Risk-Based Approach – Facility Siting Addressing Hazardous Dispersions Impacting Process Plant Permanent and Portable Buildings

Combining Exceedance Curves, Structural and Human Vulnerability Criteria

An ioMosaic White Paper

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Abstract

A detailed risk-based approach is proposed for addressing flammable and toxic dispersions impacting occupied buildings. The approach is based on the results from a complete quantitative risk-based assessment, which provides the following information per each outcome impacting the target location under analysis: (1) individual frequency of occurrence; (2) outdoor concentration; (3) exposure time; and (4) indoor concentrations by considering building air infiltration. Exceedance curves per hazard type (flammability or toxicity) and per chemical can be generated, which allow the user to decide whether a target building should be introduced in the mitigation plan as per API Recommended Practice 752 and API Recommended Practice 753, or if the target location can be within the acceptable risk region. Additionally, the proposed approach allows the construction of dedicated FN curves per location being impacted by toxic dispersions. The results from the proposed approach allow decision-makers to decide if there is the need to install the most cost-effective risk reduction measures based on the identified target locations to be in an unacceptable risk region.

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Introduction

This manuscript focuses on the impact of Loss of Containment scenarios (LOCs) of hazardous materials that could lead to flammable and toxic dispersions to portable and fixed buildings. The 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, etc.) **[1]**. These models are important because they provide input data to the dispersion models and the accuracy from these models is dependent upon the accuracy in the source term computation. Detailed information on the mathematical source term and dispersion models can be found in reference **[2]**.

During the development of the quantitative risk-based assessment, it is critical to properly locate all structures/buildings present in a process facility **[3]**. Accordingly, all identified LOCs **[4]** are analyzed and modeled following criteria established in references **[5]**, **[6]**, **[7]**, **[8]** and **[9]**. Note that these cited references provide the knowledge for quantitative risk-based assessment development, which is the basis of the proposed approach **[9]**. In this manuscript, a risk-based approach is focused on identifying which occupied buildings in a process facility could be impacted by hazardous dispersions due to toxic and flammable releases is defined and characterized.

Furthermore, the building occupant vulnerability is determined based on damage criteria illustrated in the manuscript. Finally, when no potential hazardous dispersion outcomes which could adversely affect the target building are identified, it is justified that no further analysis is required; i.e., the building is located within an acceptable risk region.

Based on API Recommended Practice (RP) 752 **[10]** and API Recommended Practice (RP) 753 **[11]**, a risk-based facility siting assessment may be expressed as numerical values of individual risk, aggregate risk, or exceedance values. They can also be expressed as graphical formats which include cumulative frequency versus consequence curves, or matrices with numerical axes.

The proposed risk-based approach combines exceedance curves **[3]** with worldwide recognized flammable and toxic thresholds **[6]** with the aim to identify which buildings are affected at a cumulative frequency of interest by high concentration/dose thresholds, to propose mitigation measures intended to reduce the actual risk to a tolerable if ALARP or tolerable risk regions. The ALARP concept is defined in reference **[1]**.

Note that another approach to identify areas impacted by high values of flammable or toxic concentration/dose at a cumulative frequency of interest would be the development of flammable and toxic risk contours evaluated at different concentrations or dose thresholds. While this is considered as the first step to identify affected areas, it is important to understand that the risk contours are not dedicated to specific locations **[1]**.

The proposed approach consists of the development of dedicated FN curves **[3]** (i.e., exceedance curves which correlate the expected number of fatalities of building occupants with cumulative frequencies). Consequently, the proposed approach is capable of technically identifying if a building requires to be included in the mitigation plan (i.e., according to API RP 752 **[10]** and API RP 753 **[11]**) and provides the basis for conducting effective and economic sensitivity analysis for ensuring that most suitable risk reduction measures are considered during the decision-making process.

Exceedance Curves Development

A risk-based quantitative assessment development allows acquiring knowledge on all the dispersion outcomes which impact a given location of interest; e.g., occupied building. A valid tool for managing and interpreting all this information is the exceedance curve. The exceedance curve approach was developed following the issue of the 2003 version of the Chemical Industries Association (CIA) guidance **[12]** and is widely used for characterizing facilities. Exceedance curves can be used as a probabilistic description of the potential for a target location to experience various levels of effects; i.e., concentrations or dose from dispersions.

An exceedance curve correlates the cumulative frequency of occurrence with any given parameter being exceeded; e.g., heat flow received by fires, overpressure received by explosions and concentration/dose received by flammable or toxic dispersions. When addressing flammable or toxic dispersions, the exceedance curves may be called Flammable Concentration Exceedance Curves (FCECs) or Toxic Concentration Exceedance Curves (TCECs). The construction of a FCEC/TCEC is based on identifying all hazardous dispersions that impact a given location under analysis and sorts the values of each concentration/dose in descending order. Inherently, the consequence modeling of atmospheric dispersion outcomes must be conducted specifying different concentration or dose thresholds of interest; i.e., as more thresholds are evaluated, more accurate the exceedance curve will be. The steps required to construct an exceedance curve are explained in **[3]**. FCECs or TCECs can be applied for identifying and selecting which buildings require a more detailed analysis or which should be included in the mitigation plan if these do not meet specific criteria; i.e., according to API RP 752 **[10]** and API RP 753 **[11]**.

Based on criteria used for facility siting, if the exceedance concentration/dose level is lower than the minimum exceedance threshold value evaluated, it can be concluded that the building is in a tolerable risk region. Otherwise, the building is identified to be impacted by concentrations / doses at a cumulative frequency greater than the tolerability criteria and thus, further analysis needs to be performed; i.e., implementation of mitigation measures to reduce the risk to a tolerable limit.

Table 01 lists the key results obtained from a risk-based quantitative assessment: (1) cumulative frequency of occurrence at a given exceedance hazardous concentration selected value, (2) exceedance hazardous concentration value and (3) total number of hazardous dispersion outcomes that impact the location under analysis at the evaluated exceedance concentration value. Note that as discussed above, the more concentration thresholds are defined in the damage criteria for consequence modeling, the more detailed information will available for facility siting analysis.

