statistical normal distribution such that between 5 and 95% fatality, a small increase in thermal dose results in a proportionally small increase in fatality rate. At high fatality rates (>95%), a much larger dose increase is required for the same fatality rate increase. This could be described as a fatality 'tail off.'. Similarly, at low fatality rates (<5%), the rate of rise of fatality with dose is low. Accordingly, linear models cannot account for this "tail off" at the extremes of fatality rate and are weaker because of this. However, it is unlikely that there will ever be a sufficiently large sample of injuries recorded from a well-defined event to confirm the validity of a probit and the normal distribution is preferred for this application.

The Probit parameter, Y, is given by: $Y = A + B \ln D$

$\boldsymbol{Y}$: Probit; i.e., value range 2.67 – 8.09 representing 1 – 99.99% fatality. It is a measure of the percentage of the vulnerable resource that might sustain damage. Fatality probability can then be determined by evaluation of $\boldsymbol{Y}$ on a probit transformation. The values $\boldsymbol{A}$ and $\boldsymbol{B}$

are constants which depend on the level of damage due to the hazard. D is the overpressure or impulse depending on the selected probit criteria. Further information related to probit analysis can be found in reference **[8]**.

Human Vulnerability

Explosions generate overpressures and drag forces that in turn result in damage directly to humans, buildings and structures. Explosions can generate missiles such as fragments of damaged structures, window glass shards, or loose objects. The effects of overpressure on humans are normally categorized: direct and indirect **[8]**.

Explosion Direct Effects

The rapid compression and decompression of a blast wave on the human body results in transmission of pressure waves through the tissues. Resulting damage is primarily at junctions between tissues of different densities (bone and muscle), or at the interface between tissue and airspace. Lung tissue and the gastrointestinal system (both contain air) are particularly susceptible to injury. The tissue disruptions can lead to severe hemorrhage or to air embolism; either can be rapidly fatal. Direct overpressure effects do not extend out as far from the point of detonation as other effects and are often masked by the drag force effects. In the event of a vapor cloud explosion, the overpressure levels necessary to cause injury to the public are typically defined as a function of peak overpressure, without regard to exposure time. Persons who are exposed to explosion overpressures have no time to react or take shelter; thus, time does not enter into the relationship **[9]**.

The main parts of the body directly susceptible to the damaging effects of overpressure are the eardrums and lungs. Lung damage can be fatal and an example of the consequences in terms of probability of injury or fatality, as suggested by the Australian Petroleum Production and Exploration Association Limited (APPEA), is listed in **Table 01**.

Table 01: Explosion Overpressure Effects

Overpressure [barg]	Damage Description
0.210	20% probability of fatality to personnel inside 0% probability of fatality in the open
0.350	50% probability of fatality to personnel inside 15% probability of fatality in the open
0.70	100% probability of fatality inside or in unprotected structures

Overpressures lower than those in **Table 01** can cause non-fatal injuries such as lung damage and eardrum rupture. Lung damage is a relatively serious injury, usually requiring hospitalization, even if not fatal; whereas eardrum rupture is a minor injury, often requiring no treatment at all. The threshold level of overpressure for an un-reinforced, un-reflected blast wave that can cause lung damage is about 1.0 atmosphere. A blast wave in the order of 0.25 bar to 0.5 bar is the range for the threshold for eardrum perforation. The overpressure associated with a 50 percent probability of eardrum rupture is about 1.0 bar **[9]**.

The direct effect of explosion overpressure is normally displayed in the form of fatality as a function of overpressure and duration of the blast wave. Depending on the orientation of a body to a blast wave or a reflective surface the overpressure effects can increase or decrease. Casualties requiring medical treatment from direct blast effects are typically produced by overpressures between 1.0 and 3.4 bar. However, other effects (such as indirect blast injuries and thermal injuries) are so predominant that casualties with only direct blast injuries make up a small part of an exposed group **[9]**.

Explosion Indirect Effects

Typical injuries or fatalities due to explosions indirect effects are the following:

- Impacting fragments
- Body Displacement; i.e., people falling or "flying" and subsequently hitting a solid object
- Building and structure damage; i.e., Buildings or other structures falling or being disintegrated. Note that dedicated criteria to address facility siting due to explosions can be found in reference **[1]**
- Burn effects already addressed later in the document when explaining human vulnerability due to fires

Impacting Fragments

The following contents are based on reference **[9]**. The drag forces of the blast winds produced by a vapor cloud explosion may be sufficient to result in the breakup of structure, plant, or equipment resulting in fragmentation and missile formation. Thus, multiple and varied missile injuries may result, increasing their overall severity and significance.

Flying fragments from an explosion are usually more dangerous than the overpressure. Fragments may be debris from demolished equipment or structures caused by the explosion or loose equipment. Fragments from glass breakage are very common and extremely dangerous. The possibility of harm from glass fragments must be determined during an analysis of explosion effects. Estimates of the pressure needed for breakage of conventional glass **[10]** are the following:

- 1% level glass breakage: 0.017 bar
- 90% level glass breakage: 0.062 bar

The velocity to which missiles are accelerated is the major factor in causing injury. The probability of a penetration injury increases with increasing velocity particularly for small, sharp missiles such as glass fragments. Small, light objects are accelerated to speeds approaching the maximum (blast) velocity.

Other missiles are also produced because of explosion and their effects should also be addressed. **Table 02** provides guidance based on **[10]** for the expected effects from missiles produced as the result of explosion.

Table 02: Injuries from Missiles

Injury Threshold	Overpressure [kPa]	Impact Velocity [$m \cdot s^{-1}$]	Impulse [$Ns \cdot m^{-2}$]
Skin laceration	7.0-15	15	512
Serious wound	15-20	30	1024
Serious wounds near 50% probability	25-35	55	1877
Serious wounds near 100% probability	50-55	90	3071

In addition, reference **[11]** provides the following data on impact from glass fragments in the event of explosion (**Table 03**):

Table 03: Probability of Penetration of Glass Fragments into Abdominal Cavity

Mass of Glass Fragment [g]	Impact Velocity [$m \cdot s^{-1}$]		
	1%	**50%**	**99%**
0.1	78	136	243
0.6	53	91	161
1	46	82	143
10	38	60	118º

Body Displacement

The following contents are based on reference **[9]**. During the body displacement, blast overpressure and impulses interact with the body in such a manner that it is effectively projected. In such events, the head is the most vulnerable part of the body from the effects of displacement and subsequent impact on to a solid surface. The displacement (acceleration) is a function of the size, shape and mass of the person and the blast forces. The following conclusions are from reference **[10]**:

- 50% of the people being projected with a speed more than 0.6 $m \cdot s^{-1}$ will suffer minor injuries
- 1% of those with a speed of about 4 $m \cdot s^{-1}$ will suffer injuries like ruptured organs and bone fractures
- 40% will suffer major injuries if thrown against a solid wall

Effects from whole body displacement can be estimated from data listed in **Table 04**:

Table 04: Probability of Fatality from Whole Body Displacement

Total Body Impact Tolerance	Related Impact Velocity [$m \cdot s^{-1}$]
Most "Safe"	3.05
Fatality Threshold	6.40
50% Fatality	16.46
100% Fatality	42.06

Reference **[11]** provides further information on the probability of injuries and fractures as listed in **Table 05**.

Table 05: Probability of Injury from Whole Body Displacement

Probability of Injury	Velocity [$m \cdot s^{-1}$]	
	Non-Fatal	Fatal
1%	2.6	6.6
50%	6.6	17
99%	16.5	23.9

Notes:

- Overpressure of 0.21 bar (3 psi) can throw the human body, causing 1% fatality.

- For external gas explosions, overpressures above 0.35 bar (5 psi) have been considered to project personnel who are outside into the sea and trap personnel who are inside under debris.
- A simple assumption can be made that 50% of people inside the 0.35 bar region are fatalities and none outside it **[12]**. However, a more conservative approach is to use 100% fatalities within 0.2 – 0.3 bar or the gas cloud Lower Flammability Limit (LFL), whichever is greater **[13]**.

Building and Structure Damage

The following contents are based on reference **[14].** Overpressure duration is important for determining effects on structures. The positive pressure phase of the blast wave can last from 10 to 250 ms, or more, for typical Vapor Cloud Explosions (VCEs). The same overpressure level can have markedly different effects depending on the duration or impulse. Therefore, some caution should be exercised in applying simple overpressure criteria for buildings or structures, which can in many cases cause overestimation of structural damage. If the blast duration is shorter than the characteristic structural response time, the structure may be able to withstand higher overpressures. Baker et al. **[15]** provides guidance on structural response due to explosions and AIChE/CCPS **[16]** provides an extensive review of risk criteria.

The thresholds for buildings suggested in reference **[17]** are represented in **Table 06**.

Table 06: Thresholds of Damage Overpressure for Buildings

Overpressure [kPa]	Damage Description
4.8	Minor damage to the building
6.9	Partial demolition of the building; it remains non-inhabitable
34.5-48.3	Almost total destruction of building

Table 07 summarizes different effects of overpressure on structures reported in the literature **[18]**, **[19]**. Window panes are particularly prone to breakage at low levels of overpressures **[20]**.

Table 07: A Response of Structural Elements to the Different Levels of Overpressure

Element	Overpressure [kPa]	Damage Description
Window Pane	0.7 – 1.0	5% Broken
	1.4 – 3.0	50% Broken
	3.0 – 6.0	90% Broken
Building	1.4 – 3.0	Inhabitable after repair damage to roof, windows and tiling
	3.0 – 6.0	Limited minor structural damage. Partitions and joinery was wrenched from fixings. Damage to a building roof. 90% of window glass is broken
	6.0 – 9.0	Door and window frames are broken
	9.0	Steel frame of clad building is slightly distorted
	14 – 28	Uninhabitable; partial or total collapse of roof, partial demolition of one or two external walls, severe damage to load-bearing partitions. Concrete or cinder block walls, not reinforced, shattered
	30	Destruction of all buildings that were not designed to withstand explosions
	35 - 80	50%-70% external brickwork destroyed or rendered unsafe
	80 – 260	Almost complete demolition
	50 - 100	Displacement of cylindrical storage, failure of pipes

Stephen **[21]** and Lees **[18]** give peak values of overpressure and the level of damage to structures as listed in **Table 08**.

Table 08: Thresholds of Damage Overpressure for Buildings [17]

Overpressure [kPa]	Damage Description
x > 3.5	Light damage
x > 17	Moderate damage
x > 35	Severe damage
x > 83	Total destruction

The combined impact of overpressure and impulse are indicated in **Table 09** and **Figure 01**. These values can be used as thresholds. The values of overpressure and impulse corresponding to points A, B, C and D in **Table 09** are also represented in **Figure 01** and are in a good agreement with the level of damage 1, 2 and 3 (see **Figure 01** legend). **Figure 01** can be used to estimate the degree of damage caused to buildings for peak overpressure and impulse of the blast wave.

