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

Phillip Hodge, Process Safety Senior Consultant, Baker Engineering and Risk Consultants, Inc., 11011 Richmond Avenue, Suite 700, Houston, Texas, USA 77042-6702

T. Anderson, M. Gandhi, D. Black, A. Raibagkar, K. Vilas, Baker Engineering and Risk Consultants, Inc.

P. Smith, BakerRisk Europe Ltd.

Refineries and chemical plants use a myriad of protective layers around their sources of hazards in an effort to reduce the frequency or mitigate the consequences of potentially catastrophic incidents; however, the risk of a release of hazardous materials still exists. When such events occur, plants often depend on critical pieces of equipment to safely shut down the plant and prevent escalation of the incident. As a result, it is important that this equipment, including the power and electronics required to activate these systems, survives the impact of the events they are intended to protect.

Properly protecting and siting this equipment is a key step in ensuring its survivability in the aftermath of an event. Current facility siting and occupied building risk assessment methodologies often focus solely on loss of life or loss of large product inventories and are prone to miss the vulnerability of safety critical systems. Occupied buildings may be assessed for consequence or risk with respect to building occupants; however, the analysis may not consider the specific vulnerabilities associated with damage to the safety systems contained in the building. Furthermore, there may be a multitude of additional buildings containing safety critical equipment that have been filtered from the study and receive minimal analysis because they do not qualify as occupied.

When considering safety critical equipment, one must consider the specific failure modes and vulnerabilities of the safety systems being assessed. Applying the same criteria as a typical occupied building assessment may be inadequate to model the risk to the system. Another important consideration is that safety critical equipment housed in buildings may respond significantly differently than if located outdoors.

This paper outlines a method of screening indoor safety critical equipment in the chemical and refining industries for blast and fire vulnerability and risk using data already available in the occupied building risk assessment. This methodology is then applied to develop a case study for a chemical facility that identifies safety critical equipment warranting further study or requiring damage mitigation, and outlines solutions to improve the availability of these systems in the event of an accident.

Introduction

Events over the last few years have demonstrated that despite careful risk management, the potential impact of fires, explosions, and natural hazards can result in a greater loss than anticipated. When considering such events, often the first instinct is to add safety systems to mitigate the consequence or prevent escalation. The more severe or likely the event, the more protective layers are put in place. However, it is important that these protective layers are reliable, available, and operate as intended.

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 refer to a wide range of items within a plant such as deluge systems, pressure relief devices, etc. Often these systems depend on elements not typically classified as safety critical, for example motor controls, electrical transformers or switchgears, generators, firewater tanks, cable trays, and pipe racks. These systems may be damaged by the very event they are designed to mitigate. Based on the need for weather protection, SCE may be located outdoors or inside of buildings. SCE 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.

Proper design, siting, and protection of key equipment are critical steps in ensuring its survivability in the aftermath of an event. However, protective systems are often located based on cost or convenience. In addition, key pieces of SCE may be unintentionally excluded in a typical siting study which may only focus on personnel injury or major inventory losses. The information available in a siting study or QRA can be easily modified to include the hazards and risk to SCE to screen for scenarios that warrant further investigation. These scenarios can then be developed to explore the specific vulnerability of the SCE. The consequence of losing a given piece of SCE can also be studied through the use of detailed event trees. The same techniques can then be used to examine mitigation options. 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.

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 whatever method is used it is important to 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.

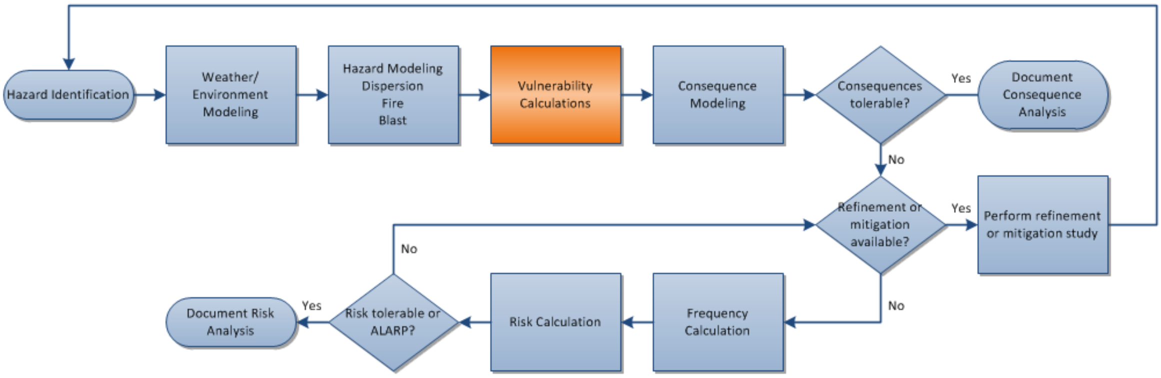

Figure 1. Flowchart of a Typical QRA Methodology

Blast Equipment Vulnerability

Blast equipment vulnerability (EV) represents the likelihood that a piece of equipment within a building 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.

