Comparison of Building Design: Design Accidental Loads vs. Risk-Based

Rafael Callejas-Tovar and Joshua Bruce-Black, BakerRisk Europe Ltd., Thornton Science Park (Bldg. 49), Pool Lane, Ince, Chester CH2 4NU, United Kingdom, rcallejas@bakerrisk.com, jbblack@bakerrisk.com

There are a variety of building design approaches that can be considered and employed to mitigate risks to building occupants. Although the preferred and safest approach is to design buildings for worst-case explosion, fire, and toxic events after completion of a consequence study, this can often be infeasible or cost-prohibitive. An alternative building design approach considers the frequency of each scenario and can be achieved through the use of frequency-consequence exceedance curves to determine a design accidental load (DAL) or by use of risk calculations from a Quantitative Risk Analysis (QRA). Using example case studies, the benefits and shortcomings of developing a building design basis employing frequency-consequence exceedance curves versus using a risk-based approach will be examined. Although a risk-based approach may require more complex modelling, additional effort and time compared to determining a DAL, it is important to consider each load (blast, fire, toxic) and the duration of each load to assess the vulnerability to occupants and fully quantify the effectiveness of a building design.

Keywords: Consequence Analysis, Facility Siting, Risk Assessment, Design Accidental Load, Risk-Based Building Design

Introduction

Explosions, fires, and/or toxic releases are potential hazards inherent to the operations of many facilities. New buildings in such facilities are typically designed considering mitigation of these hazards to the extent practical. Companies often employ a consequence-, frequency-, or risk-based building design approach or a combination of these approaches based on the hazard. There are a variety of building design approaches that can be considered and employed to mitigate risks to building occupants [CCPS 1999], [DOD 2009], [Arendt 2003], [Khan et al. 1998].

The preferred and safest approach is to design buildings for the worst-case explosion, fire, and toxic consequence (load, concentration, etc.) predicted from a set of maximum credible scenarios without consideration of the likelihood of the events. However, this approach can often be infeasible or cost-prohibitive due to the predicted severity of these worst-case events.

An alternative building design approach which considers not only the consequence of the events but also the likelihood is becoming more prevalent throughout industry. This alternative building design approach can be achieved through the use of frequency-consequence exceedance curves to determine a design accidental load (DAL) at a given frequency tolerance threshold or by use of risk calculations from a Quantitative Risk Analysis (QRA) that considers multiple potential building designs to meet a risk tolerance criterion.

Due to the increased prevalence of buildings designed considering the likelihood of events, this paper focuses on the benefits and shortcomings of developing a building design basis employing frequency-consequence exceedance curves versus using a risk-based approach using example case studies for explosion, fire, and toxic hazards.

Background

Companies utilise results of consequence or quantitative risk assessments to design buildings within their facilities. A diagram showing the major steps of a consequence and risk assessment is shown in Figure 1. Consequence analyses typically provide the impact of each scenario on a building in terms of the hazard: explosion (pressure and impulse), fire (thermal radiation flux and exposure time), and toxic (concentration and exposure time). These impacts are subsequently converted to occupant vulnerabilities (OVs) based on building construction, occupancy distribution, and probit equations. OVs are a representation of the fraction of the population that will sustain life-threatening injuries as a result of the impact [Dyer, et al. 2015].

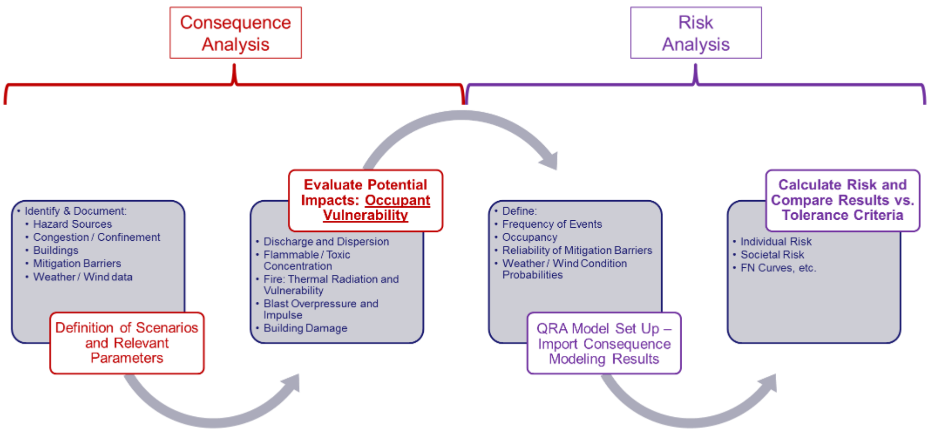


Figure 1: Major Steps of a Consequence and Risk Assessment

Building explosion OVs are typically calculated using blast damage models (pressure-impulse diagrams) which define the structural capacity of a building [Dyer, et al. 2014]. The P-i curves for a building represent curves of constant response (damage) and are typically broken up into multiple building damage levels (BDLs) as shown in Figure 2. Each region of constant damage has a different OV. The explosion OV accounts for multiple variables including the BDL, population distribution, windows, and construction type [Dyer, et al. 2013].