Table 09: Combined Effect of Overpressure and Impulse on the Level of Damage [20]

Overpressure [kPa]	Impulse [kPa·s]	Damage Description	Figure 01
3.6	0.10	Minor structural damages	A
14.6	0.30	Moderate structural damages: failure of some load-bearing elements	B
34.5	0.52	Partial distraction: 50-75% of walls destroyed	C
70.1	0.77	Total destruction of buildings	D

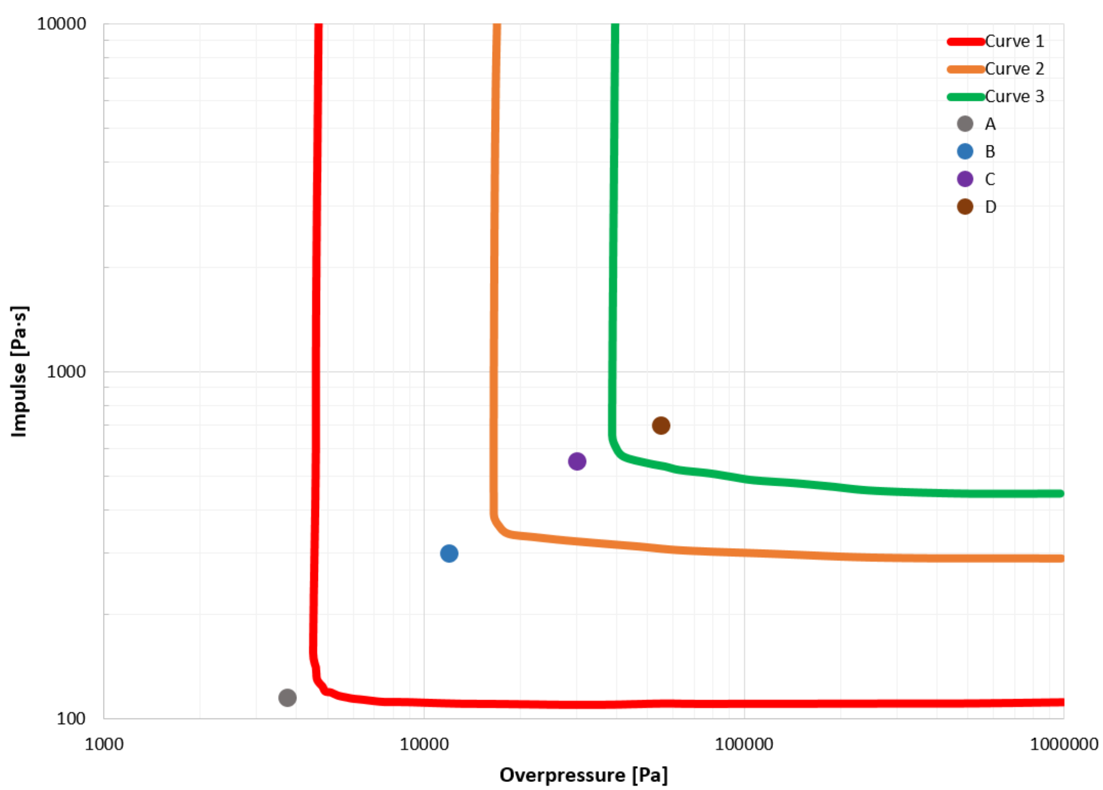

Figure 01: P-I Diagram of a High Explosive Charge on the Ground [22]

Legend:

- Curve 1: light damage
- Curve 2: structural damage
- Curve 3: collapse

Notes:

- Note that **Figure 01** provides some generic criteria for structural response predictions. The given pressure-impulse diagram is representative for a wide variety of structures that could have different structural behavior.

- Note that the U.S. Department of Defense (DoD) provided dedicated pressure-impulse diagrams for sixteen (16) different building types and is a more accurate and detailed criterion for building structural response. Note that the DoD criteria is considered by applying a risk-based approach for structural response and human vulnerability purposes and can be found in reference **[1]**.

Probit Criteria

Probit analysis can also be applied for explosion fatality estimates. For the purposes of risk assessment, it should be sufficient to know what is the required dose to induce pain, to cause a fatality (i.e., 1-5%), to incur a 50% fatality probability and to incur a 95-100% fatality probability.

The HSC report **[23]** into the transportation of dangerous goods by road and rail suggests the following probit equation for blast over pressure fatality: $Y = A + B \ln D$; where: $\boldsymbol{A}$**:** 5.13; $\boldsymbol{B}$**:** 1.37; and $\boldsymbol{D}$**:** peak overpressure in barg units.

Opschoor et al. **[24]** and the TNO Green Book **[25]** provide further information related on probit equations to predict human fatality (see **Table 10**). Finally, the TNO Green Book **[25]** reports several useful probits for damage to objects and people. Two probit equations ($Y = A + B \ln D$) for the estimation of fatality probability from head and body impact are illustrated in **Table 11**.

Table 10: Explosion Probit Parameters

Damage	*A*	*B*	*D*
Deaths from lung hemorrhage	-77.1	6.91	P_0
Eardrum ruptures	-15.6	1.93	P_0
Structural damage	-23.8	2.92	P_0

Damage	*A*	*B*	*D*
Glass breakage	-18.1	2.79	P_0
Deaths from impact	-46.1	4.82	*I*
Injuries from impact	-39.1	4.45	*I*
Injuries from flying fragments	-27.1	4.26	*I*

Table 11: Specific Probit Equations for Head and Body Impact

Damage	*A*	*B*	*D*
Head Impact	5.0	-8.49	$D = \frac{2430}{P_0} + \frac{4.0E08}{P_0 I}$
Body Impact	5.0	-2.44	$D = \frac{7380}{P_0} + \frac{1.3E09}{P_0 I}$

Note: $\boldsymbol{P_0}$: peak overpressure in Pa; and $\boldsymbol{I}$: impulse in Pa·s

Risk-Based Quantitative Damage Criteria Based on CPR18E

Since most applicable regulations are based on the probability of fatality, most risk-based quantitative assessments mainly account for lethal effects as final results. However, certain levels of injury are applicable for specific purposes.

Specific Criteria from CPR18E – Purple Book

This section is intended to provide guidance to guidance to estimate the probability of fatalities from an explosion and the fatality fraction in each population. (see **Figure 02**). Detailed exposure and damage criteria due to explosions being used during a risk-based quantitative assessment is proposed in the CPR18E **[26]**. The following parameters are introduced:

- $\boldsymbol{P_E}$: Probability of Fatality of an individual, which is assumed to be outdoors and unprotected. This parameter is used for the estimation of Individual Risk Contours.
- $\boldsymbol{F_{E,in}}$: Probability of fatality of the fraction of the population indoors at a certain location due to explosions exposure. It is considered that part of the population is protected by staying indoors and wearing protective clothing. This parameter is used for the estimation of the Societal Risk.
- $\boldsymbol{F_{E,out}}$: Probability of fatality of the fraction of the population outdoors at a certain location due to the explosions exposure. It is considered that population outdoors is unprotected. This parameter is used for the estimation of the Societal Risk.

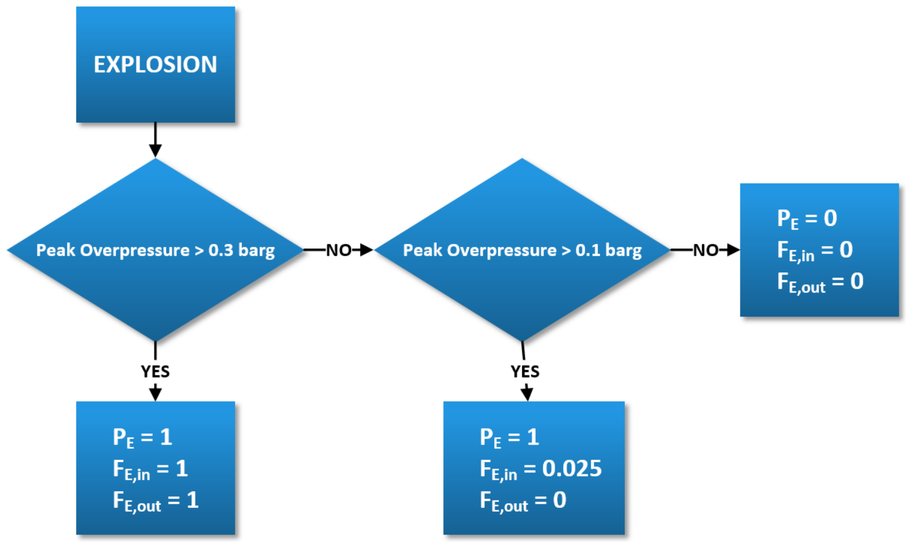

Figure 02: Exposure and Damage Criteria to Vapor Cloud Explosion

Additional Criteria

Another summary relating fatality and serious injury rates due to explosion can be found in **[16]**. **Table 12** details a criterion selected for the risk analysis for both fatalities and serious injuries. It can be observed in **Table 12** that zero percent fatality or serious injury level is the level at which fatalities or serious injuries could begin to occur. Data listed in **Table 12** is consistent with thresholds previously explained above.

Table 12: Fatality and Serious Injury Rates

Event	Fatality	Serious Injury	Notes
Explosion: Overpressure	10% fatality at 1 psi	5% injury at 0.3 psi	**Note 1**

Note 1: Based on **[16]**, occupants of a building experience 10% fatality at 1 psi for an unreinforced masonry or wood framed building. Injuries produced at 0.3 psi overpressure assumed to be 5% as per the probability of serious damage.

Domino Effect and Escalation

The interaction of blast waves with plant structures and buildings is a complex process. There are a multitude of scenarios in a typical chemical processing plant that can lead to a Loss of Containment (LOC), subsequent dispersion and ignition leading to an explosion. These scenarios can range from a small leak to a catastrophic vessel failure **[27]**. The severity of the resulting explosion is influenced by the chemical reactivity, release phase and conditions, confinement and release geometry and atmospheric wind speed and stability. **[28] [29]**. A blast assessment uses these variables to reinforce facility siting decision-making, structural response of occupied and un-manned buildings and/or process equipment and associated human vulnerability analysis **[1]** and domino effect analysis.

Two escalation vectors are credible when analyzing explosion primary events: (1) missile projection in case of mechanical explosions and Boiling Liquid Expanding Vapor Explosions (BLEVEs) and (2) blast wave interaction due to Vapor Cloud Explosions (VCEs) and explosions resulting from pressure equipment bursts such as confined explosions, mechanical explosions and BLEVEs. Although the present study focuses on blast wave interaction, the following are intended to describe escalation triggered by missile projection, an analysis requires the definition of the following two parameters: (1) distance between target equipment and missile projection, (2) associated LOC of target equipment after impact.

Based on **[30]**; **[31]**, **[32]**, when conducting domino effect analysis, the impulse of a blast wave can be conservatively discarded (assuming quasi-static regime) based on the following:

- Far-field interactions between the explosion source and the target equipment are of concern
- Relatively low-pressure explosions are considered (i.e., maximum peak static overpressure is lower than 7.25 psi, as in most industrial explosions)

Consequently, the damage caused by a blast wave may be effectively correlated to the peak static overpressure only.

The following section illustrates the equipment damage and escalation criteria.

Equipment Damage Criteria

An extensive literature review on blast damage to process equipment was performed in references **[33]** and **[34]**. The review demonstrated some degree of uncertainty since threshold values for equipment ranged over an order of magnitude **[33]** and **[34]**. This data variability is mainly caused by two reasons: (1) different definitions used for structural damage; e.g., buckling, complete collapse, rupture of connected pipes; and (2) design characteristics of target equipment are usually not considered by the original references when reporting the damage thresholds. With an attempt to correct this mentioned data dispersion, several authors pointed that overpressure thresholds should refer to a specific damage definition and should take into account the specific structural resistance of the equipment. As a result, broad equipment categories having similar characteristics may be considered.

The following contents are based on references **[35]**, **[36]** and **[37]** and are intended to technically justify and define escalation and equipment damage criteria based on overpressure threshold values. It is important to mention that process equipment is characterized by many properties (e.g., strength, shape, construction method, material) and the same damage phenomenon does not mean to result in a same damage level for different equipment categories. Additionally, the intensity of loss of containment due to equipment damage depends on damage level and on process conditions of the equipment contents; e.g., pressurized or atmospheric (i.e., pressurized material leaks faster through same shape hole). Based on this rationale, two Damage States (DS) are defined, but critical structural damage levels are different for different equipment categories **[35]**:

- **DS1**: light damage to the structure or to the auxiliary equipment.
- **DS2**: intense, catastrophic damage, or even total collapse of structure, which is certainly followed by an intense LOC.