Table 01: Hazardous Dispersions Impacting a Given Building Location

Concentration [ppm]	Cumulative Frequency [yr-1]	Number of Outcomes [-]
5.00	1.10E-04	125
10.0	7.15E-05	121
25.0	2.06E-05	114
50.0	1.73E-05	109
75.0	1.60E-05	89
100	1.46E-05	75
125	1.41E-05	51
150	9.03E-06	34
175	7.98E-06	28
200	5.89E-06	21
225	5.45E-06	16
250	5.05E-06	11

From **Table 01** it can be observed that 125 hazardous dispersion outcomes are identified to impact the building under analysis. While this value can seem to be huge, it can be a reasonable value based on accounting for all LOCs that could generate a potential hazardous dispersion when a facility handling hazardous materials is analyzed. From these 125 hazardous dispersions, 11 of them impact the target location at an exceedance concentration of 250 ppm (i.e., 250 ppm or more), 16 hazardous dispersions (the 11 hazardous dispersions that impact the building at 250 ppm or more plus 5 hazardous dispersions that impact at an exceedance concentration of 225 ppm) and so on.

Note that knowledge on the individual frequency of occurrence of each outcome is available from the quantitative risk-based assessment results and this information is extremely valued and used for later usage. Therefore, accurately estimating the likelihood of occurrence of all LOCs is a very important step to predict which buildings are impacted by hazardous dispersions at a cumulative frequency of interest. Detailed information on how to estimate the frequency of occurrence of a LOC can be found in **[5]**.

Based on the results listed in **Table 01**, the construction of an exceedance curve allows identifying whether a building is impacted or not with a hazardous concentration at a cumulative frequency of interest. Based on these results, accurate corrective actions can be established during the decision-making process.

Toxic and Flammable Damage Criteria for Occupied Buildings

Sophisticated models and correlations have been developed for dispersion modeling; e.g., SuperChems™ **[13]**, providing valuable tools for characterizing the source of the release of material or energy associated with the hazard being analyzed, estimating the transport of the material and/or the propagation of the energy in the environment to a target of interest, identifying the effects of the propagation of the energy or material and quantifying the health, safety, environmental, or economic impacts on the target of interest.

Dispersion modeling is conducted with the aim to quantify the effects and consequences of identified LOCs and it entails the characterization of the sources of release of material or energy associated with the hazard being analyzed and the quantification of the impacts on a target of interest. Dispersion modeling results are drastically influenced by source term characterization; i.e., the source strength, duration and phase must be determined accurately. These parameters are a function of storage conditions and the thermo-physical properties of the chemical(s) in question and can be determined from fluid flow equations: Pressurized/non-pressurized liquid discharge, Gas discharge, Two-phase flow, Flash atomization and Liquid rain-out. The accuracy from the dispersion models is dependent upon accuracy in the source term computation. SuperChems™ **[13]** includes the most up-to-date source term models for accurate and advanced calculations for pressure relief systems, flares and consequence analysis, including dispersion modeling.

Dispersion modeling is mainly intended to predict the expected number of injuries or casualties or, in some cases, exposure to certain levels of energy or concentrations of substances within areas or zones of interest, or even more specific target locations; e.g., occupied buildings. Accordingly, concentration endpoints or thresholds (flammable and toxic damage criteria) are considered with the aim to define the extent of the hazard.

When facility siting is the main purpose of a quantitative risk-based assessment development, hazard endpoints based on a well-known human impact are of interest.

The analysis of building human vulnerability must be based on recognized damage criteria. Several toxic damage thresholds and probit analysis are available for the evaluation of human vulnerability as a function of concentration and exposure time (i.e., toxic dose). Detailed information of flammable and toxic damage criteria can be found in reference **[6]**. However, it has been decided to introduce the basics of damage criteria in the following two sections, with the aim to highlight which are key parameters needed to cover the tasks to be completed during the proposed facility siting risk-based approach.

Damage Criteria Based on Thresholds

Toxic Damage Criteria

One of the most recognized toxic damage criteria are the Emergency Response Planning Guidelines (ERPGs), which are values developed by the American Industrial Hygiene Association (AIHA) Guideline Foundation's Emergency Response Planning (ERP). The ERPGs are primary focused on providing guideline levels for once-in-a-lifetime, short-term (typically 1-hour) exposures to airborne concentrations of acutely toxic, high-priority chemicals **[14]** and three different levels are developed as listed in **Table 02**.

Table 02: ERPG Levels

Level	Definition
ERPG-1	Maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 hour without experiencing more than mild, transient adverse health effects or without perceiving a clearly defined objectionable odor.
ERPG-2	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 an individual's ability to take protective action.
ERPG-3	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.

It is recognized for example to use the ERPG-3 level as a toxic damage criterion for facility siting purposes. Note that toxic damage criteria based on ERPGs is a given example (worldwide recognized) for illustrating how toxic damage criteria based on concentration thresholds is valuable for quantitative risk-based assessments, including facility siting purposes. Other criteria exist and is also valid depending on the specific purpose of the assessment to be performed. Examples are the AEGLs (Acute Exposure Guidelines Levels), IDLH (Immediately Dangerous to Life and Health). Therefore, based on the results of a robust quantitative risk-based assessment development and by constructing dedicated exceedance curves per each target building under analysis, it is possible to identify if a given location is being impacted by a concentration higher than the selected damage criteria (e.g., ERPG-3) and if that actual concentration is expected to occur at a higher or lower frequency of occurrence than the selected tolerable risk level.

For example, the ERPG-3 values extracted from AIHA **[14]** of selected chemicals are listed in **Table 03**.