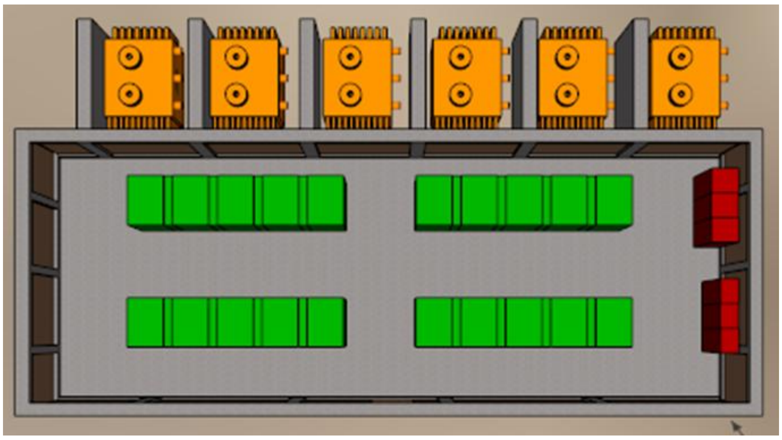

Figure 2. Example Substation Layout with High EV

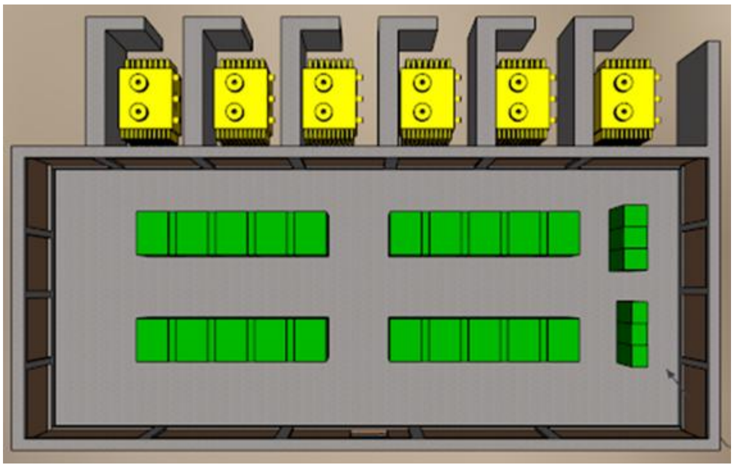

Figure 3. Example Substation Layout with Lower EV

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. Relationship Between BDL and EV

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

Fire Equipment Vulnerability

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 equipment vulnerability (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/m^3)	C_p (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%

Risk Determination

Once the EV determination is complete, consequence modelling should be done to determine the impact of the failure. The consequence of losing a given piece of SCE will vary 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 to more adequately represent the loss of the SCE. 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.

Case Studies

The following three case studies illustrate different uses for finding the EV of SCE. The first case uses data from a QRA to conduct a screening study for a greenfield site. The second example uses risk based contours to develop locations for the placement of an electrical substation. The final example uses more detailed consequence modelling to explore the hazards to the fire water pump house and the associated equipment.

Case 1 - Greenfield Screening

During the design phase of a chemical plant, the project safety engineers requested that a QRA be completed for the site. Of the 178 buildings on site, 74 were deemed to be functionally occupied and were assessed for typical occupant vulnerabilities. The remaining 104 buildings included analyser shelters, remote instrument enclosures, unit substations, motor control centres, and deluge buildings. Typically these buildings would be excluded from the study, however, the project elected to assess them for EV. Of the buildings analysed, 36 of the buildings were predicted to experience negligible risk (<1E-5 failures per year). Forty of the buildings did not house SCE and were deemed to have negligible consequence upon failure. Of the remaining 28 buildings, 5 had risk in excess of 1E-3 failures per year. The project identified these buildings as candidates for further analysis and potential mitigation. Table 5 shows the 5 identified buildings and the mitigation measures used to bring their risk below 1E-3 failures per year.

