CHEMICAL ENGINEERING TRANSACTIONS
VOL. 48, 2016
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Eddy de Rademaeker, Peter Schmelzer

ISBN 978-88-95608-39-6; **ISSN** 2283-9216
DOI: 10.3303/CET1648081

A Methodology for Determining Blast and Fire Risk to Safety Critical Equipment in the Chemical and Refining Industries

Thomas Anderson[a], Murtaza Gandhi[a], David Black[a], Anay Raibagkar[b], Peter Smith[c], Karen Vilas[a], Phillip R. Hodge*[a]

[a]Baker Engineering and Risk Consultants, Inc., 3330 Oakwell Court Suite 100, San Antonio, TX 78218-3024
[b]BakerRisk Canada, 5515 North Service Road, Suite 304, Burlington, Ontario, Canada L7L
[c]BakerRisk Europe Ltd, Thornton Science Park (Bldg. 49), Pool Lane, Ince, CH2 4NU, United Kingdom
PHodge@BakerRisk.com

Refineries and chemical plants use a myriad of protective layers around their sources of hazards in an effort to reduce the frequency of catastrophic losses; however, releases of hazardous materials still occur. When such events occur, plants often depend on critical pieces of equipment to safely shut down the plant and prevent escalation. As a result, it is important that this equipment, including the power and electronics to run these systems, survive the events for which they are designed to protect.
Properly protecting and siting this equipment is a key step in ensuring its survivability in the aftermath of a loss of containment event; however, current facility siting methodologies often focus on loss of life or loss of large product inventories. While buildings housing critical equipment may be assessed for consequence or risk, they may not consider the specific vulnerabilities associated with these safety systems. This paper outlines a method of assessing the blast and fire vulnerability, and the blast and fire risk to safety critical systems in the chemical and refining industries, which historically contribute the bulk of accident financial impact. This methodology is used to develop several case studies and offers solutions to improve the availability of these systems in the event of an accident.

1. Introduction

Common techniques for assessing the risk of fires and explosions (HAZOP, LOPA, quantitative risk assessments (QRA), etc.) often focus on the vulnerability of plant personnel. Other studies such as insurance risk assessments or business interruption assessments often focus on large inventories or key pieces of process equipment. Even though an underlying assumption in many of these studies is that equipment is available to safely shut down a unit to prevent escalation, rarely do these studies explicitly look at the quantitative risk posed to safety critical equipment (SCE). If these systems are assessed for risk or consequence, they may be assessed using overly simplistic means which do not account for the specific equipment vulnerabilities (EV).

SCE can encompass a wide range of items within a plant. Common equipment may include but are not limited to motor controls, electrical transformers or switchgears, fire water pumps, generators, deluge systems, pressure relief systems, the associated tanks, piping, wiring, cable trays, and racks associated with the equipment. Based on the need for weather protection, SCE may be located outdoors or inside of buildings. SCE equipment located outdoors may be impacted directly by hazards. SCE located indoors may experience the same event in a different manner due to the response of the surrounding structure. This paper details a method for predicting the damage from fires and explosion to SCE located within buildings in the process industries. Three applications of the methodology are presented using either a risk or consequence based approach.

Please cite this article as: Hodge P., Anderson T., Smith P., Vilas K., Black D., Gandhi M., Raibagkar A., 2016, A methodology for determinging blast and fire risk to safety critical equipment in the process industries, Chemical Engineering Transactions, 48, 481-486 DOI:10.3303/CET1648081

2. Methodology

This section outlines the methodology used to determine the risk to SCE in a process facility and assumes that information from a comprehensive QRA or similar study is available. The analysis and case studies presented in this paper utilize Baker Engineering and Risk Consultants, Inc.'s (BakerRisk®) proprietary dispersion, fire, and blast modelling software, SafeSite$_{3G}$©, to model thousands of fire and blast scenarios. Other methods of conducting the hazard analysis and QRA are available (AIChE/CCPS, 2000), but should consider the range of possible conditions (magnitude, duration, wind direction, weather conditions, etc.) that would impact each building housing SCE. Figure 1 below shows a flowchart of a typical QRA methodology. This paper focuses on the vulnerability portion of the assessment.