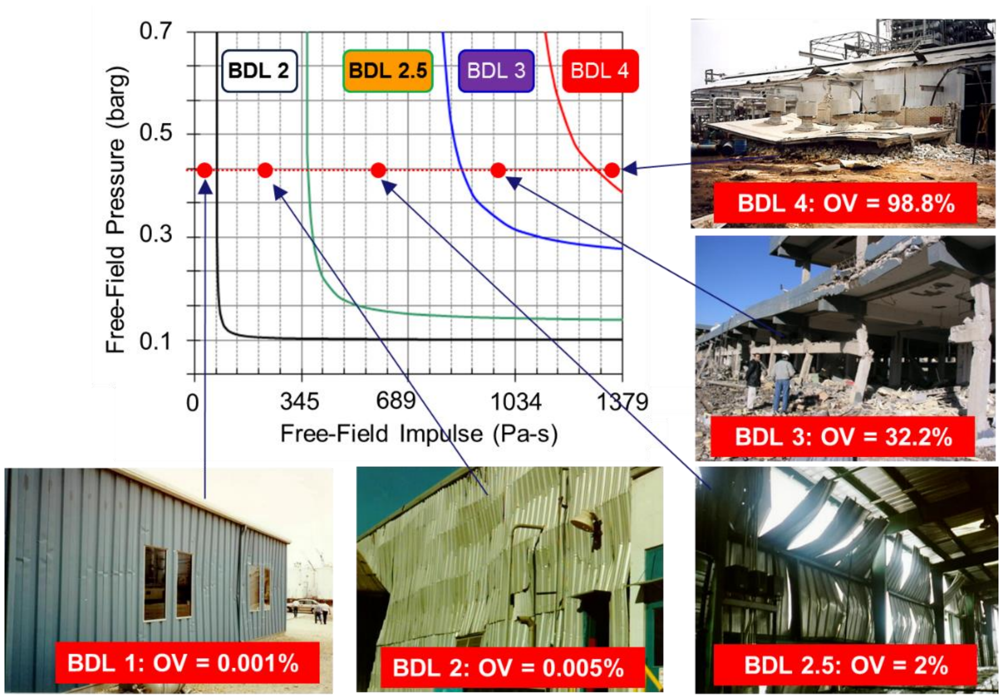


Figure 2: Example Pressure-Impulse Diagram and BDLs for same Overpressure and Different Impulses (Durations)

Vulnerabilities for thermal and toxic events are typically assessed based on integrating probit equations of dose (concentration with time) as occupants evacuate or shelter-in-place (SIP). Vulnerability of occupants directed to evacuate in case of a thermal or toxic event are typically assessed assuming egress at a given rate in one or multiple directions. Vulnerability of occupants that shelter-in-place are typically assessed based on the internal temperature or toxic concentration that accounts for external thermal radiation/toxic concentration as well as building characteristics such as thermal resistance, heating venting and cooling (HVAC) air exchange rate, building infiltration rate, and HVAC isolation reliability [Sarrack 2016].

Occupant vulnerabilities are converted to consequences (predicted number of fatalities or probability of fatality) using building occupancy data. Event frequencies combine release frequencies with conditional probabilities for wind speed and weather stability category, release / wind direction, ignition probability and timing, and time slot. The risk of each scenario combines the consequence with the frequency of that scenario. The overall risk to a building is calculated by adding the risk of each scenario assessed, since risk is additive.

Risk to buildings is typically presented in terms of individual and societal (aggregate) risk. Building individual risk is the risk to an individual (one person) continually present in a building and is measured in terms of annual probability of death (APoD) while building societal risk is the risk to a group of people and accounts for the average occupancy of a building.

Building design approaches that consider the likelihood of events require extensive calculations and data from not only a consequence assessment but also a quantitative risk assessment including, at a minimum, impact and frequency calculations. Utilising this information, frequency-consequence exceedance curves can be developed by sorting consequences from highest to lowest and calculating a cumulative frequency to show the frequency of scenarios that exceed a given impact (pressure, thermal radiation, toxic concentration, etc.). These frequency-consequence exceedance curves can then be used to determine a design accidental load (DAL) for a building for each hazard based on a frequency tolerance threshold. A risk-based building design approach requires additional calculations to convert impact calculations to occupant vulnerabilities and then finally to consequences using occupancy data. Examples of a frequency-consequence exceedance building design approach and risk-based building design approach for explosion hazards are shown in Figure 3 and Figure 4, respectively.

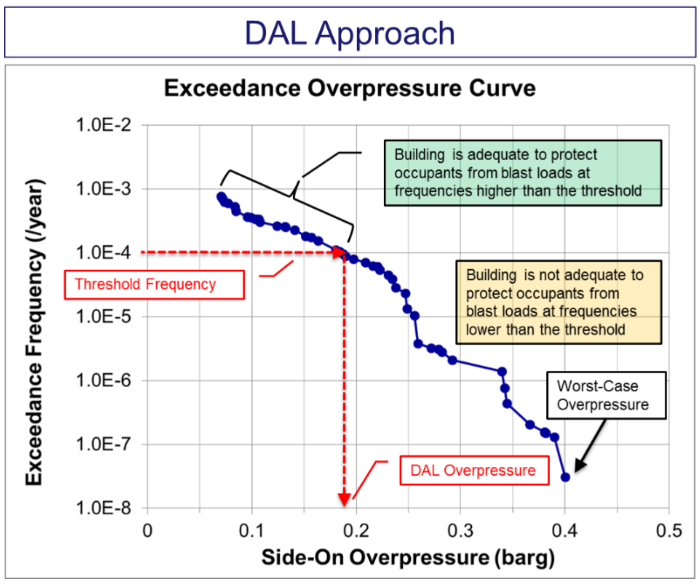
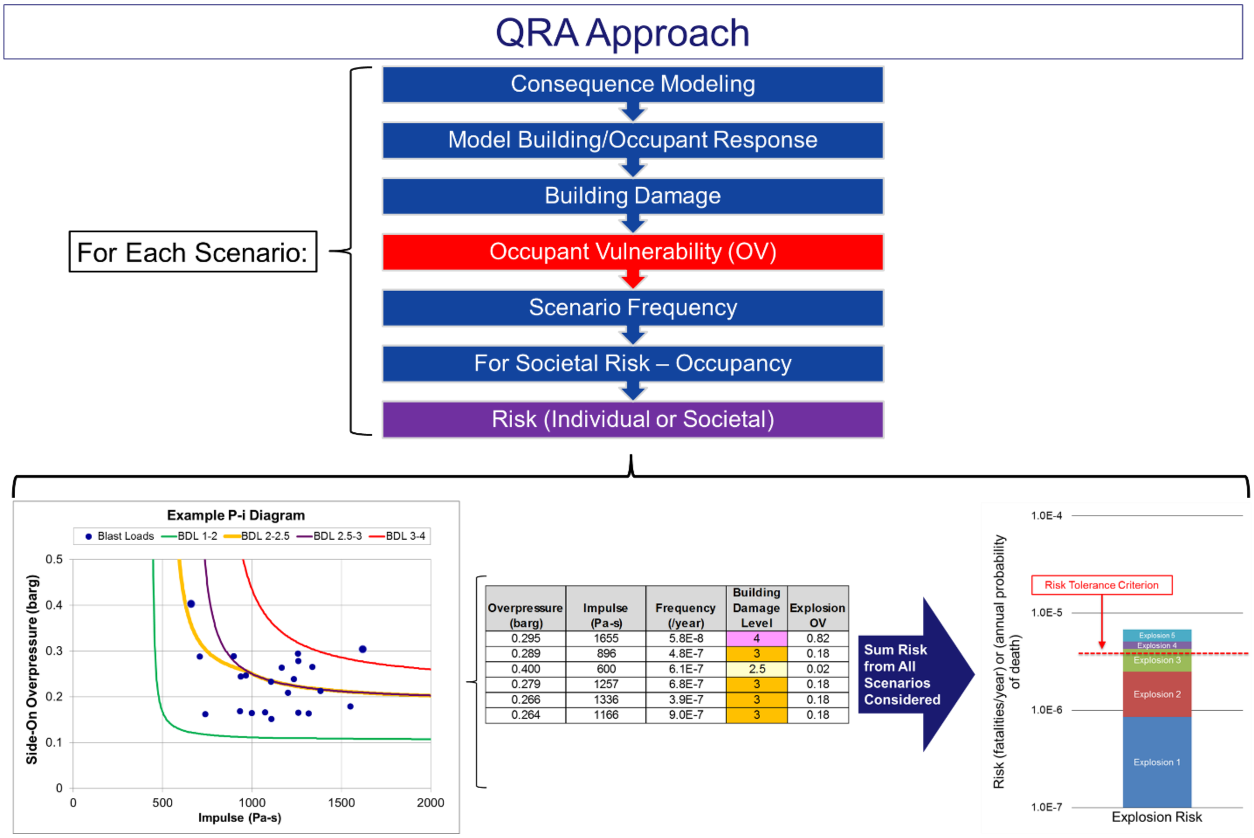


