Risk-Based Analysis and Engineering of Safe Distances Between Occupied Structures and Processing Equipment

J. E. Johnstone, M. D. Spangler, C. S. Heitzman, G. A. Wimberley, and **A. R. Flores,** Contek Solutions

Summary

Determining the optimal distance between explosive, flammable, and toxic hydrocarbon sources and occupied structures is a constant concern for engineers working to design safe facilities. Over the years, many incidents have occurred during which workers were injured or killed by flying shards of glass and debris, explosive forces, fire, or exposure to toxic gases when occupied structures were not located properly in relation to process equipment. This paper presents newly developed techniques to allow the engineer to locate occupied structures optimally to ensure that the risk of harm to personnel is minimized.

The analysis of determining the placement for an occupied structure involves many variables that the engineer must evaluate. These variables include the properties of the hydrocarbons that are being processed, toxic components (e.g., hydrogen sulfide), operating parameters, loss-of-containment scenarios, prevailing winds, occupancy loads, building construction, safety systems, and operating and maintenance practices. Each of these different variables can have a significant impact on where a building should be located within or adjacent to a facility. The engineer must consider these variables for impacts to the structure caused by fire, blast, or toxic-gas infiltration.

Recognized industry best practices and regulatory requirements require that blast loads, which commonly present the most-severe hazard to a building, be evaluated when locating an occupied structure. Often, it is not practical to design or locate a building to withstand the "worst-case" blast scenario. For this reason, a risk-based approach, in conformance with recognized best practices, has been developed to site buildings properly at oil and gas facilities.

This paper presents a viable risk-based approach for the siting of occupied structures at oil and gas facilities. The technique presented in the paper enables the engineer to gather the information needed for the analysis quickly, evaluate credible scenarios, and then make the necessary calculations to determine impacts to the occupants. The result of using this technique is that an occupied structure is located properly and constructed to reduce the risk of harm to the occupants to a tolerable level.

Introduction

The siting of buildings at upstream and midstream oil and gas facilities is described in *API RP 752, Management of Hazards Associated with Location of Process Plant Permanent Buildings* (2009). Buildings covered by this recommended practice include rigid structures intended for permanent use in fixed locations. *API RP 752* (2009) sets the bar for recognized and generally accepted good-engineering practices for the oil and gas industry.

This paper (SPE 173507) was accepted for presentation at the SPE E&P Health, Safety, Security, and Environmental Conference—Americas, Denver, 16–18 March 2015, and revised for publication. Original manuscript received for review 18 December 2014. Revised manuscript received for review 24 February 2015. Paper peer approved 19 March 2015.

API RP 752 (2009) allows for the evaluation of building locations to use three different assessment approaches:

1. Consequence-based analysis: This approach generally requires that the impacts from maximum credible events (MCEs) be calculated or modeled to determine the impact on a structure.
2. Risk-based analysis: Use of risk-based analysis involves conducting a quantitative analysis to determine risk on the basis of the consequence and the frequency of the hazardous event.
3. Spacing-tables approach: Under *API RP 752* (2009), the spacing-table approach is to be used only when determining the minimum distance from a fire to a building. These tables are not appropriate for toxic or explosive events for which the consequence is dependent on the release rate, length of release, wind direction, material released, and many other factors.

API RP 752 (2009) was developed primarily for use at facilities that include natural-gas plants, natural-gas-liquefication plants, and other onshore facilities covered by the Occupational Safety and Health Administration (OSHA) process-safety management standard (OSHA 1992). *API RP 752* (2009) provides an excellent overview of the issues and factors regarding hazards associated with buildings and provides references as to where additional information can be obtained. The recommended practice does not provide information relating to an oil-production or a gas-treatment facility, detailing out critical items such as MCEs, impacts from hazardous incidents, acceptatble risk criteria, and risk analaysis.

The objective of this paper is to present a detailed approach that can serve as the basis for determining safe distances between buildings and processing equipment.

Consequence-Based Analysis

A consequence-based analysis should be conducted first to determine if a structure can be impacted by an explosion, toxic release, or a fire. This technique looks at the on-site "manned" structures and the hazards presented by process equipment and storage vessels on occupied buildings. Modeling software can use pure chemicals or mixtures for its dispersion modeling. The dispersion models are created by use of a wind blowing directly toward the equipment to the building under analysis to determine the worst case. The instructions given in *API RP 752* (2009) should be strictly followed for determining impacts on any buildings. This analysis reveals the presence of any underlying proximity issues and offers specific scenarios and their related impacts, in addition to identifying the highest consequence each piece of equipment presents.

For existing buildings, it may be found that a building will provide either enough protection for the occupants or not. New buildings must be designed to protect the occupants on the basis of the results of the impacts from the hazardous event. A mitigation plan must be developed for existing buildings that do not meet the siting-evaluation criteria.

Mitigation measures are categorized as being passive, active, or procedural. These measures may require the operator to eliminate