Three classes of Loss Intensity (LI) can be defined by following criteria established in the well-known "Purple Book" **[26]**:

- **LI1**: "MINOR LOSS", defined as the partial or total loss of inventory in greater than ten minutes from the impact of the blast wave.
- **LI2**: "INTENSE LOSS", defined as the total loss of inventory between one and ten minutes
- **LI3**: "CATASTROPHIC LOSS", defined as the complete loss of inventory within one minute

The review of DS and LI defined in the **Table 15**, **Table 16**, **Table 17** and **Table 18** illustrated below demonstrate that many observed overpressure values with great deviation were assigned to the same DD **[37]**. With the aim to solve this drawback, the entire probability range of damage was divided into three probability ranges **[36]**: (1) range of 0-30% (LOW), (2) range of 30-70 (MEDIUM) and (3) rage of 70-100% (HIGH). **Table 13** lists the damage thresholds of 30 % and 70% based on the equipment type:

Table 13: Damage Overpressure Thresholds

Target Equipment	Damage Threshold 30%	Damage Threshold 70%
Atmospheric	OP > 2.18	OP > 4.79
Pressurized	OP > 4.64	OP > 8.41
Elongated	OP > 3.48	OP > 6.67
Small	OP > 4.21	OP > 8.12

***** OP: Maximum peak side-on overpressure

Equipment Escalation Criteria

The analysis carried out in the previous section confirms that while severe damage states often lead to large loss intensities and consequently to severe secondary scenarios, minor structural damages can also trigger severe secondary consequences if specific operating conditions are met and certain material hazards are present. Therefore, specific escalation thresholds for structural damage should be used in the analysis of escalation. **Table 14** lists threshold values for damage and escalation obtained for several accident scenarios. The thresholds in the table were obtained from the analysis of literature data and from simplified structural models, validated based on a wide number of representative case studies. A sensitivity analysis of all factors affecting the escalation possibility was also performed to assess critical values for the different parameters **[35]** and **[37]**.

Table 14: Escalation Overpressure Thresholds

Target Equipment	Damage Threshold [psia]	Escalation Threshold [psia]
Atmospheric	OP > 1.02	OP > 3.19
Pressurized	OP > 2.90	OP > 2.90
Elongated (Toxic)	OP > 2.31	OP > 2.90
Elongated (Flammable)	OP > 2.31	OP > 4.45

*****OP: Maximum peak side-on overpressure

Correlation Between Equipment Damage and Escalation Criteria

Based on the equipment damage criteria and equipment escalation criteria sections above, **Table 15**, **Table 16**, **Table 17** and **Table 18** summarize the key information intended to address escalation effects this topic based on equipment type **[35]**.

Table 15: Damage to Atmospheric Equipment Caused by Peak Side-On Overpressure – Literature Review [39]

Overpressure [psi]	Damage Description	DS	LI	Reference
0.75	Minor damage, cone roof tank (100% filled)	1	1	**[38]**
0.75	Minor damage, cone roof tank (50% filled)	1	1	**[38]**
0.88	1% Structural damage of equipment	1	1	**[39]**
1.02	Failure of connection	1	1	**[40]**
1.02	Collapse of atmospheric tank roof	1	1	**[25]**
1.02	Partial damage to atmospheric tank	1	1	**[41]**
1.45	Failure of atmospheric equipment	2	2	**[42]**
1.45	Fixed roof tank damage	1	1	**[43]**
1.45	50% Damage of atmospheric tank	2	2	**[44]**
2.03	Minor damage of atmospheric tank	1	1	**[45]**
2.71	Minor damage, floating roof tank (50% filled)	1	1	**[38]**
2.71	Catastrophic failure, cone roof tank (50% filled)	2	3	**[38]**
2.90	Displacement of steel supports	1	1	**[46]**
2.90	Deformation of atmospheric tank	1	1	**[45]**
2.90	100% damage, atmospheric tank	2	3	**[44]**
3.05	Destruction of fixed roof atmospheric tank	2	3	**[41]**
3.48	20% Of structural damage of steel floating roof petroleum tank	2	2	**[47]**
3.63	Atmospheric tank destruction	2	3	**[45]**
5.08	80% Damage of process plant	2	3	**[44]**
6.17	Minor damage, floating roof tank (100% filled)	1	1	**[38]**
6.17	Catastrophic failure, cone roof tank (100% filled)	2	3	**[38]**
6.53	Catastrophic failure, floating roof tank	2	3	**[41]**
19.73	Catastrophic failure, floating roof tank (50% filled)	2	3	**[38]**
19.73	Catastrophic failure, floating roof tank (100% filled)	2	3	**[38]**
19.74	99% Structural damage of floating roof tank	2	3	**[49]**
19.87	99% Damage (destruction) of floating roof petroleum tank	2	3	**[48]**

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Table 16: Damage to Pressurized Equipment Caused by Peak Side-On Overpressure – Literature Review [39]

Overpressure [psi]	Damage Description	DS	LI	Reference
2.90	Displacement of steel supports	1	1	**[46]**
2.90	Tubes deformation	1	1	**[45]**
4.35	Failure of pressure vessel	1	1	**[42]**
5.51	Partial damage of pressure vessel	2	2	**[41]**
5.66	Structural damage to pressure vessel	2	2	**[49]**
5.67	Minor damage, pressure vessel horizontal	1	1	**[38]**
6.09	Pressure vessel deformation	1	1	**[45]**
7.65	Minor damage, tank sphere	1	1	**[38]**
7.69	Pressure vessel failure	2	2	**[45]**
7.69	Failure of spherical pressure vessel	2	2	**[45]**
7.98	20% Of structural damage of spherical steel petroleum tank	2	2	**[47]**
8.88	Catastrophic failure, pressure vessel horizontal	2	3	**[38]**
10.15	Failure of pressurized storage sphere	2	2	**[50]**
11.84	Minor damage, pressure vessel vertical	1	1	**[38]**
12.04	20% Structural damage of vertical cylindrical steel pressure vessel	2	2	**[47]**
12.83	Catastrophic failure, pressure vessel vertical	2	3	**[38]**
13.82	99% Structural damage of vertical, steel pressure vessel	2	3	**[48]**
14.07	99% Damage of vertical cylindrical steel pressure vessel	2	3	**[47]**
15.79	Catastrophic failure, tank sphere	2	3	**[38]**
15.79	99% Structural damage of spherical, pressure steel vessel	2	3	**[48]**
15.95	99% Damage (destruction) of spherical steel petroleum tank	2	3	**[47]**

Table 17: Damage to Elongated Equipment Caused by Peak Side-On Overpressure – Literature Review [39]

Overpressure [psi]	Damage Description	DS	LI	Reference
1.02	Failure of connection	1	1	**[40]**
1.45	Failure of atmospheric equipment	1	1	**[42]**
2.03	Minor damage of cooling tower	1	1	**[45]**
2.47	Minor damage, distillation tower and cylindrical steel vertical structure	1	1	**[51]**
2.90	Displacement of steel supports	1	1	**[37]**
2.90	Tubes deformation	1	1	**[45]**
4.21	Distillation tower and cylindrical steel vertical structure failure	1	1	**[51]**
5.08	Damage to fractionating column	1	1	**[25]**
5.18	Minor damage, fractionation column	1	1	**[38]**
5.43	Catastrophic failure, pipe supports	2	2	**[38]**
5.51	Deformation of non-pressure equipment	1	1	**[45]**
6.09	Tubes failure	2	2	**[45]**
6.17	Minor damage, extraction column	1	1	**[38]**
6.66	Catastrophic failure, fractionation column	2	3	**[38]**
6.82	Failure of non-pressure equipment	2	2	**[38]**
10.11	Catastrophic failure, extraction column	2	3	**[38]**

Table 18: Damage to Small Equipment Caused by Peak Side-On Overpressure – Literature Review [39]

Overpressure [psi]	Damage Description	DS	LI	Reference
1.02	Failure of connection	1	1	**[40]**
2.71	Minor damage, reactor: cracking	1	1	**[38]**
2.90	Displacement of steel supports	1	1	**[46]**
2.90	Tubes deformation	1	1	**[45]**
3.67	Minor damage, reactor chemical	1	1	**[38]**
5.43	Catastrophic failure, pipe supports	2	2	**[38]**
6.09	Tubes failure	2	2	**[45]**
7.15	Minor damage, heat exchanger	1	1	**[38]**
8.63	Catastrophic failure, reactor chemical	2	3	**[38]**
8.63	Catastrophic failure, heat exchanger	2	3	**[38]**
11.10	Catastrophic failure, reactor: cracking	2	3	**[38]**
11.84	Minor damage, pump	1	1	**[38]**
15.79	Catastrophic failure, pump	2	3	**[38]**

Fires

Introduction

The main intention of the present section is to provide information on human vulnerability and domino effect and escalation due to fires. Within this second section that addresses fires, the first part focuses on fatality criteria based on risk-based quantitative assessments. Additionally, injury thresholds are also identified where appropriate. Note that the human vulnerability criteria and guidance illustrated in this manuscript are applicable to personnel working within the facility under analysis and the general population outside the installation boundary fence. Thus, it can be used for risk-based quantitative assessments addressing onsite and offsite risks. The second part addresses domino effect and escalation due to fires. Three concepts should be clearly understood when assessing a domino accident: (1) primary event, (2) secondary target and (3) secondary scenario. A primary event is defined as the accident scenario of concern and its final outcomes are expressed in terms of physical effects such as thermal radiation and overpressure. Secondary targets are equipment items that may be damaged by the primary event and, if damaged, the associated secondary scenarios have the potential to cause final outcomes escalating the primary event.

When focusing on human vulnerability due to fires (depending on the duration, intensity and area of exposure), the effects of fire range from pain, first, second and third degree burns and fatality. Additionally, the type of fire (pool, flash, jet and fireballs) is important to be identified to establish the relationship between fire type and potential effects to humans (see **Table 19**) **[52]**. Note that BLEVEs (Boiling Liquid Expanding Vapor Explosions) are a fireball involving pressurized liquefied gases.

Table 19: Characteristics of Process Fire Incidents

Fire Type	Radiated Heat Flux [kW·m^{-2}]	Hazard
Pool Fire (Open)	50-150	Radiation, Smoke, Engulfment
Pool Fire (Severe or Confined)	100-250	Radiation, Smoke
Jet Fire (Open)	50-250	Radiation, Smoke
Jet Fire (Confined)	100-300	Radiation, Smoke
Flash Fire	170	Engulfment

Humans are vulnerable to fire in the following ways: (1) engulfment by the fire; (2) thermal radiation from the fire; and (3) inside a building that is exposed to fire/radiation.

Three different approaches can be used for defining damage criteria of fires:

- Thermal Flux:
- Thermal Radiation Dose,
- Probit Analysis

The **thermal flux** is defined as the intensity of the fire, which is the power of the fire per unit area; i.e., $kW \cdot m^{-2}$.

The **thermal radiation dose** is defined as a unit of measurement used in the process industry to measure exposure to thermal radiation. It is a function of intensity and exposure time.

$$D = \left(I^{4/3}\right) t$$

$\boldsymbol{D}$**:** thermal radiation dose $[(kW \cdot m^{-2})^{4/3} s]$

$\boldsymbol{I}$**:** thermal flux $[kW \cdot m^{-2}]$

$\boldsymbol{t}$**:** exposure duration [s]

Probit functions are based on the statistical normal distribution so that between 5 and 95% fatality, a small increase in thermal dose results in a small fatality rate increase. At high fatality rates (>95%) a much larger dose increase is required for the same fatality rate increase. For a complete explanation on the probit analysis, please refer to the explosions – introduction section of the present manuscript.

Human Vulnerability

Thermal Flux Criteria

The effects of thermal radiation depend strongly on the thermal radiation flux, the duration of exposure (i.e., fire type), the type of clothing worn, the ease of sheltering and the individual exposed. Well-known thermal flux thresholds are illustrated in **Table 20 [8]** and provide guidance on the range of effects rather than exact relationships between thermal radiation and their effects for all circumstances.