Figure 3: Schematic of DAL Approach



Overpressure (barg)	Impulse (Pa-s)	Frequency (/year)	Building Damage Level	Explosion OV
0.295	1655	5.8E-8	4	0.82
0.289	896	4.8E-7	3	0.18
0.400	600	6.1E-7	2.5	0.02
0.279	1257	6.8E-7	3	0.18
0.266	1336	3.9E-7	3	0.18
0.264	1166	9.0E-7	3	0.18

Figure 4: Schematic of QRA Approach

Building Design Discussion

There are three main differences in employing a frequency-consequence approach versus using a risk-based approach in building design. These differences include:

1. Event Duration
2. Occupant Vulnerability
3. Occupancy

These key differences are discussed below in detail using building design examples to highlight and illustrate potential benefits and shortcomings of using a frequency-consequence approach with exceedance curves versus a risk-based approach.

Event Duration

Occupant vulnerability calculations are dependent not only on the magnitude of the impact (pressure, thermal radiation flux, toxic concentration) at a building but also the duration of the event. This concept is illustrated in the blast damage model in Figure 2 above, which shows that building damage and associated vulnerability is a function of the pressure and duration of that pressure (impulse). Frequency-consequence exceedance curves can straightforwardly provide a design accidental load (pressure, thermal radiation, toxic concentration) but they do not typically provide the duration of this load. Therefore, if this DAL is provided to building design firms or engineering, procurement, and construction companies (EPCs) without an associated duration, there is a high likelihood of receiving wildly different building designs from each company.

This concept is demonstrated in an example with 20 explosion scenarios defined by a pressure, impulse, and frequency in Table 1.

Table 1: Example 1 – Blast Loads

Blast Load ID#	Overpressure (barg)	Impulse (Pa-s)	Frequency (/year)
1	0.295	1255	5.8E-8
2	0.289	896	4.8E-7
3	0.289	708	6.1E-7
4	0.279	1257	6.8E-7
5	0.266	1336	3.9E-7
6	0.264	1166	9.0E-7
7	0.247	965	8.4E-7
8	0.245	935	8.8E-7
9	0.239	1233	1.1E-6
10	0.233	1106	1.8E-6
11	0.213	1383	7.5E-6
12	0.209	1201	8.4E-6
13	0.179	1548	5.7E-6
14	0.169	932	5.5E-6
15	0.167	1072	9.8E-7
16	0.165	1259	1.6E-6
17	0.165	998	6.6E-6
18	0.164	1315	2.5E-6
19	0.163	738	4.9E-6
20	0.152	1108	7.9E-6

The resulting frequency-pressure (F-P) exceedance curve is shown in Figure 5 with a frequency tolerance criterion of 1E-5/year resulting in a design pressure of 0.23 barg for the building. Figure 6 illustrates three potential building designs of the same building type (different blast damage models with the same occupant vulnerabilities) which meet the design pressure at different durations. The individual risk results in Table 2 show that the risk for these three building designs varies widely and is much lower than the frequency tolerance criterion of 1E-5.

Due to the importance of event duration in building design it is recommended that a long duration be assumed for building design (>200 ms) to maintain conservatism and prevent potential design of a building that incurs occupant vulnerability at higher event durations. If impulses associated with each pressure are known, then a preferred and improved approach would include utilization of the maximum impulse from scenarios that contribute to the cumulative design frequency criteria. In Table 2, this would be 1548 Pa-s.