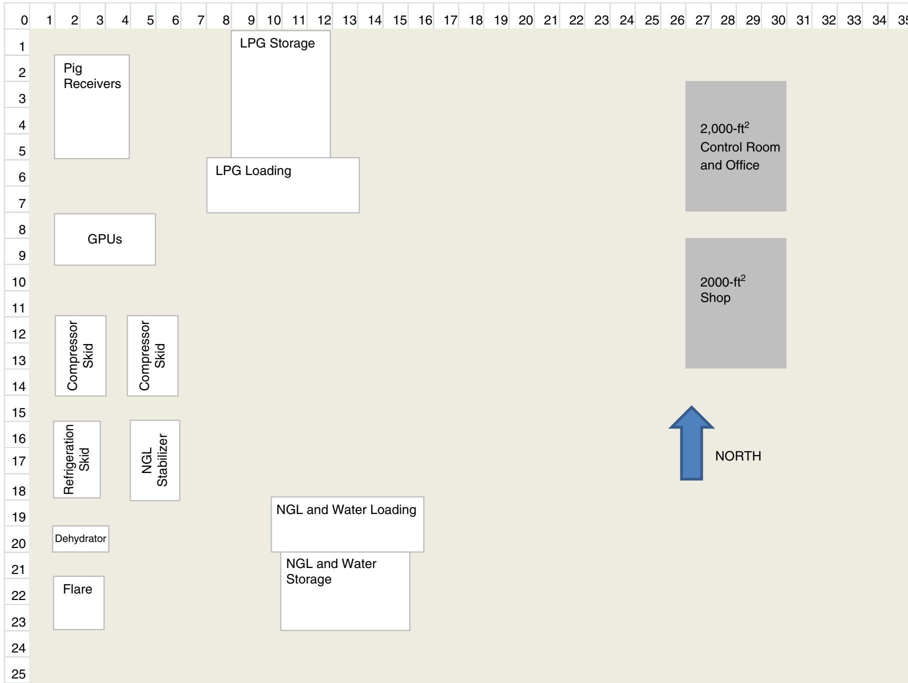

Fig. 1—Site layout.

the hazard, prevent or control the size or the release, and/or mitigate effects to the building occupants. Mitigation measures can prove to be very costly and often difficult to implement, particularly for older facilities.

Risk-Based Analysis

The risk-based analysis delves deeper than the consequence-based analysis by estimating the probability of each consequence and the risk value for each scenario. This analysis accounts for the hourly occupancy of each building and attempts to encompass all potential hazards presented at the facility. Modeling of multicomponent streams can be developed, if required, to better model dispersion given a loss of containment. All cardinal and ordinal wind directions are used in the modeling process, along with different wind speeds (calm, average, and gusts). An in-depth loss-of-containment event tree is developed to calculate the probability of failure for each hazardous piece of equipment, and once combined with the modeling consequences, the risk can be estimated. The effectiveness of the operator's current safeguards and mitigation measures are accounted for in the event tree and help provide a quantitative value of their safety. The resulting risk values are then compared with the operator's accepted-risk matrix.

If the risk is determined to be outside of the operator's acceptable-risk range, recommendations will then be developed. The recommendations are intended to reduce and manage the risk to an acceptable level. The analysis will provide the risk-reduction values of each recommendation so that no further analysis is required once the operator has implemented each of the recommendations successfully.

Step-by-Step Process for Determining Safe Building Location

The example problem presented in this paper is intended to guide the user in conducting a building-siting study by use of both the consequence-based approach and the quantitative risk-analysis (QRA) approach.

For this example, the objective is to locate a 2,000-ft^2 control room/office and a similar-sized warehouse on a location measuring 350×250 ft (2 acres). The initial plot plan shows the building to be located opposite the processing equipment with the distance maximized for the size of the pad. The operator has specified that the buildings will be constructed of reinforced concrete, which is designed and built to withstand a 3.5-psi blast pressure. A thermal-flux tolerance of 10 kW/m^2 will also be specified for the building, indicating that no exposed wood will be used in its construction.

At the site, there will also be a produced-gas-conditioning facility consisting of compression, dehydration, and produced-liquids removal. A mixed stream of propane and butane [liquefied petroleum gas (LPG)] will be stored in pressurized "bullet" tanks. The pentane and heavier hydrocarbons [natural-gas liquids (NGLs)] will be stored in 300-bbl atmospheric tanks. All liquids will be trucked from the site. The plot plan is shown in **Fig. 1,** where GPU means gas-processing unit.

Step 1: Determine Buildings To Be Included in the Analysis. All buildings intended for occupancy should be included in the analysis. Typically, these include control rooms, offices, change houses, guard houses, shops, conference rooms, warehouses, and buildings that may become occupied over time or during an emergency. A thorough review of all existing buildings should be completed to ensure that "local" work areas do not become established in buildings such as motor control centers.

Open structures, such as welding covers, smoking canopies, and truck-loading canopies, are not included. Buildings that do not have personnel assigned to them and that require only intermittent access are also exempt from siting studies. These might include MCCs, analyzer buildings, and equipment enclosures.

For this example, both of the buildings will be included in the study because they meet the requirements of occupied structures.

Step 2: Conduct a Consequence-Based Study To Determine Areas of Impact. The second step is to determine for each maximum credible event (MCE) the impact areas for fire, blast, and toxicity.

A. Data about the process and equipment must first be gathered. A process-block flow diagram or piping-and-instrumentation diagram can provide the engineer with equipment and line sizes. Pressures, compositions, and rate data can be obtained from a process modeling run for the facility **(Fig. 2).**