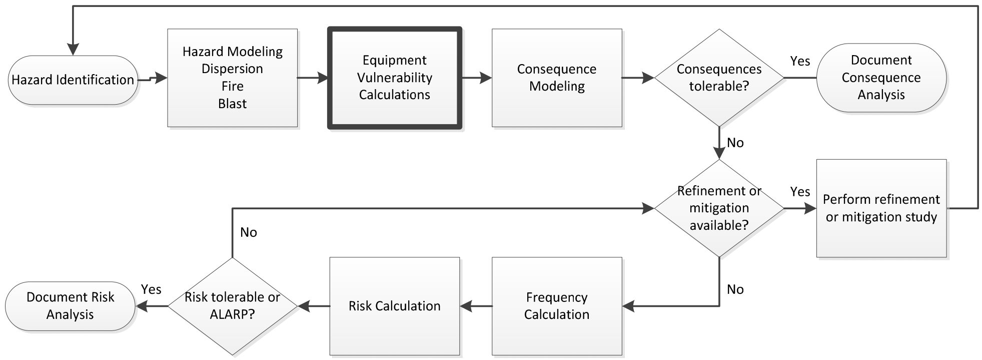

Figure 1: Typical QRA methodology

2.1 Blast EV

Blast EV represents the fraction of equipment within a building that will sustain damage to the point of losing functionality as a result of overall building damage experienced during an explosion. Blast EV is dependent on the predicted building damage level (BDL), the location of the equipment within the building floor plan, the sensitivity of the equipment to sudden movement or impact, and the equipment support conditions. The BDL is dependent on the construction of the building and the pressure and impulse of the blast wave hitting the building. Various methods exist for calculating the BDL. The case studies utilize the method described by Baker, 2002.

The support conditions for the equipment are influenced by the age of the supports, the potential for slippage, and the strength of the attachment. The primary factor, however, is the location of the attachment. Equipment is, in general, sensitive to sudden movement and excessive vibrations. Surface (wall or ceiling) mounted equipment would be subjected to the response of the surface to which they are mounted. Therefore, it is anticipated that the EV values would be significantly greater than that of non-surface-mounted equipment for the same predicted BDL. Based on equipment mounting, Figure 2 and Figure 3 show a building with high EV and low EV respectively. Table 1 describes the five BDLs and the potential equipment damage associated with the BDL. Based on evidence collected through numerous industrial accident investigations, BakerRisk has determined that there is a significant increase in potential EV for surfaced-mounted equipment. As such, EV values are developed for both types of mounting and are reported in Table 2.