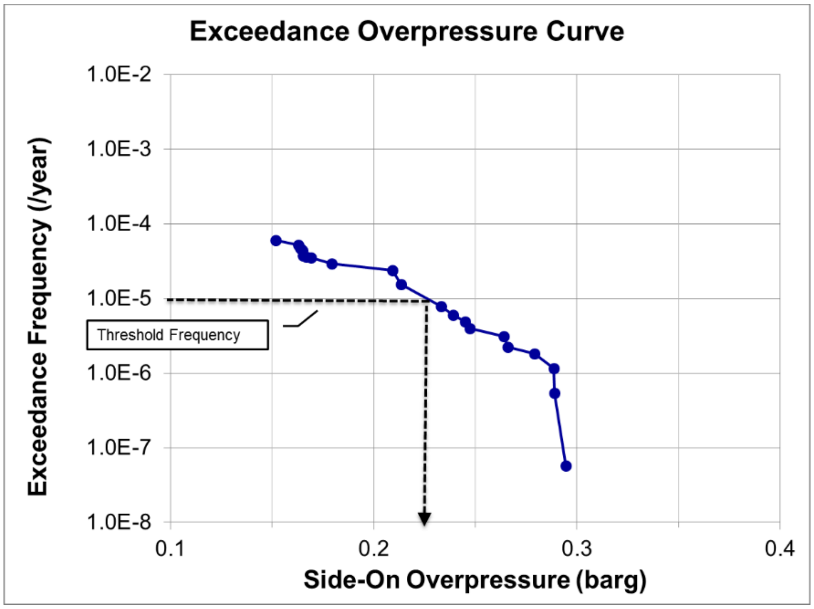


Figure 5: Example 1 – Exceedance Overpressure Curve

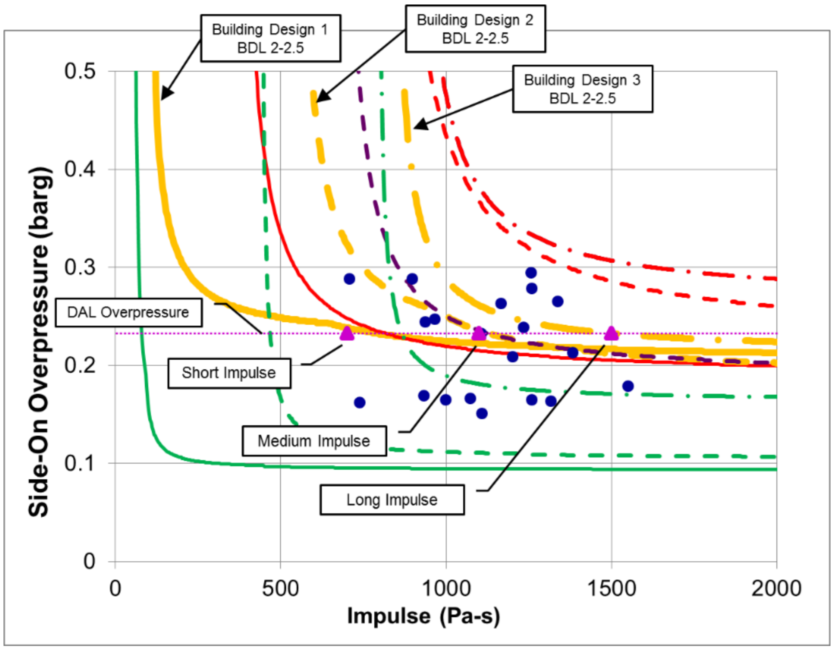


Figure 6: Example 1 – P-i Blast Scatter Plot for Three Building Designs of the Same Construction Type

Table 2: Example 1 – Blast Loads and Associated Damage Level and Risk for Different Building Designs

				Building Damage Level			Explosion Occupant Vulnerability			Explosion LSIR (APoD)		
Blast Load ID#	Overpressure (barg)	Impulse (Pa-s)	Frequency (/year)	Steel-Frame Design 1	Steel-Frame Design 2	Steel-Frame Design 3	Steel-Frame Design 1	Steel-Frame Design 2	Steel-Frame Design 3	Steel-Frame Design 1	Steel-Frame Design 2	Steel-Frame Design 3
1	0.295	1255	5.8E-8	4	3	2.5	1	0.39	0.025	5.8E-8	2.3E-8	1.4E-9
2	0.289	896	4.8E-7	4	3	2	1	0.39	0	4.8E-7	1.9E-7	0.0E+0
3	0.289	708	6.1E-7	4	2	1	1	0	0	6.1E-7	0.0E+0	0.0E+0
4	0.279	1257	6.8E-7	4	3	2.5	1	0.39	0.025	6.8E-7	2.7E-7	1.7E-8
5	0.266	1336	3.9E-7	4	3	2.5	1	0.39	0.025	3.9E-7	1.5E-7	9.8E-9
6	0.264	1166	9.0E-7	4	3	2.5	1	0.39	0.025	9.0E-7	3.5E-7	2.3E-8
7	0.247	965	8.4E-7	4	2	2	1	0	0	8.4E-7	0.0E+0	0.0E+0
8	0.245	935	8.8E-7	4	2	2	1	0	0	8.8E-7	0.0E+0	0.0E+0
9	0.239	1233	1.1E-6	4	3	2	1	0.39	0	1.1E-6	4.4E-7	0.0E+0
10	0.233	1106	1.8E-6	4	2	2	1	0	0	1.8E-6	0.0E+0	0.0E+0
11	0.213	1383	7.5E-6	4	2	2	1	0	0	7.5E-6	0.0E+0	0.0E+0
12	0.209	1201	8.4E-6	2	2	2	0	0	0	0.0E+0	0.0E+0	0.0E+0
13	0.179	1548	5.7E-6	2	2	2	0	0	0	0.0E+0	0.0E+0	0.0E+0
14	0.169	932	5.5E-6	2	2	1	0	0	0	0.0E+0	0.0E+0	0.0E+0
15	0.167	1072	9.8E-7	2	2	1	0	0	0	0.0E+0	0.0E+0	0.0E+0
16	0.165	1259	1.6E-6	2	2	1	0	0	0	0.0E+0	0.0E+0	0.0E+0
17	0.165	998	6.6E-6	2	2	1	0	0	0	0.0E+0	0.0E+0	0.0E+0
18	0.164	1315	2.5E-6	2	2	1	0	0	0	0.0E+0	0.0E+0	0.0E+0
19	0.163	738	4.9E-6	2	2	1	0	0	0	0.0E+0	0.0E+0	0.0E+0
20	0.152	1108	7.9E-6	2	2	1	0	0	0	0.0E+0	0.0E+0	0.0E+0
									Total =	**1.5E-5**	**1.4E-6**	**5.1E-8**

The importance of event duration can also be illustrated with building design for thermal and toxic events. Frequency-toxic concentration and frequency-thermal exceedance curves are shown in Figure 7 with a frequency tolerance criterion of 1E-5, resulting in a design accidental load of 1,024 ppm and 205 kW/m^2. Similar to the example with explosion scenarios above, the DALs do not provide the duration of this load and building design can vary widely if these design loads are specified for 10 minutes, 30 minutes, 60 minutes, etc.

