Appendix S

Risk Assessment Documentation

Appendix S-1

Risk Assessment Report

–PUBLIC–

RISK ASSESSMENT FOR THE VENTURA COMPRESSOR STATION MODERNIZATION PROJECT

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RISK ASSESSMENT FOR THE VENTURA COMPRESSOR STATION MODERNIZATION PROJECT

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RISK ASSESSMENT FOR THE VENTURA COMPRESSOR STATION MODERNIZATION PROJECT

EXECUTIVE SUMMARY

Southern California Gas Company (SoCalGas) retained Quest Consultants Inc.® (Quest) to identify and assess the potential hazards and risks associated with the Ventura Compressor Station. This study first evaluated the hazards and risks associated with accidental releases of natural gas at the existing Ventura Compressor Station, in order to provide a baseline for evaluating the Ventura Compressor Station Modernization Project (Proposed Project). A quantitative risk analysis (QRA) was used to analyze the risk of potentially life-threatening events occurring, due to accidental releases of natural gas from the compressor station. The scope of the QRA includes compressors and associated equipment that contain natural gas, excluding gas transmission pipeline assets at the compressor station.

Alternatives to the Proposed Project were evaluated by application of a qualitative analysis of various elements of risk. The qualitative analysis combined with the QRA forms the full risk assessment study that is applied to the Proposed Project.

Quantitative Risk Analysis Results

Assessment of the results from the QRA for the Proposed Project finds the following:

- The offsite risks for the Proposed Project are similar in magnitude to the existing Ventura Compressor Station, and primarily impact industrial or commercial areas.
- Based on a set of published international risk criteria, the risk posed by the Proposed Project are within acceptable levels for all of the listed criteria, including for residential housing areas or sensitive developments (for example, the school to the east).
- In comparison, the risk posed by the Proposed Project to offsite areas is less severe than other potentially fatal, commonplace accidental events, such as health issues (heart disease, cancer, influenza), motor vehicle accidents, and falls.

Qualitative Assessment of Risk

The qualitative assessment of risk evaluated various elements of risk associated with natural gas hazards to persons in the vicinity of a compressor station. The findings include the following:

- All of the evaluated alternatives to the Proposed Project would result in a larger qualitative risk profile, as compared to the Proposed Project.
- The Supplemental Electric-Driven Compression alternative would have the smallest increase in risk, as compared to the Proposed Project, although this increase would be expected to be due to offsite risk.

1.0 INTRODUCTION

Southern California Gas Company (SoCalGas) retained Quest Consultants Inc.® (Quest) to identify and assess the potential hazards and risks associated with the Ventura Compressor Station. The existing Ventura Compressor Station is located at 1555 North Olive Street in Ventura, California. This study first evaluated the hazards and risks associated with accidental releases of natural gas at the existing Ventura Compressor Station, in order to provide a baseline for evaluating the Ventura Compressor Station Modernization Project (Proposed Project). The Proposed Project seeks to replace aging infrastructure and compensate for the loss of local California producer supply in a discrete and targeted manner, without increasing SoCalGas's footprint or seeking to extend its pipeline system. The approach taken for this study was a quantitative risk analysis (QRA). Risk is based on the combination of both the severity and likelihood of a life-threatening event occurring. The risk analysis serves to evaluate the Proposed Project in comparison to existing site conditions.

The Proposed Project is subject to a Certificate of Public Convenience and Necessity (CPCN) from the California Public Utilities Commission (CPUC) and California Environmental Quality Act (CEQA) review. This QRA has been prepared as part of the Proponent's Environmental Assessment (PEA), submitted in accordance with the CPUC Guidelines for Energy Project Applications Requiring CEQA Compliance: Pre-Filing and Proponent's Environmental Assessments. Part of that assessment is an evaluation of the frequency and consequence of potential loss of containment scenarios, as well as identification of risk from such scenarios. This requirement is accomplished by a QRA, as described in this report. Additionally, this risk assessment qualitatively evaluates risks to the alternatives to the Proposed Project identified in the PEA. The qualitative analysis combined with the QRA forms the full risk assessment study that is applied to the Proposed Project.

1.1 Basis of the QRA

The QRA analyzes the potential risk of fatality due to accidental releases of natural gas from the existing compressor station. This measure of risk is used as a baseline to compare to the Proposed Project. The scope of the QRA included compression systems that contain (or will contain) natural gas, which excludes gas transmission pipeline assets at the compressor station. The methodology used in this study includes five primary steps:

Step 1: Identify the hazards inherent with the system being evaluated.
Step 2: Determine the potential equipment failure cases that could result in life-threatening conditions in and around the facility.
Step 3: For each failure case defined in Step 2, calculate the set of potential hazard zones associated with a range of unique release events.

Step 4: For each unique release event identified in Step 3, derive the annual probability of the event, based on failure rates and conditional probabilities.

Step 5: Using a consistent and accepted methodology, combine the consequence from Step 3 with the corresponding event probabilities from Step 4 to arrive at measures of the risk posed by the facility. Compare the risk results to applicable criteria to develop an assessment of the overall risk.

This methodology is explained further in Section 2, as well as in Appendix E.

1.2 Qualitative Assessment Overview

For the Proposed Project alternatives, a hazard identification and risk assessment approach was implemented. This qualitative assessment, which covers the viable alternatives to the Proposed Project, is separate and independent of the QRA, and is explained in Section 4.

1.3 Description of the Facility

The Ventura Compressor Station is situated on 8.42 acres in the City of Ventura at 1555 North Olive Street. There are industrial land uses to the north, west, and south. Across Olive Street to the east are a school property, residences, and commercial properties. The facility supports SoCalGas's delivery of natural gas for two distinct yet interrelated purposes: (a) to serve core and non-core customer demand in the North Coastal System; and (b) to supply gas to the La Goleta Storage Field for injection and storage, which, in turn, supports future customer demand and reliability both in the North Coastal System and across the entirety of SoCalGas's system. The compressor station pulls natural gas from lower pressure pipelines to provide a source of higher pressure natural gas to the North Costal System and the La Goleta Storage Field.

The existing compressor station contains an inlet scrubber, three gas-fueled compressors, and three fan-cooled heat exchangers, along with control systems and piping interconnect systems. This system has a gas throughput capacity of 90 million standard cubic feet per day (MMSCFD). The layout of the existing compressor station is shown in Figure 1-1.

The Proposed Project would replace the existing compressor station equipment with new equipment — consisting of two inlet filters, a compressor building with four compressors (two fueled by gas and two electrically driven), four fan-cooled heat exchangers, and an outlet scrubber. The new equipment will provide a gas throughput capacity of up to 160 MMSCFD. All gas transmission pipeline facilities and their connections to the compressor station will remain intact. The layout of the Proposed Project is shown in Figure 1-2. The facility will continue to be operated remotely and monitored 24 hours per day, 365 days per year by the SoCalGas Control Center. Maintenance and operations personnel will be on site to inspect and maintain equipment at the facility during normal business hours.

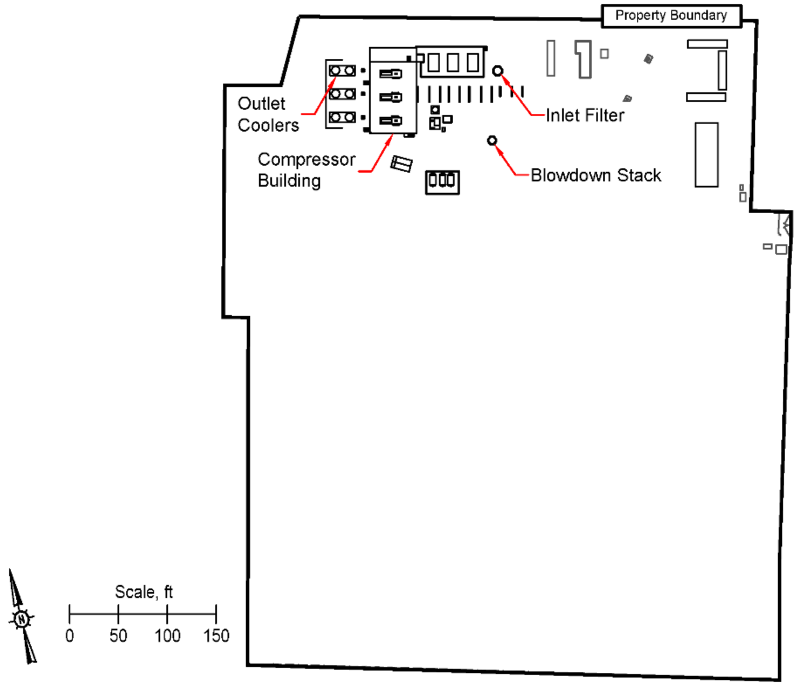

Figure 1-1
Layout of the Existing Ventura Compressor Station

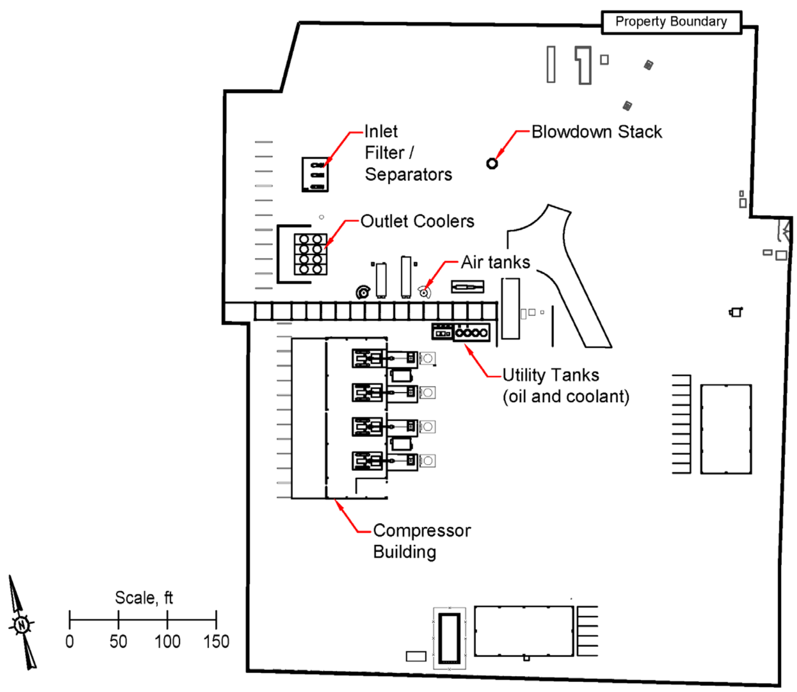

Figure 1-2
Layout of the Proposed Ventura Compressor Station Modernization Project

1.4 Local Meteorological Data

The weather conditions at the time of an accidental release – a loss of containment (LOC) event – can influence the extents and directions of the resulting hazards. For the purposes of a risk-based study, a set of weather conditions – consisting of atmospheric stability, wind speed, and wind direction – must be assigned for each calculation. Data collected onsite is the most representative of site meteorological conditions and is preferable to data from other locations. Site-specific meteorological data collected at the Ventura station was provided by SoCalGas and used in this evaluation. This is the same data set that was approved by the Ventura County Air Pollution Control District (VCAPCD) and used in the dispersion modeling for the health risk assessment which was part of the air permit application package submitted to the VCAPCD in March 2020. Detailed information regarding the meteorological data is provided in Appendix A.

1.5 Overview of Applicable Regulations and Standards

The Proposed Project will be designed, constructed, operated and maintained in accordance with the applicable parts of Title 49 Code of Federal Regulations, Part 192 (49 CFR 192), the California Building Code (CBC), the California Occupational Safety and Health Administration (Cal/OSHA) guidelines, California Process Safety Management Regulations, applicable National Fire Protection Association (NFPA) standards, and good engineering practices.

49 CFR 192 is comprised of 16 subparts, which are listed below.

Subpart A, General
Subpart B, Materials
Subpart C, Pipe Design
Subpart D, Design of Pipeline Components
Subpart E, Welding of Steel Pipelines
Subpart F, Joining of Materials Other Than by Welding
Subpart G, General Construction Requirements for Transmission Lines and Mains
Subpart H, Customer Meters, Service Regulators and Service Lines
Subpart I, Requirements for Corrosion Control
Subpart J, Testing Requirements
Subpart K, Uprating
Subpart L, Operations
Subpart M, Maintenance
Subpart N, Qualification of Pipeline Personnel
Subpart O, Transmission Pipeline Integrity Management
Subpart P, Distribution Pipeline Integrity Management

1.6 Acronyms and Abbreviations

A set of acronyms and abbreviations, and their meanings, are provided in Table 1-1.

Table 1-1
Acronyms and Abbreviations

Acronym or Abbreviation	Meaning
AIChE	American Institute of Chemical Engineers
Btu/hr-ft^2	British thermal units per hour per square foot (thermal radiation measurement)
CBC	California Building Code
CCPS	Center for Chemical Process Safety
CEQA	California Environmental Quality Act
49 CFR 192	Title 49 of the Code of Federal Regulations, Part 192
CPCN	Certificate of Public Convenience and Necessity
CPUC	California Public Utilities Commission
CSA	Canadian Standards Association
CSChE	Canadian Society for Chemical Engineering
HSE	Health and Safety Executive (United Kingdom)
kW/m^2	Kilowatts per square meter (thermal radiation measurement)
LFL	Lower flammable limit
LOC	Loss of containment
LSIR	Location-specific individual risk
MMSCFD	Million standard cubic feet per day (gas flow rate)
NFPA	National Fire Protection Association
Proposed Project	the Ventura Compressor Station Modernization Project
psi	Pounds per square inch
PEA	Proponent's Environmental Assessment
PES	Potential explosion site
PHA	Process hazards analysis
QRA	Quantitative risk analysis
SEDC	Supplemental electric-driven compression
VCAPCD	Ventura County Air Pollution Control District
VCE	Vapor cloud explosion

2.0 ELEMENTS OF QUANTITATIVE RISK ANALYSIS

The calculation of risk due to materials that may pose a risk to people follows the five steps introduced in Section 1 of this report. Those steps are explained in more detail in this section, within the context of the Ventura Compressor Station and Proposed Project. The analysis was constrained by the following factors:

- The hazard assessment focused on impacts to people outdoors – the public and compressor station employees;
- The scope of the analysis involves accidental loss of containment (LOC) events from the existing compressor station and the Proposed Project; and
- Risk was calculated for acute hazards associated with natural gas in the compression facility.

In this context, risk is defined as a quantitative product of the consequence or impact of a hazard — in this case a fatality — and the associated probability of that realized consequence. The methodology presented below, also described in Appendix E, is consistent with published, industry standard guidance for QRA studies, including from:

- The methodology published by the Center for Chemical Process Safety (CCPS), part of the American Institute of Chemical Engineers (AIChE)[1];
- The Netherland's risk analysis guidance[2]; and
- Methodology included in the National Fire Protection Association (NFPA) standard 59A, as used in evaluating risk for liquefied natural gas facilities[3].

2.1 Step 1: Hazards Identification

The potential hazards associated with the Ventura Compressor Station are common to similar natural gas facilities worldwide and are a function of the properties of the process fluid—in this case, natural gas—within the facility, the process and storage conditions (e.g. pressure, temperature, and flow rate), and the process control or safety systems in place.