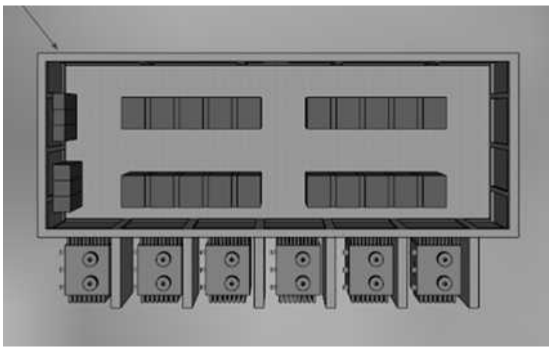

Figure 2: Example substation layout with high EV

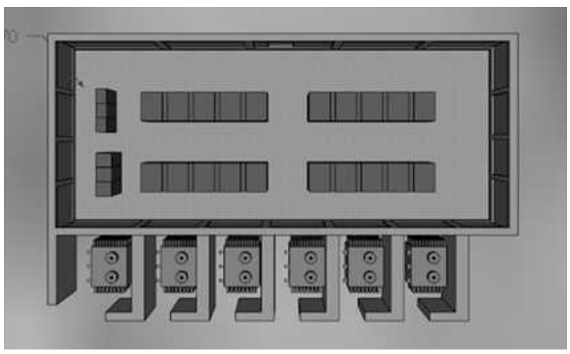

Figure 3: Example substation layout with lower EV

Table 1: BDL descriptions and potential equipment damage

BDL	Potential building damage	Potential equipment damage	
		Surface-mounted	Not surface-mounted
BDL 1 Minor Damage	Walls sustain the onset of visible damage. Repairs are necessary for cosmetic reasons only.	A very low probability of equipment failure is predicted when exterior walls sustain the onset of visible damage and equipment is mounted to these surfaces.	No loss of equipment functionality is anticipated.
BDL 2 Moderate Damage	Localized damage. Walls facing the blast sustain moderate damage, while other walls and the roof sustain minor to moderate damage. Building can be repaired and reused.	A moderately high probability of equipment failure is predicted when an exterior wall sustains moderate damage.	A very low probability of equipment failure is predicted when exterior walls or the roof sustains moderate damage and equipment is mounted off exterior surfaces.
BDL 2.5 Heavy Damage	Widespread building damage. Walls facing the blast fail or sustain major damage, while other walls and the roof sustain moderate damage. Building repair may not be practical.	A high probability of equipment failure is predicted when an exterior wall fails or sustains major damage.	A moderate probability of equipment failure is predicted when an exterior wall fails or sustains major damage due to damage to key pieces of equipment resulting from debris.
BDL 3 Major Damage	Walls facing the blast fail, while other walls have compromised structural integrity. This may cause eventual collapse of the building. Building repair is not practical.	The equipment is predicted to completely lose functionality due to exterior wall failure.	A high probability of equipment failure is predicted when exterior walls fail due to damage to the majority of equipment resulting from debris.
BDL 4 Building Collapse	Primary and secondary structural members fail or sustain major damage resulting in building collapse.	The equipment is predicted to completely lose functionality due to building collapse.	The equipment is predicted to completely lose functionality due to building collapse.

Table 2: BDL vs EV

BDL	EV	
	Surface-mounted	Not surface-mounted
1	1%	0%
2	70%	1%
2.5	90%	50%
3	100%	90%
4	100%	100%

2.2 Fire EV

In general, a heat flux value of 25 kW/m^2 is used as a guideline for the onset of damage for process equipment (Barry, 1995). However, this value does not represent damage to the more vulnerable electrical systems controlling the equipment. Most SCE will include electronic controls either in the form of power management or remote control of start-up, which will likely be the most sensitive part of the equipment.

The key metrics to determine the fire EV of the SCE are the thermal load on the exterior of the building, the duration of the flame, the thermal resistance of the building, the air mixing within the building, the location of the equipment within the building, and the failure mode of the electronics within the building. Values for the thermal resistance of generic metal and concrete masonry unit (CMU) buildings are provided in Table 3 below. A 1-D transient heat transfer analysis was used to calculate the temperature rise in the building. For a screening-level analysis, the electronics have been assumed to be located on the wall impacted by the jet fire, the air inside the building is assumed to be perfectly mixed to maintain conservatism, and the HVAC system is assumed to fail quickly and provide minimal cooling to the exposed building. However, more rigorous modelling can be used to remove conservatisms.

The recommended screening-level thermal EVs are presented in Table 4 below. The number, type and make-up of the electrical controls used in a typical chemical processing facility can range between a few hundred to thousands; therefore, it would not typically be cost effective to assess the vulnerability of each type of equipment separately. Moreover, the vulnerability of the equipment can range from 0% to 100% over a wide range of temperatures. For a screening level study, a value of 50° C is recommended as a threshold value to model a 100% failure of all electronic controls with an EV of 0% for building temperatures below 50° C. This binary form of vulnerability assessment is conservative as 50° C represents a lower bound value for most electrical devices (Scheffey, 1990). For a more detailed analysis, these assumptions could be altered to reflect the specifics of the electronics.