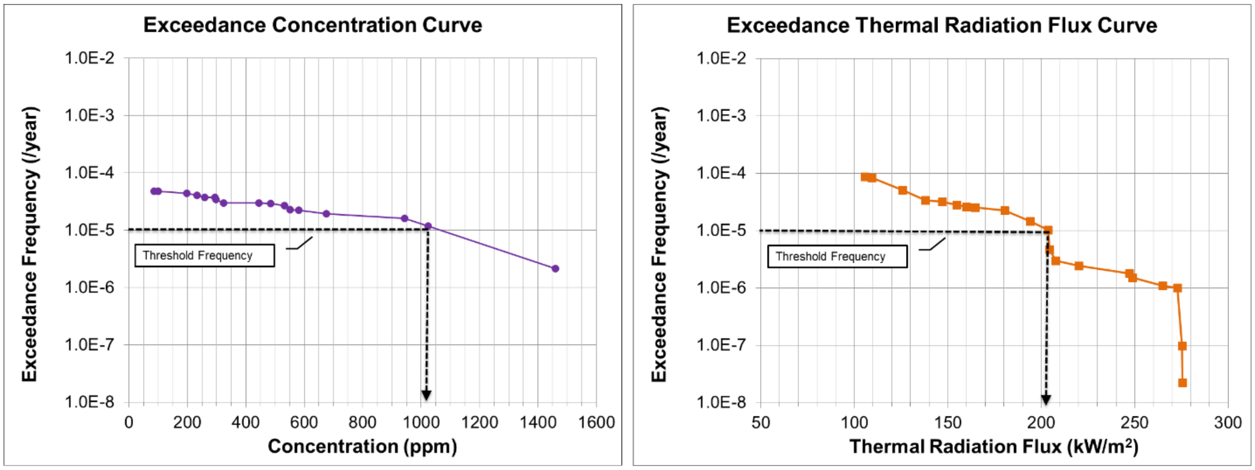


Figure 7: Frequency-Toxic and Frequency-Thermal Exceedance Curves

Occupant Vulnerability

Designing buildings using frequency-consequence exceedance curves does not require occupant vulnerability calculations, which makes the process much simpler and more straightforward than a risk-based process. However, since occupant vulnerability is not explicitly calculated, the inherent assumption in a frequency-based approach is that the vulnerability of all the scenarios that exceed the design criteria is 1 (i.e. 100% probability of fatality). This assumption is very conservative since occupant vulnerability varies from 0 to 1, which may result in much greater building design expenditures than actually required from a risk-based building design approach.

This concept is demonstrated with the same example presented above with 20 explosion scenarios defined by a pressure, impulse, and frequency in Table 1. The resulting frequency-pressure (F-P) exceedance curve is shown in Figure 5 above with a frequency tolerance criterion of 1E-5/year, resulting in a design pressure of 0.23 psig for the building. Figure 8 illustrates three potential identical building designs constructed with different materials (identical blast damage models with different occupant vulnerabilities) including a pre-engineered metal building, a steel-frame building, and a reinforced CMU building, which all meet the design pressure. The different building construction types have different occupant vulnerabilities for each building damage level, and thus results in varying individual risk levels as shown at the bottom of Table 3.

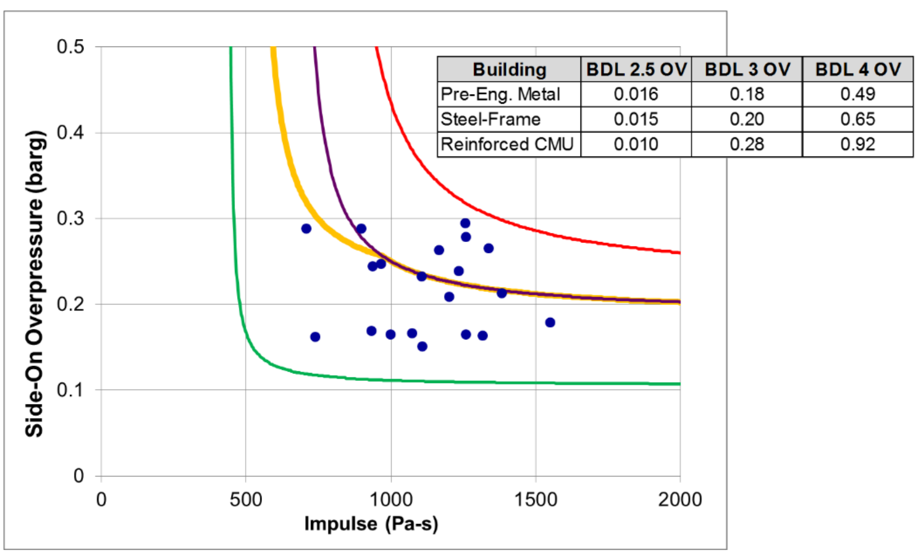


Figure 8: Example 2 – P-i Blast Scatter Plot for Three Identical Building Designs Constructed with Different Materials

Table 3: Example 2 – Blast Loads and Associated Damage Level and Risk for Three Identical Building Designs Constructed with Different Materials