Table 5. Greenfield Screening Study EV Risk Summary

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

Four of the buildings failed due to blast risk. For the Unit 1 Substation, an alternate location was available. The building was relocated in the model, and the sensitivity study was reassessed. It was found that moving the building to the new location reduced the risk to under 1E-3 failures per year. The Unit 3 Deluge Building could not be relocated due to a lack of available land. Instead, the structural design of the building was examined. Equipment and instrument panels were removed from the walls allowing the lower EV values to be used. The overall blast response for the building was improved using standard dynamic design considerations. The original and adjusted Pressure-impulse curves for the building are shown in Figure 4 and Figure 5. A similar analysis was performed for the Unit 3 MCC, but only the removal of wall and ceiling mountings were deemed necessary. The Unit 4 Substation could not be relocated and strengthening the building was not practicable for the project. Instead the leading blast scenarios were refined using Computational Fluid Dynamics (CFD). The CFD cases resulted in lower pressures that were able to drop the risk to the building below 1E-3 failures per year. The Unit 5 Deluge Building exceeded the project’s risk tolerance due to thermal hazards. Additional thermal insulation was added to the building in order to increase the survivability of the SCE.

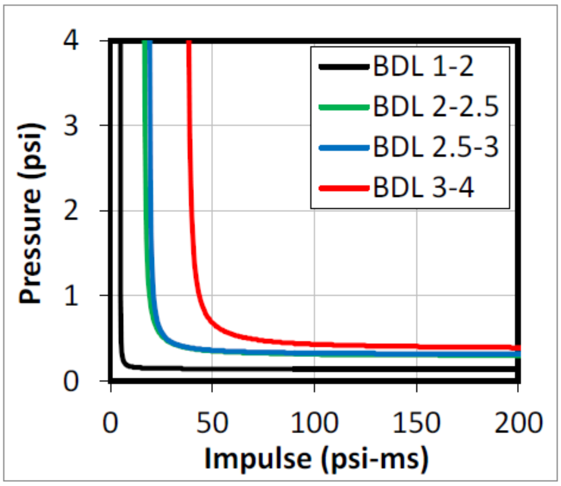

Figure 4. Original Pressure-impulse Curves

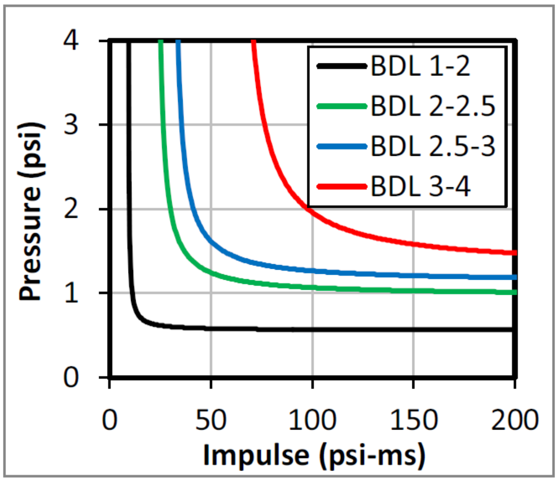

Figure 5. Adjusted Pressure-impulse Curves

Case 2 - Placement of Electrical Substation

As part of an expansion project, a chemical facility 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 in order that the data could be utilized to determine the EV for 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 6 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 7. 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.

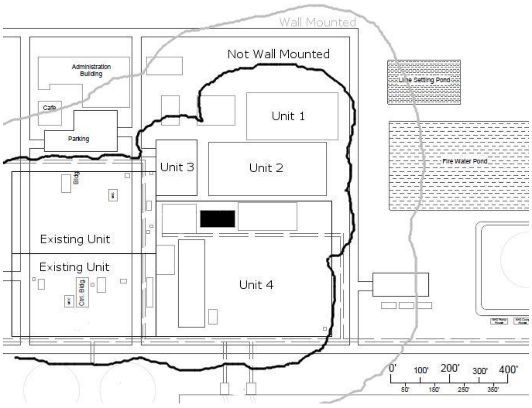

Figure 6. Four Unit Iso-Vulnerability Contours

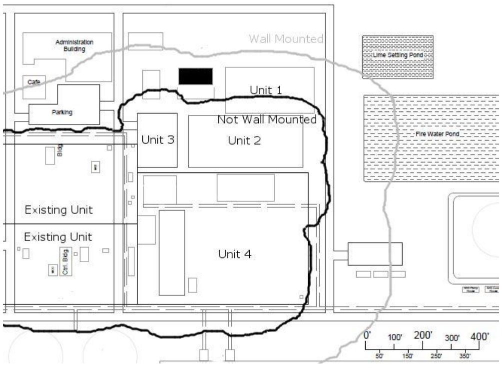

Figure 7. Three Unit Iso-Vulnerability Contours

Case 3 - Detailed Fire Water Pump Analysis

Due to concerns raised by an environmental impact study, a refinery had built its fire water pump house in the centre of the plant surrounded by units containing highly flammable and explosive materials. The refinery was concerned that an explosion or fire could damage the fire water pump, making it unavailable to respond to the event. The pump was expected to experience risk in excess of 1E-4 failures per year, which the facility deemed to be intolerable. The refinery wanted to reduce the risk to the fire water pumps so a plan was developed to upgrade the building to lower the risk of unavailability.