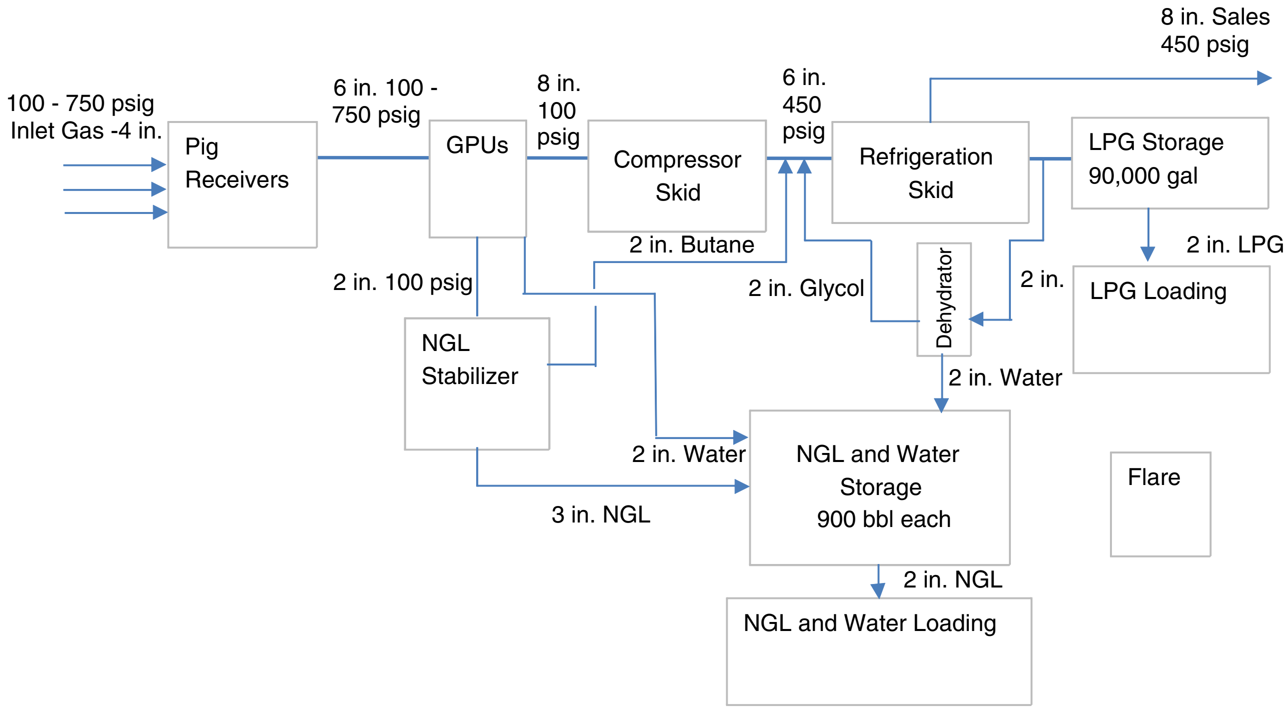

Fig. 2—Block flow diagram.

B. Data about the proposed site need to be obtained. Site data should include a scaled plot plan showing equipment layout (Fig. 1), the physical location of the facility, and basic meteorological data. Average temperature, humidity, and windspeed data obtained from a credible weather service (Iowa State University of Science and Technology 2015) can be used in the consequence study.

MCEs are defined as a hypothetical explosion, fire, or toxic event that has the potential maximum consequence to the occupants of the building under consideration from among the major scenarios evaluated. The major scenarios are realistic and have a reasonable probability of occurring considering the chemicals, inventories, equipment, and piping design (Center for Chemical Process Safety 2012). Credible causes of MCEs are typically

- Rupture of small-bore piping
- Leak from process equipment
- Pump/compressor seal failure
- Gasket failure
- Loading/unloading hose failure
- Loss of containment from operational activities such as filter changing
- Process upsets such as overfilling of tanks

For this example, the operator assumed that the MCE would be a small-bore line break related to each process step at the facility. A table was developed (**Table 1**) that lists the stream or process and the maximum size (equivalent diameter) of a leak for different MCEs. Typically, MCE tables should be developed by operations, engineering, and safety personnel. The shaded boxes represent the governing or largest release for a particular piece of equipment.

C. Each of the different MCEs must be modeled to determine the areas of impact. The program “Areal Locations of Hazardous Atmospheres” (ALOHA) (EPA 2014) is one program of many available to determine the areal extent of blast, heat, and toxicity effects of the MCEs identified.

The ALOHA model allows the user to enter a single case at a time. The time to run hundreds of cases was reduced greatly by developing a preprocessor for the program, which allowed the users to run thousands of ALOHA data sets in a fraction of the time usually needed for complex analyses.

Blast-pressure models that use the Baker-Strehlow-Tang (Pierorazio et al. 2005) method, as cited in API RP 752 (2009) are used by ALOHA. The ALOHA program uses the Baker-Strehlow-Tang blast curves coupled with an air-dispersion model for determining the mass of the explosive fuel. Use of air-dispersion modeling instead of the filled-congested-volume approach is consistent with recommendations from the American Institute of Chemical Engineers (Center for Chemical Process Safety 1994).

An example graph showing the 750-psig inlet stream is presented in Fig. 3. Use of these types of graphs allows the user to quickly determine the impact from various-sized leaks for different hydrocarbon compounds found in the facility. Fig. 3 shows the maximum impact distances for toxicity [immediately dangerous to health or life (IDHL)], fire (10 kW/m2), and blast (3.5 psi).

D. The data from the modeling runs are entered into **Table 2,** which shows the distance of impact for each MCE identified in the preceding.

Step 3: Determining the MCE Impact on Buildings. The data from Table 2 are examined to determine the hazardous events that place the buildings in peril. The shaded boxes show events that would have a detrimental impact on the control room or the warehouse. Examination of the data shows:

1. Toxicity. The data show that the occupants of the buildings would be in peril because of a loss of containment from (a) the 3-in. line leading from the refrigeration skid to the bullet tanks, (b) the 4-in. line on an NGL tank, and (c) the 2-in. line or loading hose at the LPG storage area or loading rack.

Stream	Piping Rupture (in.)	Leak Diameter (in.)	Seal-Failure Equivalent Diameter (in.)	Gasket-Failure Equivalent Diameter (in.)	Hose Rupture (in.)	Loss of Containment	Process Upsets
Facility inlet (750 psig)	4.0	< 0.5	NA	< 1.0	NA	4-in. pig receiver	NA
Gas-processing units (100 psig)	4.0	< 0.5	NA	< 1.0	NA	NA	NA
Gas to compressors	8.0	< 0.5	NA	< 2.0	NA	NA	NA
NGL to tanks	2.0	< 0.5	NA	< 0.5	NA	NA	NA
NGL stabilizer							
C5+ to tanks	2.0	< 0.5	NA	< 0.5	NA	NA	NA
C4 (pump discharge)	2.0	< 0.5	< 1.0	< 2.0	NA	NA	NA
Compressor discharge (450 psig)	6.0	< 0.5	< 2.0	< 1.0	NA	NA	NA
Refrigeration skid	6.0	< 0.5	NA	< 1.0	NA	NA	NA
Residue gas discharge	8.0	< 0.5	NA	< 1.0	NA	NA	NA
Glycol dehydration	2.0	< 0.5	NA	< 0.5	NA	1-in. line on filter	NA
Propane discharge	3.0	< 0.5	NA	< 1.0	NA	NA	NA
NGL storage (0 psig)	4.0	< 0.5	NA	< 1.0	NA	NA	200 B/D
Y-grade storage and loading	2.0	< 0.5	NA	< 0.5	2.0	NA	NA

Table 1—MCEs.