				Building Damage Level			Explosion Occupant Vulnerability			Explosion LSIR (APoD)		
Blast Load ID#	**Overpressure (barg)**	**Impulse (Pa-s)**	**Frequency (/year)**	**Pre-Eng. Metal**	**Steel-Frame**	**Reinforced CMU**	**Pre-Eng. Metal**	**Steel-Frame**	**Reinforced CMU**	**Pre-Eng. Metal**	**Steel-Frame**	**Reinforced CMU**
1	0.295	1255	5.8E-8	3	3	3	0.18	0.2	0.28	1.0E-8	1.2E-8	1.6E-8
2	0.289	896	4.8E-7	3	3	3	0.18	0.2	0.28	8.7E-8	9.7E-8	1.4E-7
3	0.289	708	6.1E-7	2	2	2	0	0	0	0.0E+0	0.0E+0	0.0E+0
4	0.279	1257	6.8E-7	3	3	3	0.18	0.2	0.28	1.2E-7	1.4E-7	1.9E-7
5	0.266	1336	3.9E-7	3	3	3	0.18	0.2	0.28	7.1E-8	7.9E-8	1.1E-7
6	0.264	1166	9.0E-7	3	3	3	0.18	0.2	0.28	1.6E-7	1.8E-7	2.5E-7
7	0.247	965	8.4E-7	2	2	2	0	0	0	0.0E+0	0.0E+0	0.0E+0
8	0.245	935	8.8E-7	2	2	2	0	0	0	0.0E+0	0.0E+0	0.0E+0
9	0.239	1233	1.1E-6	3	3	3	0.18	0.2	0.28	2.0E-7	2.3E-7	3.2E-7
10	0.233	1106	1.8E-6	2	2	2	0	0	0	0.0E+0	0.0E+0	0.0E+0
11	0.213	1383	7.5E-6	2	2	2	0	0	0	0.0E+0	0.0E+0	0.0E+0
12	0.209	1201	8.4E-6	2	2	2	0	0	0	0.0E+0	0.0E+0	0.0E+0
13	0.179	1548	5.7E-6	2	2	2	0	0	0	0.0E+0	0.0E+0	0.0E+0
14	0.169	932	5.5E-6	2	2	2	0	0	0	0.0E+0	0.0E+0	0.0E+0
15	0.167	1072	9.8E-7	2	2	2	0	0	0	0.0E+0	0.0E+0	0.0E+0
16	0.165	1259	1.6E-6	2	2	2	0	0	0	0.0E+0	0.0E+0	0.0E+0
17	0.165	998	6.6E-6	2	2	2	0	0	0	0.0E+0	0.0E+0	0.0E+0
18	0.164	1315	2.5E-6	2	2	2	0	0	0	0.0E+0	0.0E+0	0.0E+0
19	0.163	738	4.9E-6	2	2	2	0	0	0	0.0E+0	0.0E+0	0.0E+0
20	0.152	1108	7.9E-6	2	2	2	0	0	0	0.0E+0	0.0E+0	0.0E+0
									Total =	**6.6E-7**	**7.3E-7**	**1.0E-6**

The impact of occupant vulnerability calculations on shelter-in-place (SIP) building designs can also be illustrated with thermal and toxic hazards. Consider the building of concern shown in Figure 9, which is susceptible to toxic impacts from multiple H2S sources. The exceedance concentration curve in Figure 7 above shows that for a threshold frequency of 1E-5/year, the concentration is 1,024 ppm. This external toxic concentration does not provide any information on the internal toxic concentration or occupant vulnerability associated with the internal toxic concentration. The impact of the building infiltration rate (0.1 ACH, 0.3 ACH, and 3 ACH) and HVAC isolation reliability (success 90%, failure 10%) on the internal concentration (at 60 minutes from start of the release) and the associated occupant vulnerability is shown in Table 4. The toxic individual risk results are shown in Table 5. Note that the risk results are dependent not only on the external concentration at the building, but also vary significantly depending on the toxic design of the building, which affects the internal concentration [Sarrack 2014]. Similarly, thermal individual risk results are dependent not only on the external thermal radiation at the buildings, but also vary significantly based on the thermal resistance of the building design.