Table 20: Summary of Thermal Radiation Exposure Effects

Radiation $[kW \cdot m^{-2}]$	Effect
1.20	Received from the sun at noon in summer
2.00	Minimum to cause pain after 1 minute

Radiation [kW·m^{-2}]	Effect
< 5.00	Will cause pain in 15 to 20 seconds and injury after 30 seconds' exposure
> 6.00	Pain within approximately 10 seconds; rapid escape only is possible
12.5	Significant chance of fatality for medium duration exposure
	Thin steel with insulation on the side away from the fire may reach thermal stress level high enough to cause structural failure
	Wood ignites after prolonged exposure
25.0	Likely fatality for extended exposure
	Spontaneous ignition of wood after long exposure
	Unprotected steel will reach thermal stress temperatures that can cause failure
35.0	Significant chance of fatality for people exposed instantaneously
	Cellulosic material will pilot ignite within one minute's exposure

Specific Criteria Addressing Jet and Pool Fires

Table 21 lists thermal radiation criteria applicable to longer fire durations, i.e., to jet fires and pool fires, for which the exposure duration is more dependent on the ability to escape than on the fire duration **[8]**.

Table 21: Thermal Radiation Criteria for Jet and Pool Fires

Radiation [kW·m^{-2}]	Effect
4.0	Impairment of temporary scape embarkation areas
6.0	Impairment of escape routes
12.5	Extreme pain within 20 seconds; movement to shelter is instinctive; fatality if escape is not possible: Outdoors/offshore: 70% fatality Indoors onshore: 30% fatality
20	Incapacitation, leading to fatality unless rescue is effected quickly
35	Immediate fatality; 100% fatality

*****Note that people indoors are only vulnerable if they have line-of-sight exposure to thermal radiation, hence a lower fatality than for people outdoors. **Table 22** lists exposure times to the pain threshold and second degree burns for different thermal radiation levels **[8]**.

Table 22: Exposure Times to the Pain Threshold and Second-Degree Burns

Radiation [kW·m^{-2}]	Exposure Time [s]	
	Second Degree Burns	Pain Threshold
1	663	115
2	187	45
3	92	27
4	57	18
5	40	13
6	30	11
8	20	7
10	14	5
12	11	4

Specific Criteria Addressing Flare Systems

API Standard 521 **[53]** indicates that many investigations have been conducted to determine the effect of thermal radiation on human skin. Using human subjects, Stoll and Greene **[54]** found that with an intensity of 6.3 kW·m^{-2}, the pain threshold was reached in 8 seconds and blistering occurred in 20 seconds. This data is consistent with reported values in reference **[8]**. The same report indicated that an intensity of 23.7 kW·m^{-2} caused burns on the bare skin of white rats in approximately 6 seconds. **Table 23** lists Buettner's **[55]** exposure times necessary to reach the pain threshold as a function of radiation intensity. These experimental data were derived from tests given to people who were radiated on the forearm at room temperature. The data state that burns follow the pain threshold quickly. Buettner's data agree well with the data from Stoll and Greene **[54]**.

Table 23: Exposure Times to the Pain Threshold

Radiation [kW·m^{-2}]	Time to Pain Threshold [s]
1.74	60
2.33	40
2.90	30
4.73	16
6.94	9
9.46	6

Radiation [kW·m^{-2}]	Time to Pain Threshold [s]
11.67	4
19.87	2

Since the allowable radiation level is a function of the length of exposure, factors involving reaction time and human mobility should be considered. In emergency releases, a reaction time of 3-5 seconds may be assumed. Five seconds more may elapse before the average individual could seek cover or depart from the area, which would result in a total exposure period ranging from 8 to 10 seconds.

Two additional factors should be considered regarding thermal radiation levels:

- The intensity of solar radiation is in the range of 0.79-1.04 kW·m^{-2}. Solar radiation may be a factor for some locations, but its effect added to flare radiation will have only a minor impact on the acceptable exposure time. Regardless of its impact, solar radiation should be considered in the total radiation computation.
- Clothing provides shielding, allowing only a small part of the body to be exposed to full intensity. In the case of radiation emanating from an elevated point, standard personnel protective measures, such as wearing a hard hat, may reduce thermal exposure.

Heat radiation is frequently the controlling factor in the spacing of equipment such as elevated and ground flares. **Table 24** presents recommended total design radiation levels for personnel at grade or on adjacent platforms. The extent and use of personal protective equipment may be considered as a practical way of extending the times of exposure beyond those listed.

Table 24: Recommended Total Design Radiation

Radiation [kW·m^{-2}]	Time to Pain Threshold [s]
15.77	Heat intensity on structures and in areas where operators are not likely to be performing duties and where shelter from radiant heat is available (for example, behind equipment).
9.46	Heat intensity at design flare release at any location to which people have access (for example, at grade below the flare or a service platform of a nearby tower); exposure should be limited to a few seconds, sufficient for escape only.
6.31	Heat intensity in areas where emergency actions lasting up to 1 minute may be required by personnel without shielding but with appropriate clothing.
4.73	Heat intensity in areas where emergency actions lasting several minutes may be required by personnel without shielding but with appropriate clothing.
1.58	Heat intensity at any location where personnel with appropriate clothing may be continuously exposed.

Specific Criteria for Population Indoors

People inside buildings may be vulnerable to a building catching fire if combustible building material is exposed to the fire (either to a directly impinging fire or to radiation).

Two types of ignition are recognized:

- Piloted ignition, resulting from the flame impinging directly on a surface
- Spontaneous ignition, resulting from exposure to thermal radiation from a fire

Normally, only the outdoor populations present within the flammable boundaries of vapor cloud fires, pool fires, fireballs and flame jets are assumed to perish due to: (1) exposure to high thermal radiation fluxes from the vapor cloud fires, pool fires, fireballs, or flame jets, (2) direct flame contact, (3) secondary fires of clothing and (4) inhalation of hot combustion products.

It is assumed that people inside buildings will not be injured or killed unless they are near windows. It is also assumed that people inside buildings which are ignited by flash fires, flame jets, fireballs, or pool fires will be able to escape from the burning structure without direct thermal impact injuries. This is because the flames will ignite buildings from the outside-in and it will take some time for the fires to penetrate inside. Note that people can be exposed to high doses of thermal radiation from fireballs and flame jets if they are near windows. People inside a building are also vulnerable if escape routes are exposed to thermal radiation. In this case the criterion of 6 $kW \cdot m^{-2}$ given in **Table 21** can be applied.

However, the "Purple Book" **[25]** considers that people located inside a building are protected from heat radiation until the building catches fire. The threshold for the ignition of buildings is set at 35 $kW \cdot m^{-2}$. If the building is set on fire, a probability of fatality of 1.00 is assumed if the heat radiation exceeds 35 $kW \cdot m^{-2}$ and if lower, no fatalities are considered.

Thermal Dose Criteria

Table 25 lists the spread of selected experimental burn data for infrared radiation **[52]**. Very little third degree burn data is available and some non-threshold data has not been selected. Ultra-violet radiation data has not been considered because typical emissions from hydrocarbon fires mainly comprise infrared radiation, which is found to produce burns at lower doses **[56]**. Ultra-violet radiation data has been used historically and frequently since Eisenberg interpreted nuclear bomb fatalities as a thermal radiation probit **[39]**.

Table 25: Thermal Dose Criteria

Effect	Thermal Dose [$(kW \cdot m^{-2})^{4/3}s$]	
	Mean Value	**Range**
Pain Threshold	92	86-103
First Degree Burn Threshold	105	80-130
Second Degree Burn Threshold	290	240-350
Third Degree Burn Threshold	1000	870-2600

It is expected that an individual, either in pain from a thermal dose received or suffering from first degree burns, should escape rapidly as the injury should not be sufficient to impede movement yet too uncomfortable to bear standing still.

An individual with second degree burns will have even greater motivation to escape, commonly referred to as the fight or flight response. However, at this level of injury, any exposed skin will be very uncomfortable and difficult to use in contact with another surface. Simple tasks, such as turning door handles or dressing in survival equipment will take longer if they are at all possible. Depending on the location and extent of injury, more difficult tasks, such as operating control panels or turning valves may be impossible.

With third degree burns an individual will be in severe pain and will certainly realize that they are in immediate danger of losing their life. Individual response is hard to predict. However fine control of injured extremities will be impossible and other functions will be severely impaired. Escape will probably incur further injury as skin may fall away from the wound. Individuals with third degree burns should be considered as casualties who cannot evacuate unaided.

Specific Criteria Addressing Fireballs

The evaluation of the effects of the fireball phenomena requires specific criteria due to the short exposure times; i.e., up to a few tens of seconds. Therefore, the effects of fireballs are better described by using thermal radiation dose **[8]** (see **Table 26**).

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Table 26: Thermal Dose Criteria for Addressing Fireball Effects

Thermal Dose [$(kW \cdot m^{-2})^{4/3}s$]	Effect
1000	1% fatality
1800	50% fatality, members of the public
2000	50% fatality, offshore workers
3200	100% fatality

Specific Criteria Addressing Offshore Facilities

Table 27 summarizes the estimated thermal dose to produce the relevant harm criteria. The dose is relevant for a typical offshore population on a typical offshore platform, where the source of the radiation is a hydrocarbon flame from a jet-, pool- or flash-fire or a fireball.

Table 27: Thermal Dose Harm Criteria Guidance for Offshore Facilities

Thermal Dose [$(kW \cdot m^{-2})^{4/3}s$]	Effect
290	Escape impeded
1000	1-5% fatality offshore
1800	50% fatality offshore with radiation to the front or back (i.e., fireball)
2000	50% fatality offshore
3500	100% fatality offshore

Notes:

- The 50% fatality level is an estimate based on the assumption that, prior to clothing ignition, less than 50% of individuals will become fatalities and following clothing ignition more than 50% of individuals will become fatalities. As most offshore clothing is nominally identical, the threshold of piloted clothing ignition is taken as a conservative value. Where only one side of an individual is presented to a fire, only half the normal dose is required for the same effect. This will only occur with short duration (less than 10 seconds) events.
- 1% fatality is a conservative estimate based on **[56]**, which concluded that serious burns may be received or a small % of onshore workers would die following exposure to 1000 $(kW \cdot m^{-2})^{4/3}s$. It is assumed that the training and clothing of offshore workers is generally superior to that of onshore workers, but the increased

difficulty of escape etc. nulls this advantage. It is assumed that the exposure to 1000 $(kW{\cdot}m^{-2})^{4/3}s$ is evenly distributed to the front and back of the victim, due, for example, to a winding escape route.

- Even second-degree burns impede escape, however unassisted escape is still possible until the onset of third degree burns over a large body area or sensitive areas, or until clothing ignition occurs.
- The 100% fatality level is difficult to distinguish from some lower levels. In the interest of setting a guiding figure, 3500 $(kW{\cdot}m^{-2})^{4/3}s$ is estimated. However, 100% fatality may occur at slightly lower doses. At 3500 $(kW{\cdot}m^{-2})^{4/3}s$, un-piloted ignition of clothing will occur, thus even 100% clothed individuals will not survive. At this level of thermal dose, self-extinguishment is unlikely due to injury from heat transmitted through the clothing unless fire protective clothing (PPE) is worn.

Probit Criteria

Probit analysis can also be applied for thermal radiation fatality estimates. For the purposes of risk assessment, it should be sufficient to know what is the required dose to induce pain, to cause a fatality (i.e., 1-5%), to incur a 50% fatality probability and to incur a 95-100% fatality probability. **Table 28** provides three probit equations typically used during a risk-based quantitative assessment.

Table 28: Probit Equations Used in Risk Assessments

Probit Equation	Source	Reference Number
$Y = -14.9 + 2.56 \ln D$	Eisenberg et al. (1975)	**[39]**
$Y = -12.8 + 2.56 \ln D$	Tsao and Perry (1979)	**[57]**
$Y = -10.7 + 1.99 \ln D'$*****	Lees (1996)	**[18]**

*****Note that $D' = f \cdot D$, where f is a factor accounting for variation in exposed skin area (0.5 for normally clothed population and 1.0 if clothing has been ignited).