2. Fire. No thermal effects on the buildings from a fire were observed. The most-severe impact from a fire would be if the 8-in. residue gas pipe failed. However, the building would still be outside of the 10-kW/m^2 limit.
3. Blast. Modeling shows that the buildings could be impacted from (a) a loss of the 2-in. line on the NGL pump-discharge line and (b) a failure of the 3-in. line leading from the refrigeration skid to the LPG bullet tanks.

Step 4: Eliminate or Mitigate Hazards to the Buildings. Mitigation measures to reduce the consequence or frequency of scenarios if any hazards are found should be examined to determine if such measures are applicable or practical. These mitigation measures may be passive, active, or procedural to eliminate the hazard, prevent a release, control the size of the scenario, or mitigate the effects on the building occupants. **Table 3** shows possible mitigation measures for this example for the operator to undertake to mitigate the hazards resulting from the MCEs identified.

Often, it is impossible to implement mitigation measures for a particular building to render it totally safe without looking at risk factors. In this case, to eliminate the risk of a blast or the effects of a toxic-release scenario on the building totally, it would be necessary to either move the building or stop the processing of hydrocarbons at the site. The operator desired to continue to operate at the site and was not willing to move the buildings to another location.

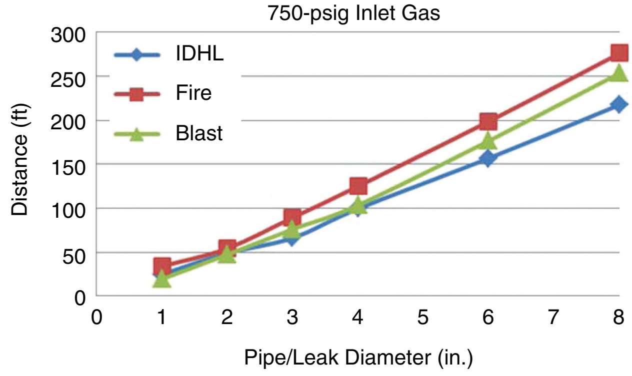

Fig. 3—Example modeling data for the inlet gas stream at 750 psi.

Step 5: Conduct a QRA. Many of the items listed in the preceding steps, such as adding procedural or active mitigation measures, may indeed achieve an acceptable level of risk for the occupants of the building, but it is important to evaluate how effective the measures would be in reducing the consequence or the frequency of the scenario. For this reason, it is often necessary to conduct a QRA to determine if planned mitigation measures will be sufficient to reduce the risk to an acceptable level.

Determine Acceptable-Risk Criteria. The acceptable risk, both to an individual and to a group of individuals, must be determined first to serve as the "hurdle" or acceptable value of risk to achieve when conducting the QRA. Typically, both the maximum individual and societal or aggregate values are determined. Maximum individual risk is defined as the risk to the most-exposed individual occupant of the building. Societal or aggregate risk reflects the likelihood that a major incident will affect more than one occupant in the building.

A typical industry average-risk criteria ranking is illustrated by the frequency vs. number of fatalities graphs, shown in **Fig. 4** (Sutton 2011). The area of judgment is often referred to as "as low as reasonably practical" (ALARP) risk. The primary concept behind ALARP is that the risk should be reduced to a level that is as low as possible and that further efforts greatly exceed the benefits gained.

Gather Site Data for Event-Tree Analysis. Many items of data need to be gathered for generating the event trees needed to determine the risk for the buildings. These items include

- Building-occupancy data: The control room is to be occupied 24 hours per day, 7 days per week. The warehouse is only occupied during day-shift hours. Day-shift hours are assumed to be from 0700 to 1700 hours. The average daily-occupancy data per building are presented in **Table 4.**
- Probability of wind speed and wind direction: Dispersion models are heavily impacted by wind speed and wind direction. For the QRA, six wind directions (winds blowing from

Stream	Leak Diameter (in.)	Distance to Limit (ft)			Building Distance (ft)
		IDHL	Fire	VCE	
Facility inlet (750 psig)	4.0	99	125	103	220
Gas-processing unit discharge (100 psig)					
Gas	8.0	79	117	91	210
NGL	2.0	75	42	20	210
NGL stabilizer					
C5+	2.0	150	51	0	200
C4 (pump discharge)	2.0	0	123	255	200
Compressor discharge (450 psig)	6.0	138	158	136	205
Refrigeration skid					
Residue gas discharge	8.0	0	208	161	233
Propane discharge	3.0	1,251	159	279	233
NGL storage (0 psig)	4.0	459	96	96	125
Y-grade storage and loading	2.0	236	37	79	143

Table 2—Consequence-analysis results.

Mitigation Measure	Example Measure
Eliminate hazard	Do not process gas at the site
Prevent release	Shut in or reduce well rate
	Upgrade equipment
	Add safety instrumented systems
	Mechanical integrity program
	Work permits
Control size of scenario	Reduce equipment sizes
	Fire dectors
	Firefighting systems
	Reduce inventory
Building occupants injury reduction	Relocate
	Issue personal protective equipment
	Upgrade building
	Use ERP
	Add heating, ventilation, and air-conditioning shutdown

Table 3—Mitigation measures.