Natural gas is a common fuel primarily used for heating purposes and is comprised mostly of methane. As a pure substance, methane is a colorless, odorless, tasteless gas. Methane is not toxic to humans but can act as a simple asphyxiant (displacing oxygen in air) at high

[1] CCPS (2000), Guidelines for Chemical Process Quantitative Risk Analysis - Second Edition. Center for Chemical Process Safety of the American Institute of Chemical Engineers, 3 Park Avenue, New York, New York, 10016, 2000. (ISBN 0-8169-0720-X)

[2] RIVM (2009), Reference Manual Bevi Risk Assessments, Version 3.2, National Institute of Public Health and the Environment (RIVM) Centre for External Safety, P.O. Box 1, 3720 BA Bilthoven, The Netherlands. January 7, 2009.

[3] NFPA 59A (2023), Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG). National Fire Protection Association, Quincy, Massachusetts, November 2022.

concentrations. When transported by pipeline (including all scenarios within this analysis), natural gas will contain an odorant (for example, methyl mercaptan) to aid in leak detection.

While methane (and by extension natural gas) is lighter than air, or buoyant, when released, pressurized releases will form a jet that does not necessarily exhibit buoyant properties. Methane is flammable (in other words, can be ignited) at concentrations between 5% and 15% in air. This means that concentrations greater than 15% in air are too rich to support combustion or be ignited, and mixtures less than 5% in air are too lean to support combustion. Natural gas's flammable limits can vary but are typically close to those for methane.

If a release of methane occurs, and it mixes with air, an ignition source is required for hazards to develop. Methane has an autoignition temperature of about 1,000°F, and hot surface ignition requires much higher temperatures. Sources such as open flames and sparks are generally sufficient to ignite a flammable mixture. When in an open area, ignited mixtures of natural gas do not create a damaging explosion. However, if a flammable mixture of natural gas and air is within an enclosed space or congested space, and is ignited, a damaging explosion is possible.

The hazards identified in this assessment are associated with accidental releases of natural gas from compressor station equipment and piping, and include jet fires, flash fires, and vapor cloud explosions (VCEs), which all require an ignition of the released natural gas.

Definitions
Jet fire – an ignited release of natural gas that forms a velocity-driven fire *Flash fire* – delayed ignition of released natural gas that has mixed with air to form a flammable vapor cloud *Vapor cloud explosion* – the ignition of a flammable vapor cloud (a flash fire) that forms a damaging blast wave. The strength of the blast depends on fuel reactivity, confinement, or enveloping repeated small obstacles

This set of hazards is consistent with that found in risk analysis guidance established by the California Department of Education for evaluation of natural gas pipeline hazards that may affect a school site[4].

2.2 Step 2: Failure Case Definition

Accidental releases of natural gas that could result in the hazards listed above are referred to as failure cases. Failure cases are selected to characterize a group of equipment that have similar behaviors following a loss of containment event.

[4] California Department of Education (2007), Guidance Protocol for School Site Pipeline Risk Analysis, prepared by URS Corporation, February 2007.

Quest personnel reviewed the provided operations and systems data and defined a set of failure cases for the Ventura Compressor Station. The failure cases were determined based on experience with similar process systems, good engineering practices, and knowledge concerning the behavior of gas processing systems. Each portion of the facility whose systems, given an LOC event, would result in similar consequences is defined as, and described by, a failure case. This step in the analysis also defines the conditions prior to the LOC for each failure case. These conditions include:

- Initial natural gas temperature and pressure;
- System normal flow rate and inventory;
- Location of the equipment involved in the failure case.

The list of failure cases, along with their initial conditions (prior to the LOC) are listed in Appendix C.

Each potential failure case represents a portion of the compression system where an LOC event could occur but does not specifically address the cause of the LOC. The specific location within the failure case where the LOC occurs could be anywhere within the portion of the system designated for that failure case. Each failure case includes many potential failures of the containment systems (release sources) that might result from:

- Instrument connection leaks or failures;
- Seal or gasket failures;
- Failed welds;
- Drain/vent valves inadvertently left open;
- Mechanical damage during maintenance, construction, or other operations;
- Vibration-induced piping fatigue failure;
- Third-party damage;
- Piping/equipment failures due to metallurgy problems or corrosion; or
- Other failure modes that result in a loss of natural gas to the environment.

The selection of failure cases is intended to cover all potential unintentional releases from the natural gas system, regardless of the cause of the event. This approach provides a risk analysis that describes the potential consequences of all LOC events. While the consequences are covered, the frequency of all possible events may not be covered. The range of events included in failure rate databases (e.g., the above list) encompasses most LOC events (see also Section 2.4), but the frequency of certain events (e.g. sabotage) cannot be reliably determined. Thus, while some events cannot be reliably assigned a frequency of occurrence, the risk analysis provides inclusion through the consequence analysis and the frequencies of a range of potential events.

The terminology used for failure cases and subsequent events and outcomes are defined below, within the context of this analysis, and demonstrated in Figure 2-1.

2.3 Step 3: Hazard Zone Analysis

For a hazard associated with any one of the failure cases from the compression facility to be realized, there must first be an LOC event. If natural gas is released, the resulting hazards can be represented, using consequence modeling, by a specific hazard zone that describes the physical extents of the hazard impact.

Definitions
Failure Case – A potential accidental loss of containment of natural gas that could result in the hazards of concern. Failure cases are developed and defined as an initial part of the consequence and risk analysis study. *Loss of Containment* – An unplanned or uncontrolled release of natural gas, typically following a failure of physical equipment (including piping), characterized by a specific hole size. *Event* – A set of possibilities that follow from within a failure case to create a unique set of circumstances. A unique event may involve a release orientation, ignition or non-ignition of the natural gas, and a set of weather conditions. *Outcome* – The result of an event described by one or more of the natural gas hazards. Outcomes can also include no hazard (dissipation).

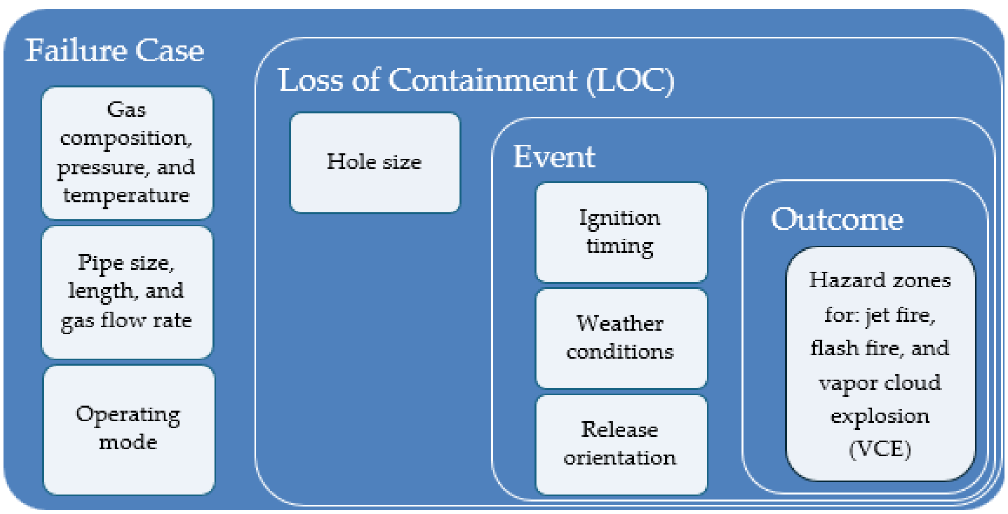

Figure 2-1
Relationships Between Failure Case Divisions

Beginning with the set of failure cases (see Appendix C), an expanded set of potential accidental events was developed through the application of a wide range of representative parameters. Thus, the QRA involved the evaluation of hundreds of potentially fatal events achieved through variations and combinations of the following parameters.

- Release hole size
- Release orientation (horizontal or vertical)
- Weather conditions
  - Wind speed variations for jet fires
  - Wind speed and atmospheric stability combinations for vapor dispersion
- Ignition type (immediate, delayed, or none)

Definitions
Consequence Modeling – The use of computerized mathematical models to predict the potential magnitude of the hazard extents resulting from a specific accident event. *Hazard Zone* – The area or zone affected by a given hazard from a unique accident event, whose boundary is defined by the hazard endpoint. *Hazard Endpoint* – The calculation value used to define a hazard zone, based on a pre-defined level of impact associated with that hazard.

The general process applied to the definition of hazard zones is described in the subsequent sections. Details and background information regarding the parameters and endpoints applied to the modeling are further explained in Appendix A.

2.3.1 Consequence Modeling

With a set of accidental events defined, the magnitudes of the hazard impacts (hazard zone sizes) are calculated with consequence models. This step in the process provides estimates of the natural gas release rate and natural gas properties for each unique event, which then provides input for the hazard zones models.

2.3.2 Consequence Analysis Models

The ability to accurately model releases of natural gas and the subsequent hazards is important if an accurate assessment of potential impacts to people is to be attained in consequence and risk analysis studies. For this reason, Quest has developed a modeling package, CANARY by Quest®, which contains a set of complex models that calculates the potential magnitude of hazards—such as fires, flammable as clouds, and explosions. CANARY contains models that account for the following:

- Thermodynamics and physical properties;
- Time-varying fluid releases;
- Released fluid densities; and
- Heat transfer effects from the atmosphere and surrounding area.

The failure case conditions, as well as the varied modeling parameters discussed above, are input into CANARY to determine the hazard area associated with each unique event. CANARY contains a set of complex models that calculates the hazards for:

- Vapor dispersion from momentum-dominated jets;
- Radiation from a jet fire; and
- Overpressure from vapor cloud explosions.

More information on the CANARY consequence models can be found in Appendix B.

2.3.3 Potential Explosion Sites (PESs)

A separate portion of the consequence assessment task is to identify locations for potential vapor cloud explosions (VCEs), in order to model representative explosion events. Locations within the facility that are confined or include congestion are referred to as potential explosion sites, or PESs. Most vapor cloud ignitions that occur within an unconfined, unobstructed region will only produce a weak blast wave. As the amount of confinement or degree of obstruction increases, so does the potential strength of the blast wave that could be created by a burning vapor cloud within that region. Further discussion regarding the PESs and their definition is provided in Appendix A.

2.3.4 Hazard Impact Criteria

In order to present the risks associated with the various hazards associated with natural gas, a common measure of the hazard impacts must be defined. The basis for this QRA study is an impact level that is capable of causing fatality. When comparing a fire radiation hazard (heat flux) to an explosion hazard (overpressure), the type of impact is very different. To make a valid comparison, the severity of the hazard's impact on humans must be equivalent, in this case a fatality. It would not be meaningful, within the context of a QRA, to compare a nonlethal level of overpressure from an explosion (e.g., something that may break windows) to a lethal level of thermal radiation (e.g., fire that causes burns resulting in death within a few seconds).

Endpoints for each hazard type presented above must be established to evaluate the potential impacts to persons. The modeling endpoints applied in this study are presented in detail in Appendix A. Table 2-1 summarizes the endpoints applied to all parts of the study. The dispersion of (flammable) natural gas is measured in concentration of released natural gas in air. As the natural gas dilutes in air, the mixture will at some point reach a limit, beyond which it is too lean to be ignited and lead to a flammable hazard. That dilution point (natural gas in air) is the lower flammable limit (LFL). If the released natural gas is ignited, the flammable portion of the vapor cloud, defined by the LFL, can burn resulting in a flash fire. This fire also results in a continuous fire at the release source, termed a jet fire, whose impacts are defined by the thermal radiation being emitted from the fire. Thermal radiation is measured in British thermal units (Btu) per square foot, per hour (Btu/hr-ft^2) or kilowatts per square meter (kW/m^2). If the flash fire burns through an area of confinement or congestion, a damaging explosion could result.

The explosion impacts people by a blast wave whose magnitude is measured in pounds per square inch (psi) of overpressure.

Table 2-1
Hazard Modeling Endpoints

Receptor	Hazard	Endpoint	Notes
Unprotected Persons Outdoors	Flammable Vapor	LFL	100% fatality
	Fire Radiation	28.4, 14.3, 7.3 kW/m^2 (9003, 4533, 2314 Btu/hr-ft^2)	99%, 50%, and 1% fatality after 30 seconds of exposure
	Explosion Overpressure	72.0, 13.1, 2.4 psi	99%, 50%, and 1% fatality

2.3.5 Maximum Hazard Distances

The hazard zones calculated in this study, expressed as the maximum hazard distances as measured from the accidental release location, are presented in Appendix D. The extents of hazards associated with jet fire radiation were the most significant—with distances ranging from 5 feet (for the fuel gas line) to 625 feet (for the high-pressure discharge header). Hazards associated with the production of a flammable vapor cloud extended up to 280 feet (also from the high-pressure discharge header), and no overpressure impacts, based on the defined endpoints, from explosions of a flammable vapor cloud were achieved.

2.4 Step 4: Failure Frequency Definition

Frequencies for the various unique events within each given failure case can be estimated by using a combination of:

- Historical experience;
- Failure rate data on similar types of equipment;
- Conditional probabilities of contributing factors; and
- Service factors and/or engineering judgment.

The general methodology applied to failure frequency definition is described in the subsequent sections. Details and background information regarding this methodology is further explained in Appendix A.

2.4.1 Historical Failure Rates

For a single component failure (e.g., pipe failure), the frequency can be determined from industrial failure rate databases. The various failure rates (frequencies) from several databases that were applied in this study are presented in Appendix A. In most cases, these failure rates are expressed as LOC events per year, per piece of equipment. For piping, failure rates are expressed per foot of pipe per year, such that an estimated length of pipe is required to develop the total failure rate. The events represented by these failure rates are the frequency of any LOC event for all potential failure modes.

2.4.2 Equipment Count Methodology

Each failure case will represent a defined, physical portion of the compressor station's equipment that have similar process conditions. Failure cases are identified in this analysis for portions of the process where a release from any piece of equipment within the bounds of the failure case would result in similar *consequences* (i.e. a leak from a flange or a leak from a pipe would produce similar outcomes). Because of this, an LOC from one piece of equipment can be treated the same as another within the failure case, even though they have independent and unique *failure rates*. This means that the frequency estimation for a failure case can be developed by summing the failure rates (frequencies) for the various pieces of equipment found within the boundaries of the failure case, assuming that the failures of different pieces of equipment are independent events.

Within each failure case, the presence of each valve, vessel, heat exchanger, compressor, flanged connection, or instrument connection increases the likelihood of a failure and subsequent LOC, because each individual piece of equipment has a frequency at which it is expected to fail. Therefore, to assess the frequency of LOC events within the failure case and the probability of realizing the hazards associated with a set of unique events, it is necessary to count all equipment within the failure case and include unique failure rates for each type of equipment in the overall risk analysis. The combined failure frequencies of all equipment within a failure case—based on a count of all valves, instrument connections, pressure vessels, lengths of pipe, etc.—represents the failure frequency for a failure case as a whole and can be associated with one or more physical locations within the facility.

2.4.3 Conditional Probabilities

Once the equipment counts are developed and multiplied by the historical failure rates, there are several values that are applied to arrive at an expected probability for each unique event. These values are referred to as conditional probabilities. Within any of the five categories shown below, the set of conditional probabilities will add up to one. For example, given that there is an LOC, a unique event *must* be characterized by one of the specified hole sizes, so all of the probabilities for the chosen hole sizes will add up to one. Conditional probabilities are applied for the following categories:

- Hole size;
- Release orientation (horizontal or vertical);
- Wind speed, atmospheric stability, and wind direction;
- Ignition type (immediate, delayed, or none); and
- High flow, low flow, and standby mode frequencies (see Appendix A for details).