Table 3: Heat transfer analysis properties

Type	K (W/m·K)	Rho (Kg/m3)	Cp (J/kg·K)
Metal	0.05	28	1,700
CMU	1.6	114	920

Table 4: Screening study fire EVs

Temperature inside building	EV
Above 50° C	100%
Below 50° C	0%

2.3 Risk determination

The consequence of losing a given piece of SCE will vary substantially based on the nature of the SCE and the magnitude of the event. Consequences can be left as simple failures of the SCE for screening studies, or detailed event trees can be constructed. Loss of containment failure rates can be determined via a simple parts count approach or detailed fault trees as warranted by the scope of the study. The case studies presented in this paper use a parts count approach to the frequency calculation and a combination of different approaches to arrive at the consequence of the event.

3. Case Studies

The following three case studies illustrate different uses for finding the EV of SCE. The first is for a screening study of a large greenfield project. The second looks at finding an appropriate location for SCE within a designed facility. The final case study shows how an EV assessment can prompt changes to existing facilities.

3.1 Greenfield screening

During the FEED stage of a new chemical plant design, the project requested that a QRA be conducted for the proposed site. Functionally occupied buildings were assessed for risk using occupant vulnerabilities and unoccupied buildings were to be assessed for EV. This resulted in 166 buildings analysed for EV, 58 of which were predicted to experience negligible risk (<1E-5 failures per year). Another 72 buildings were dismissed as not being critical to the safe shutdown of the plant or post-incident response. Of the remaining 36 buildings, 7 had risk in excess of 1E-3 failures per year and were identified as candidates for further analysis. Using the screening methodology allowed the project to identify their high risk areas and prioritize resolving those issues early in the design stage.

Table 5: Greenfield screening study EV risk summary

Building	Blast Failures/year	Fire Failures/year	Total Failures/year	Mitigation Plan
Unit 3 Deluge Building	4.2E-3	5.0E-5	4.2E-3	Building relocated
Unit 3 Substation	4.2E-3	4.7E-5	4.2E-3	Building strengthened and wall mounting removed
Unit 4 MCC	3.3E-3	5.1E-7	3.3E-3	Wall mounting removed
Unit 3 MCC	3.2E-3	2.9E-5	3.2E-3	Building relocated
Unit 5 Deluge Building	2.9E-7	3.2E-3	3.2E-3	Thermal insulation added
Unit 1 Instrument Enclosure	2.7E-3	4.8E-7	2.7E-3	Refined modelling lowered risk to acceptable range
Unit 4 Substation	1.5E-3	4.4E-5	1.5E-3	Refined modelling lowered risk to acceptable range

3.2 Placement of electrical substation

As part of an expansion project, a refinery was installing a new substation to handle four new units. During the HAZOP for the units, a loss of power scenario was identified for one of the units that would result in a large hydrocarbon release and significant damage to the process equipment. There were no significant impacts to the other three units on a loss of power. A detailed fault tree was performed to determine the frequency of loss of power. A backup generator was added to the project to improve the availability of the system should power from the neighbouring CoGen facility be lost. However, a single point of failure was identified for the system. The power from both the CoGen plant and the backup generator was routed through the substation.
A QRA was conducted for the expansion and the data could be utilized to determine the EV of the substation. As the project was in the early stages of design, there was opportunity to move the substation. The project requested that iso-vulnerability contours be drawn to determine a safe location for the substation. Both surfaced-mounted and non-surface-mounted options were considered to generate Figure 4 below.
The generated contours showed that the current location of the substation was inadequate, but a viable alternative was not available. The project determined that the unit in question could be removed from the analysis. They did this on the grounds that if a major accident occurred within this unit, it would no longer be a concern if the substation remained operational. The other three units could be shut down safely without the substation. A refinement was done to remove the unit from the analysis, which generated the contours in Figure 5. The refinery then used these contours to determine an acceptable location for the substation using equipment that was not wall or ceiling mounted. Risk contours were also generated, but the project elected to use a consequence based approach.