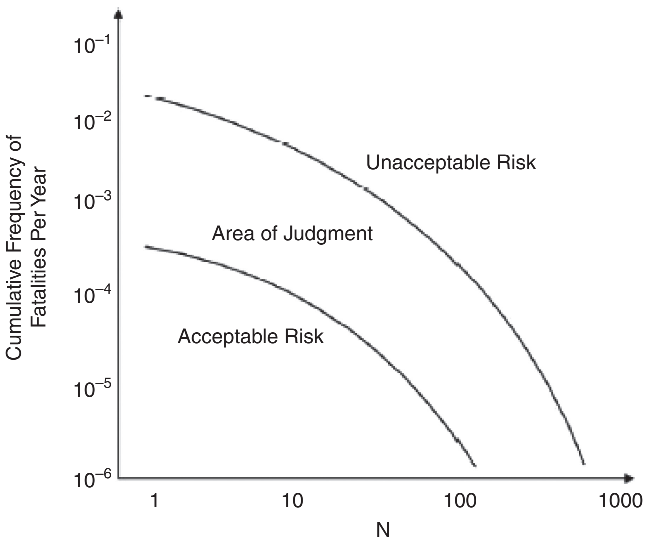

Fig. 4—Acceptable-risk graph.

the north, northeast, northwest, south, southeast, and southwest) and three wind speeds (1.91, 9.0, and 20.0 miles/hr) were selected for every wind direction, as well as calm conditions for dispersion-model scenarios. Eastern and western winds were removed from the dispersion modeling because of the infrequency of the wind blowing from those directions. The average probabilities for these wind data are described in **Tables 5 and 6.**

Event-Tree and Probability Analysis. *Event Trees.* Event trees are mapping tools used to help identify initiators and map out the sequence of events that could possibly lead to the realization of a hazard and its associated consequence. Event trees should take into account all of the plausible scenarios, the leading credit to current safeguards, and the manner in which they affect each scenario. In this analysis, three event trees were used to obtain the overall probability of occurrence for each possible outcome: (1) operational event tree, (2) loss-of-containment event tree, and (3) ignition/final-consequence event tree.

Safety modification factors of 10 to 0.1 were used, where applicable, to adjust the generic-failure frequencies per International Association of Oil & Gas Producers (IOGP, formerly OGP) Report No. 434-1 (OGP 2010) and *API RP 581, Risk-Based Inspection Technology* (2008). These modification factors take into account the presence and effectiveness of the facility's mechanical-integrity-management systems. These factors are used to modify the generic probability according to the system and safeguards currently in place. Application of modification factors needs to be used with caution because the data will be affected by the management sys-

Building	Day-Shift Occupancy	Night-Shift Occupancy	Day-Shift Time (%)	Night-Shift Time (%)
Control room	5	1	0.42	0.58
Warehouse	2	0	0.42	0.58

Table 4—Average daily-occupancy data per building.

Direction	Time (%)
North	11.2
Northeast	8.5
Northwest	6.6
South	36.9
Southeast	15.2
Southwest	8.7
Calm	12.9
Total	100.0

Table 5—Probability of wind by direction.

Speed (miles/hr)	Time (%)
1.9	26
9.0	47
20.0	27
Total	100

Table 6—Probability of wind by speed.

Probability of Facility in Normal Operation	
Assumptions	
Annual hours of operation	8,760 hr/yr
Annual shutdown time	72 hr/yr
Annual human-error probability	0.01 times/yr
Human-error weight factor	0.1
Probability of abnormal conditions	96 hr/yr
Calculations	
Shutdown annual probability	0.00822/year

Table 7—Operational event-tree assumptions and calculations.

tems that were in place when and where the data were gathered. For example, North Sea offshore-facility data may not be fully representative of a US onshore facility. Examples of management systems that could reduce risk are the joint-management process or torquing management for disturbed joints and performance in completing relief-valve inspection and testing and nondestructive-examination inspections on schedule.

Operational Event Tree. The operational event tree was developed to determine the probability that the facility would be in operation. The risk analysis assumes that the facility must be in operation with hydrocarbons present for an incident to occur. The annual hours of operation were obtained from the operator. The TNO "Red Book" (Schüller et al. 1997) was used for determining the annual human-error probability. **Table 7** lists the assumptions and calculations used for the event tree. The operational event tree is shown in **Fig. 5.** The operational event tree determined that the facility would be in operation 99.7% of the time.

Loss-of-Containment Event Tree. The loss-of-containment event tree was used to determine the probability of loss of containment resulting from failures of different components in the tank and piping system. Associated piping, fitting, and valve failures that were used in this analysis were corrosion holes, full-bore pipe ruptures, and flange and valve leaks. In addition to piping-related failures, failures that occur from overpressure of the vessels, truck unloading of the tanks, and human error were also taken into account.

The OGP Risk Assessment Data Directory, Report No. 434-1 (OGP 2010) was used to determine pipe- and pressure-vessel-related leaks and releases. The TNO Red Book (Schüller et al. 1997) was used for human-error probabilities. The TNO Purple Book (Uijt de Haag and Ale 2005) was used as a reference for pressure-safety-valve (PSV) failure, hose leaks, and truck releases. The PSV-failure data were from the Chemical Process Safety Table 12-1 in Crowl and Louvar (2011).

Safety-modification factors were credited to this event tree to account for any active or passive safety devices or protocols that the operator currently has in place. The effects of these safeguards on the probability results can be seen in the fault tree presented in **Fig. 6.** Results from the loss-of-containment event tree indicate that the annual probability for a loss-of-containment event is 2.75×10^{-3}.

Ignition/Final-Consequence Event Tree. The ignition/final-consequence event tree was used to determine the probability of consequences after a loss of containment has occurred. This event tree takes into account the wind direction and wind speed (see Tables 5 and 6) and the probability of ignition and ignition type; and finally, it calculates the overall probability of individual consequences occurring. The probability of ignition, ignition from the tank truck, ignition resulting in a jet fire, and ignition resulting in an explosion were obtained from the TNO Purple Book (Uijt de Haag and Ale 2005). A summary of these factors is shown in **Table 8.**

Each release type is independent from the others; so, these individual consequences were then added together with other similar consequences [i.e., jet fire, vapor-cloud explosion (VCE), and toxic-vapor-cloud release] to achieve the overall probability of the consequences of containment loss. This overall probability was then used along with the consequence type to rank the risk of each scenario. Results from the ignition event tree for the overall consequence of an LPG product release can be seen in **Table 9.** The event tree can be examined in **Fig. 7.**

Wind-Direction Enabler Probabilities for VCE. The probability of a VCE is also dependent on wind direction. ALOHA modeling shows that the wind must be either calm or directed toward the