Once the failure frequency and all conditional probabilities are applied to each unique event, the values are transformed into probabilities for use in the QRA. It is worth noting that through the application of conditional probabilities for ignition, not every LOC event will result in a hazard being realized. Because there is a finite probability of non-ignition, some events result in natural gas dissipation where no hazard zone results.

Example
Consider a hypothetical event that has a historical frequency of one in ten per year (1.0×10^{-1} per year). If we are interested in that event occurring on a day with winds blowing from the south (the event AND southernly winds occur), we need a conditional probability. The probability of southern winds in the Ventura area is 9.94% (see Appendix A for more weather data information). A conditional probability of 0.0994 is applied to the event frequency, resulting in an event probability of 9.94×10^{-3} per year, or one chance in about 101 per year. The remaining probability (9.9006×10^{-2} per year) represents the event occurring during any wind direction other than south.

2.5 Step 5: Risk Quantification and Assessment

The final step in the calculations is risk quantification or risk mapping by combining the consequence analysis and frequency analysis results. When the consequences of each unique event are combined with its frequency and all potential events are summed together, accounting for the location of each unique event, the results can be expressed by several measures of risk. These may include location-specific individual risk (LSIR) contours which are a graphical depiction of risk around a facility; societal risk in the form of an F-N curve, which relates the cumulative frequency (F) to causation of fatalities (N) in the areas surrounding the facility due to accidental releases; and other measures of risk per specific project requirements.

In this analysis, risk is depicted as LSIR, a set of composite risk contours that show the annual probability of fatality within and surrounding the facility. These contours represent the chance (probability) that an individual will be exposed to a fatal hazard during a year-long period at any location along a contour. Inherent to the LSIR measure of risk is an assumption that an individual stays in that location for 24 hours per day, 365 days per year. This is referred to as continuous occupancy and is the default assumption for LSIR contours, especially when being compared to tolerability criteria.

The LSIR risk is represented numerically, with each contour being assigned an annual probability of fatality. Table 2-2 lists the numerical value, the short-hand representation of that value as it is used in this report, and the value expressed in terms of chances per year. For example, a 10^{-6} risk contour defines the locations of 1.0×10^{-6} per year fatality risk, or those locations where an individual would have a one-in-one million chance of fatality per year.

Table 2-2
Risk Level Terminology and Numerical Values

Numerical Value	Shorthand Notation	Chance per Year of Fatality
1.0×10^{-3}	10^{-3}	One chance in 1,000 of fatality per year
1.0×10^{-4}	10^{-4}	One chance in 10,000 of fatality per year
1.0×10^{-5}	10^{-5}	One chance in 100,000 of fatality per year
1.0×10^{-6}	10^{-6}	One chance in 1,000,000 of fatality per year

The LSIR measure of risk can then be used in the last step of the study – an assessment of the QRA analysis results. Assessment of the risks associated with the Proposed Project, through comparison to the risk at the existing facility, industry risk tolerability standards, or to other measures of risk, provides a means of interpretation for the study results. The results of the quantitative risk analysis, and the subsequent risk assessment, are presented in Section 3.

3.0 QRA RESULTS AND ASSESSMENT

3.1 Location-Specific Individual Risk (LSIR)

Risk results for the Ventura Compressor Station and the Proposed Project were developed for two scenarios, based on the facility throughputs:

- High flow mode (100% compression capacity), assumed to be active 100% of the year; and
- "Combined" modes, where high flow, low flow (a reduced compression capacity), and standby (no compression) modes are combined according to the details in Appendix A (see Tables A-1 and A-13).

LSIR contours were constructed for the existing Ventura Compressor Station, as well as for the Proposed Project, in the two scenarios listed above. The LSIR contours in Figure 3-1 illustrate the annual fatality risk from all hazards associated with LOC events for outdoor persons in or near the existing Ventura Compressor Station for the high flow case. Figure 3-2 shows the annual fatality risk from all hazards associated with LOC events for outdoor persons in or near the existing Ventura Compressor Station for the combined modes.

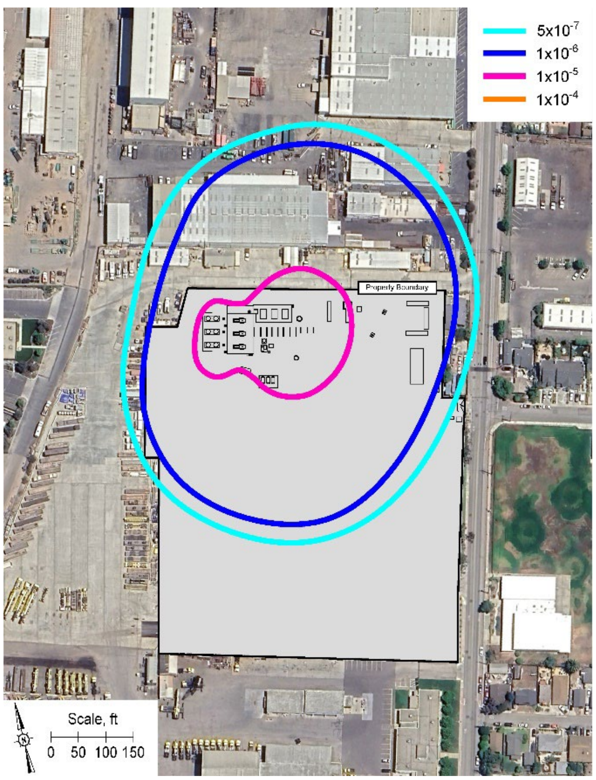

Figure 3-1
Location-Specific Risk for Outdoor Persons – Existing Compressor Station (High Flow)

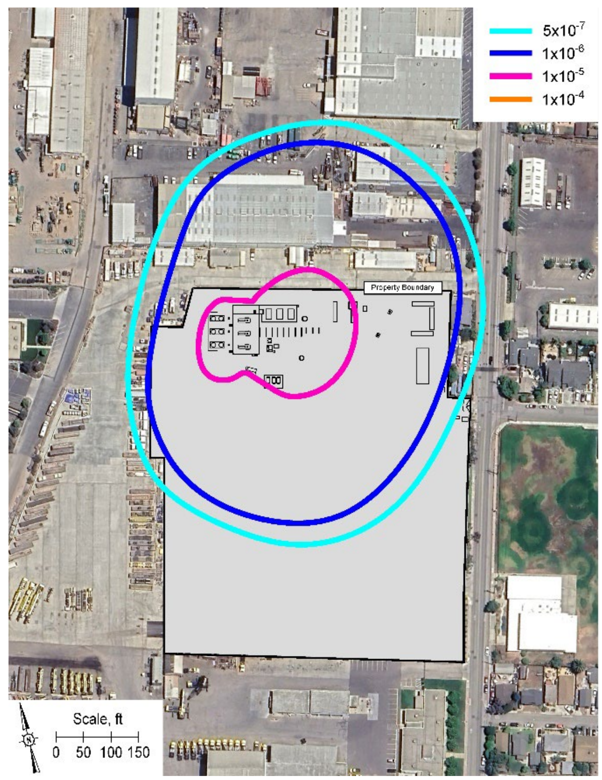

Figure 3-2
Location-Specific Risk for Outdoor Persons – Existing Compressor Station (Combined Modes)

The LSIR contours in Figure 3-3 illustrate the annual fatality risk from all hazards associated with LOC events for outdoor persons in or near the Proposed Project for the high flow case. Figure 3-4 shows the annual fatality risk from all hazards associated with LOC events for outdoor persons in or near the Proposed Project for the combined modes.

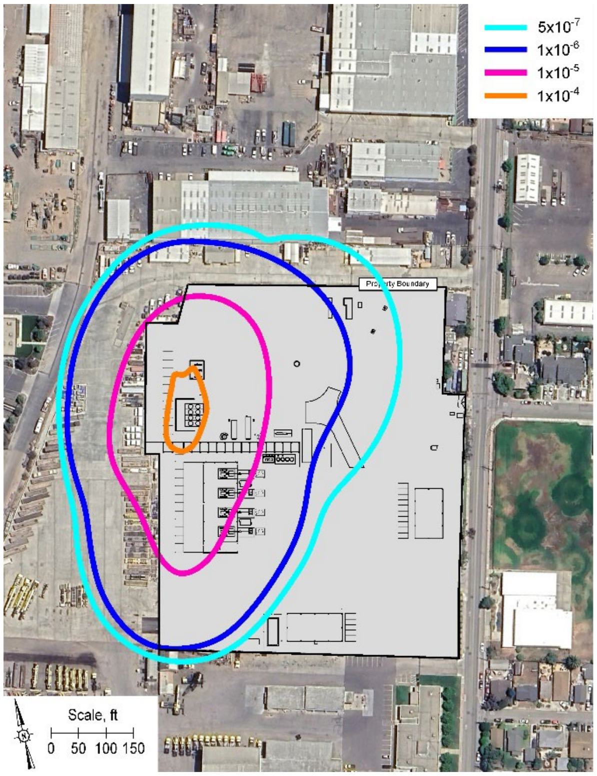

Figure 3-3
Location-Specific Risk for Outdoor Persons – Proposed Project (High Flow)

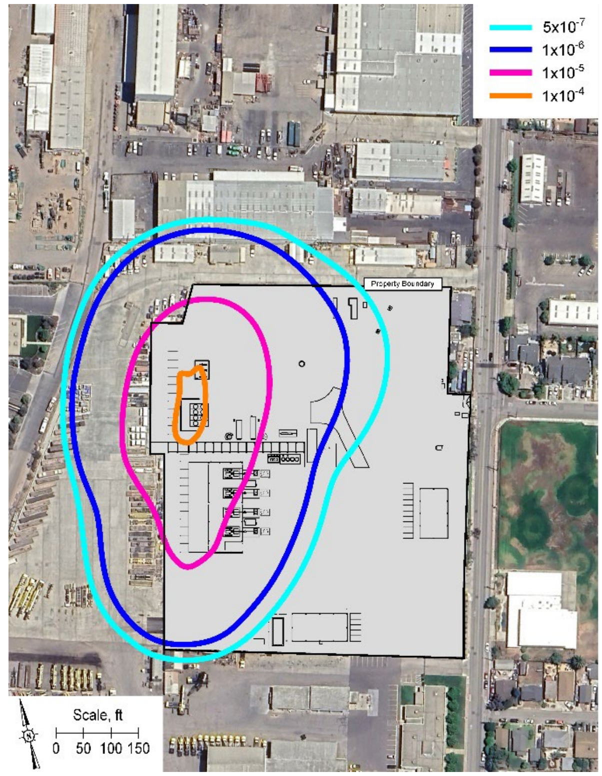

Figure 3-4
Location-Specific Risk for Outdoor Persons – Proposed Project (Combined Modes)

Each risk contour shown in Figures 3-1 through 3-4 represents a specific level of risk, where risk is defined by potentially fatal exposure to any of the hazards associated with the failure cases modeled for this facility. Because the risk contours are based on annual data, this level of risk is dependent on an individual being at the location where a contour is shown for 24 hours a day, 365 days per year. (This applies equally to all presented LSIR contours.) For example, the contours labeled 10^{-5} in the figures (the magenta contours) represent one chance in one-hundred thousand per year of being exposed to a fatal hazard due to a flash fire, **OR** jet fire radiation, **OR** a vapor cloud explosion, assuming continuous occupancy at a location where the contour is shown. Any location with individual occupancy less than a full year (i.e., not continuous occupancy) would result in lower risk to persons in that area than is shown in the contours.

3.2 Risk Assessment

The results of the risk analysis presented above require some level of professional interpretation, typically called an assessment. The assessment for the Proposed Project involves three parts: comparison to the existing Ventura Compressor Station, comparison to various published criteria, and comparison to more commonplace risks.

3.2.1 Comparison to Existing Risk

The results for the existing Ventura Compressor Station were presented in Figures 3-1 and 3-2. Onsite risk was found to be less than 1.0×10^{-4} per year. Risk in the range of 1.0×10^{-5} per year was found to exceed the property boundary to the north by less than 50 feet into an open area (primarily a driveway and parking area). The 1.0×10^{-6} per year risk extends beyond the property boundary by more than 250 feet. Additionally, the 1.0×10^{-6} per year risk does reach the residence at the northeast corner of the station's property. However, these risk contours are based on continuous exposure for outdoor persons. The residence, as well as other buildings in the area, provide protection against the hazards evaluated. This, when combined with non-continuous occupancy, results in actual risk being less than predicted.

By comparison, the Proposed Project (see Figures 3-3 and 3-4) is expected to create risk at the 1.0×10^{-4} per year order of magnitude within the property lines. This result can be attributed to the increased amount of equipment (compressors, pipe, vessels, etc.) for the Proposed Project as compared to the existing system. The Proposed Project includes modern processing systems, updated control systems, and more instrumentation, which may contribute to risk reduction (in comparison to the existing site's equipment). However, these effects cannot be adequately quantified due to the lack of supporting data related to this issue in the failure rate databases.

Fatality risk of 1.0×10^{-5} per year exceeded the western plant boundary by about 75 feet, and 1.0×10^{-6} per year risk by about 150 feet. The 1.0×10^{-6} per year risk also exceeded the northern property boundary by approximately 80 feet. In a general sense, the offsite risks posed by the Proposed Project are roughly similar to those of the existing Ventura Compressor Station. The offsite areas exposed to risk up to 1.0×10^{-6} per year are all industrial sites. At the residence at the northeast corner of the site, risk from the Proposed Project is less than 1.0×10^{-6} per year, which represents a reduction in offsite risk to that area.

Table 3-1 provides a summary of the findings when risk of the Proposed Project is compared to the existing Ventura Compressor Station. The risk values shown in Table 3-1 are approximate, representing general geographic regions. All risk values less than 1.0×10^{-6} per year are assumed to be sufficiently negligible such that they are classified as "$< 1.0 \times 10^{-6}$ per year."

Table 3-1
Proposed Project Risk Comparison

Location	Approximate Existing Annual Risk Due to the Ventura Compressor Station	Approximate Annual Risk Due to the Proposed Project	Approximate Change in Risk
Highest Risk Location Within the Ventura Compressor Station Boundaries	$< 1.0 \times 10^{-4}$	$> 1.0 \times 10^{-4}$	Increase
Residence at the Northeast of the Facility	1.0×10^{-6}	$< 1.0 \times 10^{-6}$	Decrease
Industrial Area North of the Facility Property Line	1.0×10^{-5}	1.0×10^{-6}	Decrease
Industrial Area West of the Facility Property Line	$< 1.0 \times 10^{-6}$	1.0×10^{-5}	Increase
Industrial Area South of the Facility Property Line	$< 1.0 \times 10^{-6}$	$< 1.0 \times 10^{-6}$	Same
East of the Facility Property Line, Olive Street	$< 1.0 \times 10^{-6}$	$< 1.0 \times 10^{-6}$	Same
Residences to the East of the Facility (across Olive Street)	$< 1.0 \times 10^{-6}$	$< 1.0 \times 10^{-6}$	Same
E.P. Foster Elementary School	$< 1.0 \times 10^{-6}$	$< 1.0 \times 10^{-6}$	Same

3.2.2 Review of Risk Criteria

There have been a few attempts to define acceptability criteria for human risk, both for workers and for the general public. In general, risk criteria have been developed to help regulatory agencies define what land uses are tolerable near industrial areas or hazardous materials facilities that present a risk of fatality due to accidental releases or upset conditions. Several recognized international standards are described below. Each of these standards addresses the tolerability of fatality risk to the public in areas around industrial facilities.