Table 03: Example of ERPG-3 Values for Selected Chemicals

Toxic Chemical	ERPG-3 [ppm]
Ethyl Acrylate	300
Hydrogen Chloride	150
Hydrogen Sulfide	100

Flammable Damage Criteria

Damage criteria due to flammable dispersions normally considers the intrinsic flammable properties of the chemicals in the cloud. The Lower Flammability Level (LFL), or more restrictive concentrations; e.g., ½ LFL are normally used.

Damage Criteria Based on Probit Analysis

Toxic Damage Criteria

The probit analysis is also used for toxic damage criteria purposes, which is an approach capable of including the effects from transient changes in toxic concentrations. The use of probits or vulnerability models are suitable to be used in quantitative risk-based assessment results because when coupled with probits, consequence models can associate a probability of fatality or probability of a certain level of injury.

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:

$$Y = A + B \ln D$$ **Equation 01**

$\boldsymbol{Y}$: probit unit; 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. For example:

- 1% fatality corresponds to a probit value $\boldsymbol{Y}$ equivalent to 2.67
- 99.9% fatality corresponds to a probit value $\boldsymbol{Y}$ equivalent to 8.09

$\boldsymbol{D}$**:** hazard dose of an airborne toxic gas. It 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 $\boldsymbol{t}$.

$D = C^n t$ **Equation 02**

$\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{n}$: constants which depend on the toxic chemical

$\boldsymbol{t}$: exposure time

For example, the probit constants extracted from SERIDA **[15]** of selected chemicals are listed in **Table 04**.

Table 04: Example of Probit Constant for Selected Chemicals

Toxic Chemical	A [-]	B [mg·m^{-3}]	N [min]
Ethyl Acrylate	-18.68	1	2
Hydrogen Chloride	-37.3	3.69	1
Hydrogen Sulfide	-11.5	1	1.9

Flammable Damage Criteria

For flammable dispersions, the probit analysis is not normally necessary to be applied as the probability of fatality is a function of the flash fire envelope, which is equal to the LFL contour at the time of ignition:

- if population is located within the flash fire envelope, the probability of fatality is assumed to be 100%
- if population is located beyond the flash fire envelope, the probability of fatality is assumed to be 0%

The Importance of Building Air Infiltration

Once the damage criteria are selected, the dispersion modeling can be performed with the aim to evaluate the impacting hazard at a target location. It is important to mention that dispersion models normally used during the development of a quantitative risk-based assessment account for atmospheric conditions and other cited parameters capable of predicting concentration profiles outdoors; i.e., outdoor concentration reaching the target location before being infiltrated into the building. Therefore, when conducting detailed facility siting analyses with the aim to characterize the risk of occupants located in a building, building infiltration characteristics (i.e., exchange of air outside a building with the air inside the building) must be addressed and the outdoor concentration should be corrected with the aim to estimate an accurate indoor concentration. This procedure cancels over prediction and non-credible conservative results. As a result, a model intended to calculate concentration variations of airborne toxic and flammable materials within indoor compartment(s) (i.e., buildings) and the surrounding is needed.

The concept of building infiltration can be defined as the air change rate associated with a specific building, the outdoor concentration reaching the building and the exposure duration. The air change rate is defined as the ratio of the air-contaminant flow through the building (hazardous cloud reaching the building with the predicted outdoor concentration) and the total volume of the room/building. Normally, the air change rate can be characterized as a function of the building properties and characteristics (see **Table 05**).

Table 05: Typical Natural Ventilation Rates in Residences

Room or Building Type	Air Changes per hour	
	Non-Insulated Space	Insulated Space
Rooms without windows or exterior doors	0.5	0.33
Rooms with windows or exterior doors on one side	1.0	0.67
Rooms with windows or exterior doors on two sides	1.5	1.0
Rooms with windows or exterior doors on three sides	2.0	1.33
Entrance halls	2.0	-

The values listed in **Table 03** are extracted from references **[13]** and **[16]**.

Air change rates were derived from air leakage measurements of residential houses in the US **[17]**. Reported values varied from 0.07 air changes per hour for a tight house under mild weather conditions to over 1.5 air changes per hour under severe weather conditions. **Table 04** reproduces the air infiltration rate of US residential houses estimated using LBL model **[18]** under different weather conditions.

Table 06: Derived Air Change Rates of US Residential Houses

Weather Condition	Air Change Rate [h^{-1}]		
	Tight House	Typical House	Leaky House
Mild	0.07	0.1	0.4
Moderate	0.2	0.3	1.0
Severe	0.3	0.5	1.6

SuperChems™ **[13]** includes a dedicated "Indoor Dispersion Model" intended to handle multiple compartments and capable of processing inlet streams as well as gas releases from other source-term models. All mass and energy balance-including those contributed from natural ventilation are accounted for. The differential pressure that exists between the outside of a compartment and the inside stagnation pressure, often referred to as air infiltration, is also considered. Note that the model has a few limitations:

- Effect of interior partitions on the infiltration process is not considered
- Details of mixing uses an empirical efficiency factor and buoyancy effects are neglected
- No chemical reactions considered between the contaminant and air or volume walls
- Contaminant is not removed from air due to settling or precipitation

With the aim to provide with a simplified and illustrative mathematical derivation on how to convert the outdoor concentration reaching the building under analysis with the pursued indoor concentration being infiltrated, the ideal mixing assumption is included in the list of assumptions that have been stated above.

The change of indoor concentration with time is described by using **Equation 03**, which expresses the mass balance of the change of indoor concentration with time:

$$V dC_{in} = \dot{V}_{in} C_{out} dt - \dot{V}_{out} C_{in} dt$$ **Equation 03**

where:

- $\boldsymbol{V}$: Volume of the compartment (e.g., room, building); [m^3]
- $\dot{\boldsymbol{V}}_{\boldsymbol{in}}$: Volumetric flow rate into or out of the building ($\dot{V}_{in} = \dot{V}_{out}$); [$m^3 \cdot h^{-1}$]

- C_{out}: Hazardous concentration outdoor [ppm]
- C_{in}: Hazardous concentration indoor [ppm]

If there is no hazardous material inside the building before the toxic or flammable cloud reaches the building, **Equation 03** can be analytically integrated by providing the indoor concentration as a function of exposure time (see **Equation 04**):

$$C_{in} = C_{out} - \left[C_{out} e^{-N\Delta t}\right] \qquad \textbf{Equation 04}$$

where

- N is the air changes per hour of the building [h^{-1}]

Knowledge of the outdoor concentration reaching the target building under analysis, the exposure time and the number of air changes per hour of the building, allows the user to estimate the indoor concentration history (i.e., indoor concentration at different exposure time durations) by using **Equation 04**.