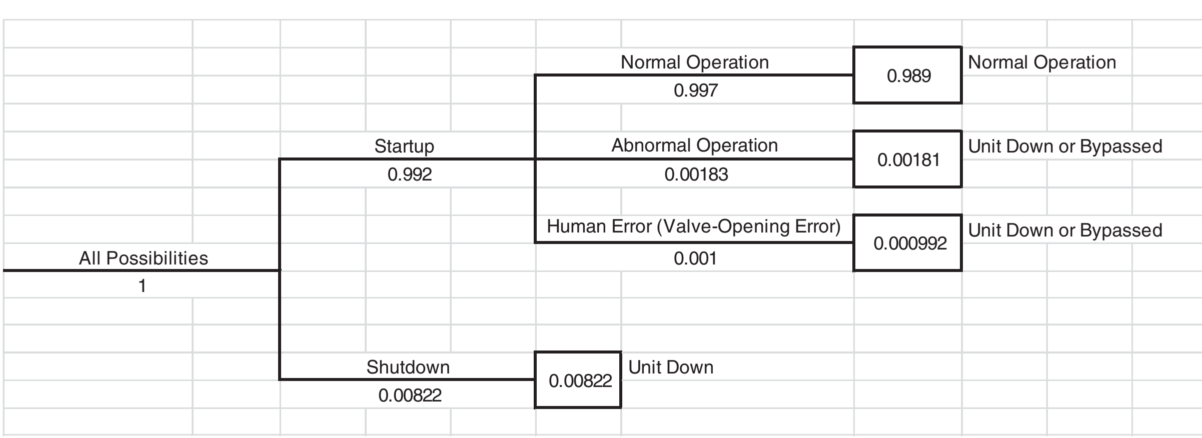

Fig. 5—Operational event tree.

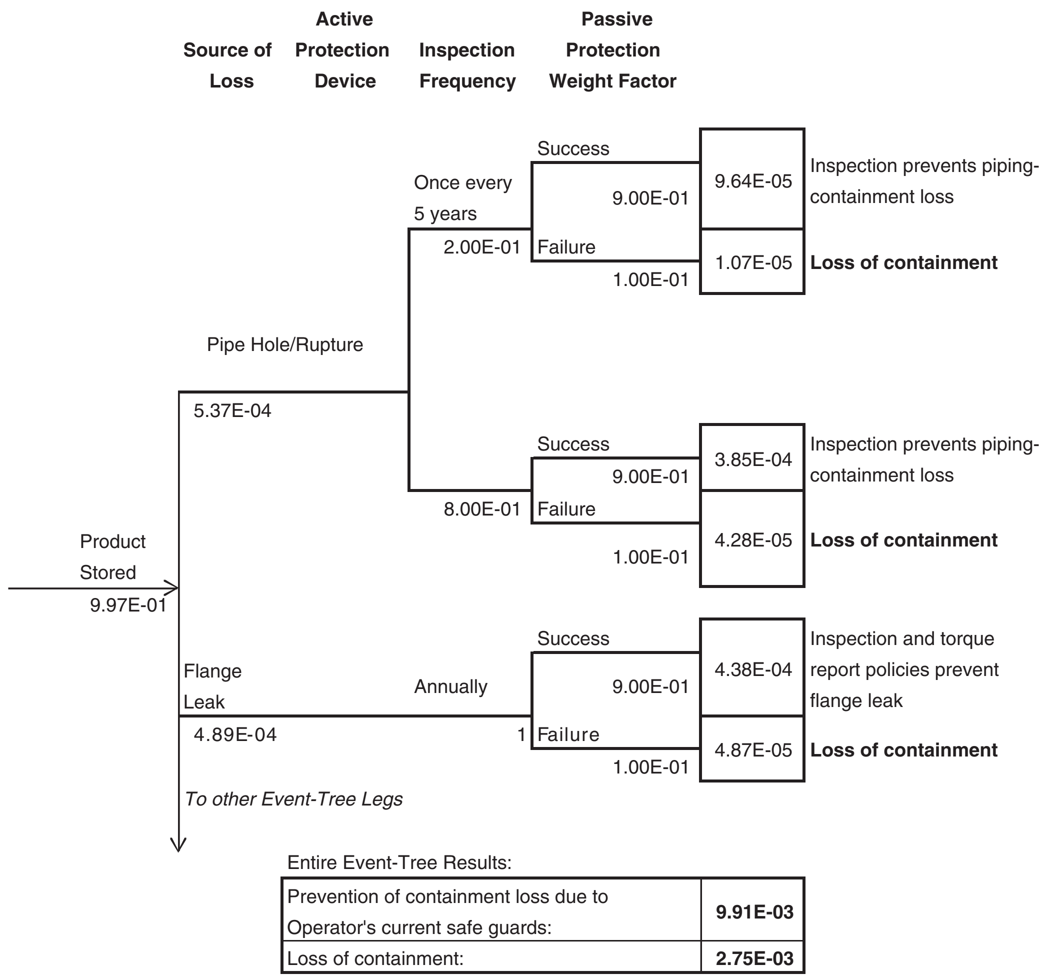

Fig. 6—Excerpt from loss-of-containment event tree.

buildings for a VCE is to impact the buildings. The wind blowing the leaking hydrocarbons away from the buildings greatly diminishes or eliminates the VCE pressure-wave impact on the buildings. VCE calculations for the various wind speeds (see Table 6) blowing from the southwest were used to determine the probability of the blast pressure exceeding the 3.5-psi limit. It is noted that the lower explosive limit was never achieved for a 20-miles/hr wind for the NGL stabilizer because of dispersion. The results of this analysis are shown in **Table 10.** A value of 12.1% (maximum value) was used as the wind-velocity-probability multiplier for this analysis.

Prevention Measures. *Facility Safeguards*. The facility incorporates several safeguards to prevent leaks, spills, and incidents within the process area. These safeguards include

- Level alarms on vessels
- PSVs on vessels
- Plant automated emergency-shutdown valves
- Point-source gas detection in the processing areas
- Labeled valves and piping destinations
- Mechanical inspection and recording procedures

The safeguards outlined in this section of the report are the passive and active safeguards that were credited in the event-tree analysis. From the loss-of-containment event tree, it was calculated that these safeguards help to prevent loss of containment. The resulting prevention annual probability was calculated to be 9.91×10^{-3}.