Australia - EPA of Western Australia

The Environmental Protection Agency of Western Australia[5] established the following criteria for fatality risk from industrial installations.

[5] WA-EPA (2000), Guidance for the Assessment of Environmental Factors (in accordance with the Environmental Protection Act 1986) – Guidance for Risk Assessment and Management: Off-site Individual Risk from Hazardous Industrial Plant. (No. 2), Environmental Protection Authority of Western Australia, July 2000.

- Risk levels lower than 1.0 x 10^{-6} per year in residential areas are defined as acceptable.
- Risk levels lower than 5.0 x 10^{-7} per year at sensitive developments (hospitals, schools, childcare, etc.) are defined as acceptable. Risk levels up to 1.0 x 10^{-6} per year are acceptable in intermittently occupied areas such as gardens and parking lots.
- Risk levels lower than 5.0 x 10^{-6} per year in commercial areas (retail, offices, restaurants, etc.) are defined as acceptable.
- Risk levels less than 1.0 x 10^{-5} per year in areas between industrial and residential areas (buffer zones) are defined as acceptable.

With the exception of intermittently occupied areas that are part of sensitive developments, this standard requires the calculation of annualized risk without consideration of occupancy for all risk evaluations.

United Kingdom - HSE

The Health and Safety Executive (HSE) is the regulatory authority for hazard identification and risk assessment studies in the United Kingdom. The HSE[6] published a document that discusses their process for risk-based decision making. In *Reducing Risks, Protecting People*, the HSE presents a set of risk tolerability limits that are intended as guidelines to be applied with common sense, not with regulatory rigidity.

- Risk levels lower than 1.0 x 10^{-6} per year for any population group are defined as broadly acceptable.
- For members of the public, risk levels greater than 1.0 x 10^{-4} per year are unacceptable.
- Risk levels between 1.0 x 10^{-4} and 1.0 x 10^{-6} for the public are considered tolerable if the risk is "in the wider interest of society" and the risk minimized to the extent possible.

These criteria do not address occupancy (how often people can be found in various areas). Thus, it is assumed that risk is to be calculated and assessed using a continuous occupancy approach.

Canada – CSA Z276

An LNG standard published by the Canadian Standards Association (CSA), Z276, *Liquefied natural gas (LNG) — Production, storage, and handling*[7], presents a full risk analysis methodology with acceptability criteria. The CSA Z276 public fatality risk criteria to be used in a risk assessment for LNG facilities are as follows. While these do not specifically apply to non-LNG facilities, the general principles of risk tolerability do apply.

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[6] HSE (2001), Reducing Risks, Protecting People; HSE's Decision-making Process. Health and Safety Executive, United Kingdom, 2001 (ISBN 0 7176 2151 0).

[7] CSA Z276:22 (2023), *Liquefied Natural Gas (LNG) – Production, Storage, and Handling*. Update No. 1, CSA Group, Toronto, Ontario, Canada M9W 1R3, April 2023.

- Risk levels less than 1.0×10^{-6} per year are considered broadly acceptable and no further risk control measures are necessary.
- Risk levels greater than 1.0×10^{-4} per year are intolerable.
- Risk levels between 1.0×10^{-6} and 1.0×10^{-4} per year shall be tolerable if the risk can be demonstrated to be as low as is reasonably practicable.

These criteria do not address occupancy, so are assumed to be used with a continuous occupancy assumption.

Canada – MIACC

The Risk-based Land Use Planning Guidelines document[8] originally created by the Major Industrial Accidents Council of Canada, a voluntary alliance of interested parties, provides a set of criteria that are more directed to specific land uses around industrial installations. This document is now maintained by the process safety management division of the Chemical Institute of Canadian Society for Chemical Engineering (CSChE). The presented criteria include the following.

- Risk levels lower than 1×10^{-6} per year are acceptable for areas that include high density and institutional uses.
- Risk levels lower than 1.0×10^{-5} per year are considered acceptable for commercial and low-density residential areas.
- Risk levels between lower than 1.0×10^{-4} are considered acceptable for industrial areas, parks, and open spaces.
- Risk levels greater than 1.0×10^{-4} per year are considered unacceptable when beyond the risk source property line.

These criteria do not address occupancy, so are assumed to be used with a continuous occupancy assumption. Figure 3-5 presents the same risk criteria in graphical form.

USA – NFPA 59A

The National Fire Protection Association (NFPA), in its more recent editions of 59A, *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*[9], has included a chapter addressing risk-based plant siting. In addition to a full set of guidelines for the risk analysis methodology, 59A presents a set of risk tolerability criteria. These criteria do not address occupancy, so a continuous occupancy approach is assumed.

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[8] CSChE (2004), Risk Assessment – Recommended Practices for Municipalities and Industry. Canadian Society for Chemical Engineering, ISBN No. 0-920804-92-6, 2004.

[9] NFPA 59A (2023), *Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)*. National Fire Protection Association, Quincy, Massachusetts, November 2022.

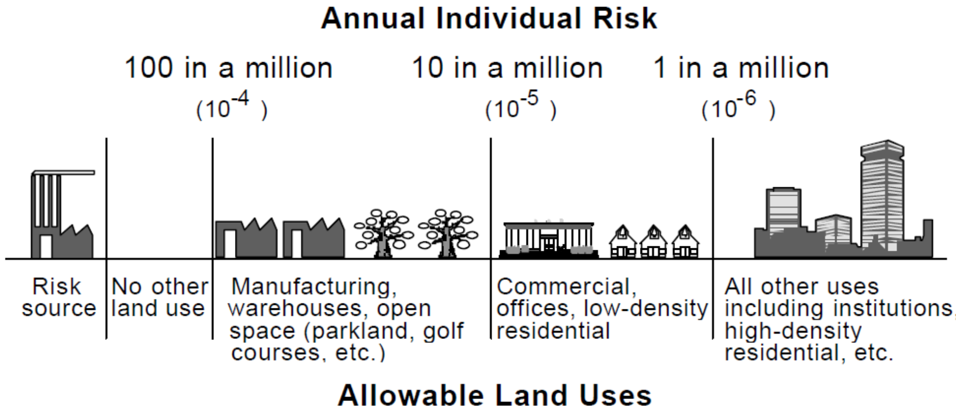

Figure 3-5
MIACC/CSChE Risk Criteria

- Risk levels less than 3.0 x 10^{-7} per year are tolerable; no land use restrictions.
- Risk levels greater than 5.0 x 10^{-5} per year cannot extend beyond land areas in control of the plant operator or subject to a legal land use agreement.
- Risk levels between 3.0 x 10^{-7} and 5.0 x 10^{-5} are considered tolerable for the public, with the exception of sensitive establishments (schools, hospitals, prisons, etc.)

California – Department of Education

In its *Guidance Protocol for School Site Pipeline Risk Analysis*[10], a risk analysis methodology is established for evaluating the location of schools relative to pipelines. The guidance establishes an individual risk level to be used as a tolerability threshold.

- According to the guidance, individual risk levels lower than 1.0 x 10^{-6} per year are defined as insignificant.
- According to the guidance, risk levels greater than 1.0 x 10^{-6} per year are defined as significant.

These criteria were developed for evaluation of school sites in relation to the hazards potentially posed by pipelines. The risk methodology does allow for occupancy at a school site (the fraction of time students and personnel are present) to be accounted for in the risk calculations.

California – County of Santa Barbara

The County of Santa Barbara Planning and Development Department has adopted thresholds for risk assessment during review of hazardous facility projects within the county that require

[10] California Department of Education (2007), Guidance Protocol for School Site Pipeline Risk Analysis, prepared by URS Corporation, February 2007.

discretionary permits[11]. While their published criteria are primarily focused on societal risk measures (which were not in scope for this study), they do provide a general guidance for threshold offsite risk.

- Annual risk of 1.0×10^{-6} is sufficient to trigger a comprehensive risk analysis.

The measurement of risk is based on the calculation of individual risk, with potential adjustments for occupancy. This QRA constitutes a comprehensive risk analysis.

3.2.3 Comparison to Other Risks

Another way to evaluate the risk imposed by the Proposed Project on the public is by using fatality rates from other activities or accidental events. Table 3-2 lists several potential causes of death (primarily things that the general public may be exposed to) in the form of odds of death in a one-year period and approximate annual probability of fatality. Table 3-2 is based on statistics for 2020, the latest year for which these values are available[12,13]. The likelihood or frequency of fatality values presented are based on the total U.S. population for 2020 (330 million), and so represent the risk of fatality for the general population of this country.

An examination of Table 3-2 reveals that there are many potential causes of death (including accidental falls, accidental drowning, and weather-related deaths) that have a higher probability of fatality, when compared to the risk of fatality imposed by the Proposed Project on the public. Several location-specific risk values, as predicted for the Proposed Project, are inserted into Table 3-2; Each of these is the calculated risk, as presented earlier in this report, with continuous occupancy as an assumption.

3.3 Conservatism Built Into the Risk Analysis Study

As with any consequence or risk analysis study, assumptions and engineering approximations are made in order to calculate the risk associated with the facility. In general, assumptions are made that tend to overpredict the risk due to LOC events from the system. Thus, the predictions of risk presented in this report are conservative – in other words, they show the risk to be higher than it really may be.

[11] County of Santa Barbara (2021), Environmental Thresholds and Guidelines Manual, County of Santa Barabara Planning and Development Department, January 2021 revision.

[12] National Vital Statistics Reports, Vol. 72, No. 10, September 22, 2023

[13] https://injuryfacts.nsc.org/

Table 3-2
Odds of Early Fatality Data from the National Vital Statistics and National Safety Council
(*Comparison Values for Proposed Project Based on Continuous Occupancy Outdoor Risk*)

Cause of Death	Annual Number of Deaths in U.S. Population†	Odds of Death in a One-Year Period (one chance in…)	Approximate Annual Probability of Fatality
Heart disease	696,962	474	2.11×10^{-3}
Cancer	602,350	549	1.82×10^{-3}
Stroke	160,264	2,062	4.85×10^{-4}
Accidental poisoning	87,404	3,781	2.64×10^{-4}
Influenza or pneumonia	53,544	6,172	1.62×10^{-4}
Motor vehicle accidents	42,339	7,805	1.28×10^{-4}
Falls	42,114	7,847	1.27×10^{-4}
Hazards of Proposed Project; at Western Property Line, Industrial Area	--	~33,300	$\sim 3.0 \times 10^{-5}$
Pedestrian (motor-vehicle accident)	7,904	41,810	2.39×10^{-5}
Complications of medical/surgical care	5,361	61,642	1.62×10^{-5}
Accidental choking	4,912	67,277	1.49×10^{-5}
Accidental drowning	4,177	79,115	1.26×10^{-5}
Exposure to smoke, fire, or flames	2,951	111,983	8.93×10^{-6}
Exposure to forces of nature	1,805	183,082	5.46×10^{-6}
Mechanical suffocation	1,804	183,184	5.46×10^{-6}
Electrocution	277	1,193,008	8.38×10^{-7}
Bitten or struck by dog or other mammals	136	2,429,876	4.12×10^{-7}
Hazards of Proposed Project; at Residence at Northeast Corner of Facility	--	~4,000,000	$\sim 2.5 \times 10^{-7}$
Hazards of Proposed Project; at E.P. Foster Elementary School, Northwest Corner of Recreation Area Along Olive Street	--	~13,333,300	$\sim 7.5 \times 10^{-8}$
Lightning	19	17,392,797	5.75×10^{-8}

A few of the conservative assumptions (that lead to risk overprediction) are listed below. The contributions of these factors cannot be explicitly quantified. They are presented here to provide qualitative reasons why the actual risk would be expected to be lower than predicted.

- **Overprediction of Public Presence**: The LSIR calculations assume that people are present 24 hours a day, 365 days a year, at locations outside of the Ventura Compressor Station. Thus, the risk to offsite persons is less than predicted due to non-continuous occupancy.
- **Ignoring Human Response Time**: For persons exposed to fire radiation from a pool fire or jet fire, it was assumed that the duration of exposure was equal to thirty (30) seconds. This means that no protective or evasive action is taken by that individual for a full 30 seconds. If an individual moves away from the fire or finds shelter behind a solid object, their exposure to radiant energy will be reduced. Thus, the assumption of a 30-second exposure results in an overprediction of risk.
- **Release Orientation**: Horizontally oriented releases were assumed to be oriented such that they are pointing in the direction the wind is blowing. This assumption allows the released material to travel the maximum distance before diluting below the lower flammable limit, or, if ignited, for the jet fire to extend the greatest distance from the release point. Any other release direction (upwind, crosswind, etc.) would result in smaller impact zones. The net effect is an overprediction of risk.
- **Block Walls**: The QRA did not account for the presence of the site's block walls. These could potentially limit the extent of a flammable vapor cloud and could provide a barrier against a jet fire extending off site. While the wall does not completely shield against thermal radiation from all events (especially elevated jet fires), it does provide some shielding against thermal radiation. Overall, if the walls were to be accounted for in the QRA, the predicted risk would be less.

3.4 Proposed Project Risk Assessment

Using the information presented in the previous sections, the results from the QRA for the Proposed Project can be assessed. The following conclusions can be drawn:

- The offsite risks for the Proposed Project are similar in magnitude to the existing Ventura Compressor Station.
- Similar to the existing compressor station, the Proposed Project is predicted to create offsite risk greater than 1.0×10^{-6} per year, but only in industrial or commercial areas.
- There are no nearby outdoor offsite areas where people would be expected to remain for extended periods of time; thus, risk will be less than presented because of the continuous occupancy basis for the risk calculations.
- Based on the risk criteria presented above, the risk posed by the Proposed Project does not exceed the unacceptable level offsite for residential housing areas or sensitive developments.
- The offsite risk greater than 1.0×10^{-6} per year posed by the Proposed Project only impacts industrial or commercial areas offsite.

- The maximum predicted offsite risk for the Proposed Project is approximately 3.8 x 10^{-5} per year at the western boundary; thus, the Proposed Project does not exceed the unacceptable risk level for any of the listed criteria.
- When compared to other potentially fatal events, the maximum risk posed by the Proposed Project to offsite areas is less than health issues (heart disease, cancer, influenza), motor vehicle accidents, and falls. When considering occupancy of the adjacent industrial areas, the risks are less than many other causes of accidental death, such as drowning, electrocution, and exposure to fire or smoke.

4.0 QUALITATIVE ASSESSMENT OF RISK FOR ALTERNATIVES

To evaluate potential alternatives to the Proposed Project, this assessment work applied a qualitative hazard identification and risk assessment approach. This allowed a comparison of the Proposed Project to its alternatives, in a qualitative framework, within the context of the hazards of natural gas at a compressor station.

4.1 Alternatives

In the submitted Proponent's Environmental Assessment (PEA)[14], SoCalGas identified several alternatives to the Proposed Project in Section 4 of that document that meet the objectives and purposes of the Proposed Project. Within the context of this analysis, the alternatives considered for evaluation are all categorized as "pipeline" alternatives since they involve the movement of natural gas within the existing SoCalGas North Costal System. None of the non-pipeline alternatives are included in this risk assessment.