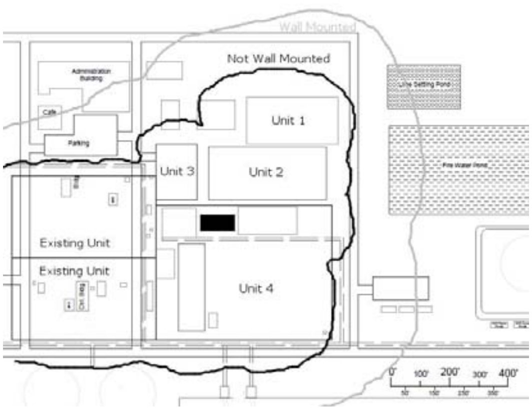

Figure 4: 4 unit iso-vulnerability contours

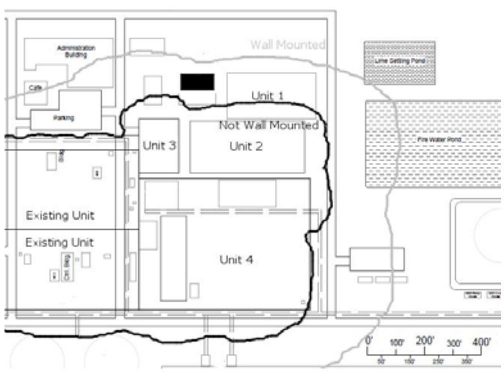

Figure 5: 3 unit iso-vulnerability contours

3.3 Detailed fire water pump analysis

Due to concerns with an environmental study, a chemical plant built its fire water pump house in the middle of the facility surrounded by units containing highly flammable materials. During the course of a QRA, the plant requested an assessment of the risk to the fire water pump from the surrounding units to determine the

likelihood of firewater unavailability. The results of the EV study showed that the firewater pump had risk in excess of 1E-4 failures per year with the majority of the risk from blast sources.
The plant wished to reduce this risk of fire water unavailability to below 1E-4 failures per year. The fire water pump had a remote start panel that was wall-mounted. A risk based design of the building was performed to strengthen the walls of the fire water pump house and a recommendation was made to move the remote start panel off of the wall to a location near the pump. The resulting risk showed over an order of magnitude decrease. See Table 6 below for the change in risk values.

Table 6: Firewater pump house equipment risk

Case	Blast Failures/year	Fire Failures/year	Total Failures/year
Existing	7.8E-4	1.3E-5	7.9E-4
Mitigated	5.7E-5	1.3E-5	6.0E-5

4. Conclusions

When considering plant safety, safety critical equipment is often assumed to be available in the aftermath of a loss of containment without rigorous consideration of the validity of the assumption. Information available from a facility siting study or quantitative risk assessment can be used to quantitatively perform this analysis and improve the reliability of the system. Key considerations for the study are the presence of surface-mounted equipment and the thermal sensitivity of electrical components in the building under consideration. In general, removing surface-mounted equipment from the walls and ceilings potentially exposed to blast loads can significantly reduce the predicted blast EV. Increasing the thermal resistance of a building and ensuring that cable trays are not exposed to significant fire hazards are methods of reducing the fire EV. When possible, these considerations should be done early in the design phase of a project when it is still feasible to move equipment and reduce hazards to improve the safety of the plant. When relocation is no longer an available option, building upgrades can be implemented to improve the building response to blast and fire hazards.

Reference

AIChE/CCPS, 2000, Guidelines for Chemical Process Quantitative Risk Analysis 2nd Edition, Center for Chemical Process Safety, American Institute of Chemical Engineers, New York, NY, USA.

Baker QA, 2002, Explosion Risk and Structural Damage Assessment Code (ERASDAC), 30th DoD Explosive Safety Seminar, Department of Defense Explosive Safety Board, Arlington, VA, USA

Barry T.F., 1995, An Introduction to Quantitative Risk Assessment in Chemical Process Industries, The SFPE Handbook of Fire Protection Engineering, 3rd Edition, NFPA, Quincy, MA, USA.

Scheffey JL, Jona LA, Toomey TA, Byrd R, and Williams FW, 1990, Analysis of Quick Response Fire Fighting Equipment on Submarines-Phase II, Full Scale Doctrine and Tactics Tests, NRL Memorandum Report 6632, Naval Research Laboratory, Washington, DC, USA.