Figure 01 illustrates the expected indoor concentration as a function of exposure time for different air change rates, from 0.1 to 2 air changes per hour. This margin of air change rates has been selected with the aim to cover the lowest and highest credible values as listed in **Table 05** and **Table 06**.

Note that the outdoor concentration reaching the target building has been considered constant over the time simulated and it has been assumed to be equal to 100 ppm for illustrative purposes. No pollutant has been initially considered inside the building; i.e., initial indoor concentration is zero.

Based on the results illustrated in **Figure 01**, the following can be observed:

- When considering the “worst case” scenario (i.e., the highest number of air changes per hour: 2.0), it is required a minimum exposure time of 2.5 hours for reaching the maximum outdoor concentration inside the building
- When considering the “best case” scenario (i.e., the lowest number of air changes per hour: 0.1), it is required an exposure time of more than one day for reaching the outdoor concentration inside the building

It is required a long exposure time duration to equalize outdoor and indoor concentrations.

Figure 02 provides a zoomed view of the results illustrated in **Figure 01**, considering a maximum exposure time of 2 hours (considered to be a long exposure time), which allows to extract more detailed conclusions. Note that the exposure time can be defined as the time that would take the cloud to reach and go throughout the building. Thus, based on the hazardous scenarios normally considered during a quantitative risk-based assessment development, e.g., LOCs from catastrophic vessel failures and small leaks and accounting for the maximum release times that normally are considered as credible (e.g., maximum release times about 30 min or 45 min), the consideration of an exposure time of 1 hour may still be conservative.

For illustrative purposes, even considering 1 hour of exposure time, there is an important percentage reduction between the outdoor and indoor concentration. For example:

- When considering 0.1 air changes per hour (best case), the indoor concentration after 1 hour of exposure is expected to be 10% of the outdoor concentration
- When considering 1 air changes per hour (intermediate case), the indoor concentration after 1 hour of exposure is expected to be 63% of the outdoor concentration
- When considering 2 air changes per hour (worst case), the indoor concentration after 1 hour of exposure is expected to be 87% of the outdoor concentration

Figure 01 and **Figure 02** results have been illustrated with the aim to emphasize the non-credible level of conservatism that would be needed when assuming equivalent outdoor and indoor concentrations without performing infiltration analysis.