The alternatives qualitatively evaluated in this study, in comparison to the Proposed Project, are:

- Avocado site;
- Devil's Canyon Road site;
- Ventura Steel site; and
- Supplemental Electric-Driven Compression.

Two other pipeline alternatives were proposed in the PEA but are not specifically addressed by this analysis: all electric compression, and 3/1 Hybrid. (These were also not further analyzed in the PEA by SoCalGas since they do not meet the objectives and purposes of the Proposed Project.)

The "no project" alternative, which is not evaluated in the qualitative assessment, is the current Ventura Compressor Station operation that was the basis for comparison in the QRA portion of this study. Given the four alternatives for further consideration, three are alternative sites and one is an alternate configuration of the existing site. For the qualitative assessment, the Proposed Project is compared to its alternatives, within the context of risk to offsite persons in the vicinity of a compressor station. While this assessment of risk is informed by the QRA presented earlier in this report, the elements of risk used for assessing risk of the alternatives are independent and separate from the QRA.

[14] SoCal Gas, *Proponent's Environmental Assessment for the Ventura Compressor Station Modernization Project*, prepared by Dudek, August 2023.

4.2 Alternatives Evaluation Methodology

A qualitative approach was developed and implemented to compare the Proposed Project to its alternatives. One primary assumption applied to this evaluation:

- The scope and purpose of any new compression station at one of the pipeline alternative sites would be effectively identical to the Proposed Project. This means that the equipment would be the same as the Proposed Project, and the operating conditions (temperatures, pressures, throughput, and operating modes) would also be the same.

The qualitative evaluation involves the following steps, for each alternative.

A. Identify and discuss any unique aspects or threats of the alternative that may affect the compression system, and the resultant risk of such a system.
B. Assess and explain any additional risks associated with a compressor station that may be introduced due to the alternative that are associated with expected infrastructure enhancements.
C. Using the quantitative information set (generated from the QRA) for the Proposed Project, provide a qualitative assessment of risk due to fire and explosion hazards for the alternative.
D. Compare and contrast the alternative to the current (existing) site with qualitative factors (i.e., risk is greater than, less than, or about the same as the existing site) for the issues identified in A, B, and C above.
E. Provide a final assessment of the alternative (including natural gas pipeline extensions where applicable) compared to the existing compressor station.

The intent of the above-described evaluation is to show, within the context of risk associated with natural gas compression, how the alternatives compare to the existing compressor station and the Proposed Project. This assessment should serve to complement the information presented in the PEA.

4.3 Alternatives Discussion

For each of the four considered alternatives, the factors described in Steps A, B, and C above are detailed in the following sections. The issues raised are intended to be the major ones that would affect risk to persons in the vicinity of the compressor station but may not be a comprehensive list of all risk factors.

As discussed in previous sections of this report, the Proposed Project would modernize the Ventura Compressor Station, at the current site. This would be done without site expansion, pipeline modifications, or roadway additions. The Proposed Project does include expansion and/or upgrading of the block walls along the property borders and some utility modifications. The surrounding areas and their occupants (primarily industrial or commercial but including a school and some residences) would remain the same. The Proposed Project and its associated risk form the basis for comparison to the alternatives.

4.3.1 Avocado Site

This proposed alternative location is situated about ¾ mile to the west-northwest of the current Ventura Compressor Station. The site is approximately 15 acres and adjacent to an avocado orchard. The land is currently undeveloped and has significant terrain (hillside) features. The site is close to several of the existing SoCalGas pipelines that serve the North Costal System.

To make this site suitable for a compressor station, several modifications to the site and surrounding areas would be required.

- The site would need to be partially graded and leveled to provide space for the compressor station equipment. The slope of the land would require significant soil stabilization efforts and would leave portions of the property unusable for a compressor station.
- Taylor Ranch Road would need to be widened, regraded, and paved to make the site accessible for the facility (and construction purposes) as well as meeting fire department standards.
- Approximately 0.36 miles of pipeline would need to be installed to connect to the North Costal System lines.

4.3.2 Devil's Canyon Road Site

The second potential alternative site is situated slightly more than 1 mile to the north of the current Ventura Compressor Station, on land used for oil and gas exploration activities. The site is generally level ground measuring 12.9 acres and is bordered by the Ventura River to the east with oil and gas infrastructure or undeveloped lands on other sides. The land is currently occupied by several oil wells and related equipment.

To make this site suitable for a compressor station, several modifications to the site and surrounding areas would be required.

- The site will require some degree of clearing and/or grading to make it suitable for a compressor station.
- Minor upgrades to local roads would be required to make the site accessible for the facility and for construction purposes.
- Approximately 1.9 miles of pipeline would need to be installed to connect to the existing North Costal System lines.

4.3.3 Ventura Steel Site

The third proposed alternative location is situated about 1 ½ miles to the north-northeast of the current Ventura Compressor Station. The site is generally level ground measuring 10 acres and is surrounded by industrial uses. The land is currently occupied by several active oil wells and related equipment.

To make this site suitable for a compressor station, several modifications to the site and surrounding areas would be required.

- The site will require some degree of clearing and/or remediation, with minor site grading, to make it suitable for a compressor station.
- Approximately 6.4 miles of pipeline would need to be installed to connect to the North Costal System lines, including a segment beneath North Ventura Avenue. Pipeline construction would also require development of an approximately 0.7-mile road to access the pipeline corridor during construction.

4.3.4 Supplemental Electric-Driven Compression

The Supplemental Electric-Driven Compression (SEDC) alternative is a hybrid solution that would be located within the current Ventura Compressor Station property. The existing 1980's era compressor system would remain and be maintained in its current configuration, and all connections to pipelines would remain. Additional compression with electric drivers would be added similar to the configuration of the Proposed Project, although on a smaller scale. This would provide the station with enhanced capacity to serve future needs, as well as installing compressors the have a minimized greenhouse gas emissions profile.

This alternative would use the existing site and existing compressor station equipment; no new pipelines, roads, or other utilities would be required.

4.4 Alternatives Risk Assessment

The potential risks of each alternative to the Proposed Project are evaluated below. A qualitative ranking system was applied to the Proposed Project and each of the alternatives. Comparison of several risk elements is made to the risk at that location that *currently exists* at a given location. Thus, this qualitative assessment is an evaluation of the change in risk at a particular location.

In this assessment, risk is defined as the potential for adverse consequences due to natural gas releases, including from the compressor station and pipelines, as well as may affect the natural gas operations to cause such an event. All hazards are safety issues that may affect people, both onsite and offsite. The risk elements considered are as follows.

- **Compressor station risks onsit**e – These are the risks driven by the natural gas hazards as informed by the details presented in the QRA.
- **Geographical** – Consideration of the location for the alternative is given within the context of contributing to the hazards associated with natural gas compression. These factors may include the current land use, unexpected terrain concerns, underground utility conflicts, and contaminated soil.
- **Offsite compressor station risks** – These risks arise from the natural gas hazards at a compressor station that reach beyond the property line. These are, qualitatively, the risks analogous to the quantitative results presented in the QRA portion of this report and are constrained to the concept of individual risk (as presented in the QRA).
- **Offsite pipeline risks** – This element aims to capture the inherent risk to persons around natural gas pipelines. The hazards that comprise this risk are the same as those evaluated in the QRA study. With the Proposed Project for comparison, relative risk is generally proportional to the length of new pipelines installed, as well as the locations where those pipelines must be installed.
- **Adjacent land use** - If the adjacent land uses feature higher population densities or more sensitive populations (e.g., residences), the impacts during an LOC event may be higher; industrial or undeveloped land may result in smaller impacts. Additionally, the acceptability of imposing risk on different populations is factored into this assessment (e.g., industrial area impacts vs. residential area impacts).
- **Adjacent activities** – This element considers the potential for neighboring activities to impact the compressor station and contribute to the hazards of natural gas. This may manifest as external forces that contribute to LOC events, potential for operational disruption, and factors such as site security and potential sabotage.
- **Emergency access/egress** – This risk element addresses potential emergency access and personnel egress at each site. Concerns regarding access within this category include multiple approach routes for emergency vehicles, roadway quality, and general accessibility. Egress concerns include means for personnel to exit in the event of an emergency situation, including on foot or in vehicles. These considerations modify how emergency response activities (both onsite and from offsite) may affect the inherent hazards, and resulting risk, of a compressor station.

4.4.1 Proposed Project

Based on the QRA results presented in Section 3 of this report, the level of offsite risk due to the Proposed Project is approximately equal to the existing compressor station. While the exposed offsite areas are different, the size of area covered, and type of area covered are roughly the same. The primary offsite risk impacts are to industrial or commercial areas. The Proposed Project results in a lower risk to the residence at the northeast corner of the property.

The QRA results demonstrate that the Proposed Project results in increased onsite risk when compared to the existing facility. This is primarily due to the expanded capacity of the facility (from 90 to 160 MMSCFD) and the update to modern processing and control systems, more and larger piping, and instrumentation systems. These changes provide more equipment that could fail, as well as larger inventories that increase the magnitude of natural gas releases. While these modern systems may contribute to risk reduction, these effects cannot be adequately quantified. Thus, the consideration of modern systems can only provide a qualitative reduction in the increased quantitative risk that is predicted.

For the Proposed Project, existing pipelines will be used; thus, no additional risk due to new pipeline installation will be introduced (i.e., the pipeline risk is unchanged). The adjacent land use and activities are also identical to the existing Ventura Compressor Station so are both known and equal to the current operating facility. While the plot space within the facility boundaries will be different with the Proposed Project (as compared to the existing), all land use and underground utility issues are known due to the long history of SoCalGas at this site. Additionally, because the site is not changing, emergency access and egress issues are effectively unchanged compared to the existing operation.

4.4.2 Avocado Site

The Avocado site, like all alternative sites, would have identical equipment and operating characteristics as the Proposed Project. Because of this, the natural gas hazards would be of the same magnitude and frequency as predicted for the Proposed Project. The extent of these hazards into adjacent areas (offsite impacts) would be dependent on the specific layout and arrangement of the compression equipment on the site. Thus, because the equipment layout and land utilization would be different, the specific offsite individual risk profile (in the form of risk contours) cannot be known. However, the same overall magnitude of onsite risk as predicted for the Proposed Project would be expected to exist within the plant boundaries if a compressor station is built at this location.

Due to its terrain features, the Avocado site would require site leveling, soil stabilization, landslide prevention, and storm water management activities. This would limit the placement of compressor station equipment and could force the compressor systems toward one edge of the property. The qualitative effect of these factors would be expected to result in offsite risks that are similar to what has been calculated for the Proposed Project, due to the systems' potential proximity to property lines. This assessment is reached despite the larger plot size (15 acres vs. 8.4), as significant portions of the property would be expected to be unusable for the requisite compressor station equipment.

The risk due to new pipelines for the Avocado site would be a slight increase in offsite risk, as compared to what exists at the site now. This contribution would be greater than the existing Ventura Compressor Station or the Proposed Project, due to the need for approximately 0.36 miles of pipeline installation where none exists currently.

The adjacent land uses in this area are primarily agricultural, so the potential impacts to the public would be expected to be minimal. While this does not change the prediction of individual risk (in the form of risk contours), the overall impacts of natural gas hazards would be less due to the low occupancy in this area. Likewise, the agricultural activities and semi-remote nature of the site would be expected to result in minimal disruption from adjacent areas. However, the local terrain, as well as the remote location, could be detrimental factors in site security. Additionally, soil stability hazards that would not be present at a more level site could lead to equipment damage escalating to an LOC.

The emergency access and egress concerns for this site are significantly more than for the Proposed Project. Because the site would only be reached by one road, access for offsite emergency services could be restricted, or compromised by the hazards of an LOC event. The terrain features of the site could also make access to specific areas of the facility difficult and could constrain egress should there be an LOC event.

4.4.3 Devil's Canyon Road Site

The Devil's Canyon Road site, like all alternative sites, would have identical equipment and operating characteristics as the Proposed Project. As the natural gas hazards would have the same magnitude and frequency as predicted for the Proposed Project, the potential natural gas impacts would generally be the same. The extent of these hazards onto offsite areas would be dependent on the specific layout and arrangement of the compression equipment on the site. Thus, because the equipment layout and land utilization would be different, the specific offsite individual risk contours cannot be known. Additionally, the same overall magnitude of onsite risk as predicted for the Proposed Project is expected to exist within the plant boundaries if a compressor station is built at this location, due to the assumed identical equipment and its use.

The assessment of offsite risk for this site brings consideration of several factors. First, the site is larger (12.9 acres) than the existing compressor station (8.4 acres), which would normally facilitate minimization of offsite risk. Unknowns arise due to the existing oil and gas activity on the site. It is possible that this site would require soil remediation, avoidance of underground utilities or oil/gas pipelines, or constrained use due to existing wells. This could limit the placement of compressor station equipment and could force the compressor systems toward certain property lines. The qualitative effect of these factors would be expected to result in offsite risks that are similar to what has been calculated for the Proposed Project. Because the equipment layout and land use would be different, the specific offsite risk profile cannot be known.

The need for pipeline extensions at this alternative site would increase offsite risk, compared to what exists now, above and beyond any compressor station offsite risk. The installation of approximately 1.94 miles of new pipelines along Devil's Canyon Road also increases the risk to persons that may be in or traveling along those areas.

The area surrounding this site is lightly used, with active oil and gas facilities on the site and in the area. The site is somewhat remote, being located across the Ventura River from the City of Ventura in an area with little other development (beyond the oil and gas activities).

Consequently, the adjacent human activities would not be expected to have impacts on a compressor station. Potential impacts could be realized due to the oil and gas activities on and around the site. These may include well blowouts or (non-associated) pipeline failures, which could result in some of the same natural gas hazards as exist for the compressor station, as well as related hazards from crude oil systems. Thus, the potential for operational disruption or escalation to a compressor station LOC event could exist. Site security could be slightly more of a risk at this site due to the semi-remote nature of the location.

The Devil's Canyon Road site would introduce limited roadway access for external responders. The area would be accessible from the City of Ventura by one primary road, although access to multiple sides of the site would likely be possible. Human egress in the event of an LOC event would be adequate due to the generally level and unconstrained terrain in the immediate area.

4.4.4 Ventura Steel Site

Similar to the other alternative sites, the Ventura Steel site would be equipped with the same systems for natural gas compression as the Proposed Project. The natural gas hazards would be of the same magnitude and frequency, producing the same potential natural gas hazard impacts. The same overall magnitude of onsite risk as predicted for the Proposed Project is expected, although the equipment layout and arrangement will be different. The extent of the natural gas hazards onto offsite areas would be dependent on how the compressor equipment is laid out and placed at the site. While the equipment and purpose of the site would be identical to the Proposed Project, the equipment layout and land utilization would be different, leading to different offsite individual risk contours.

This site features a 10 acre piece of land compared to the existing 8.4 acres, which could provide for more opportunities to reduce risk offsite when compared to the Proposed Project. However, the site is more rectangular in shape, resulting in equipment placements that could be potentially closer to a site boundary. In addition, the existing and active oil and gas systems at the property would likely eliminate portions of the property from future use due to well locations, buried pipelines, or soil contamination. The qualitative effect of these factors would be expected to result in increased offsite risks when compared to what has been calculated for the Proposed Project.