Opschoor et al. **[24]** provide probit functions for first and second degree burns as well as lethality from exposure to heat radiation within the infra-red part of the spectrum (**Table 29**).

Table 29: Green Book Probit Models

Damage	Probit
Fatal Injury – People Unprotected	$Y = -36.38 + 2.65\,ln\left(t^{4/3}\right)$
Fatal Injury – People Protected	$Y = -37.23 + 2.56\,ln\left(t^{4/3}\right)$
Non-Fatal Injury – First Degree Burns	$Y = -39.83 + 3.02\,ln\left(t^{4/3}\right)$
Non-Fatal Injury – Second Degree Burns	$Y = -43.14 + 3.02\,ln\left(t^{4/3}\right)$

Note: that these are the probit models proposed in the Green Book **[25]**.
Note: the last probit function reported in **Table 29** above accounts for clothing protective influence on fatality for humans. It assumes that 20% of the body area remains unprotected for an average population. As a result, the fatality for protected bodies is about 14% of the fatality for unprotected bodies.

The influence of running away from a location with high heat radiation to a location where the level of heat radiation is safe (e.g., 1 kW·m^{-2}) is important for the assessment of injury and fatality from heat radiation. The probits presented in **Table 29** can be modified to take that "running away" factor into account by replacing the exposure time ***t*** by an effective exposure time t_e:

$$t_e = t_r + 0.6\frac{x}{u}\left[1-\left(1+\frac{u}{x}t_v\right)^{-5/3}\right]$$

where, t_r is the reaction time and is about 5 seconds, ***x*** is the distance to 1 kW·m^{-2}, ***u*** is the run velocity in m·s^{-1} and t_v is the time to reach 1 kW·m^{-2}.

Risk-Based Quantitative Damage Criteria Based on CPR18E

Specific Criteria from CPR18E – Purple Book

This section is intended to provide guidance to determine the probability of fatality due to fires given the exposure and the fraction of the population for whom exposure is fatal (see **Figure 03** and **Figure 04**). Detailed exposure and damage criteria due to fires being used during a risk-based quantitative assessment is proposed in the CPR18E **[26]**. Flash fires, BLEVEs, Pool Fires and Jet Fires are addressed after introducing the following key parameters:

- P_E: Probability of Fatality of an individual, which is assumed to be outdoors and unprotected. This parameter is used for the estimation of Individual Risk Contours.
- $F_{E,in}$: Probability of fatality of the fraction of the indoor population due to fire exposure. It is assumed that part of the population is protected by staying indoors and wearing protective clothing. This parameter is used for the estimation of the Societal Risk.
- $F_{E,out}$: Probability of fatality of the fraction of the outdoor population at a certain location due to the fire exposure. It is assumed that the outdoor population outdoors is unprotected. This parameter is used for the estimation of the Societal Risk.

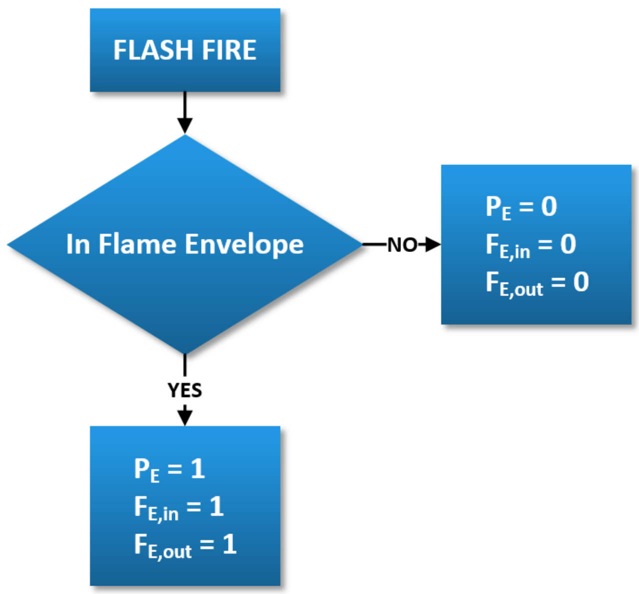

Figure 03: Exposure and Damage Criteria to Flash Fires

Note: Flash fire envelope is equal to the Lower Flammability Level (LFL) contour at the time of ignition.

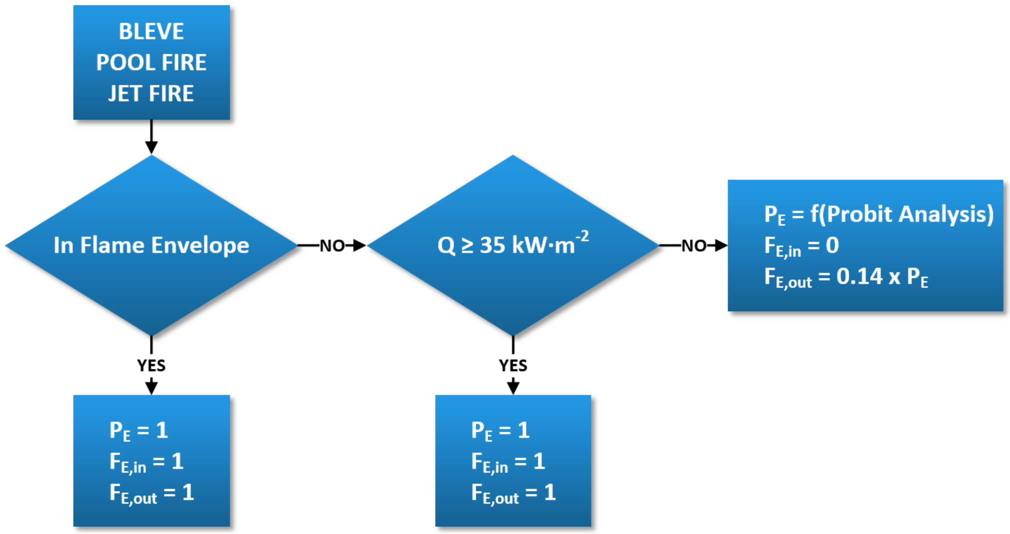

Figure 04: Exposure and Damage Criteria to BLEVEs, Pool Fires and Jet Fires

Notes:

- The exposure time is equal to the duration of the fire. However, the exposure time is limited to a maximum of 20 seconds.

- For the Societal Risk calculation, it is assumed that people outdoors are protected from heat radiation by clothing until it catches fire. The protection of clothing reduces the number of people dying by a factor of 0.14 compared to no protection of clothing. The threshold for the ignition of clothing is set at 35 kW·m^{-2} and people die if clothing catches fire at this threshold. Hence, 100% probability of fatality if the heat radiation exceeds 35 kW·m^{-2} and 14% probability of fatality if the heat radiation is less than 35 kW·m^{-2}.

- Probit Analysis based on the following equation: $Y = -36.38 + 2.56 \ln D$

Additional Criteria

Finally, another summary correlating fatality with serious injury rates due to fire can be found in **[58]**. **Table 30** lists criteria for the risk analysis for both fatalities and serious injuries. In this table, the zero percent fatality or serious injury level is the level at which fatalities or serious injuries could begin to occur. Data listed in **Table 30** is consistent with thresholds previously provided in this section of the manuscript.

Table 30: Fatality and Serious Injury Rates

Event	Fatality	Serious Injury	Notes
Flash Fire	30% fatality within the LFL envelope	100% injury within the LFL	**Note 1**
		50% injury within the ½ LFL	
Thermal Flux Jet or Pool Fire	100% fatality within flame jet area	100% injury at 10 kW·m^{-2}	**Note 2**
	11% fatalities at 10 kW·m^{-2}	10% injury at 5 kW·m^{-2}	
Thermal Dose BLEVE, Fireball	18% fatalities at 250 kJ·m^{-2}	100% injury at 150 kJ·m^{-2}	**Note 3**
		10% injury at 40 kJ·m^{-2}	

Note 1: Assumes 30% of the population is outdoors and would suffer 100% fatalities within the LFL. Assumes indoor population would not suffer more than serious injury due to subsequent fire and damage. Outdoor population percentage is estimated.

Note 2: Based on Handbook of Chemical Hazards Analysis Procedures **[58]**, exposure to 10 kW·m^{-2} produces second-degree burns in 14 seconds, 10% fatalities at 60 seconds based on Eisenberg Probit Equation **[39]**. Injury based on time to second-degree burns of less than 1 minute for 10 and 5 kW·m^{-2}.

Note 3: Based on total energy integration over boiling liquid expanding vapor explosion duration using the jet fire energy rate.

Criteria Summary

Flash fires are characterized based on the extension of the LFL envelope. If people are within the envelope, then 100% fatality is expected. People outside the LFL envelope are not expected to suffer injuries.

A heat radiation of 5 kW·m^{-2} will cause second-degree burn injuries on bare skin if the duration of exposure is about 45 seconds,10 kW·m^{-2} will quickly cause third-degree burns that are likely to lead to fatality. These two levels are typically used in determining Injury and fatality hazard zones. See reference **[59]**, which contents are consistent with values listed in **Table 04**. A heat flux in excess of 150 kJ·m^{-2} could be fatal for humans due to irreversible skin tissue damage. A lesser level of 40 kJ·m^{-2} could cause pain or mild second-degree burns. These two values have been used to define the safe separation downwind distances from a fireball for fatality and injury, respectively (based on contents illustrated in reference **[58]**).

Domino Effect and Escalation

In this section, focus is on the impact of Loss of Containment scenarios (LOCs) of flammable materials that could lead to fires to structures; e.g., buildings, process equipment. Fire outcomes are based on the source term models which consider released material properties and behavior; conditions of the release; and various phenomena that accompany the release of hazardous materials under such conditions (e.g., expansion, choked flow, two phase flow, aerosolization, rainout) **[60]**. These models are important because they provide input data to the fire models and the accuracy from the fire models is dependent upon the accuracy in the source term computation. Despite the large number of possible fire events, few categories of industrial fires are relevant for facility siting leading to occupant fatalities located inside a building; i.e., jet fires, pool and tank fires, fireballs and flash fires **[35].**

Despite the large number of possible fire events, only jet fires and pool fires are relevant for escalation leading to domino effect. Further explanation on the types of fires and damage criteria can be found in **[65]**. For domino effect and escalation analysis due to fires, Heat Flux Exceedance Curves (HFECs) are constructed in order to identify which structures/protected equipment are impacted by LOCs leading to fires at a certain threshold of interest, which is 35 $kW{\cdot}m^{-2}$ as reported by BEVI **[25]**. **Table 31** classifies and correlates the different fires identified in the process industry with escalation criteria based on the heat load received by the target **[35]**. Based on contents listed in **Table 31** and assuming that all potential fires impacting a target location (equipment) have been already identified and characterized during the risk-based quantitative assessment, the analysis of the domino effect can be performed by categorizing the type of process equipment (atmospheric or pressurized) and the type of fire. This categorization allows the user to perform a dedicated domino effect analysis by using dedicated heat flow thresholds (i.e., Q_{HL} in [$kW{\cdot}m^{-2}$]) as a function of process equipment type.

Table 31. Fires Showing Escalation Based on Heat Load Received by the Target

Q_{HL} in [kW·m^{-2}]: Thermal Flow received by the fire

Note 1: Flammable vapors ignition for floating roof tanks

Features Relevant for Escalation	Confined Jet fire	Open Jet Fire	Confined Pool/Tank Fire	Open Pool Fire	Fireball	Flash Fire
Combustion Mode	Diffusive	Diffusive	Diffusive	Diffusive	Diffusive	Premixed
Total Heat Load [kW·m^{-2}]	150-400	100-400	100-250	50-150	150-280	170-200
Radiative Contribution [%]	66.7-75	50-62.5	92-100	100	100	100
Convective Contribution [%]	25-33.3	37.5-50	0-8	0	0	0
Flame Temperature Range [K]	1,200-1,600	1,200-1,500	1,200-1,450	1,000-1,400	1,400-1,500	1,500-1,900
Atmospheric Equipment - Escalation Criteria for Fire Impingement	Possible	Possible	Possible	Possible	$Q_{HL} > 100$	Note 1
Pressurized Equipment -Escalation Criteria for Fire Impingement	Possible	Possible	Possible	Possible	Unlikely	Unlikely
Atmospheric Equipment - Escalation Criteria for Distance Source Radiation	$Q_{HL} > 15$	$Q_{HL} > 15$	$Q_{HL} > 15$	$Q_{HL} > 15$	$Q_{HL} > 100$	Unlikely
Pressurized Equipment - Escalation Criteria for Distance Source Radiation	$Q_{HL} > 40$	$Q_{HL} > 40$	$Q_{HL} > 40$	$Q_{HL} > 40$	Unlikely	Unlikely

Additionally, in the event of a fire, an important parameter to be evaluated is the Time to Failure (TTF), which represents the available time lapse for the activation of emergency procedures and mitigation devices. This includes the deployment of emergency teams aimed at the mitigation and/or suppression of the primary fire.