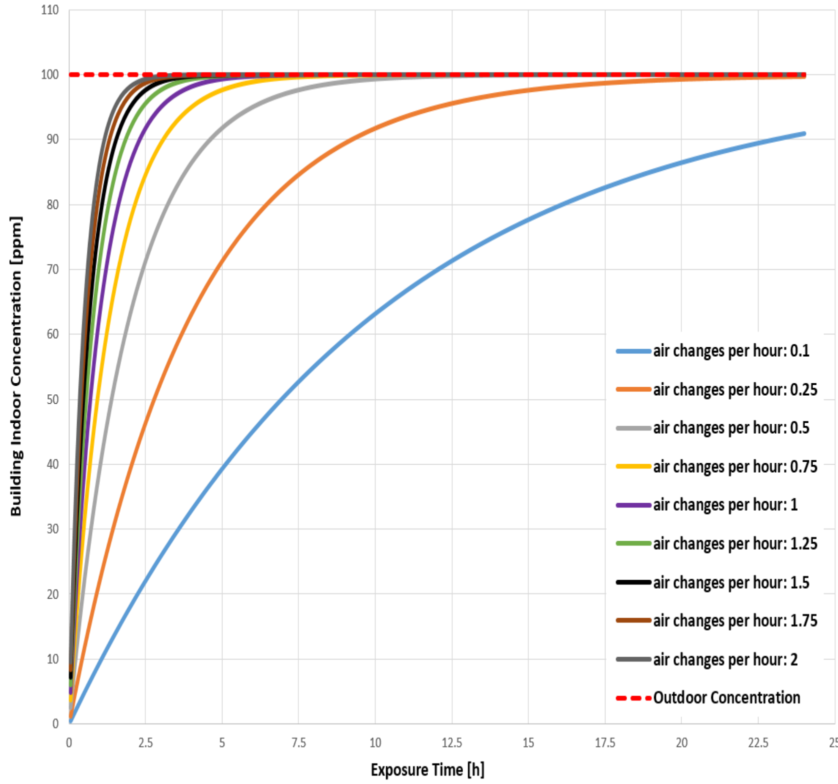

Figure 01: Building Indoor Concentration History

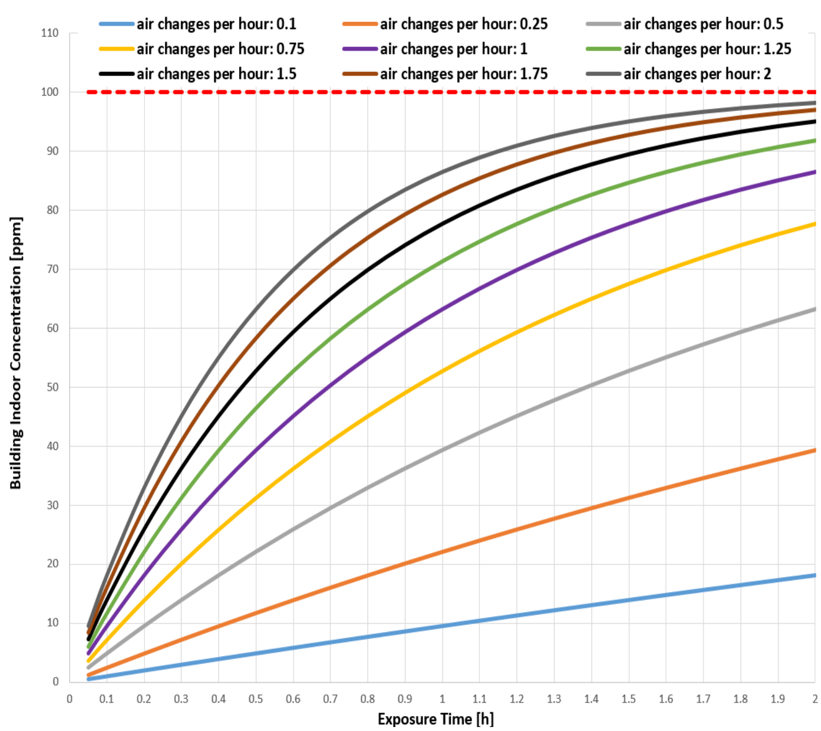

Figure 02: Building Indoor Concentration History – Zoomed

Dedicated Toxic FN Curves per Target Building

The identification of which target buildings comply with the applicable tolerable risk level is possible by using damage criteria based on thresholds. This approach also provides detailed information on which are the LOCs that more contribute to the risk level of interest and allows the user to decide which risk reduction measure should be implemented.

The scope of the proposed approach can be expanded with the aim to provide dedicated FN curves (see reference **[3]**) capable of predicting the total number of expected fatalities of building occupants due to toxicity as a function of cumulative frequency. The FN curve construction requires correlating the indoor concentration being infiltrated in the building and the associated exposure time with the probability of fatality of one individual inside the building. As a result, the probit analysis is applicable for this purpose:

- Estimation of the indoor concentration and exposure time via consequence modeling during the development of the quantitative risk-based assessment per each dispersion outcome identified at a given target location
- Calculation of the associated dose by using **Equation 02**
- Calculation of the unit probit value by using **Equation 01** given the probit constants as a function of chemical
- Estimation of probability of fatality ($\mathbf{P}_f$) by relating the unit probit value with the probit function

Therefore, the probability of fatality for a certain number of occupants ($\boldsymbol{P_N}$) can be estimated based on the probability density function of a multinomial distribution:

$$\mathrm{P}_N = \frac{X!}{N!\,(X-N)!} \cdot (\mathrm{P}_f)^N \cdot (1-\mathrm{P}_f)^{(X-N)}$$ **Equation 05**

where:

- $\boldsymbol{X}$: Number of building occupants
- $\boldsymbol{N}$: Number of fatalities
- $\mathbf{P}_f$: Probability of Fatality
- $\boldsymbol{P_N}$: Probability of fatality for N occupants

The number of building occupants, X (with the associated presence factor) and the estimated probability of fatality, P_f, are the two key parameters to be considered when developing FN curves. Note that each toxic dispersion outcome will generate $X+1$ values of probabilities as a function of number of fatalities, N.

Based on this information, a dedicated occupied building F-N curve is constructed by cumulating frequencies of all toxic dispersion outcomes that cause the same number of fatalities. This FN curve (which is also an exceedance curve) allows identifying the expected number of fatalities at a given risk tolerable level. These results complete the relevant information that can be provided to decision-making managers for most optimized risk reduction measures to be implemented when needed. **Figure 03** illustrates an example of an FN curve which highlights the expected number of fatalities at the given risk tolerable criteria is one.

Note that the dedicated FN curve development is applied to toxic dispersion outcomes and does not include flammable dispersions. It is important to recall that the probability of fatality due to flash fires is always 1 or 0, depending on whether population is located within the flammable envelop or not. Accordingly, the FN curve development is not applicable.