The extensive set of new pipelines – approximately 6.4 miles – that would need to be installed for this site would increase the offsite risk to people, not just in the immediate area around the site, but extending for several miles away. While pipeline risk is generally low due to the infrequent failure rates (see Appendix A, Section A-3.1), the addition of a pipeline underneath Northern Ventura Boulevard would also create a concern for exposure of higher population density areas to the inherent natural gas hazards.

Adjacent land uses around the Ventura Steel site are industrial, with several locations serving the oil and gas operations in the area. Adjacent human activities would be expected to have only moderate potential for impacts to a compressor station. Potential impacts could be realized due to the active oil and gas wells on and around the site, including well blowouts or (non-associated) pipeline failures. Thus, the potential for operational disruption or escalation to a compressor station LOC event could exist due to some of the same natural gas hazards and related hazards from crude oil systems. Site security for this location would be approximately the same as the existing site, due to its location within the city.

The roadway access to this site is somewhat constrained, as Ventura Boulevard is the primary route to the site. Alternate access does exist but would require longer travel times. There are roadways on several sides of the site for emergency access. Egress from the site is expected to be straightforward due to the developed nature of the area and existing roadways.

4.4.5 Supplemental Electric-Driven Compression (SEDC)

For the SEDC alternative, the existing Ventura Compressor Station equipment would remain operational and new equipment would be added to expand the facility capacity and reliability. The natural gas hazards that would exist with this alternative would be identical to the existing compressor station and the Proposed Project. On an overall risk basis, this represents a combination of (1) the existing site's risk and (2) a portion of the Proposed Project's risk, as were presented in Section 3 of this report. Because of these factors, the net effect for onsite risk would be expected to be greater than the existing site due to the addition of equipment, but less than the Proposed Project due to the limited scope of the equipment being added.

As compared to the Proposed Project (and the existing site as well), offsite risk would be expected to cover larger areas with the same levels of risk. This occurs due to the same hazards being realized for a larger set of equipment distributed over a larger portion of the site.

The SEDC alternative will use existing pipelines, so no additional risk due to pipelines would be introduced. Any increase in offsite risk would be due to compressor equipment only.

As with the Proposed Project, the adjacent land uses and activities would be identical to what exists today. The potential for impacts to offsite areas would increase due to the combination of the existing compressor equipment and new systems. However, no substantially new areas (by land use) would be exposed, and the potential to impact residential or school areas is expected to remain equal to what exists currently.

Likewise, emergency access and egress for this alternative would be identical to what exists currently.

4.4.6 Assessment Ranking Scale

For assessment of the elements listed above, the qualitative risk grading system applied to this study includes the following terms:

- Much Less – significant reduction in risk due to the subject risk element;
- Less – small reduction in risk due to the subject risk element;
- Same – no change in the risk due to this element;
- Slight – small increase in risk due to this element;
- More – moderate increase in risk due to this element; and
- Much more – significant increase in risk due to this element.

4.5 Alternatives Assessment Summary

The qualitative assessment results for the seven risk elements discussed in the previous sections are summarized in Table 4-1. The context of this comparison is each alternative's qualitative assessed risk as compared to the Proposed Project.

These results demonstrate that each alternative has its positive (or neutral) elements of risk, as well as negative ones. A review of the table shows that the SEDC alternative would have the smallest increase in risk, as compared to the Proposed Project, within the context of the criteria applied in this assessment. However, the single area of increased risk for the SEDC alternative is offsite risk, which could be weighed more heavily than other elements.

While the Proposed Project would have some aspects of increased risk compared to the existing Ventura Compressor Station (see the Section 3 QRA results), each of the pipeline alternatives to the Proposed Project that were evaluated in this assessment would have higher overall risk (qualitatively) than the Proposed Project.

Table 4-1
Qualitative Assessment of Risk: Comparison of Alternatives to the Proposed Project

Risk Element	Qualitative Risk Grade			
	Avocado Site	Devil's Canyon Road Site	Ventura Steel Site	SEDC
Compressor Station Onsite Risk	Same	Same	Same	Same
Geographical	More	More	More	Same
Compressor Station Offsite Risk	Same	Same	Slight	More
Pipeline Risk Offsite	Slight	More	Much More	Same
Adjacent Land Uses	Much Less	Less	Less	Same
Adjacent Activities	Same	Slight	Slight	Same
Emergency Access/Egress	Much More	More	Slight	Same

5.0 CONCLUSIONS

This study was focused on risk to persons in the vicinity of the natural gas compression systems operated by SoCalGas. The analysis assessed the risk from:

1. The existing Ventura Compressor Station
2. The proposed Ventura Compressor Station Modernization Project (Proposed Project)
3. Alternatives to the Proposed Project

Items #1 and #2 were evaluated with a quantitative risk analysis (QRA). The QRA study calculated the consequences of (1) jet fires, (2) flash fires, and (3) explosions following accidental releases of natural gas, over a wide range of potential conditions. It also developed and predicted the probability of each unique event using historical failure rate data and conditional probabilities. The consequences and frequencies were combined to develop a measure of risk – location specific individual risk (LSIR) – that is used to evaluate the potential impacts to persons in the area. This measure of risk incorporates several conservative assumptions (that will make the predicted risk higher). The main factor among these assumptions is the continuous occupancy assumption that is inherent in the LSIR contours. To the extent that people are not present within and around the compressor station, an individual's actual risk will be lower than predicted in this analysis.

For the existing system, onsite risk was found to be less than 1.0×10^{-4} per year. Risk in the range of 1.0×10^{-5} per year was found to exceed the property boundary to the north by less than 50 feet. The 1.0×10^{-6} per year risk extends beyond the property boundary by more than 250 feet.

For the Proposed Project, areas of 1.0×10^{-4} per year risk were found within the site boundaries, around the inlet filters and outlet coolers. This result can be attributed to the increased amount of equipment for the Proposed Project as compared to the existing system, which includes modern processing systems, more and larger piping, extra control systems, and more instrumentation. Fatality risk of 1.0×10^{-5} per year exceeds the western property line by about 75 feet. The 1.0×10^{-6} per year risk exceeds the western boundary by about 150 feet and exceeds the northern property boundary by approximately 80 feet. Similar to the existing compressor station, the Proposed Project is predicted to create offsite risk greater than 1.0×10^{-6} per year, but only in industrial or commercial areas. Specifically, at the E.P. Foster Elementary School site to the east of the facility across Olive Street, the risk is less than 1.0×10^{-6} per year, including continuous occupancy. This finding shows that the Proposed Project satisfies all of the risk criteria presented in Section 3.2.2 for the school site (i.e., the risk would be found acceptable when these criteria are applied).

A risk assessment using several international risk acceptability criteria showed that the predicted levels of risk associated with the Proposed Project would not be found unacceptable by any of the criteria that are presented. Additionally, the risks imposed to persons around the compressor station are less than many potential causes of accidental death, including automotive accidents, falls, and accidental poisoning.

The alternatives to the Proposed Project were evaluated with a qualitative hazard identification and risk assessment approach that utilized quantitative data from the above-described QRA, paired with information about each alternative to develop a comparative evaluation. Several elements that may contribute to risk in the area of a compressor station were assessed and compared to the Proposed Project. While these factors are intended to be representative of the risk to persons in the vicinity of a compressor station due to natural gas hazards, they may not constitute a comprehensive list of all risk factors, and do not address financial, temporal, or future regulatory issues, nor other elements of impact that are addressed in the PEA.

The findings from the qualitative assessment show that the SEDC alternative would have the smallest increase in risk, as compared to the Proposed Project. All the evaluated alternatives to the Proposed Project would result in a larger qualitative risk profile, as compared to the Proposed Project, within the context of the criteria applied in the qualitative assessment of risk.

Risk due to the Proposed Project will be managed and maintained as low as reasonably possible. During future design phases of the Proposed Project, various process hazard analyses (PHAs) will be performed to identify, address, and mitigate risks or process upsets. Recommendations from the PHAs would be implemented in the detailed design phase of the Proposed Project to lower both on-site and off-site risks & enhanced safety of the station. The planned PHAs can be found in the 'Response to PEA Completeness Review, September 2023' in Table 5.9-2 on page RTC-11[15].

[15] https://www.socalgas.com/sites/default/files/Response_to_PEA_Completeness_Review.pdf

APPENDIX A
STUDY BASIS DOCUMENT

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A-1 GENERAL ITEMS

A-1.1 Meteorological Data

The weather conditions at the time of an accidental release (an LOC event) can influence the extents of the resulting hazards. For the purposes of a risk-based study, a set of weather conditions – consisting of atmospheric stability, wind speed, and wind direction – must be assigned for each calculation. Atmospheric stability classes are designated by the letters A through F. In general, the most unstable atmosphere is characterized by stability class A. Stability class A corresponds to an atmospheric condition where there is strong solar radiation and moderate winds. This combination of solar radiation and wind allows for rapid fluctuations in the air and thus greater mixing of the released gas with time. Stability class D is characterized by fully overcast or partial cloud cover during both daytime and nighttime. The atmospheric turbulence is not as great during class D conditions as during class A conditions; thus, the gas will not mix as quickly with the surrounding atmosphere. Stability class F corresponds to the most "stable" atmospheric conditions. Stability class F generally occurs during the early morning hours before sunrise (thus, no solar radiation) and under low wind. The combination of low wind and lack of solar heating allows for an atmosphere which appears calm or still and thus restricts the ability to actively mix with the released gas.

Probabilistic meteorological data are used in the quantitative risk analysis (QRA). In general, this requires data collected over multiple years in the form of wind speed, atmospheric stability class, and wind direction triplets. Data collected onsite is the most representative of site meteorological conditions and is preferable to data from other locations. Site-specific meteorological data collected at the Ventura site was provided by SoCalGas and used in this evaluation. This is the same data set that was approved by the VCAPCD and used in the dispersion modeling for the health risk assessment which was part of the air permit application package submitted to the VCAPCD in March 2020.

A summary of the data is presented in Figure A-1 as an annual wind rose. The length and width of a particular arm of the rose define the frequency and speed at which the wind blows *from* the direction the arm is pointing (i.e. a "north" wind blows *from* the north *to* the south). Reviewing Figure A-1 shows that the most common winds blow from the north and north-northeast, with south and south-southwest winds accounting for much of the remaining probability. A comparison of the data gathered from the Ventura site to data from the nearby Oxnard airport (obtained from the National Centers for Environmental Information[1]) was conducted. The findings of this comparison showed that while the wind *directions* at the Oxnard airport are very different from the Ventura site, other weather parameters were similar and consistent.

[1] National Centers for Environmental Information (NCEI), Data Collected for Oxnard Airport, California, December 2023.

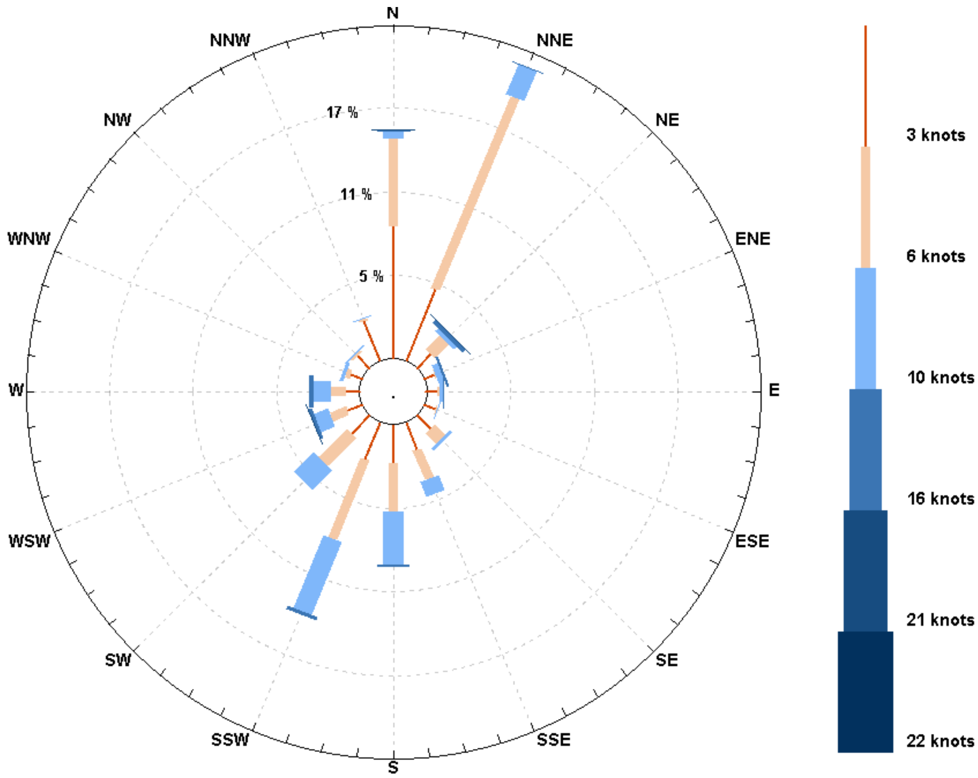

Figure A-1
Wind Rose Data for the Ventura, CA Site

Since atmospheric stability data were not collected at the site, an atmospheric stability distribution was developed from the Oxnard Airport data and applied to the Ventura site data for use in this QRA. Likewise, relative humidity data from the Oxnard Airport data was used in the QRA.

The available data was analyzed to develop atmospheric stability classification, then processed to define probabilistic values for combinations of wind speed (6 ranges), atmospheric stability (6 classes), and wind direction (16 directions). The meteorological data indicates 21 wind speed and stability class combinations. These 21 combinations will be applied to all outdoor vapor dispersion events. For fire radiation, all cases will be run in all six wind speed categories (atmospheric stability is not applied to fire models). All outdoor hazards are also mapped in the risk analysis using the 16 wind directions.

An annual average for the temperature was extracted from the data set and used in all consequence modeling. Seasonal variations were not modeled in this study. The following annual averages were applied:

Average annual air temperature	=	60°F
Average annual relative humidity	=	80%

A-1.2 Process Data

SoCalGas provided piping and instrumentation drawings (P&IDs), process flow diagrams (PFDs), heat and material balances (H&MB), plot plans, and other project technical documents were used in the analysis.

A-2 CONSEQUENCE MODELING

A-2.1 Failure Case Definition

LOC events from all portions of the compressor station are defined based on process and storage equipment with similar operating properties. These top-level events, labeled or designated as failure cases, each represent one or more potential releases of natural gas. The selection of failure cases is based on the following factors.

1) Failure cases are selected based on their ability to result in a fatal impact to persons or an adverse impact to facility assets.
2) Failure cases are selected to incorporate all major pieces of equipment.
3) Failure cases are selected to incorporate all major modes of operation.

The methodology applied for failure case generation is to select release locations such that all potential, significant LOC events are included in the analysis. All hazards evaluated in this study are considered to exist due to an LOC event. Because the probability for each failure case event is determined using process equipment failure rate databases (see Appendix A), no analysis is done to determine the means by which each failure case may occur. Thus, using this approach, no special treatment is required for evaluating failure modes unless unique conditions exist for specific portions of, or systems within, the facility.

A list of the selected failure cases, along with their initial process conditions, is provided in Appendix C.

Assumption: Standby Mode
For this analysis, when the compressor station is in standby mode, it is assumed to be in "hot standby" such that the system holds pressure until becoming operational again. A cold standby mode (depressurized) is not evaluated or given a probability of occurrence.