At the same time, external diesel tanks which held the fuel for the pump were considered. The site wanted assurance that the tanks could survive the maximum blast loads. A detailed consequence analysis was performed using CFD techniques to model the blast loads hitting the tanks and the response of the tanks and the support structures. It was determined the tanks did not fail under the maximum loads predicted to impact them. Figure 8 below shows the effective stress on the tanks as they are loaded by a blast wave.

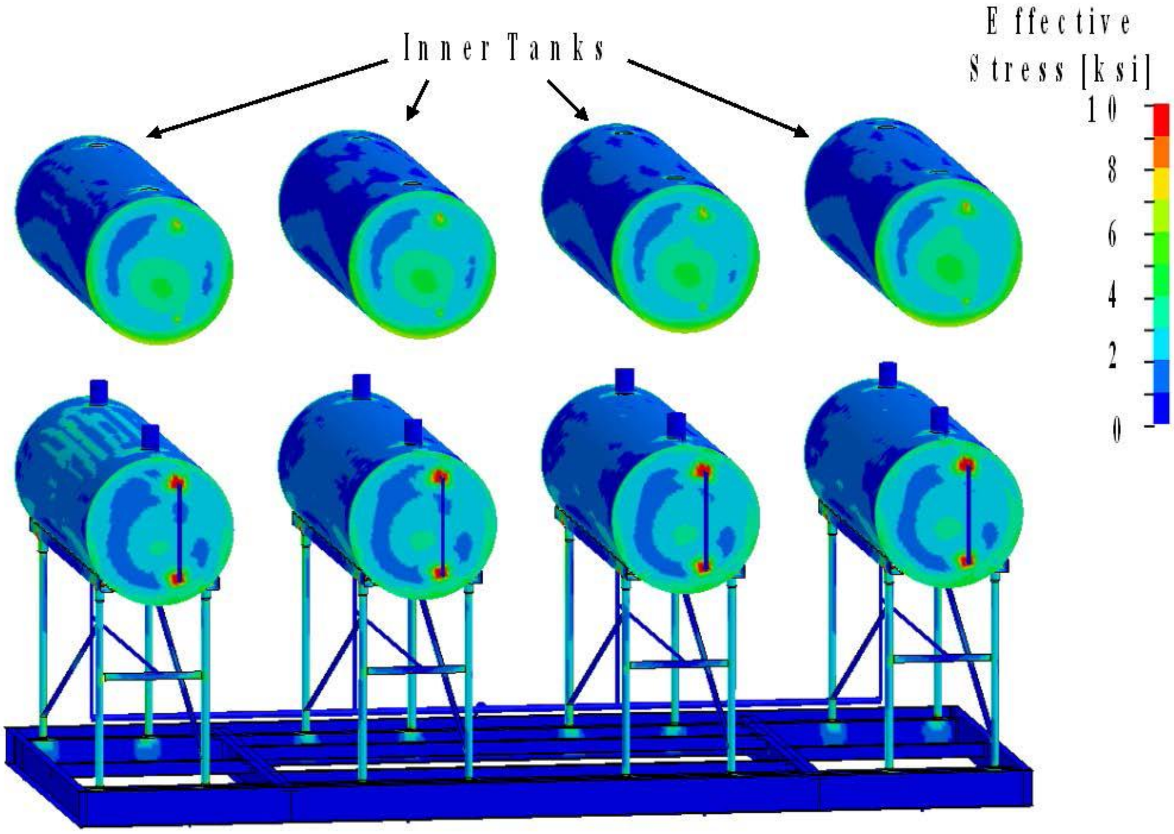

Figure 8. Outdoor Storage Tanks

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. Screening studies can utilize information available from a facility siting study or quantitative risk assessment to quantitatively assess the availability of SCE after a blast or fire event. The main addition to the QRA is the determination of EV. The EV screening analysis proposed in this paper is primarily affected by 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, removing windows, and ensuring that cable trays are not exposed to significant fire hazards are methods of reducing the fire EV. This paper also shows how refinements to the screening level EV and risk model can be used to refine the analysis. 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.

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