Risk Ranking of Events. The fatality risk was calculated once the probability of a VCE, jet fire, or toxic release and the probability that the wind would be blowing toward the structures were determined.

The probability of an annual fatality is calculated as
Probability of the facility in operation
× Probability of loss of containment (including facility safeguards)
× Probability of ignition (explosion and toxic-vapor cloud)
× Probability of the wind blowing toward the buildings
× Probability of a person in the buildings (personal and societal risk)
= Probability of a fatality.

Probability of Direct Ignition:		
For stationary installation of average reactive gas	0.7	Uijt de Haag and Ale (2005), Table 4.5
From tank wagon truck	0.8	Uijt de Haag and Ale (2005), Table 4.6
Resulting in jet fire	0.6	Uijt de Haag and Ale (2005), Section 4.8
Resulting in explosion	0.4	Uijt de Haag and Ale (2005),Section 4.8

Table 8—Probabilities for ignition tree events.

Calculated Event	Annual Probability
Probability of jet fire	1.32×10^{-3}
Probability of vapor-cloud explosion	8.08×10^{-4}
Probability of toxic vapor cloud	5.50×10^{-4}

Table 9—Results from the ignition/final event.

Loss of Containment of Product	Ignition Probability	Ignition Type	Probability of Consequence	Consequence
		Jet Fire	1.32 x 10^{-3}	Jet Fire (Thermal Effects)
	Ignited	6.00 x 10^{-1}		
	8.00 x 10^{-1}	Explosion	8.80 x 10^{-4}	VCE (Overpressure)
		4.00 x 10^{-1}		
2.75 x 10^{-3}				
	Not Ignited		5.50 x 10^{-4}	Toxic Vapor Cloud (Toxic Effects/Affixation)
	2.00 x 10^{-1}			

Fig. 7—Ignition event tree.

From the consequence analysis, it was determined that a line failure on the discharge of the NGL pump at the refrigeration skid or at the LPG loading rack would place the occupants of the building in peril only for a VCE or a toxic-cloud release. The probability of a hazardous event and the wind-velocity probability were multiplied by the occupancy load in each of the buildings to develop the fatality risk for the control room and the warehouse. The fatality-risk table is shown in **Table 11.**

Results. The results of this analysis show that the control room and warehouse and the personnel working within these areas are at greatest exposure from a leak from the refrigeration skid, NGL stabilizer, NGL storage tanks, and the LPG storage and loading areas. This could result in a VCE causing an overpressure substantial enough to yield permanent damage to buildings and personnel or could result in a toxic cloud exceeding IDHL limits. The severity of this overpressure could range from broken glass to the structural integrity of a building being compromised, which would become a hazard and potentially deadly to personnel. Thermal radiation was found not to be a danger to the buildings.

The value of 2.23×10^{-4} for five people in the control room approaches the risk level above the acceptable-risk range and could fall into the area of judgment. Further risk-reduction measures should be evaluated to substantiate that the residual risk is ALARP.

Step 6: Recommend Actions To Mitigate the Risk. The operator should take steps to demonstrate an ALARP design because the control-room case approaches the ALARP range. Steps should be taken continuously to decrease facility risk and increase the overall safety of the system until an ALARP design is reached. The following additional measures for improving safety should be considered.

- Installation of gas detectors on the ventilation intakes for the control room and the warehouse. The gas detectors would automatically shut in the ventilation system to prevent hazardous gases from entering the building through the ventilation system.
- Installation of line-of-sight gas-detection sensors in the processing area to help alert personnel of any containment loss before it can find an ignition source or accumulate to toxic levels. This simple gas-detection system would be sufficient to decrease the fatality risk of each building by one order of magnitude, decreasing the value to within the acceptable range in all cases.
- Installation of automatically closing valves on the discharge of the LPG storage tanks, at the NGL pump suction, and on the line leading off of the refrigeration skid to the LPG storage tanks. This would greatly reduce the quantity of any released hydrocarbons in the event of an emergency.
- Installation of additional barriers around the exposed piping of the tanks. With the addition of these barriers, the loss-of-containment human-error factor can be decreased by one order of magnitude.
- Increasing the frequency of piping inspection to reduce the likelihood of loss of containment. *API RP 574* (2009) outlines a visual-inspection routine that could be used for piping around the equipment in conjunction with current inspection and torque-joint programs.

Summary and Conclusions

Consequence- and quantitative-risk-analysis (QRA) techniques are often necessary to determine the impact of explosions, toxic releases, or fires when siting structures at facilities. A consequence analysis should always be conducted first as a "screening" tool to determine if there will be any impacts from a hydrocarbon release.

Advances in consequence-modeling tools have made it possible to analyze thousands of cases to include wind velocities, leak sizes, and other variables in the analysis. These new tools can greatly reduce the amount of time needed to perform these analyses.

QRA techniques have also evolved to enable the risk-analysis professional to better quantify the risk to personnel in occupied structures. Use of enhanced-modeling capabilities and better quantitative-risk data allows the engineer to ascertain the risk to a structure

Location	Chemical	Wind Speed (miles/hr)	Wind Speed (%)	Wind Direction	Wind Direction (%)	3.5 psi VCE (ft)	Probability (%)
NGL stabilizer 200 ft SW	Butane	Calm to 1.91	26	SW	22	471	5.6
NGL stabilizer 200 ft SW	Butane	9	47	SW	9	138	4.1
NGL stabilizer 200 ft SW	Butane	20	27	SW	9	99	0.0
Sum of applicable probabilities							9.7
Refrigeration skid 233 ft SW	Propane	Calm to 1.91	26	SW	22	426	5.6
Refrigeration skid 233 ft SW	Propane	9	47	SW	9	300	4.1
Refrigeration skid 233 ft SW	Propane	20	27	SW	9	210	2.3
Sum of applicable probabilities							12.1

SW = southwest.