Assumption: Escalation
All hazards are assumed to form based on the original failure case LOC. Escalation of an event, where one hazard creates or leads to another hazard, is assumed to not affect any persons, for the following reasons:

- Following the initial LOC, alarms (including sirens and lights) will be activated, and process shutdowns will be initiated such that the facility workforce will be notified of the event.

- The emergency response plan is assumed to include moving personnel to muster points outside of the process areas. If an event escalates, personnel will be at a safe distance from the newly created hazard within a few minutes.

A-2.2 Consequence Modeling Software

CANARY by Quest® was used to model the hazards. This software package accounts for the following phenomena that were relevant to this study:

- Multicomponent thermodynamics
- Transient fluid releases
- Momentum jet dispersion
- Vapor cloud explosion
- Jet fire

Technical model descriptions are presented in Appendix B.

Assumption: Surrounding Terrain
Due to modeling constraints, the area surrounding a release point is considered to be level, with a uniform roughness and no significant terrain effects or objects (conservative assumption for vapor dispersion).

A-2.3 Event Tree

Beginning with an LOC event, there are many potential events that could arise within each failure case. For most failure cases, the varied possibilities are represented by an event tree. Figure A-2 demonstrates an event tree for natural gas releases.

The event tree begins with the failure case on the left, and the potential events that can occur branch out to the right. Five release hole sizes are depicted; the ignition timings and outcomes are identical for each, although not listed. Ignition of natural gas is modeled with the consideration of three possibilities: immediate ignition, delayed ignition, and no ignition.

- Immediate ignition results in a jet fire
- The delayed ignition event involves a flammable cloud, defined by the lower flammability limit (LFL), potentially causing three concurrent hazards – a flash fire, a vapor cloud explosion, and a jet fire.
- A no-ignition event results in dissipation of the flammable gas. The case of an unignited vapor cloud reaching and infiltrating an occupied building was not evaluated in this study

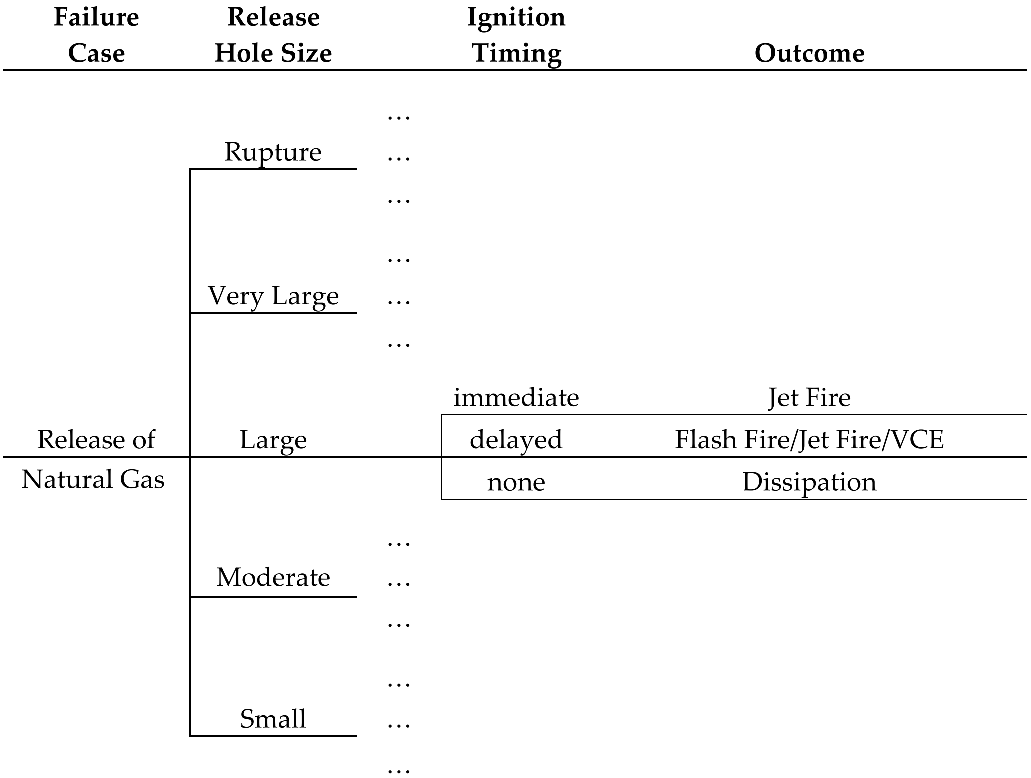

Figure A-2
Event Tree for a Natural Gas Release

Other conditional probabilities, such as release orientation, wind direction, wind speed, and atmospheric stability, are applied to the study but are not depicted in the event tree.

A-2.4 Modeling Parameters

There are many modeling parameters applied to the various failure cases, including weather parameters, release event variables (hole size, orientation), and process system data. The parameters are discussed below.

A-2.4.1 Operating Modes

This QRA uses temperatures and pressures that are representative of the values provided in the heat and material balance sheets. The composition of the natural gas remains constant between modes, as well as between the existing and proposed compressor stations; thus, one representative composition of the natural gas was used in this study.

While the heat and material balance (H&MB) sheets show several modes of operation for the proposed compressor station, the hazard analysis was simplified into three modes of operation for both the existing and proposed compressor station: high flow (100% compression capacity), low flow, and standby (no compression). The flow rates and number of operating compressor units assumed for each mode of operation, based on discussions with SoCalGas, are shown in Table A-1.

Table A-1
Compressor Station Operation Modes

Mode	Existing Compressor Station		Proposed Compressor Station	
	# Compressors	Flow (MMSCFD)	# Compressors	Flow (MMSCFD)
High Flow	3	90	4	160
Low Flow	1	30	2	50
Standby	0	0	0	0

A-2.4.2 Release Sizes

This risk-based analysis involves a range of release sizes (or equivalent hole sizes). This provides a representative range of potential accident events, from very small to very large releases, and thus can provide a more detailed indication of risk. The release hole sizes shown in Table A-2 were selected for the process equipment in this study.

Table A-2
Hole Size Distribution

Descriptor	Hole Size [inches]
Small	1/4
Moderate	3/4
Large	2
Very Large	6
Rupture	Full diameter

If a pipe diameter associated with a failure case is less than one of the chosen hole sizes, then the rupture of that pipe falls is classified within the smallest release size category that is larger than the actual pipe diameter.

A-2.4.3 Release Height

All failure cases are assumed to originate near grade level.

A-2.4.4 Release Orientation

Release orientation refers to the direction that natural gas would be released to the environment. Orientation is measured as an angle from horizontal. For outdoor releases, the orientation is constrained to the plane that aligns with the wind and is assumed to be with the wind.

Assumption: Release Orientation
While release orientation could be in any direction, two orientations were applied in this study as conservatively representative for aboveground equipment:

- Horizontally; or
- Vertically upward.

For buried piping, a crater is assumed to form when the release occurs. The horizontal release was assigned a release angle of 19 degrees (from horizontal), as the minimum angle of release from a crater[2]. Vertical releases are unaffected. Both releases are assumed to be free jets of natural gas from the buried line.

A-2.4.5 Dispersion Coefficient Averaging Time

The dispersion coefficient averaging time is a dispersion modeling parameter that is used to account for vapor cloud persistence due to natural fluctuations in wind direction. For flammable vapor dispersion, a one-minute dispersion coefficient averaging time is employed.

A-2.4.6 Vessel Inventory

The volume of process vessels is incorporated into the failure cases, where applicable. This provides an inventory of material to be released, in addition to the inventory within the piping.

[2] HSE (2009), Comparison of Risks from Carbon Dioxide and Natural Gas Pipelines. Prepared by the Health and Safety Laboratory for the Health and Safety Executive 2009. Research Report RR749.

A-2.4.7 Indoor Releases

Since no personnel are assumed to be in the compressor buildings on a regular basis, the risk to personnel when in the buildings, due to indoor releases, was not specifically considered in this study. The flammable vapor cloud and fire impacts following releases that could occur from the equipment within a compressor building was assumed to be contained by the building. The impacts of any associated vapor cloud explosion in the building were added to the risk for outdoor areas.

A-2.5 Potential Explosion Sites (PESs)

Locations within and around the site that provide confinement for flammable vapors or include congestion (repeated small obstacles) are referred to as potential explosion sites, or PESs. As the amount of confinement or degree of obstruction increases, so does the potential strength of the blast wave that could be created by a vapor cloud explosion within that area. One of the basic principles in application of CANARY's QMEFS[3] explosion model is that after a flame front exits a congested or confined space, the flame speed decays to a lower burning velocity and does not significantly contribute to the creation of overpressure. This behavior has been demonstrated in test programs[4]. Even if a flammable cloud can fill two or three distinct congested/confined locations (PESs), free space between them may prevent the concurrent generation of overpressure from all locations, and each PES can be considered independent. In practice, this limits the volume of flammable gas involved in a unique deflagration event.

The selection of specific volumes to model as explosion sources is based on the above principle. As each PES was selected, the levels of confinement and congestion were evaluated in order to define the parameters of the PES. A review of the compressor station revealed several regions where the obstacle density or confinement is sufficient to generate levels of overpressure greater than that generated by an unconfined cloud. Three unique PESs were defined in the existing station, while eight unique PESs were defined for the proposed compressor station design. These are listed in Tables A-3 and Table A-4 and shown by the orange highlighted zones in Figures A-3 and A-4.

[3] Marx, J.D. and B.R. Ishii (2017), "Revisions to the QMEFS Vapor Cloud Explosion Model". 2017 AIChE Spring Meeting & 13th Global Congress on Process Safety, San Antonio, TX, March 26-29, 2017

[4] Van den Berg, A.C. and A.L. Mos, (2005), *Research to Improve Guidance on Separation Distance for the Multi-Energy Method (RIGOS)*, HSE Research Report 369.

Table A-3
Existing System: Potential Explosion Sites and Their Modeling Parameters

#	PES Designation	Total PES Volume [ft^3]	Average Obstacle Diameter [in]	Number of Confining Planes	Volume Blockage Ratio
1	Gas Metering Area	41,600	4	1	0.030
2	Existing Compressor House	124,000	4	2.5	0.020
3	Existing After Coolers	29,200	4	2	0.030

Table A-4
Proposed System: Potential Explosion Sites and Their Modeling Parameters

#	PES Designation	Total PES Volume [ft^3]	Average Obstacle Diameter [in]	Number of Confining Planes	Volume Blockage Ratio
1	Gas Metering Area	29,800	4	1	0.030
2	Inlet Filter Area	8,100	4	1.5	0.030
3	Suction/Discharge Header Area	43,200	4	1	0.030
4	New Compressor House	308,000	4	2.5	0.020
5	Air Intake/Exhaust Area	56,400	3	1	0.030
6	Outlet Coolers	16,300	4	2	0.030
7	Utility Tank Area	25,400	2	1	0.020
8	New PDC Room	8,500	2	2	0.025

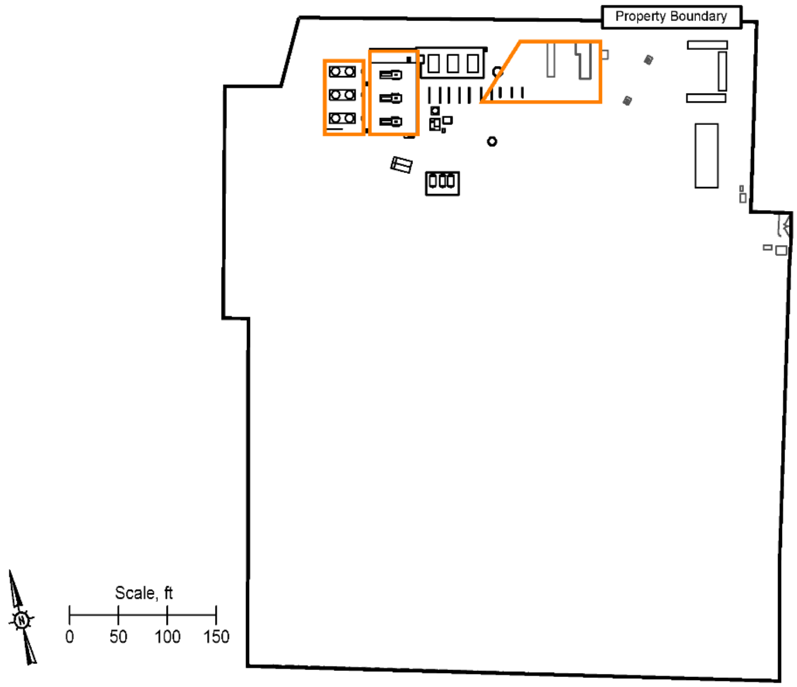

Figure A-3
Potential Explosion Sites (PESs) for the Existing Ventura Compressor Station

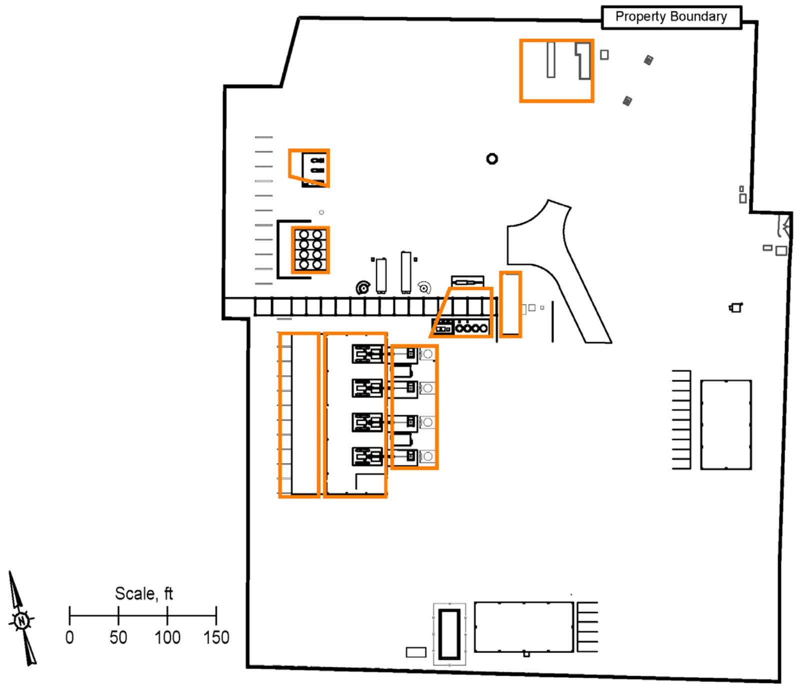

Figure A-4
Potential Explosion Sites (PESs) for the Proposed Project

The following QMEFS model parameters are defined for each VCE.

Fuel Reactivity: A fuel's reactivity is characterized by its laminar burning velocity (LBV). The QMEFS model is anchored on the BST model's high, medium, and low categories with the LBV values of ethylene, propane, and methane—the materials that were used in the original BST experiments. QMEFS was expanded using more recent explosion test data to represent "very high" and "very low" categories—characterized by hydrogen and ammonia, respectively. Use of the LBV allows other hydrocarbons, as well as mixtures, to be modeled independently of a high/medium/low classification, and the expansion allows QMEFS to extend beyond the constraints of the BST's three reactivity categories.

