# 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**


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## Abstract


This paper proposes a risk-based approach for identifying process equipment impacted by explosions with potential for escalation. The procedure is based on: (1) taking advantage of efforts conducted during the development of a risk-based quantitative assessment, (2) combination of exceedance curve with elasto-plastic Single Degree Of Freedom (SDOF) and pressure-impulse diagrams. The main purpose is to estimate the equipment damage level; i.e., ductility ratio. Once the damage level is characterized, appropriate decision-making process for the equipment affected can be conducted.

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## Introduction

## Introduction

This manuscript proposes a detailed elasto-plastic Single Degree of Freedom (SDOF) analysis for evaluating the structural damage level caused by explosions in a hazardous process facility. The proposed methodology maximizes the most reliable criteria by balancing the required level of detail with the inherent uncertainties present in the problem definition. The method of analysis used is optimized with regard that the loading effects of explosions cannot be precisely specified.

The elasto-plastic SDOF proposed approach requires the characterization of two functions:

- Blast loading function from the blast wave impacting the structure. Detailed information on how to evaluate blast loading functions from explosions identified during the development of a risk-based quantitative assessment has been addressed in reference **[1].**

- Resistance-deflection function of the structure. Detailed information on how to evaluate the resistance-deflection function of a structure being impacted by identified explosions has been addressed in reference **[2]**. Note that reference **[2]** addresses the SDOF approach and also introduces the applicability of pressure-impulse (P-I) diagrams as a valuable tool for analyzing the structure damage from explosions.

This paper illustrates a methodology focused on evaluating the potential damage level of process equipment due to explosions. The purpose of the risk-based quantitative assessment is to identify if the impacted process equipment will fail due to the blast wave and to address the potential escalation to be included in the study basis. While the escalation triggered by explosions can be addressed using overpressure thresholds, this paper proposes a more detailed approach.

This method is justified when a more precise analysis is needed to optimize the decision-making process

Note that a specific risk-based approach for addressing escalation triggered by explosions to process equipment based on overpressure threshold criteria has been addressed in reference **[3]**.

While the method presented in this paper is focused on addressing process equipment, it is also applicable for analyzing the structural response and associated human vulnerability. The US Department of Defense (DoD) developed criteria for structural response based on P-I diagrams and associated human vulnerability for 16 different classes of buildings using pre-populated P-I diagrams **[4]**. By using criteria from DoD, it is not necessary to conduct the SDOF approach to construct the associated P-I diagrams if the structure falls in one of the 16 “DoD buildings” types. A complete assessment on how DoD criteria is used in a risk-based quantitative assessment framework has been addressed in reference **[5].** This manuscript illustrates how to estimate the probability of fatality of an individual inside a building after evaluating the building damage level. Note that reference **[5]** also illustrates how dedicated F-N curves (societal risk) can be generated per building impacted by explosions. Accordingly, reference **[5]** is intended to provide guidance on facility siting for permanent and portable buildings being impacted by explosions rather than for process equipment.

The following contents explain what information is required for developing a risk-based quantitative assessment. A case study illustrates how to combine all the data developed to achieve the main objective of the analysis: characterization of escalation triggered by explosions (domino effect).

## Case Study

The following case study illustrates the proposed method for escalation characterization. A process facility is analyzed by developing a risk-based quantitative assessment. When determining the risk as a function of the population (societal risk) with F-N Curves and the individual risk (i.e., Individual Risk Contours). The likelihood of process equipment to result in domino effect and escalation as a result of explosion impact can be studied.

### Risk-Based Quantitative Assessment Development

During the development of the risk-based quantitative assessment, it was important to define on the map all equipment was defined on a plot plan for escalation evaluation. All process equipment capable of releasing hazardous materials were included. All Loss of Containment scenarios (LOCs) were analyzed and modeled following the criteria established in references **[6]**, **[7]**, **[8]**, **[9]**, **[10]** and **[11]**. Note that these cited references provide the basis for risk-based quantitative assessment, which is considered to be the foundation of the proposed approach in this paper.

The risk-based quantitative assessment evaluates all the explosions and shows which process equipment are affected. **Table 01** lists an example of key results obtained from the risk-based quantitative assessment and includes the cumulative frequency, peak-side overpressure, phase duration and total number of explosions that exceed the overpressure threshold on specific process equipment). Note that more overpressure thresholds defined during consequence modeling will result in more refined contours for the escalation analysis. Results from **Table 01** account for all explosions that impact equipment at a given exceedance overpressure threshold and the frequency. This table illustrates the cumulative frequency after summing all individual frequencies of each explosion.