The TTF can be evaluated based on correlations or Dynamic Thermal Stress Analysis (DTSA) approach. Further information regarding the threshold approach can be found in **[5]** and reference **[6]** addresses the DTSA approach for domino effect and escalation. When evaluating the TTF based on correlations, an approach is developed based on validated models **[35]**. A specific approach was introduced to define simple analytical functions for the assessment of equipment TTF in different fire scenarios **[33]**, **[61]** and **[62]**. The correlations are based on empirical functions correlating an extended dataset of TTF values obtained by applying lumped parameters modeling approaches. The dataset was obtained identifying the more important categories of secondary equipment involved in domino accidents defining reference geometrical characteristics based on typical design data used by engineering companies in the oil and gas sector. The more credible primary fire scenarios with potential for escalation (pool fires and jet fires) were selected. Further detailed information can be found in reference **[63]** and **[64]**. **Table 31** lists the simplified correlations obtained for both atmospheric and pressurized equipment from the analysis of the dataset **[35]**. Correlations in **Table 32** yield conservative data for the TTF of equipment having volumes and operating pressures within the range specified.

Table 32: Time to Failure Simplified Correlations

Equipment	VR [m^3]	DPR [MPa]	Simplified Correlation; TTF [s]
Atmospheric	25-17,500	0.1	$\ln(TTF) = -1.13 \cdot \ln(Q_{HL}) - 2.67 \cdot 10^{-5} \cdot V + 9.9$
Pressurized	5-250	1.5-2.5	$\ln(TTF) = -0.95 \cdot \ln(Q_{HL}) + 8.845 \cdot V^{0.032}$

Notes:
- **VR** Volume Range **[m^3]**
- **DPR** Design Pressure Range **[MPa]**
- **TTF** Time to Failure **[s]**
- **V** Equipment Volume **[m^3]**
- **QHL** Heat Flux **[kW·m^{-2}]**

Dispersions

Introduction

Human health effects caused by exposure to toxic substances fall into two categories: chronic and acute.

Chronic effects are those with a long period of time (several years) between exposure and injury. These effects may occur after apparent recovery from acute exposure or because of repeated exposures to low concentrations of materials over a period of years (chronic exposure). A typical example of chronic exposure and chronic effects is long term exposure to workers in an industrial setting.

Acute effects (or short-term effects) have a relatively quick onset (usually minutes to days) after brief exposure to relatively high concentrations of materials (acute exposure). The effect of such an exposure may be local or systemic. Local effects manifest themselves at the point of contact between the material and the body. This is usually the skin or the eyes, but could be the lungs if a material is inhaled. Systemic effects occur if the toxicant has been absorbed into the body, transported to other parts of the body and caused adverse effects in target organs or organ systems. Many materials cause both local and systemic effects. Common acute exposure situations include: (1) Releases at chemical manufacturing/storage facilities (single and multiphase); (2) Hazardous material transportation incidents; (3) Fires.

It is important to mention that the duration of an exposure is just as important as the level of exposure when it comes to the ultimate effect on the receptor. In the case of humans:

- The body has a capacity to handle the intake of many contaminants at a certain rate. Below a certain threshold, the body can either eliminate or process the material into a harmless substance.
- The rate at which a contaminant enters the body via inhalation is a function of the concentration, breathing rate, the length of time the body is exposed and the toxic properties of the material.
- Toxic effects via dermal contact are a function of the amount of material that contacts the body, the length of time is permitted to remain in contact and the properties of the material.
- Toxic effects via ingestion are a function of the rate of intake and the period of intake. Small doses of materials over a long period of time may not be harmful, but taking the total amount at once can be fatal.

Note that risk-based quantitative assessments are more focused on characterizing the effects of acute exposures due to LOC scenarios of hazardous materials.

A given amount of a toxic agent will elicit a given response. This is called a dose response relationship and it is the basis for the measurement of the relative harmfulness of a chemical. Dose response is a quantitative relationship between the dose of a chemical and the effect caused by the chemical. Dose response relationships are nearly all derived from animal testing on mammalian species other than humans. Thus, the results of the animal studies must be extrapolated to humans. A test organism is chosen for its ability to stimulate human response. For example, rabbits are chosen for skin tests because their response closely resembles that of humans. The dose-response relationship is based on two major factors:

- Concentration (quantity or level) of exposure
- Duration (time) of exposure

The lowest value on the response versus dose is called the threshold dose. Below this dose the body can detoxify and eliminate the agent without any detectable effects. Therefore, in a risk-based quantitative assessment framework, it is key to identify concentrations of hazardous materials that can be used to define reasonable boundaries of a hazard zone. The purpose of the hazard zone is to define the area in which the population would have to be notified, evacuated, sheltered, or otherwise protected. The focus here would be the determination of an airborne concentration of the material that can be tolerated by the exposed population. To adequately define the hazard zone, the characteristics of the material must be known as well any existing exposure limits and their respective purposes for use and applicability for emergency planning purposes. For example, see reference **[60]**.

Toxic Damage Criteria

The most used approaches addressing toxic damage criteria during the development of a risk-based quantitative assessment are the following: probit analysis and exposure threshold limits or dose values.

Probit Analysis

One approach is to use the probit models which can include the effects resulting from transient changes in toxic concentrations. The probit analysis is fully developed in reference **[66]**. The use of probits or vulnerability models is recommended for quantitative risk assessment studies (QRA). When coupled with probits, consequence models can associate a probability of fatality (or of receiving a dangerous dose) or building damage within a specific hazard zone or isopleth.

The use of the probit analysis is intended to relate the percentage of fatality and probit unit $\boldsymbol{Y}$, where $\boldsymbol{Y}$ is given by:

$$Y = A + B \ln D \quad \textbf{E.01}$$

$\boldsymbol{Y}$: Probit unit

$\boldsymbol{A}$ and $\boldsymbol{B}$: Constants which depend on the toxic chemical

$\boldsymbol{D}$**:** Hazard dose of an airborne toxic gas, which depends on the concentration of the toxic gas in the air being inhaled, $\boldsymbol{C}$ and the length of time an individual is exposed to this concentration. The hazard dose equals the product of gas concentration to an exponent $\boldsymbol{n}$ and time $\boldsymbol{t}$ in minutes. Concentration can be reported in parts per million (ppm) or milligrams per cubic meter ($mg \cdot m^{-3}$).

$$D = C^n t$$ **E.02**

The relationship between fatality and the probit function can be found in reference **[66]**, values which are based on Finney **[67].**

Two key sources of information with probit constants addressing chemicals normally handled in the process industry can be found in the following references:

- CPR-18E or “Purple Book”, **[26]**
- Safety Environmental Risk Database (SERIDA), **[68]**

There are several issues that require consideration when assessing the applicability of probits in risk analysis for toxics:

- There are few reported probits for toxic substances.
- Data are not available for human beings and the parameters are extrapolated from animal data. Typical extrapolation methods use body weight and/or body surface area as scaling factors for predicting interspecies response to toxins **[60]**, **[67]**. One potential way of providing validation for probits is through examination of previous incidents. This however requires that the release and transport models are providing accurate representation of the concentration profiles at any given location.
- Probit equations are not likely to be valid for exposure durations less than 5 minutes or more than one hour **[26]**.

SERIDA, Safety Environmental Risk Database **[68]** reports the same values reported in the CPR18 (Purple Book) **[26]** except that the SERIDA list of chemicals is more extensive.

Table 33 provides some examples of constants for toxicity probit equations.

Table 33: Constants for Toxicity Probit Equations

Chemical Name	A [-]	B [ppm]	n [min]
Acrolein	-9.931	2.049	1
Acrylonitrile	-29.42	3.008	1.43
Ammonia	-35.9	1.85	2
Carbon Monoxide	-37.98	3.7	1
Chlorine	-8.29	0.92	2
Hydrogen Chloride	-16.85	2	1
Hydrogen Cyanide	-29.42	3.008	1.43
Hydrogen Fluoride	-25.87	3.354	1
Hydrogen Sulfide	-31.42	3.008	1.43

Exposure Threshold Limits or Doses

An alternative approach is to specify a toxic concentration criterion above which it is assumed that individuals exposed to this value will be in danger. This approach has led to many criteria promulgated by several government agencies and private associations. Some of these criteria are listed in **Table 34**. These exposure limits are methods based on a combination of results from animal experiments, observations of long- and short-term human exposures and expert judgment.

Emergency Response Planning Guidelines **(ERPGs)** are prepared by an industry task force and are published by the American Industrial Hygiene Association (AIHA) **[69]**. Three concentration ranges are provided because of exposure to a specific substance:

- **ERPG-1** is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing effects other than mild transient adverse health effects or perceiving a clearly defined objectionable odor.
- **ERPG-2** is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair their abilities to take protective action.
- **ERPG-3** is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects (like **EEGLs**).

Because of the comprehensive effort to develop acute toxicity values, ERPGs are becoming an acceptable industry/government norm. Detailed information on ERPG values can be found in the following reference: AIHA, Emergency Response Planning Guidelines and Workplace Environmental Exposure Levels (Fairfax, VA: American Industrial Hygiene Association, 2016). www.aiha.org, **[69]**.

The US Environmental Protection Agency (EPA) uses the Acute Exposure Guideline Levels (AEGLs) **[70]**, which are exposure guidelines designed to help first responders deal with emergencies involving chemical spills or other catastrophic events where members of the general public are exposed to a hazardous airborne chemical. The **AEGL** is a concentration at which most people (including sensitive individuals such as old, sick, or very young people) will begin to experience health effects if they are exposed to a hazardous chemical for a specific length of time (duration). For a given exposure duration, a chemical may have up to three AEGL values, each of which corresponds to a specific tier of health effects. The three AEGL tiers are developed for five exposure periods: 10 minutes, 30 minutes, 60 minutes, 4 hours and 8 hours and are defined as follows:

- **AEGL-1** is the Airborne concentration (expressed as ppm or $mg \cdot m^{-3}$) of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.
- **AEGL-2** is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.
- **AEGL-3** is the airborne concentration of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death.
- EPA provides a dedicated website where users can access AEGLs values by entering the CAS number or name of the chemical of interest. Detailed information on compiled AEGL values can be found in .pdf format in the following link **[70]**: https://www.epa.gov/sites/production/files/2016-03/documents/compiled_aegl_update_.pdf
- The National Institute for Occupational Safety and Health (**NIOSH**) publishes Immediately Dangerous to Life or Health (IDLH) concentrations to be used as acute toxicity measures for common industrial gases. An IDLH exposure condition is defined as a condition "that poses a threat of exposure to airborne contaminants when that exposure is likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment."