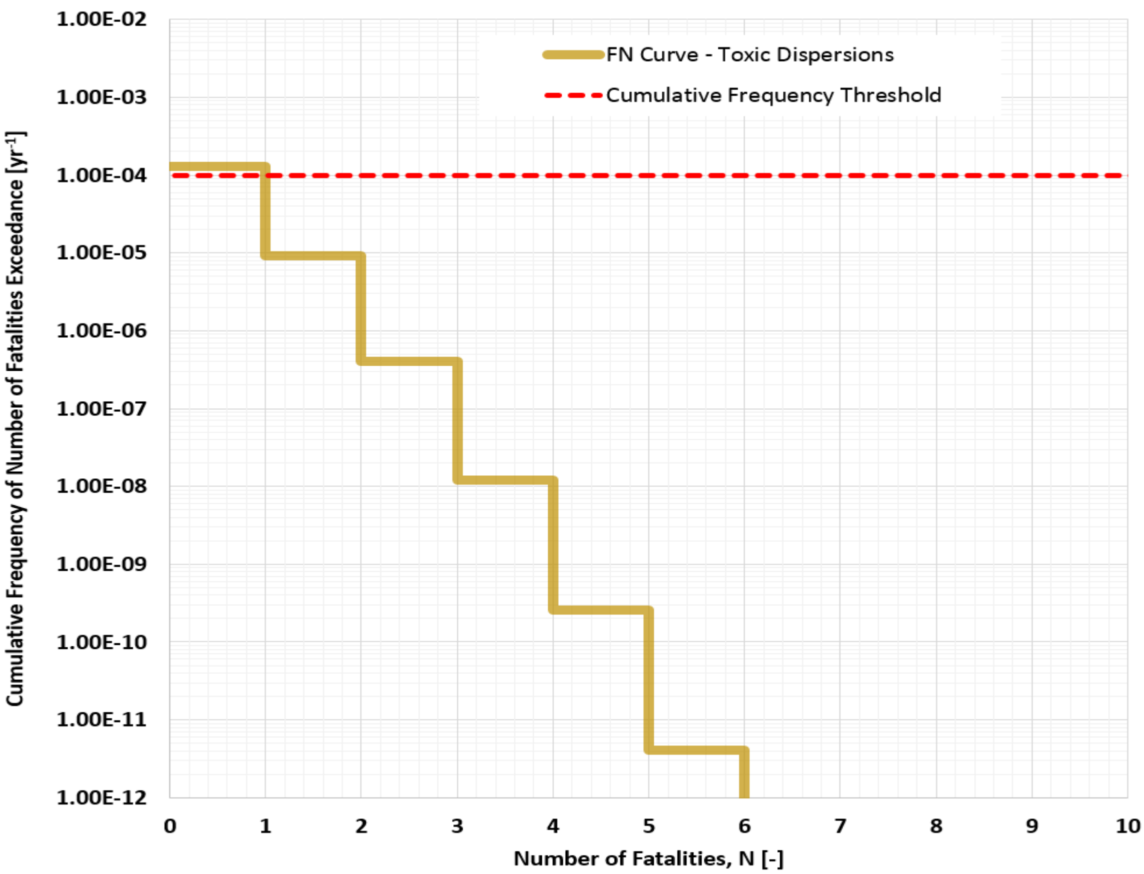

Figure 03: FN Curve Illustration Example

Facility Siting Risk-Based Approach Step-By-Step Procedure

The proposed facility siting risk-based approach requires the development of the tasks listed in **Table 07**. The following contents are intended to clarify the proposed approach:

- Tasks listed in **Table 07** complete the analysis of a unique target location. All tasks should be repeated as many times as target locations under analysis
- It is assumed that before starting the development of illustrated tasks, both risk tolerable level (e.g., 1.00E-04 yr^{-1}) and damage criteria for flammable (e.g., LFL) and toxic (e.g., ERPG-3) dispersions impacting the target location under analysis have been defined and agreed with all parties
- A robust quantitative risk-based assessment has been completed, which allows using its associated results for facility siting purposes. This information includes the location of each target building under analysis

Note that the proposed approach requires to independently analyze flammable and toxic dispersions impacting the target location. This is the reason why it is important to classify and separate the outcomes impacting the location under analysis as a function of the hazard. Once focused on analyzing flammable or toxic dispersions of interest, the approach proposes further segregate as a function of hazardous material with the aim to evaluate dedicated indoor concentration thresholds (i.e., damage criteria). For example, four (4) independent exceedance curves would be required to be constructed if results from the quantitative risk-based assessment confirm the following impacts to the target location:

- Several Flammable dispersions due to release of flammable **material F.A**
- Several Flammable dispersions due to releases of flammable **material F.B**
- Several Toxic dispersions due to releases of toxic **material T.A**
- Several toxic dispersions due to releases of toxic **material T.B**

An alternative conservative approach also could be developed, which consists of considering only one main flammable and one main toxic dispersion Exceedance curves. The conservatism is based on the collection all flammable dispersions from different flammable materials and all toxic dispersions from different toxic materials, according to the definition of the damage criteria, which should ensure the lowest flammable (e.g., LFL) and lowest toxic (e.g., ERPG-3) thresholds from all hazardous chemicals identified.

Table 07: Facility Siting Risk-Based Approach – List of Tasks

#	Task
1	Identification of all flammable and toxic dispersion outcomes impacting the target location.
2	Estimation of the indoor concentrations as a function of building characteristics (i.e., air change rate) and exposure time per each outcome identified to be impacting the target location. This task is normally performed during the consequence modeling phase of the quantitative risk-based assessment.
3	Classification of all flammable dispersion outcomes as a function of flammable material.
4	Classification of all toxic dispersion outcomes as a function of toxic material.
5	Exceedance curve development considering all flammable dispersion outcomes as a function of flammable material; i.e., FCECs.
6	Exceedance curve development considering all toxic dispersion outcomes as a function of toxic material; i.e., TCECs.
7	Dedicated FN curve considering all toxic dispersion outcomes as a function of toxic material; i.e., FN curves.
8	Identification of building occupant locations (exceedance curves analysis) that do not comply with applicable tolerable criteria.
9	If all targets of interest comply with applicable tolerable criteria, no further analysis is required; i.e., it is demonstrated that the target location is in an acceptable risk region.
10	If some cases analyzed do not comply with applicable tolerable criteria, it is necessary to include these in the mitigation plan; i.e., identification of which are the flammable and/or toxic dispersion outcomes impacting the target location with an unacceptable risk level.
11	Decision-making process by defining the most effective and economic risk-reduction measures.
12	Iterative calculation procedure by considering several proposed risk-reduction measures with the aim to verify that the risk reduction factor selected results in the target location of interest to be in an acceptable risk region.

Case Study

This case study is intended to illustrate the process on how to identify potential locations affected by flammable and/or toxic dispersions at a cumulative frequency threshold of interest and it emphasizes the importance of including the infiltration analysis. The case study assumes robust results from a quantitative risk-based assessment and it is mainly focused on addressing toxic dispersions.

All toxic dispersion outcomes impacting an occupied building under analysis were identified, filtered by toxic chemical and collected from LOCs identified in ALL process units within a process facility that could release hazardous materials or energy. Each associated individual frequency of occurrence was estimated and impact distances predicted at different selected concentration values of interest were modeled by using SuperChems™ **[13]**.

Toxic Concentration Exceedance Curves (TCECs) were developed for the three (3) toxic chemicals identified in the process facility impacting the occupied building of interest. A target frequency of occurrence of 1.00E-04 yr^{-1} was the given threshold for identifying target buildings potentially impacted by toxic dispersions based on CIA criteria **[12]**. The toxic concentration exceedance threshold was based on the ERPG-3 of each toxic chemical (see **Table 06**).

Note that **Table 08** also includes the outdoor concentration values that have been predicted at the applicable cumulative frequency threshold according to TCECs illustrated in **Figure 04**. Note that illustrated values are based on **Figure 04** exceedance curve results.