The results listed in **Table 01** are the starting point for developing exceedance curves to identify process equipment susceptible to an overpressure threshold high enough to potentially cause escalation. Note that cumulative frequency at the overpressure threshold should be compared to applicable risk tolerability criteria. The same results listed in **Table 01** can be collected for all process equipment defined in the hazardous site.

**Table 01: Summary Explosions Impacting Process Equipment**

| Overpressure [psi] | Phase Duration [ms] | Frequency [yr$^{-1}$] | Outcomes |
|---|---|---|---|
| 0.725 | 245.4 | 8.28E-05 | 486 |
| 1.00 | 240.3 | 7.15E-05 | 458 |
| 2.00 | 230.3 | 2.06E-05 | 238 |
| 3.00 | 235.3 | 1.73E-05 | 200 |
| 4.00 | 232.5 | 1.60E-05 | 182 |
| 4.35 | 171.2 | 1.46E-05 | 166 |
| 5.00 | 172.8 | 1.41E-05 | 158 |
| 8.00 | 61.8 | 5.89E-06 | 114 |
| 10.0 | 56.5 | 5.05E-06 | 92 |

Note that **Table 01** confirms that 486 blast waves impact the process equipment. While this value can seem to be huge, it is considered reasonable based on accounting for all LOCs that could generate potential explosions at a facility handling hazardous materials. From these 486 explosions, 54 of them impact the process equipment at an overpressure value of 15 psi. Ninety two explosions that impact at 10 psi include the 54 explosions that impact the equipment at 15 psi, plus 38 additional explosions that impact at 10 psi.

The individual frequency for each of the 486 explosions is used as for selection of process equipment to be included in the escalation analysis.

The risk-based quantitative assessment allows the user to consider the frequency of all identified explosions that impact the process equipment. This frequency is necessary for identifying which process equipment is impacted by explosions when compared to a frequency threshold based on tolerability criteria. For example, process equipment that experience explosions with a frequency lower than 5.00E-05 yr$^{-1}$ are considered broadly acceptable and only blast waves with a higher value should be addressed. The frequency tolerability threshold has to be based on accepted criteria.

To optimize the number of equipment for domino effect analysis, it is appropriate to focus on the overpressure that impacts the equipment at the given frequency threshold. For example, if one piece of equipment is impacted by an overpressure of 0.5 psi at 5.00E-05 yr$^{-1}$, the equipment can be disregarded for further analysis because 0.5 psi is not considered enough overpressure to cause equipment failure. It is appropriate to define the criteria for establishing the overpressure thresholds that result in potential domino effect. Reference **[3]** explains a review of equipment damage caused by overpressure. **Table 02** lists typical threshold values for damage and escalation analysis obtained for several accident scenarios. The thresholds in the table were obtained from data literature review and from simplified structural models based on a variety of recognized case studies. Reniers and Cozzani **[12]** performed a sensitivity analysis of all factors affecting the escalation to assess critical values for the different parameters.

**Table 02: 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

***Note**: Further information on target equipment type and technical justification of values listed in **Table 02** can be found in reference **[3]**.

Based on the values in Table 02, conservative “Damage thresholds,” can be designated as overpressure thresholds to conduct domino effect analysis on process equipment. The selection of process equipment candidates for further escalation analysis by structural response can follow criteria as listed in **Table 03**. For all of the equipment the threshold frequency for consideration is 5.00E-05 $yr^{-1}$.

**Table 03: Escalation Criteria for Equipment Selection***

| Target Equipment | Overpressure Criteria [psi] | Frequency Criteria [$yr^{-1}$] |
|---|---|---|
| Atmospheric | OP > 1.02 | |
| Pressurized | OP > 2.90 | |
| Elongated (Toxic) | OP > 2.31 | |
| Elongated (Flammable) | OP > 2.31 | |

* - Frequency for consideration is 5.00E-05 $yr^{-1}$

Overpressure Exceedance Curves (OECs) are useful for identifying potential affected equipment by explosions according to the thresholds values listed in **Table 03**. Note that exceedance curve development is based on the information present in **Table 01**. Detailed criteria on how to construct exceedance curves can be found in reference **[10]**. **Figure 01** illustrates exceedance curves for five pieces of process equipment identified as impacted by blast waves.