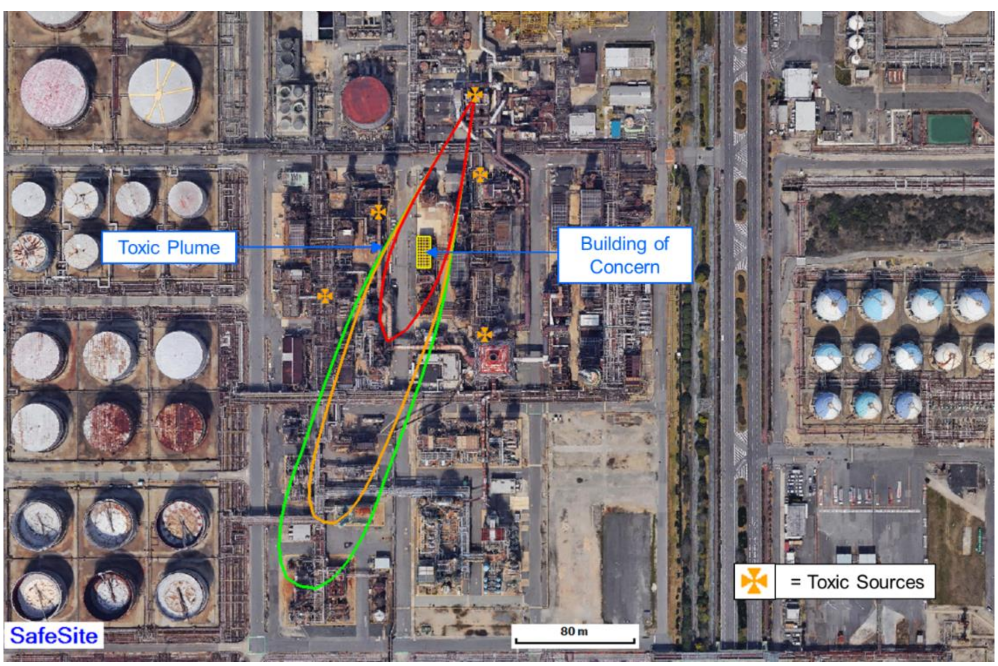


Figure 9: Example 3 – Building Susceptible to Toxic Impacts

Table 4: Example 3 – External / Internal Concentration and Toxic OV Results

			Internal Concentration (ppm)				Toxic OV			
Scenario: Weather	Scenario Frequency (/year)	External Concentration (ppm)	HVAC Isolation Success & 0.1 ACHs	HVAC Isolation Success & 0.3 ACHs	HVAC Isolation Success & 0.3 ACHs	No Isolation	HVAC Isolation Success & 0.1 ACHs	HVAC Isolation Success & 0.3 ACHs	HVAC Isolation Success & 0.3 ACHs	Toxic OV Isolation Failure
Source-X-150: D3.7/Wind Direction: 0	2.9E-6	581	55	150	552	579	0.01	0.09	0.58	0.63
Source-X-150: D3.7/Wind Direction: 22.5	3.3E-6	676	64	175	642	674	0.01	0.15	0.69	0.73
Source-X-150: D3.7/Wind Direction: 45	4.3E-7	551	52	143	523	549	0.00	0.08	0.54	0.59
Source-X-150: F1.8/Wind Direction: 0	4.7E-6	1023	97	265	972	1021	0.02	0.11	0.83	0.92
Source-X-150: F1.8/Wind Direction: 22.5	2.1E-6	1460	139	378	1387	1457	0.08	0.29	0.95	0.98
Source-X-150: F1.8/Wind Direction: 45	4.2E-6	943	90	244	896	941	0.01	0.08	0.79	0.90

Table 5: Example 3 – Toxic Risk Results

	Toxic LSIR (APoD)			
Scenario: Weather	0.1 ACHs	0.3 ACHs	3 ACHs	No Isolation
Source-X-150: D3.7/Wind Direction: 0	1.9E-7	4.1E-7	1.7E-6	1.8E-6
Source-X-150: D3.7/Wind Direction: 22.5	2.7E-7	6.8E-7	2.3E-6	2.4E-6
Source-X-150: D3.7/Wind Direction: 45	2.5E-8	5.3E-8	2.3E-7	2.5E-7
Source-X-150: F1.8/Wind Direction: 0	5.0E-7	8.9E-7	3.9E-6	4.3E-6
Source-X-150: F1.8/Wind Direction: 22.5	3.6E-7	7.7E-7	2.0E-6	2.1E-6
Source-X-150: F1.8/Wind Direction: 45	4.2E-7	6.9E-7	3.4E-6	3.8E-6
Total =	**1.8E-6**	**3.5E-6**	**1.4E-5**	**1.5E-5**

The benefit of frequency consequence exceedance curves is they do not require detailed occupant vulnerability calculations, which makes providing a DAL much simpler, easier, and straightforward. However, a DAL does not account for building construction or building design in terms of thermal or toxic resistance, which has a profound effect on the actual risk to building occupants.

Occupancy

The occupancy of a building is also not required when designing buildings utilising frequency-consequence exceedance curves. Therefore, the frequency design criterion of a building is typically the same regardless of the number of people occupying a building. This approach is similar to designing buildings based on an individual risk criterion.

Designing buildings utilising a frequency design criterion results in buildings being designed the same regardless of the potential consequence (number of people). Therefore, buildings with high occupancy will incur much greater societal risk than buildings with low occupancy. On the other hand, designing buildings employing a societal risk-based criterion results in the building design accounting for the potential consequence (number of people). Therefore, buildings designed for the same societal risk require a stronger design, greater thermal resistance, and/or greater toxic resistance for buildings with high occupancy than buildings with low occupancy.

The difference in using a frequency criterion and societal risk-based criterion in building design on the overall risk of a facility is illustrated in Figure 10. The facility has 4 buildings with varying average occupancy levels from 0.5 to 10. Each building in the left chart of Figure 10 is designed using a frequency tolerance criterion of 1E-4/year, the higher the occupancy the higher the societal risk, in this case the total societal risk of the facility is 1.8E-3 fatalities/year. On the other hand, each building in the right chart of Figure 10 is designed using a societal risk threshold of 1E-4 fatalities/year, in this case the building designs have to be improved to keep the societal risk within the threshold as occupancy increases yielding a total societal risk of 4E-4 fatalities/year. The example illustrates that the overall risk of the facility designed using a frequency tolerance criterion of 1E-4/year is 1.8E-3 fatalities/year while the overall risk of the facility designed using a societal risk tolerance criterion is much less at 4E-4 fatalities/year.

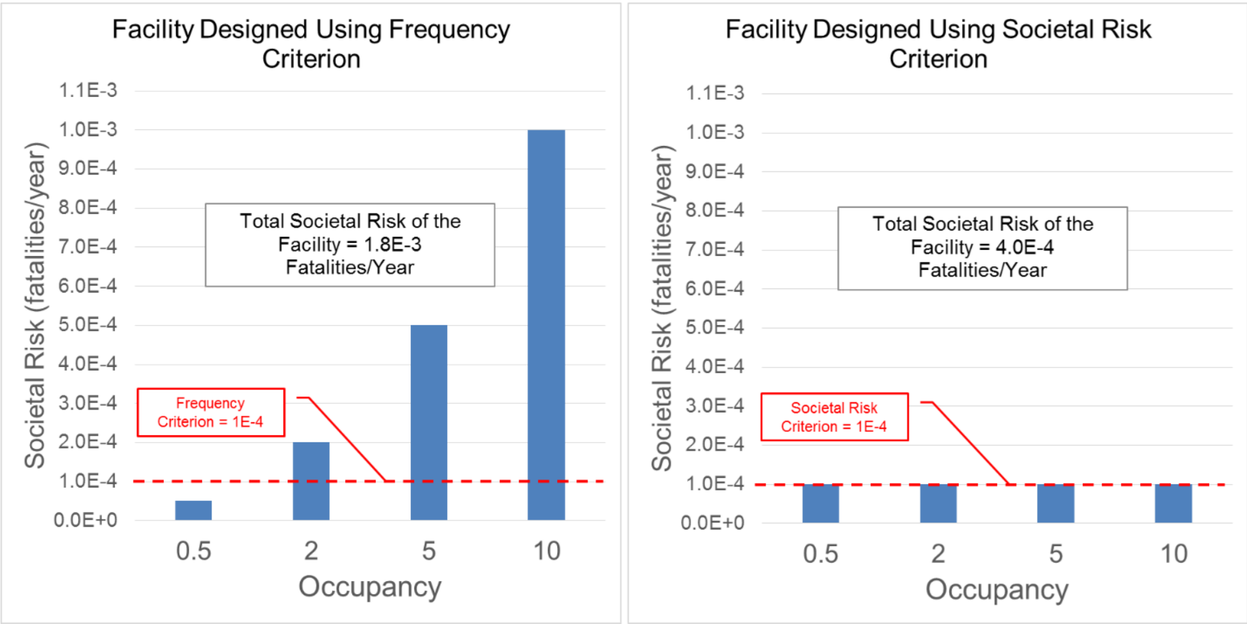


Figure 10: Difference in Using a Frequency Criterion and Societal Risk-Based Criterion in Building Design on the Overall Risk of a Facility