Table 10—Probabilities of enabling wind velocities.

Building	Shift	Occupancy	Time Occupied (%)	Fatalities Per Year
Vapor-cloud explosion				
Control room	Day	5	0.42	2.23×10^{-4}
Control room	Day	1	0.42	4.46×10^{-5}
Control room	Night	1	0.58	6.15×10^{-5}
Warehouse	Day	2	0.42	8.91×10^{-5}
Warehouse	Day	1	0.42	4.46×10^{-5}
Toxic cloud				
Control room	Day	5	0.42	1.39×10^{-4}
Control room	Day	1	0.42	2.78×10^{-5}
Control room	Night	1	0.58	3.85×10^{-5}
Warehouse	Day	2	0.42	5.57×10^{-5}
Warehouse	Day	1	0.42	2.78×10^{-5}

Table 11—Fatality-risk table.

properly and determine mitigation measures if the occupants of the structure are in peril.

References

API RP 574, Inspection Practices for Piping System Components. 2009. Washington, D.C.: API.

API RP 581, Risk-Based Inspection Technology. 2008. Washington, D.C.: API.

API RP 752, Management of Hazards Associated with Location of Process Plant Permanent Buildings. 2009. Washington, D.C.: API.

Center for Chemical Process Safety of the American Institue of Chemical Engineers. 1994. *Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs*, first edition. New York: John Wiley & Sons, Inc. http://dx.doi.org/10.1002/9780470938157.

Center for Chemical Process Safety of the American Institue of Chemical Engineers. 2012. *Guidelines for Evaluating Process Plant Buildings for External Explosions, Fires, and Toxic Releases*, second edition. New York: John Wiley & Sons, Inc. http://dx.doi.org/10.1002/9781118312995.

Crowl, D. A. and Louvar, J. F. 2011. *Chemical Process Safety: Fundamentals with Applications*, third edition. Upper Saddle River, New Jersey, USA: Series in the Physical and Chemical Engineering Sciences, Prentice Hall International.

Environmental Protection Agency (EPA). 2014. ALOHA Software, version 5.4.4. http://www2.epa.gov/cameo/aloha-software (accessed 2 April 2015).

Iowa State University of Science and Technology. 2015. Wind Roses. http://mesonet.agron.iastate.edu/sites/windrose.phtml?network=IA_ASOS&station=DSM (accessed 10 February 2015).

OGP. 2010. OGP Risk Assessment Data Directory. Report No. 434-1, International Association of Oil & Gas Producers, London (March 2010). http://www.ogp.org.uk/pubs/434-01.pdf.

Occupational Safety & Health Administration (OSHA). 1992. Title 29 Code of Federal Regulations (CFR) Part 1910.119, Process Safety of Highly Hazardous Chemicals. Washington D.C.: Federal Register.

Pierorazio, A. J., Thomas, J. K., Baker, Q. A. et al. 2005. An update to the Baker–Strehlow–Tang vapor cloud explosion prediction methodology flame speed table. *Process Saf Prog* **24** (1): 59–65. http://dx.doi.org/10.1002/prs.10048.

Schüller, J. C. H., Brinkman, J. L., Van Gestel, P. J. et al. 1997. Methods for Determining and Processing Probabilities: "Red Book". Committee for the Prevention of Disasters, The Hague. CPR 12E.

Sutton, I. 2011. ALARP (As Low as Reasonably Practicable) Risk Determining Acceptable Risk for Industrial Facilities. https://suttonbooks.wordpress.com/article/alarp-as-low-as-reasonably-practicable-2vu500dgllb4m-10/xml/ (accessed 19 January 2015).

Uijt de Haag, P. A. M. and Ale, B. J. M. 2005. Guildelines for Quantitative Risk Assessment: "Purple Book". Committee for the Prevention of Disasters, The Hague CPR 18E. http://infonorma.gencat.cat/pdf/AG_AQR_3_PB_%202005.pdf.

Jim Johnstone is President and cofounder of Contek Solutions. Previously, he worked for Atlantic Richfield and WZI Incorporated. Johnstone's interests include process safety, facility engineering, and incident analysis. He has authored or coauthored more than a dozen technical papers and holds one patent. Johnstone holds a BS degree in mechanical engineering from Washington State University. He is a member of SPE and currently serves on the SPE E&P Health, Safety, Security, and Environmental Conference Committee and on the SPE Health, Safety, Security, Environment, and Social Responsibility Advisory Committee.

Michael Spangler is the Chief Operating Officer for Contek Solutions. Previously, he worked for ConocoPhillips, Phillips Petroleum, Atlantic Richfield, and Conoco. Spangler's experience covers liquefied natural gas; onshore and offshore upstream operations, engineering, and projects; and health, safety, and environment management in North America and the United Kingdom. His current interests include process-safety management (PSM) and engineering management. Spangler holds a BS degree in chemical engineering from the University of Oklahoma and an MBA degree from Southern Methodist University, Dallas. He is a member of SPE and the American Institute of Chemical Engineers.

Corey Heitzman is a technical consultant with Contek Solutions. He has been with the company for 18 months. Heitzman's current interests include process optimization, chemical-process safety, quantitative risk assessment, and US Occupational Safety and Health Administration PSM. He holds a BS degree in chemical engineering from Texas A&M University and a certificate in chemical-process safety from the Mary Kay O'Connor Process Safety Center.

Garrett Wimberley is a technical consultant with Contek Solutions. Previously he worked for Harrison, Walker & Harper and Minnix Commercial Construction as a project engineer. Wimberley's interests include risk assessment, standard operating procedures, and process-hazard analysis. He holds a BS degree in construction technology engineering from Texas Tech University.

Alex Flores is a technical consultant and the Information Technology Manager at Contek Solutions, where he has worked for 7 years. His research interests include siting studies, fire studies, software development, and automation. Flores holds BS degrees in occupational safety and health and in computer science from Southeastern Oklahoma State University. He is a member of the American Society of Safety Engineers.