**Figure 01** confirms that the only process equipment which requires further analysis for escalation is equipment "Pressurized – Equipment 02," based on the overpressure value at the given cumulative frequency threshold of interest (5.00E-05 $yr^{-1}$). **Table 04** summarizes the results of the overpressure exceedance curve per each equipment analyzed.

**Table 04: Exceedance Curve Results Summary**

| Target Equipment | OP Criteria [psi] | OP @ Frequency Criteria [psi] |
|---|---|---|
| Atmospheric – Equipment 01 | OP > 1.02 | **0.5** |
| Pressurized – Equipment 02 | OP > 2.90 | **3.5** |
| Pressurized – Equipment 03 | OP > 2.31 | **2.0** |
| Elongated – Equipment 04 | OP > 2.31 | **0.0** |

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

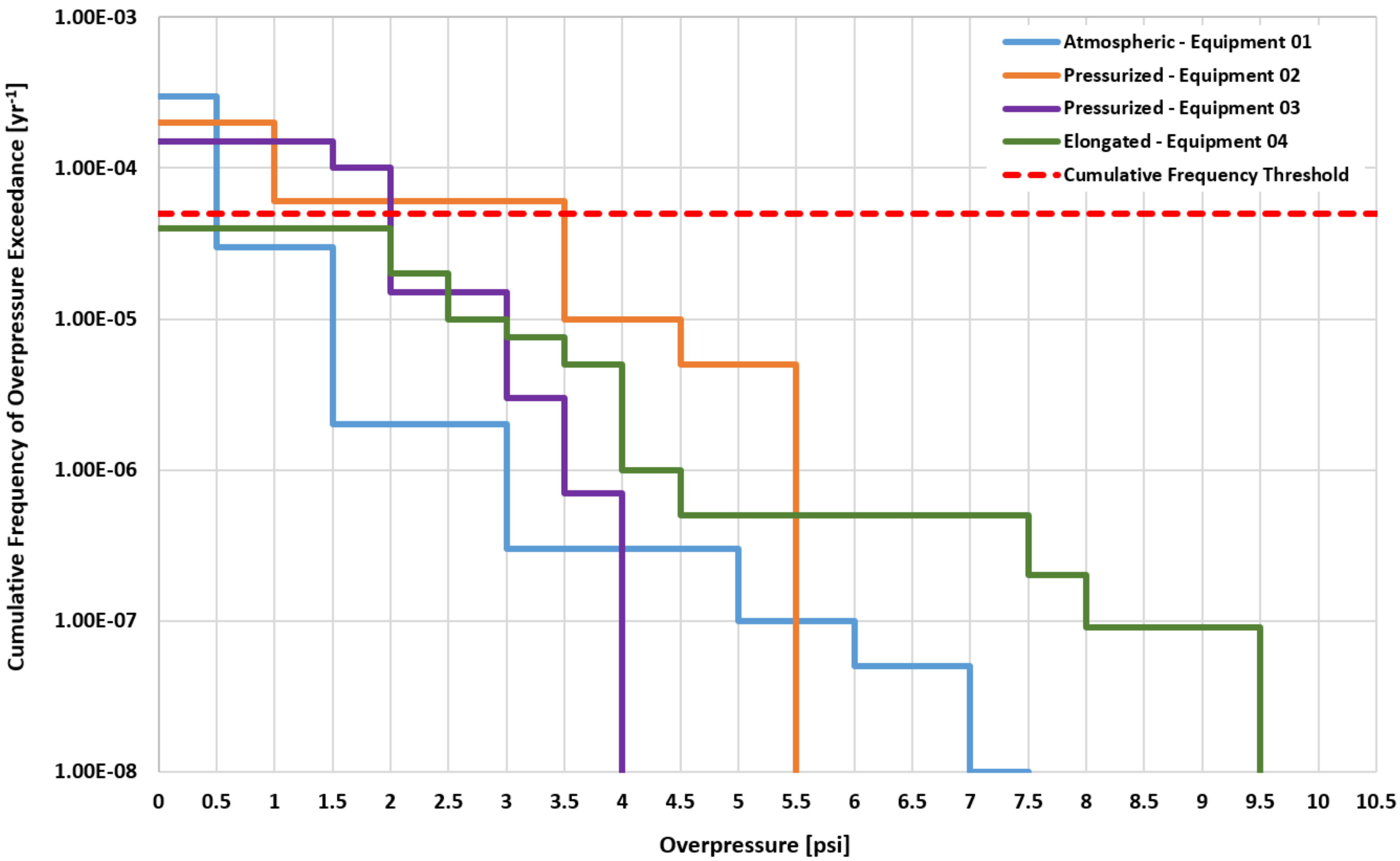


**Figure 01: Overpressure Exceedance Curve (OEC) Example**

## Generation of P-I Diagram with different Isodamage Curves

P-I diagrams are a good engineering tool for analyzing all identified explosions that can impact a given structure. A P-I diagram with different levels of damage corresponding to different levels of ductility ratio allow the user to determine the damage level of the structure. The ductility ratio ($\boldsymbol{\mu}$) is the maximum displacement of the member divided by the displacement at the elastic limit Further information can be found in reference **[2]**.