Table 34: Recognized Exposure Limits for Airborne Concentrations

Limit	Meaning	Organization	Meaning
TLV-TWA	Threshold Limit Value - Time-Weighted Average	**ACGIH**	American Conference of Governmental Industrial Hygienists
TLV-STEL	Threshold Limit Value – Short-Term Exposure Limit	**ACGIH**	American Conference of Governmental Industrial Hygienists
TLV-C	Threshold Limit Value – Ceiling	**ACGIH**	American Conference of Governmental Industrial Hygienists
ERPG	Emergency Response Planning Guideline	**AIHA**	American Industrial Hygiene Association
AEGL	Acute Exposure Guideline Level	**EPA**	US Environmental Protection Agency
IDLH	Immediately Dangerous to Life and Heath Level	**NIOSH**	National Institute for Occupational Safety and Heath
PEL	Permissible Exposure Limit	**OSHA**	Occupational Safety and Health Administration
EEGL	Emergency Exposure Guidance Level	**NRC**	National Research Council
SPEGL	Short Term Public Emergency Guidance Level	**NRC**	National Research Council
TXDS	Toxic Dispersion	**NJDEP**	New Jersey Department of Environmental Protection

*****Other thresholds and dose definitions for toxic agents are available. However, the most applicable relevant thresholds for a risk-based quantitative assessment are listed in **Table 34**.

IDLH values also take into consideration acute toxic reactions, such as severe eye irritation, that could prevent escape. The IDLH level is considered a maximum concentration above which only a highly reliable breathing apparatus providing maximum worker protection is permitted. If IDLH values are exceeded, all unprotected workers must leave the area immediately.

IDLH data are currently available for 380 materials. Because IDLH values were developed to protect healthy worker populations, they must be adjusted for sensitive populations such as older, disabled, or ill populations. For flammable vapors, the IDLH concentration is defined as one-tenth of the lower flammability limit (LFL) concentration. Also note that IDLH levels have not been peer-reviewed and that no substantive documentation for the values exists.

Detailed information on compiled IDLHs values can be found in .pdf format in the following link **[71]**: https://www.cdc.gov/niosh/docs/2005-149/pdfs/2005-149.pdf.

Since the 1940s, the National Research Council's (NRC) Committee on Toxicology has submitted Emergency Exposure Guidance Levels (**EEGLs)** for 44 chemicals of special concern to the Department of Defense. An **EEGL** is defined as a concentration of a gas, vapor, or aerosol that is judged acceptable and that allows exposed individuals to perform specific tasks during emergency conditions lasting from 1 to 24 hours. Exposure to concentrations at the **EEGL** may produce transient irritation or central nervous system effects but should not produce effects that are lasting or that would impair performance of a task.

In addition to **EEGLs**, the National Research Council has developed Short-term public emergency guidance levels (**SPEGLs)**, defined as acceptable concentrations for exposures of members of the general public. SPEGLs are generally set at 10-50% of the **EEGL** and are calculated to account for the effects of exposure on sensitive heterogeneous populations. The advantages of using **EEGLs** and **SPEGLs** rather than **IDLH** values are

- SPEGL considers effects on sensitive populations,
- EEGLs and SPEGLs are developed for several different exposure durations and
- The methods by which EEGLs and SPEGLs were developed are well documented in National Research Council publications. EEGL and SPEGL can be found in Adobe Acrobat format in the following link **[72]**: https://www.cdc.gov/niosh/docket/archive/pdfs/NIOSH-125/125-NationalAcademyofSciences2007.pdf

Certain (ACGIH) criteria may be appropriate for use as benchmarks. The ACGIH threshold limit values TLV-STELs and TLV-Cs are designed to protect workers from acute effects resulting from exposure to chemicals such as irritation and narcosis. These criteria can be used for toxic gas dispersion but typically produce a conservative result because they are designed for worker exposures. Publications related to TLVs can be purchased via the following link: http://www.acgih.org/forms/store/CommercePlusFormPublic/search?action=Feature

The PELs are promulgated by OSHA and have force of law. These levels are similar to the ACGIH criteria for TLV-TWAs because they are also based on 8-hr time-weighted average exposures. OSHA-cited "acceptable ceiling concentrations," "excursion limits," or "action levels" may be appropriate for use as benchmarks. Detailed information on compiled PEL values can be found in .pdf format in the following link **[73]**: https://www.osha.gov/dsg/annotated-pels/

The New Jersey Department of Environmental Protection uses the TXDS method of consequence analysis to estimate potentially catastrophic quantities of toxic substances, as required by the New Jersey Toxic Catastrophe Prevention Act (TCPA). An acute toxic concentration (ATC) is defined as the concentration of a gas or vapor of a toxic substance that will result in acute health effects in the affected population and 1 fatality out of 20 or less (5% or more) during a 1-hr exposure. ATC values, as proposed by the New Jersey Department of Environmental Protection, are estimated for 103 “extraordinarily hazardous substances" and are based on the lowest value of one of the following:

- Lowest Reported Lethal Concentration (LCLO) value for animal test data
- Median Lethal Concentration (LCSO) value from animal test data multiplied by 0.1
- IDLH value

Further information can be found in link **[74]**: http://www.nj.gov/dep/.

The EPA has promulgated a set of toxic endpoints to be used for air dispersion modeling for toxic gas releases as part of the EPA RMP. In order of preference, the toxic endpoint is:

- ERPG-2
- Level of Concern (LOC) promulgated by the Emergency Planning and Community Right-to-Know Act

The LOC is considered "the maximum concentration of an extremely hazardous substance in air that will not cause serious irreversible health effects in the general population when exposed to the substance for relatively short duration." Detailed information on related criteria and endpoints can be found in *.pdf* format in the following link **[75]**: https://www.epa.gov/sites/production/files/2013-11/documents/oca-chps.pdf.

In general, the most directly relevant toxicological criteria currently available, particularly for developing emergency response and land-use planning are ERPGs, AEGLs, SPEGLs and EEGLs. These were developed specifically to apply to general populations and to account for sensitive populations and scientific uncertainty in toxicological data. For incidents involving substances for which no SPEGLs or EEGLs are available, IDLH levels provide alternative criteria. However, because IDLH levels were not developed to account for sensitive populations and because they were based on a maximum 30-minute exposure period, the EPA suggests that the identification of an effect zone should be based on exposure levels of one-tenth the IDLH level. For example, the IDLH level for chlorine dioxide is 5 ppm. Effect zones resulting from the release of this gas are defined as any zone in which the concentration of chlorine dioxide is estimated to exceed 0.5 ppm. As a result, the approach is conservative and gives unrealistic results. Thus, a more realistic approach is to use a constant-dose assumption for releases less than 30 min using the IDLH level.

The use of TLV-STELs and ceiling limits may be the most appropriate approach if the objective is to identify effect zones in which the primary concerns include more transient effects, such as sensory irritation or odor perception. In general, persons located outside the zone based on these limits can be assumed to be unaffected by the release.

These methods may result in some inconsistencies because the different methods are based on different concepts. Good judgement should prevail according to the main purpose of the analysis. For a complete and detailed risk-based quantitative assessment, the use of the probit method is more convenient rather than exposure limits.

Conclusions

The present paper collects human vulnerability and structural damage criteria from well-known references available in the literature for explosions, fires and dispersions.

In the first section, i.e., Explosions, the manuscript addresses human vulnerability. Based on the contents described below, when evaluating human vulnerability due to overpressure, three parameters need to be considered: (1) overpressure, (2) impulse and (3) probit analysis. However, it is important to mention that dedicated criteria for human vulnerability based on the Department of Defense (DoD) is addressed in the following reference: **[1]** Facility Siting Addressing Explosions Impacting Process Plant Permanent and Portable Buildings, Combining Exceedance Curves, Structural Response and Human Vulnerability Criteria. After addressing human vulnerability is the following section presents several well-known overpressure thresholds for domino effect and escalation analysis. It is important to mention that even though the impulse has a potential effect on escalation triggered by explosions, it is normal to only use overpressure. Additionally, the following two references address the domino effect and escalation triggered by explosions phenomena, based on only thresholds and based on the Single Degree of Freedom (SDOF) approach: **[2]** Domino Effect and Escalation Triggered by Explosions – Combining Exceedance Curves and Overpressure Threshold Criteria; **[3]** Domino Effect and Escalation Triggered by Explosions – Combining Exceedance Curves, Single Degree of Freedom and Pressure-Impulse Diagrams.

In the second section, i.e., Fires, both human vulnerability and domino effect and escalation are addressed. With regards to human vulnerability, three parameters need to be considered: (1) thermal flux, (2) thermal dose and (3) probit analysis. Furthermore, note that the following reference is developed with the aim to address building occupant human vulnerability via a detailed risk-based approach using Heat Flux Exceedance Curves (HFECs): **[4]** Facility Siting Addressing Fires Impacting Process Plant Permanent and Portable Buildings, Combining Exceedance Curves and Human Vulnerability Criteria.

Similarly, to explosions, domino effect and escalation triggered by fires is also briefly explained in the present manuscript. The following references further address this phenomenon and include a case study based on well-known thresholds approach and the Dynamic Thermal Stress Analysis (DTSA) approach: **[5]** Domino Effect and Escalation Triggered by Fires – Combining Exceedance Curves and Time to Failure Simplified Methodologies; **[6]** Domino Effect and Escalation Triggered by Fires – Combining Dynamic Thermal Stress Analysis and Wall Segmentation Approach.

Finally, in the third section only human vulnerability due to toxic dispersions is addressed; i.e., there is no potential for domino effect triggered by toxic clouds. When addressing human vulnerability due to toxic dispersions, the damage criteria is based on: (1) probit analysis and (2) exposure thresholds limits or doses. If it is desired to evaluate flammable dispersions, the vulnerability is based only on exposure thresholds as illustrated in the fires damage criteria. Similarly, to explosions and fires, a dedicated reference is developed to specifically address facility siting for toxic dispersions: **[7]** Facility Siting Addressing Hazardous Vapor Cloud Dispersions Impacting Process Plant Permanent and Portable Buildings, Combining Exceedance Curves and Human Vulnerability Criteria

As a summary, the present manuscript collects several criteria, well-known thresholds and knowledge developed for the three hazards to be evaluated in a risk-based approach assessment or Quantitative Risk Assessment (QRA) study and addressing human vulnerability: overpressure, thermal radiation and toxicity. Furthermore, for both explosions and fires, domino effect and escalation phenomena are addressed.

References

[1] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach - Facility Siting Addressing Explosions Impacting Process Plant Permanent and Portable Buildings, Combining Exceedance Curves, Structural Response and Human Vulnerability Criteria". An ioMosaic White Paper, ioMosaic Corporation.

[2] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach - Domino Effect and Escalation Triggered by Explosions. Combining Exceedance Curves and Overpressure Threshold Criteria". An ioMosaic White Paper, ioMosaic Corporation.

[3] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach - Domino Effect and Escalation Triggered by Explosions – Combining Exceedance Curves, Single Degree of Freedom and Pressure-Impulse Diagrams". An ioMosaic White Paper, ioMosaic Corporation.

[4] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach - Facility Siting Addressing Fires Impacting Process Plant Permanent and Portable Buildings. Combining Exceedance Curves and Human Vulnerability Criteria". An ioMosaic White Paper, ioMosaic Corporation.

[5] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach – Domino Effect and Escalation Triggered by Fires – Combining Exceedance Curves and Time to Failure Simplified Methodologies." An ioMosaic White Paper, ioMosaic Corporation.

[6] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach - Domino Effect and Escalation Triggered by Fires. Combining Dynamic Thermal Stress Analysis and Wall Segmentation Approach". An ioMosaic White Paper, ioMosaic Corporation.

[7] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach – Facility Siting Addressing Hazardous Vapor Cloud Dispersions Impacting Process Plant Permanent and Portable Buildings. Combining Exceedance Curves and Human Vulnerability Criteria". An ioMosaic White Paper, ioMosaic Corporation.

[8] OGP, 2010. "Risk Assessment Data Directory – Vulnerability of Humans". International Association of Oil and Gas Producers.

[9] UK HSE. "Methods of Approximation and Determination of Human Vulnerability for Offshore Major Accident Hazard Assessment"

[10] NORSOK Z-013, 2001. "Risk and Emergency Preparedness Analysis". NORSOK Standard.