Table 08: Outdoor Concentrations at Given Tolerable Risk Level

Toxic Chemical	ERPG-3 [ppm]	Outdoor Concentration [ppm] @ 1.00E-04 yr^{-1}
Ethyl Acrylate	300	300
Hydrogen Chloride	150	200
Hydrogen Sulfide	100	150

Note that considering outdoor concentrations impacting the target building under analysis, toxic dispersions outcomes of all toxic chemicals identified are impacting the building at a risk level higher or equal than the tolerable risk level (i.e., unacceptable risk region).

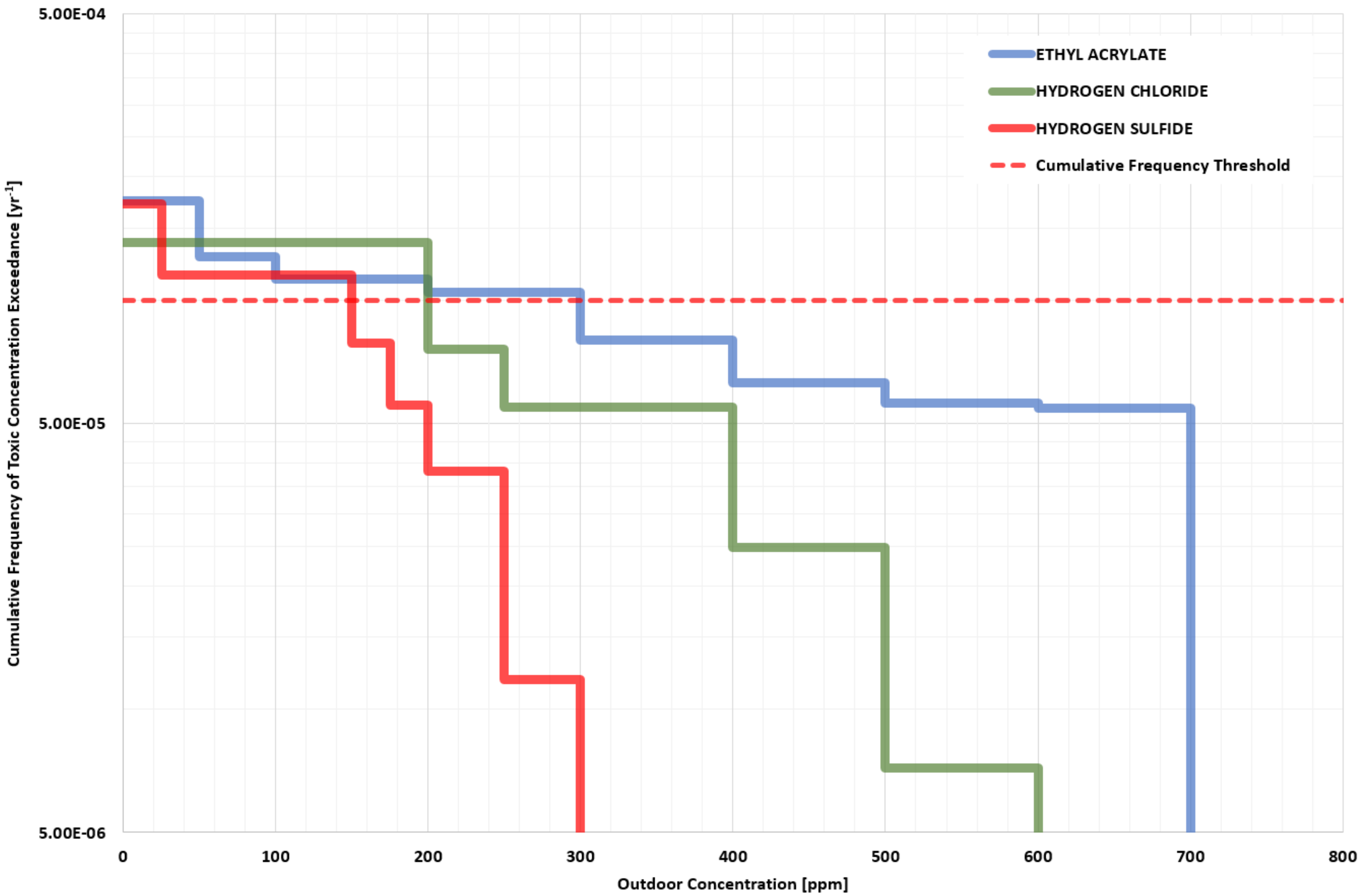

Figure 04: Toxic Concentration Exceedance Curves at a Given Location – Outdoor Concentrations

Figure 05 illustrates the TCECs by considering the air change rate of the target building (i.e., assumed to be 1.25 air changes per hour) and the associated exposure time of each toxic dispersion outcome impacting the location. **Table 09** lists the key results illustrated in **Figure 05** after predicting the pursued indoor concentrations.

Table 09: Indoor Concentrations at Given Tolerable Risk Level

Toxic Chemical	ERPG-3 [ppm]	Indoor Concentration [ppm] @ 1.00E-04 yr^{-1}
Ethyl Acrylate	300	225
Hydrogen Chloride	150	145
Hydrogen Sulfide	100	125

Based on the results illustrated in **Table 09** and **Figure 05**, it can be observed that only toxic dispersion outcomes related to hydrogen sulfide releases result an intolerable risk level as the indoor concentration predicted at 1.00E-04 yr^{-1} is greater than ERPG-3. The correction from outdoor to indoor concentrations is evidence that the toxic dispersions from ethyl acrylate and hydrogen chloride impacting the target building are in the acceptable risk level. Therefore, the decision-making process should be focused on how to address and reduce the risk associated to hydrogen sulfide releases, as the target building should be included in the mitigation plan (i.e., risk reduction measures).