The development of dedicated P-I diagrams is based on the elasto-plastic SDOF approach proposed in reference **[2]**. Once the blast loading and resistance-deflection functions are known, the SDOF can be applied and the maximum displacement of the structure can be predicted. After comparing the maximum displacement with the maximum elastic displacement of the structure, the ductility ratio is estimated. This is considered a critical parameter when evaluating the potential explosion damage of a building.

While the resistance-deflection function is unique per each structure (i.e., the resistance-deflection does not vary per structure analyzed), the blast-loading function changes per each explosion that impacts the structure. To calculate the corresponding ductility ratio per each impacting explosion, the SDOF should be applied as many times as explosions that impact the system.

For example, based on the total number of outcomes illustrated in **Table 01**, the SDOF approach should be applied 486 times to complete the analysis. This would be a very time-consuming approach. A better procedure is to capture the structural response of the equipment for all explosions impacting the structure of interest. Recent computational capabilities allow running multitude iterations for finding a plethora of blast loading functions that would satisfy the damage level of interest and for several levels of interest (e.g., ductility ratios).

There are infinite blast loads (combinations of pressures and impulses) that produce the same damage level to a given structure. Therefore, given the structure and the damage level, the system of differential equations that define the SDOF approach can provide as many combinations of pressures and impulses as necessary that satisfy the damage level and generate a complete isodamage curve, for example, at ductility of 3. A comprehensive P-I Diagram is constructed after completing the same procedure for different damages levels,

All explosions impacting the structure can be overlapped in the P-I diagram developed by considering their associated overpressures and impulses.

**Figure 02** illustrates the P-I Diagram of process equipment with all impacting blast waves. An equipment damage exceedance curve can be constructed based on overlapping all the pressure-impulse pairs for the explosions.

### Equipment Damage Exceedance Curve Construction

**Figure 02** shows the main objective of the study: the evaluation of the equipment structural response and associated damage level. For each blast wave overlapped in the P-I diagram with different isodamage curves, the ductility ratio is identified. The following information can be extracted per each explosion impacting the structure:

- Peak-overpressure
- Impulse
- Individual Frequency Level of damage between two isodamage curves. Note that if a blast load falls between isodamage curves of ductility values of 4 and 5, this explosion is considered to potentially cause the same damage as ductility ratio of 4.

All explosions falling into the same damage level can be aggregated and their individual frequency cumulated to construct a dedicated equipment damage exceedance curve. Following the same procedure as detailed for summarizing results of overpressure exceedance curves (see **Figure 01** and **Table 04**), the damage level at the frequency threshold of interest can be identified.

**Figure 03** illustrates an example of an equipment damage exceedance curve. Based on **Figure 03**, the curve crosses the frequency threshold of interest (5.00E-05 $yr^{-1}$) at a damage level of ductility ratio equal to 4.