Typical frequency-number (F-N) risk tolerance criteria from the HSE UK [HSE UK, 2001] assuming a slope of -1 shown in Figure 11 and risk matrices also illustrate the concept that as the consequence (N) increases, the tolerable frequency of events decreases and as the consequence (N) decreases, the tolerable frequency of events increases. This approach aligns with utilising a societal-based risk criterion which accounts for the potential consequence in building design as well. Due to the impact occupancy can have on the societal risk of a building it is recommended that when utilising a frequency-consequence building design approach that occupancy be considered in the frequency tolerance threshold and as occupancy increases, frequency tolerance thresholds decrease.

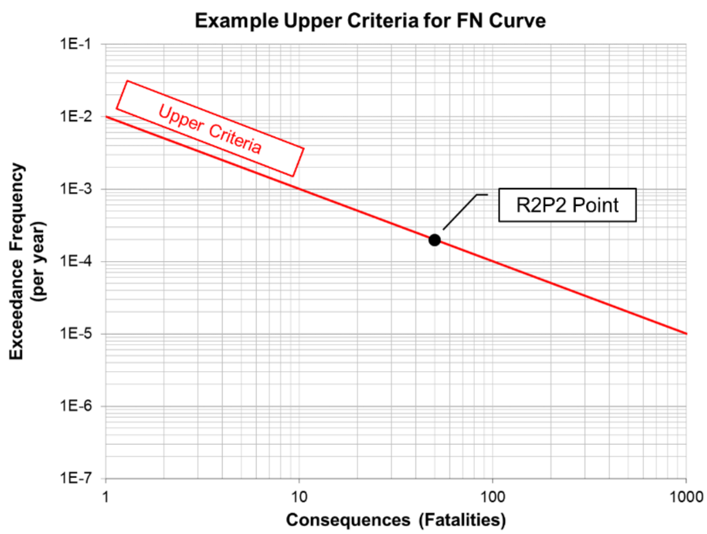


Figure 11: Example Upper Criteria for FN Curve

Conclusions

Building designs that consider the likelihood of events, such as a frequency consequence or risk-based approach are becoming more prevalent in industry. Therefore, it is important to fully understand the potential benefits and drawbacks of each approach. Regardless of utilising a frequency-consequence or risk-based building design approach, the approach should consider explosion, fire, and toxic hazards and should not just focus or be limited to a single hazard.

A frequency-based building design approach utilising frequency consequence exceedance curves requires less data and calculations than a risk-based building design approach using a QRA, which makes the frequency-based approach much simpler, easier, and straightforward than a risk-based approach. In addition, frequency-consequence exceedance curves provide a single design accidental load which simplifies the building design process for building design firms or EPCs. However, a frequency-based design approach also poses drawbacks and limitations including the lack of a specific design event duration, the additional conservatism in the design criteria from not explicitly assessing occupant vulnerability from explosion hazards, not accounting for the effect of the building construction or thermal/toxic resistance on occupant vulnerability, and not considering building occupancy.

A risk-based design approach considers the duration of each scenario assessed, explicitly calculates the occupant vulnerability of each scenario and typically considers building occupancy in the design. The drawbacks of a risk-based design approach include the additional time and effort required due to the detailed calculations and additional complexity of the approach, which can result in a longer building design process and additional expenditures during the design process. However, the detailed calculations and additional complexity (such as the explicit calculation of occupant vulnerability) also removes conservatism in the building design, which reduces the amount of building material needed to meet a tolerance criterion ultimately providing material cost savings to operating companies in excess of design process expenditures. Although a risk-based design approach may require more complex modelling, additional effort and time compared to determining a DAL, it is a much more comprehensive approach that fully quantifies the effectiveness of a building design.

References

Arendt J., 2003, "Using Quantitative Risk Assessment in the Chemical Process Industry," *Reliability Engineering & System Safety*, Volume 29, Issue 1, 1990, Pages 133-149.

CCPS 1999, *"Guidelines for Chemical Process Quantitative Risk Analysis. 2nd Edition,"* Center for Chemical Process Safety of the American Institute of Chemical Engineers, 2 Park Avenue, New York, New York, 1999.

DOD 2009, *"Approved Methods and Algorithms for DoD Risk-Based Explosives Siting,"* Department of Defense of the United States of America, Technical paper no. 14, Apt Research Inc. Huntsville AL.

Dyer, J., and Khandelwal, A., 2015, *"New Building Siting Using Risk-based Approach,"* 11th Global Congress on Process Safety, April 27-29, 2015

Dyer, J., and Smith, P., 2014, *"Building Blast Assessment and Upgrade Design Using a Risk-Based Approach,"* Hazards 24 Conference.

Dyer, J., Raibagkar, A., and Khandelwal, A., 2013, *"Design of Buildings in Petrochemical Facilities – Risk-based Approach,"* Hazards 23 Conference.

HSE UK, *"Reducing Risks Protecting People,"* Health & Safety Executive. 2001.

Khan, F., and Abbasi, S., 1998, *"Techniques and Methodologies for Risk Analysis in Chemical Process Industries,"* Journal of Loss Prevention in the Process Industries, Volume 11, Issue 4, July 1998, Pages 261-277.

Sarrack, A., *"Risk-Based Design of a Toxic Refuge,"* American Society of Safety Engineers, 12th Professional Development Conference & Exhibition, 2014.

Sarrack, A. *"Shelter-in-place Design Considerations – How Safe is Safe Enough?,"* 12th Global Congress on Process Safety, April 11-23, 2016.