Risk reduction can be achieved by implementing prevention measures (i.e., intended to reduce the frequency of occurrence of LOCs) and/or mitigation measures (i.e., intended to reduce the impacts of LOCs). API Recommended Practice 752 **[10]** lists risk reduction measures based on the decreasing reliability and are categorized by type. A sensitivity analysis performed with the aim to explore the effectiveness of potential risk reduction measures to be implemented could be performed for ensuring the target building is complying with the applicable tolerable risk criteria. For example, a possible risk reduction measure to be implemented in the building analyzed in the illustrated example would be to ensure a maximum of 0.75 air changes per hour. That would ensure a maximum indoor concentration of 75 ppm at the given cumulative frequency of occurrence, which is lower than the hydrogen sulfide ERPG-3 value.

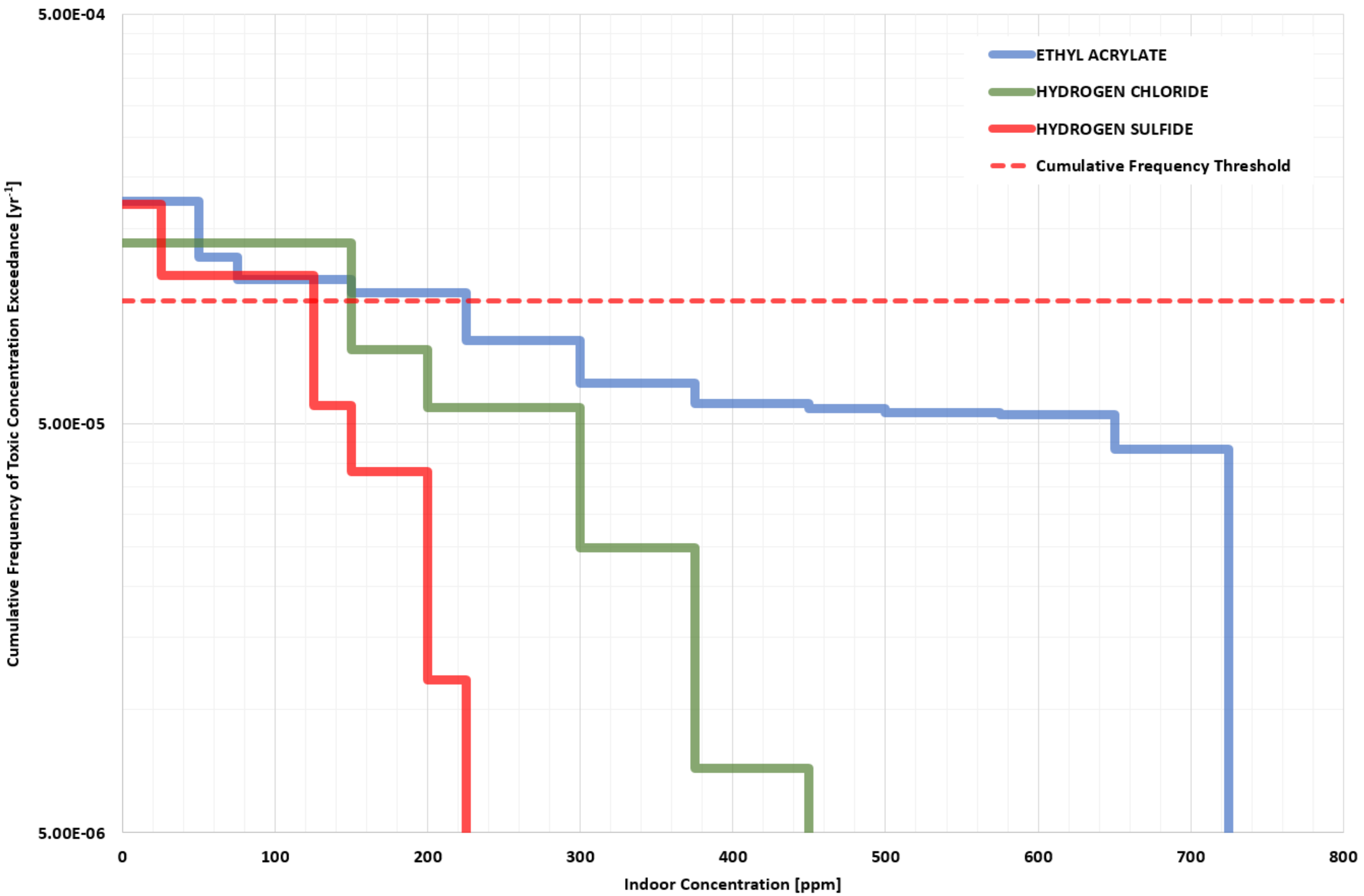

Figure 05: Toxic Concentration Exceedance Curves at a Given Location – Indoor Concentrations

Conclusions

A detailed risk-based approach is proposed to address flammable and toxic dispersions impacting occupied buildings. The approach is based on results obtained from a complete quantitative risk-based assessment, which provides the following information per each outcome impacting the target location under analysis:

- Individual frequency of occurrence
- Outdoor concentrations
- Indoor concentrations by considering building infiltration
- Exposure time

When analyzing the information listed above, dedicated exceedance curves can be constructed. These exceedance curves allow the user to identify if locations impacted by the outcomes of interest comply or not with given tolerable risk criteria. Exceedance curves per hazard type (flammability or toxicity) and per chemical can be generated. Exceedance curves allow deciding if a target building should be introduced in the mitigation plan as per API Recommended Practice 752 **[10]** and API Recommended Practice 753 **[11]**, or if already can be considered to be located in an acceptable risk region.

The proposed approach is intended to build dedicated FN curves per building being impacted by toxic dispersions. The chemical inherent toxic properties, indoor concentration and exposure time are combined by using the probit analysis with the aim to estimate the associated individual probability of fatality. Finally, the probability of fatality for a certain number of occupants is estimated based on the probability density function of a multinomial distribution.

The detailed results from the proposed approach will allow decision-makers to acquire valuable information for considering the most cost-effective risk reduction measures to be installed when target locations have been identified to be in an unacceptable risk region.

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