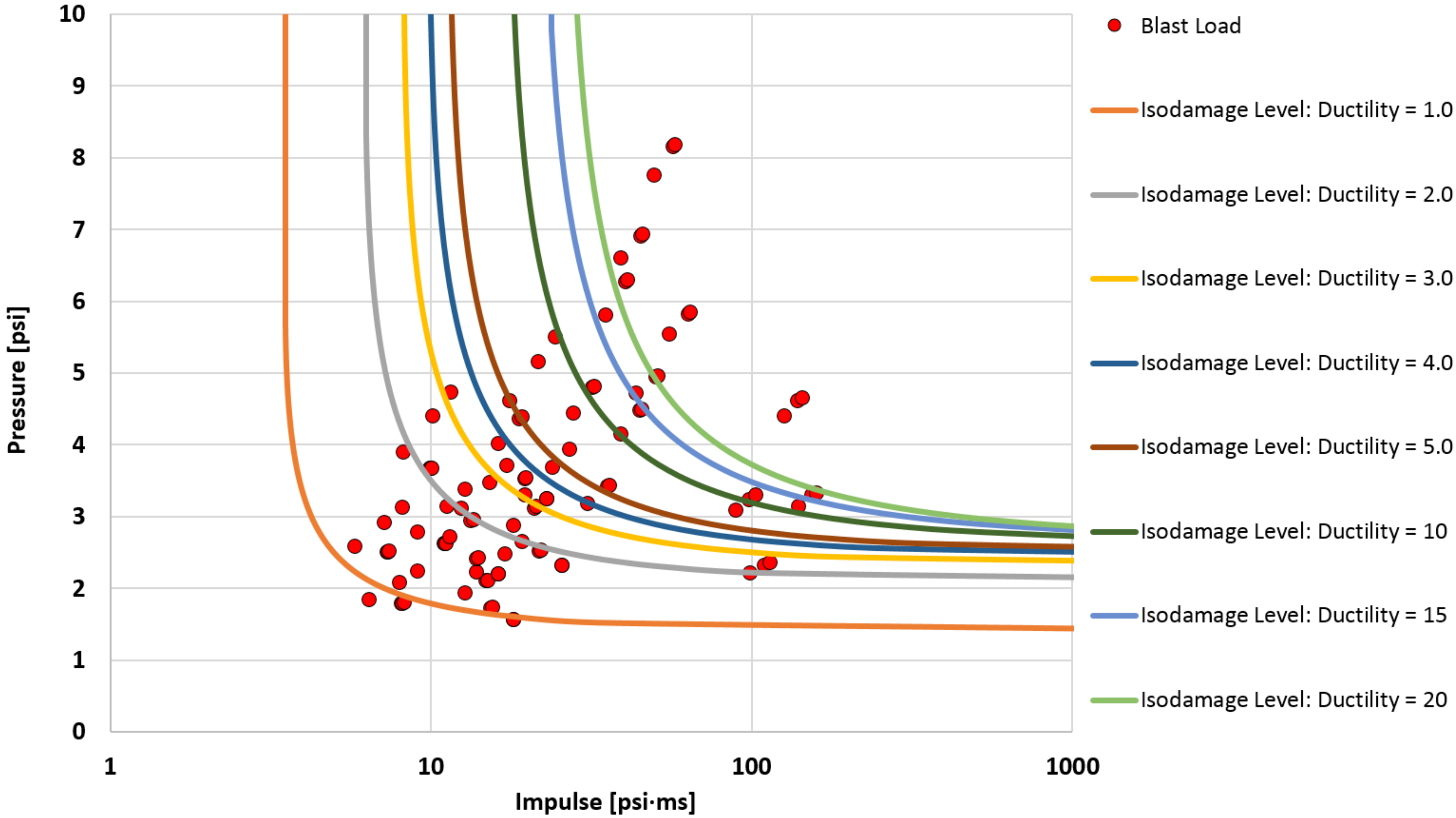


**Figure 02: P-I Diagram and Impacting Blast Waves**

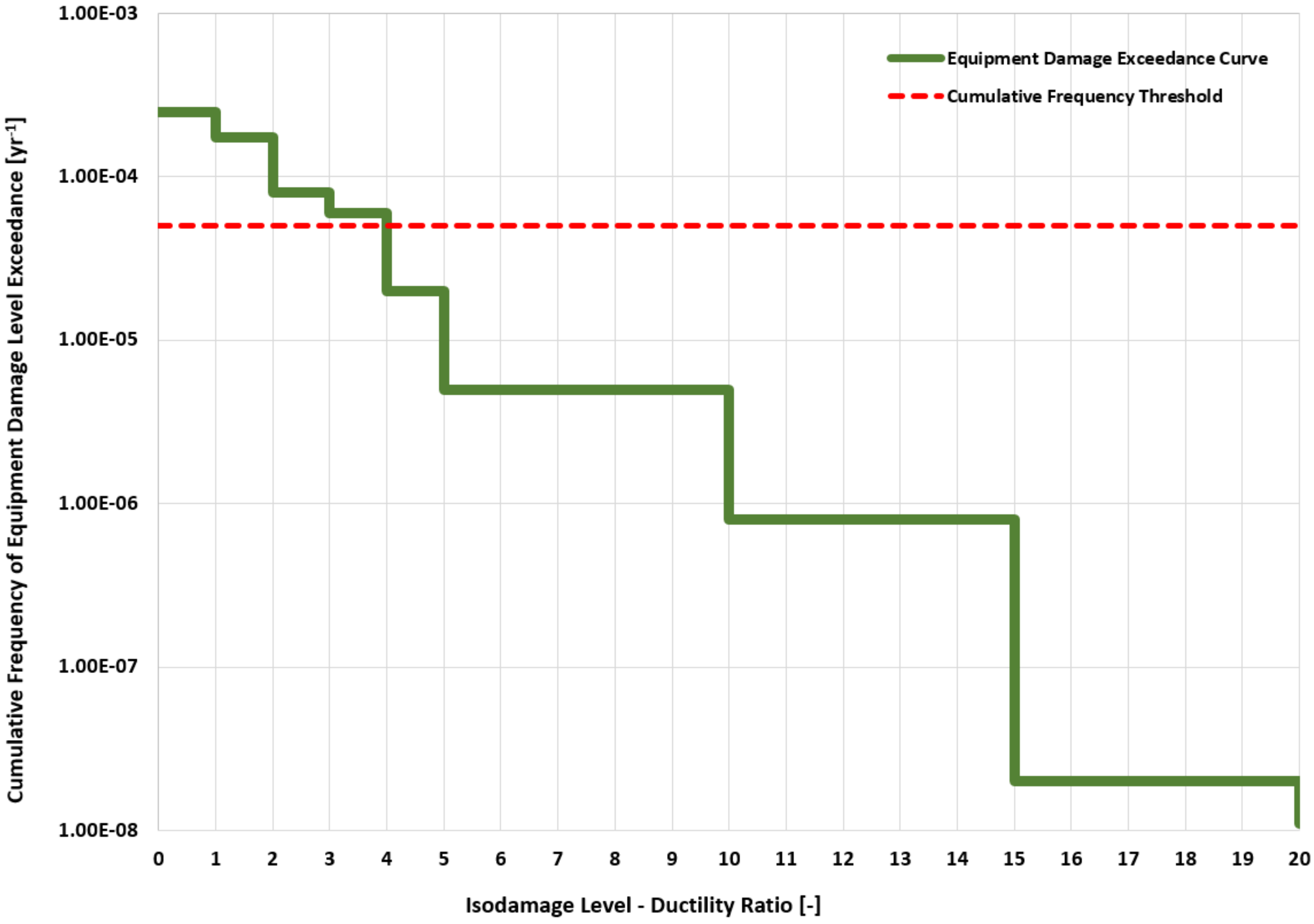


**Figure 03: Equipment Damage Exceedance Curve**

## Decision-Making Based on Equipment Damage Exceedance Curve

Response deformation limits are used to define an adequate response to blast loads. These limits are based on the type of structure, construction materials used, location of the structure and desired protection level.

Almost all published structural response criteria are presented in terms of parameters which are easily compared with simplified non-linear dynamic response calculations that involve one or several degrees of freedom models. These parameters include ductility ratio and hinge rotations, which are based on the peak deflection of the component.

Therefore, the predicted response can be compared to ductility and/or support rotation limits. The proposed method for evaluating the equipment damage level from explosions is based in the ductility ratio value, which is appropriate for structural response criteria. The decision-making process is comparing the predicted ductility ratio with the accepted applicable threshold that the process facility selected.