[11] NATO Field Manual, 1993. “Health Service Support in a Nuclear, Biological and Chemical Environment”. Department of The Army, Fm 8-10-7 Headquarters, Department of The Army, Washington.

[12] OCB/Technica, 1988: “Comparative Safety Evaluation of Arrangements for Accommodating Personnel Offshore”. Department of Energy.

[13] Spouge, J. 1999. “Guide to Quantitative Risk Assessment for Offshore Installations”. Centre For Marine and Petroleum Technology; Publication 99/100, London.

[14] Tretsiakova-McNally, S., Makarov, D. “Harm Criteria for People and Environment, Damage Criteria for Structures and Equipment” Ulster University

[15] Baker W.E., Cox P.A., Westine P.S., Kulesz J.J., Strehlow R.A., 1983. “Explosion Hazards and Evaluation”. Elsevier, New York, USA.

[16] AIChE/CCPS, 1996. “Guidelines for Evaluating Process Plant Buildings for External Explosions and Fires”. Center for Chemical Process Safety of the American Institute of Chemical Engineers. New York, New York.

[17] Mannan, S., 2005. “Lees’ Loss Prevention in the Process Industries”, 3rd Edition vol. 1. Elsevier Butterworth-Heinemann.

[18] Lees, F.P., 1996. “Loss Prevention in the Process Industry”.

[19] Scilly, N.F., High, W.G., 1986. “The Blast Effects of Explosions”. Proceedings of the 5th Internationals Symposium on Loss Prevention and Safety Promotion in the Process Industries. 39-1-39-15.

[20] Saffers, J.B., 2010. “Principles of Hydrogen Safety Engineering”. Ph.D. Thesis. University of Ulster.

[21] Stephens, M.M., 1970. “Minimizing Damages to Refineries from Nuclear Attack, Natural and Other Disasters”. Office of Oil and Gas. Department of Interior.

[22] Mercx, W.P.M., Weerheijm, J., Verhagen, T.L.A., 1991. “Some Considerations on the Damage Criteria and Safety Distances for Industrial Explosions”. 11th Symposium on New Directions in Process Safety Hazards, 124, pp. 255-275.

[23] HSC, 1991. “Report on the Major Hazard Aspects of the Transport of Dangerous Substances”. HMSO.

[24] Opschoor, G., van loo, R.O.M., Pasman, H. J., 1992. “Methods for Calculation of Damage Resulting from Physical Effects of the Accidental Release of Dangerous Materials”. An International Conference on Hazard Identification and Risk Analysis, Human Factors and Human Reliability in Process Safety, pages 21–32. Center for Chemical Process Safety, AIChE.

[25] Roos, A. J., 1992. “Methods for the Determination of Possible Damage”. Technical Report CPR 16E, TNO.

[26] VROM, 2005. “Guidelines for Quantitative Risk Assessment”. Publication Series on Dangerous Substances (PGS3), (CPR-18E).

[27] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. “Risk-Based Approach - Explosions and Blast Loading. Introduction to Explosions and Structural Blast Loading Phenomena”. An ioMosaic White Paper, ioMosaic Corporation.

[28] Amorós, M., Dunjó, J., Prophet, N., Gorski, G., 2016. “Risk Based Approach - Quantitative Risk Assessment. Foundation of Process Safety and Loss Prevention”. An ioMosaic White Paper, ioMosaic Corporation.

[29] Amorós, M., Dunjó, J., Prophet, N., Gorski, G., 2016. “Risk Based Approach – Risk Reduction. Tools for Characterization”. An ioMosaic White Paper, ioMosaic Corporation.

[30] UKOOA, 2003. “Fire and Explosion Guidance, Part I: Avoidance and Mitigation of Explosions”. UK Offshore Operators Association Limited, London, UK.

[31] Schneider, P., 1998. “Predicting Damage of Slender Cylindrical Steel Shells Under Pressure Wave Load”. Journal of Loss Prevention in the Process Industries, 11:223-228.

[32] Whitney, M.G., Barker, D.D., Spivey, K.H., 1992. “Ultimate Capacity of Blast Loaded Structures Common to Chemical Plants”. Plant/Operations Progress, 11:205-212.

[33] Cozzani, V., Gubinelli, G., Salzano, E., 2006. “Escalation Thresholds in the Assessment of Domino Accidental Events”. Journal of Hazardous Materials, 129: 1-21.

[34] Cozzani, V., Salzano, E., 2004. “The Quantitative Assessment of Domino Effects Caused by Overpressure Part I Probit Models”. Journal of Hazardous Materials, A107: 67–80.

[35] Reniers, G., Cozzani, V., 2013. “Domino Effects in the Process Industries: Modeling, Prevention and Managing”. Elsevier, Amsterdam.

[36] Mingguang, Z., Juncheng, J., 2008. “An Improved Probit Method for Assessment of Domino Effect to Chemical Process Equipment Caused by Overpressure”. Journal of Hazardous Materials, 158: 280-286.

[37] Cozzani, V., Salzano, E., 2004. “Threshold Values for Domino Effects Caused by Blast Wave Interaction with Process Equipment”. Journal of Loss Prevention in the Process Industries 17: 437-447.

[38] Nelson, R. W., 1977. “Know Your Insurer’s Expectations". Hydrocarbon Processing, August, 103.

[39] Eisenberg, N. A., Lynch, C. J., Breeding, R. J., 1975. “Vulnerability Model: a Simulation System for Assessing Damage Resulting from Marine Spills”. Rep. CG-D-136-75. Rockville, MD: Enviro Control Inc.

[40] Henrych, J., 1979. “The Dynamics of Explosion and Its Use”. Developments in Civil Engineering, Vol. 27. Elsevier Scientific Publishing Company, Amsterdam.

[41] Mecklenburgh, J. C., 1985. “Process Plant Layout”. George Goodwin, London.

[42] Bottelberghs, P. H., Ale, B. J. M., 1996. “European Seminar on Domino Effects”. Leuven (B).

[43] Kletz, T. A., 1980. “Plant Layout and Location: Method for Taking Hazardous Occurrences into Account”. Loss Prevention, 13, 147.

[44] Barton, R. F., 1995. “Fuel Gas Explosion Guidelines - Practical Application”. IChemE Symposium Series no.139 pp. 285–286. IChemE, Rugby, UK.

[45] Gugan, K., 1979. “Unconfined Vapor Cloud Explosions”. The Institutions of Chemical Engineers, Rugby, UK.

[46] Clancey, V. J., 1972. “Sixth International Meeting of Forensic Sciences”. Edinburgh, UK.

[47] Brasie, W. C., Simpson, D. W., 1968. Loss Prevention, Vol. 2. (pp. 91).

[48] Pickering, E. E. and Bockholt, J. L., 1971. “Probabilistic Air Blast Criteria for Urban Structures”. Report, Stanford Research Institute, Menlo Park, CA.

[49] Wells, G. L., 1980. “Safety in Process Plant Design”. Chichester, Wiley.

[50] HSE, 1981. “Canvey: A Second Report”. A Review of Potential Hazards from Operations in the Canvey Island/Thurrock Area three years after publication of the Canvey Report, HMSO.

[51] Schneider, P., 1997. Journal of Loss Prevention in the Process Industries, 10, 185.

[52] O’Sullivan, S., Jagger, S., 2004. “Human Vulnerability to Thermal Radiation Offshore”. Health and Safety Laboratory, Harpur Hill, Buxton, Derbyshire, SK17 9JN.

[53] API Standard 521, 2014. "Pressure-Relieving and Depressuring Systems". Sixth Edition. American Petroleum Institute.

[54] Stoll, A.M., Green, L.C., 1958. "The Production of Burns by Thermal Radiation of Medium Intensity". Paper Number 58-A219, American Society of Mechanical Engineers, New York.

[55] Buettner, J.K.J., 1957. "Heat Transfer and Safe Exposure Time for Man in Extreme Thermal Environment". Paper Number 57SA- 20, American Society of Mechanical Engineers, New York.

[56] Rew, P. J., 1996. *"LD50 Equivalent for the Effect of Thermal Radiation on Humans"*. Health and Safety Executive Contract Research Report.

[57] Tsao, C.K., Perry, W.W., 1979. "Modifications to the Vulnerability Model: A Simulation System for Assessing Damage Resulting from Marine Spills". (VM4) ADA 075 231, US Coast Guard NTIS Report No. CG-D-38-79.

[58] FEMA, 1989. "Handbook of Chemical Hazard Analysis Procedures". Federal Emergency Management Agency, US Department of Transportation, US Environmental Protection Agency.

[59] Buettner, K, 1981. "Effects of Extreme Heat and Cold on Human Skin, II Surface Temperature, Pain and Heat Conductivity in Experiments with Radiant Heat." J. Ap Phys., Vol. 3, p. 703.

[60] Melhem, G. A., 2015. "Advanced Consequence Analysis, Fluid Flow, Emergency Relief Systems Design, Thermal Hazards Assessment, Emission, Dispersion, Fire and Explosion Dynamics". ioMosaic Corporation.

[61] Landucci, G., Cozzani, V., 2009. "Simplified Assessment of Protective Measures to Prevent Fire Escalation Involving Pressurized Vessels". Sogaard, I., Krogh, H. (Eds.)., Fire Safety. Nova Science Publishers Inc, Hauppauge, NY, pp. 65-83.

[62] Landucci, G., Gubinelli, G., Antonioni, G., Cozzani, V., 2009. "The Assessment of the Damage Probability of Storage Tanks in Domino Events Triggered by Fire". Accident Analysis and Prevention 41 (6), 1206-1215.

[63] Cozzani, V., Gubinelli, G., Antonioni, G., Spadoni, G., Zanelli, S., 2005. "The Assessment of Risk Caused by Domino Effect in Quantitative Area Risk Analysis". Journal of Hazardous Material A127, 14-30.

[64] Cozzani, V., Gubinelli, G., Salzano, E., 2006. "Criteria for The Escalation of Fires and Explosions". Proceedings of the 7th Process Plant Safety Symposium. American Institute of Chemical Engineers, New York, New York, p. 225.

[65] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach – Fires. Introduction to Fires and Dynamic Thermal Stress Analysis". An ioMosaic White Paper, ioMosaic Corporation.

[66] Dunjó, J., Amorós, M., Prophet, N., Gorski, G., 2016. "Risk-Based Approach – Consequence Analysis. An Introduction to Consequence Modeling and Determination of Outcomes from Loss of Containment Scenarios". An ioMosaic White Paper, ioMosaic Corporation.

[67] Finney J.D., 1977. "Probit Analysis". London: Cambridge Univ. Press

[68] Safety Environmental Risk Database (SERIDA), 2009. Version 1.3.

[69] AIHA, 2016. "Emergency Response Planning Guidelines and Workplace Environmental Exposure Levels". American Industrial Hygiene Association, Fairfax, VA. www.aiha.org

[70] Compiled AEGL Values, March 10, 2016. https://www.epa.gov/sites/production/files/2016-03/documents/compiled_aegl_update_.pdf

[71] NIOSH, 2005. "NIOSH Pocket Guide to Chemical Hazards". US Department of Health and Human Services (DHHS), Washington, DC. (NIOSH) Publication No. 2005-149.

[72] National Research Council Committee on Toxicology, 2007. "Free Executive Summary. Emergency and Continuous Exposure Guidance Levels for Selected Submarine Contaminants". ISBN: 879-0-309-09225-8. https://www.cdc.gov/niosh/docket/archive/pdfs/NIOSH-125/125-NationalAcademyofSciences2007.pdf

[73] United States Department of Labor, Occupational Safety and Health Administration (OSHA). https://www.osha.gov/dsg/annotated-pels/

[74] State of New Jersey, Department of Environmental Protection. http://www.nj.gov/dep/

[75] United States Environmental Protection Agency, 2009. "Risk Management Program Guidance for Offsite Consequence Analysis". EPA 550-B-00-009. https://www.epa.gov/sites/production/files/2013-11/documents/oca-chps.pdf