## Conclusions

The present paper proposes a risk-based approach for identifying process equipment impacted by explosions with potential for escalation. The procedure is based on: (1) taking advantage of efforts conducted during the development of a risk-based quantitative assessment, (2) combination of exceedance curve with elasto-plastic Single Degree Of Freedom (SDOF) and (3) pressure-impulse diagrams. The main purpose is to estimate the equipment damage level in terms of the ductility ratio. Once the damage level is characterized, appropriate decision-making process for the affected equipment can be conducted.

The theoretical basis of the tools used in this paper are addressed in the following references as listed in **Table 05**.

**Table 05: Key Support References**

| Topic | Source |
|---|---|
| Risk-Based Quantitative Assessment | **[6]**, **[7]**, **[8]**, **[9]**, **[10]** |
| Exceedance Curves | **[10]** |
| Blast Loading Characterization | **[1]** |
| Single Degree Of Freedom and P-I Diagrams | **[2]** |
| Overpressure Threshold Criteria for Escalation | **[3]** |

A case study is developed to illustrate the procedure for calculating the potential for domino effect and escalation due to explosions for process equipment.

## References

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**[12]** Reniers, G., Cozzani, V., 2013. "Domino Effects in the Process Industries - Modeling, Prevention and Managing. Elsevier, Amsterdam.