Volume Blockage Ratio (VBR): The density of obstacles within the flammable cloud influences the peak overpressure due to the generation of turbulence along the flame front. VBR is defined as the fraction of a particular volume that is occupied by obstacles.

Number of Confining Planes: The number of confining planes affects the strength of an explosion, potentially limiting the expansion of the flame front. The number of planes can be any number from 0 to 6, but is typically limited to values of 1 ("3-D" flame expansion with ground reflection), 2 ("2-D" expansion, or what occurs between flat, parallel surfaces), or 1.5 ("2½-D", for situations that begin as 2-D and quickly transition to 3-D, or have one confining plane that is semi-porous or frangible).

Flame Run-up Distance: This dimension is a descriptor for the maximum distance which a flame front can travel within the burning cloud. This value is typically limited to the longest horizontal dimension of the congested area.

Average Obstacle Diameter: As the size of obstacles decreases, the turbulence generated in a burning cloud increases, which increases the peak overpressure that is produced. The default value, from the BST test series, is 2 inches.

A-2.6 Shutdown and Isolation

Following the initiation of an LOC event, the normal natural gas flow into a system continues until shutdowns are activated. Release detection (by process controls, gas detection, fire detection, visual identification, etc.), shutdown initiation time, and valve closure times all delay the shutdown and isolation of the system and cause it to continue running.

Shutdowns may be accomplished by closure of control valves, closure of emergency shutdown (ESD) valves, compressor shutdown, or a combination of the above. In each case, gas flow is assumed to continue for a fixed time period before the shutdown limits the flow of gas into the system.

For this analysis, a set of default normal flow durations (time to system shutdown or isolation) are defined by hole size. After normal flow is ended, the system continues to release material until the gas inventory is depleted or the pressure reaches atmospheric. The assumed normal flow durations are presented in Table A-5.

Table A-5
Durations of Normal Flow Applied

Hole Size [inch]	Duration of Normal Flow [minutes]	
	Existing Compressor Station	Proposed Compressor Station
1/4	30	30
3/4	15	15
2	10	10
6	5	5
Rupture	3	3

The shutdown time is a function of release detection (by process controls, gas detection, fire detection, visual identification, etc.), shutdown initiation time, equipment shutdown times, and valve closure times. Until all of these occur, material can be supplied to the system, which may add to the available inventory or release rate.

A-2.7 <u>Modeling Endpoints</u>

The outdoor personnel covered in this siting study require specific sets of modeling endpoints associated with the hazards of concern and the nature of the exposure. Dose-response relationships (e.g., probit equations) are applied in many risk-based studies. The selected endpoints are described in the following sections.

For many of the modeling endpoints, specific effects of exposure to a hazard are dependent on exposure time, as well as the magnitude of the hazard. This is easy to conceptualize with exposure to fire: a very short duration exposure (< 1 second), even direct exposure to a flame, may not result in burns, but a longer exposure (20-30 seconds) will cause burns. In this way, the hazard effects are accounted for in this analysis. For fire radiation, the exposure time is measured in seconds for burns to persons. For ignition of flammable vapor clouds (flash fire) and vapor cloud explosions, the effects are nearly instantaneous, so no consideration of exposure duration is necessary.

For many hazards, exposure levels necessary to cause fatal injuries to a person must be defined as a function of exposure time. This is typically accomplished through the use of probit equations, which are based on experimental dose-response data. A probit equation has the form:

$$Pr = a + b \bullet \ln(t \bullet K^n)$$

where: Pr = probit value
K = intensity of the hazard
t = time of exposure to the hazard
a, b, and n = constants

The product $(t \bullet K^n)$ is often referred to as the "dose factor." According to probit equations, all combinations of intensity (K^n) and time (t) that result in equal dose factors also result in equal values for the probit (Pr). Because each value of Pr is directly related to a specific level of fatality, equal doses produce equal expected fatality rates for the exposed population.

A-2.7.1 Thermal Radiation – Persons Outdoors

Impacts from fire radiation to people (either station personnel or the public) are defined by thermal radiation levels and an assumed exposure time. Several levels of vulnerability – where, in the context of the QRA, vulnerability is fatality – are used to describe the varied response between individuals.

Impacts from fire radiation to persons outdoors were predicted using the following probit equation [Tsao & Perry, 1979][5]:

$$Pr = -12.8 + 2.56 \bullet \ln\left(t \bullet I^{4/3}\right)$$

where: I = thermal radiation flux, kW/m^2
t = exposure time, seconds

Table A-6 presents the probit results for several exposure times that are applicable for fires. The fatality rates and corresponding thermal radiation levels are listed. The use of the probit function to determine the percent mortality at a given level and time of exposure is presented in Figure A-5.

[5] Tsao, C. K., and W. W. Perry (1979), Modifications to the Vulnerability Model: A Simulation System for Assessing Damage Resulting from Marine Spills. U.S. Coast Guard Report CG-D-38-79, Washington, D.C., March, 1979.

Table A-6
Fatal Thermal Radiation Levels for Various Exposure Times
Using the Tsao and Perry [1979] Thermal Radiation Probit

Exposure Time [seconds]	Probit Value	Fatality Rate [percent]	Thermal Radiation [kW/m^2]
5	2.67 5.00 7.33	1 50 99	27.80 55.02 108.88
15	2.67 5.00 7.33	1 50 99	12.20 24.14 47.76
20	2.67 5.00 7.33	1 50 99	9.83 19.45 38.49
30	2.67 5.00 7.33	1 50 99	7.27 14.39 28.47

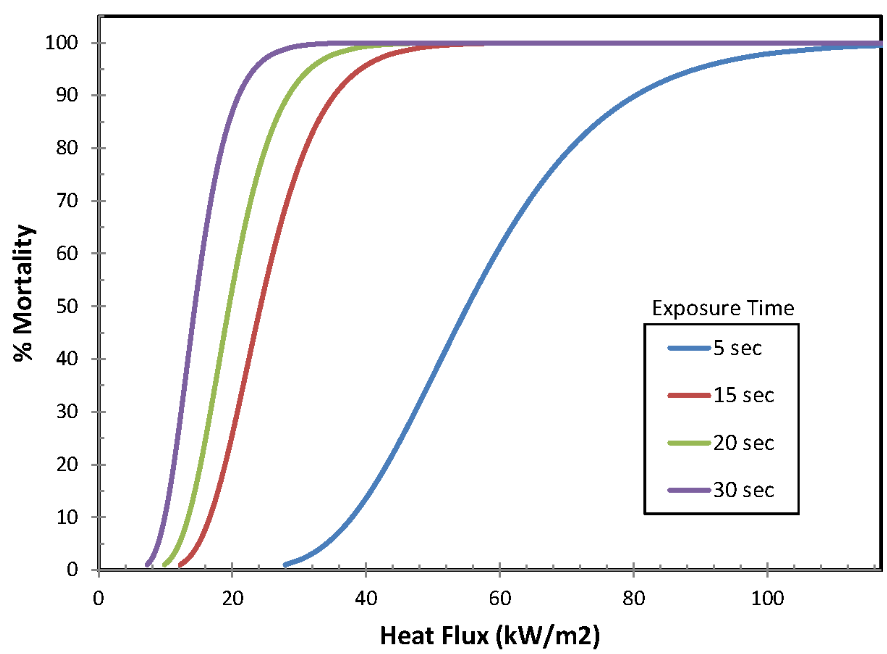

Figure A-5
Incident Radiation Probit Functions

The choice of thermal radiation flux levels is influenced by the duration of the fire and potential time of exposure to the flame by an individual. All combinations of incident heat flux (I) and exposure time (t) that result in equal values of "radiant dosage" $\left(t \cdot I^{4/3}\right)$ produce equal expected fatality rates.

The exposure time associated with radiative heat flux from a fire chosen for this analysis is 30 seconds. This is considered conservative, as persons exposed to radiant hazards are aware of the hazards and can move towards a safer location or find shelter within a short period of time.

A-2.7.2 Flammable Vapor Cloud – Persons Outdoors

When a flammable vapor cloud develops, there is a possibility that the vapor cloud may be ignited. When this happens, a flame front passes through the flammable portions of the vapor cloud, as defined by the lower flammable limit (LFL) and upper flammable limit (UFL). This burning vapor cloud is referred to as a flash fire, as the flame front often moves quickly through the flammable vapors. Exposure to a flash fire is potentially life-threatening to people due to direct flame exposure. The following vulnerabilities are applied for flash fires[5]:

- Inside the LFL boundary – 100% fatality
- Outside the LFL boundary – 0% fatality

Assumption: Flash Fire
Thermal radiation from the flash fire, or other effects outside the flammable cloud, are assumed to be negligible.

A-2.7.3 Vapor Cloud Explosion – Persons Outdoors

In the event of an ignition and deflagration of a flammable vapor cloud, the overpressure levels necessary to cause fatality to individuals are defined as a function of peak overpressure. Exposure to high overpressure levels may be fatal. If a person is far enough from the source of the explosion, the overpressure is incapable of causing fatality.

Impacts from explosion overpressure to persons outdoors were predicted using the following probit equation [HSE, 1991][6]:

$$\mathrm{Pr} = 1.47 + 1.37 \cdot \ln\ (p)$$

where: p = peak overpressure, psi

[6] HSE (1991), *Major Hazard Aspects of the Transport of Dangerous Substances*. Health and Safety Executive, Advisory Committee on Dangerous Substances, London, United Kingdom, 1991.

The graphical form of the overpressure probit equation is presented below, in Figure A-6. The probit relationship above results in the set of endpoints given in Table A-7.

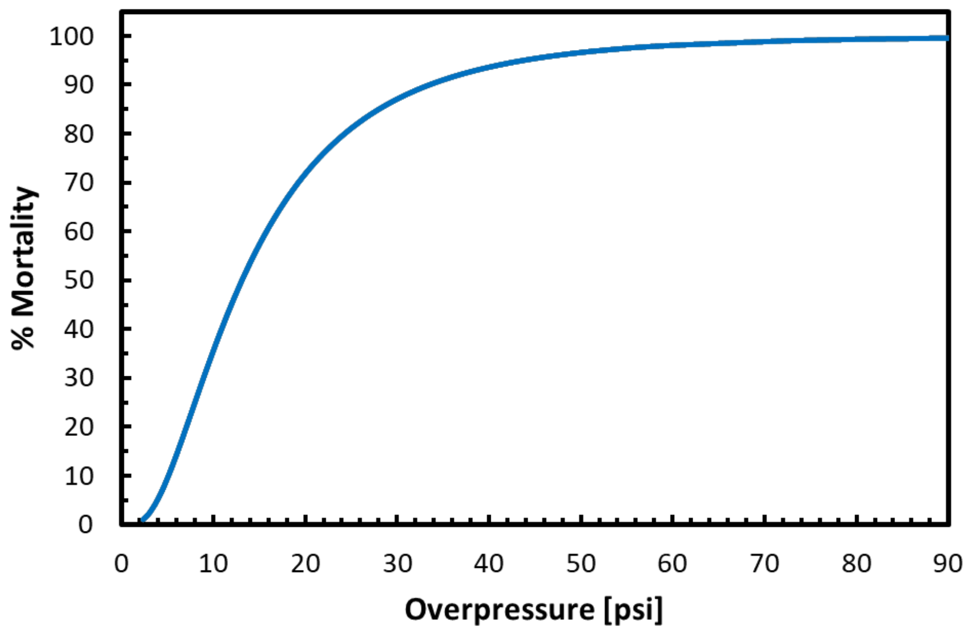

Figure A-6
Overpressure Probit Relation

Table A-7
Fatality Endpoints for Explosion Overpressure Impacts to Outdoor Populations

Hazard	Fatality Endpoints
Explosion Overpressure	1% fatality – 2.4 psi 50% fatality – 13.1 psi 99% fatality – 72.0 psi

A-3 FREQUENCY ANALYSIS

A-3.1 Failure Rates

A-3.1.1 Process Equipment

Data from the UK Health and Safety Executive (HSE) Hydrocarbon Release Database (HCRD)[7] for the years 1992 through 2019 were used to develop failure rates for each type of equipment. For each, the number of failures (and the corresponding release hole size), as well as the number of equipment years of service were recorded. In addition to overall failure rates, it is also possible to derive a hole size distribution from the information presented in the HCR database. This distribution is expressed in the form of a log-logistic cumulative distribution function (CDF)[8]:

$$C = \frac{1}{1+\left(\frac{d}{\alpha}\right)^{-\beta}}$$

Where:

C	=	Fraction of occurrences for hole sizes up to hole size d
d	=	hole diameter [mm]
α	=	alpha parameter for log-logistic equation [mm]
β	=	beta parameter for log-logistic equation [unitless]

In this application, for a given hole size, d, the CDF represents the fraction of all LOC events that will have a hole size of that diameter or smaller. When combined with the total incident rate (TIR, as calculated from the HCRD) the CDF can be used to describe the frequency of LOC events in a given hole size range:

$$f_{d_2-d_1} = TIR \cdot (C_2 - C_1)$$

Where:

C_1	=	Fraction of occurrences for hole sizes up to hole size d_1
C_2	=	Fraction of occurrences for hole sizes up to hole size d_2
TIR	=	Total incident rate for the equipment type [incidents/year]
$f_{d_2-d_1}$	=	LOC event frequency for hole size range between d_1 and d_2 [incidents/year]

With this approach, the failure rate and hole size distribution for each equipment type can be developed. The total failure rates with the calculated α and β parameters for each type of equipment are given in Table A-8.

[7] HSE (2019), Hydrocarbon Releases System. Health and Safety Executive, United Kingdom. http://www.hse.gov.uk/offshore/hydrocarbon.htm

[8] Marx, J.D, and Ishii, B.R (2021), *A New Look at Release Event Frequencies*, Journal of Loss Prevention in the Process Industries, Volume 69, 2021

Table A-8
Incident Rates and Cumulative Distribution Factors for Process Equipment
(*Equipment Types in Italics Represent Groups of Equipment Types in the HCRD Data Set*)

Equipment Type or Group	Calculated Total Incident Rate per Year	Log-Logistic Curve Fit Parameters	
		α	β
Compressors	7.122 x 10^{-3}	4.8	1.8
Filters	2.546 x 10^{-3}	3.1	1.4
Flanged Connections	1.489 x 10^{-5}	4.0	1.1
Shell & Tube Heat Exchangers	1.205 x 10^{-3}	4.4	1.6
Plate Heat Exchangers	5.267 x 10^{-3}	4.5	2.2
All Heat Exchangers	2.087 x 10^{-3}	4.4	1.9
Instruments (Small Connections)	2.266 x 10^{-4}	5.0	2.2
Pressure Vessels	1.070 x 10^{-3}	10.4	1.0
Pumps	3.615 x 10^{-3}	3.9	1.6
All Valves	7.893 x 10^{-5}	4.9	1.2

Assumption: Failure Rate Data Analysis
The HCRD data is processed to remove hydrocarbon releases that involved insignificant quantities of material, occurred at very low pressures (e.g., maintenance events), or involved hole sizes less than one millimeter. The remaining data are then used to derive the failure rates per year and hole size distribution for each type of equipment.

A-3.1.2 Process Piping

Failure rates for process piping are taken from HSE's land use planning document[9] and shown in Table A-9. These piping failure rates are deemed to be more representative of an onshore processing facility than those found in the HCRD (an offshore process system database). The hole size distribution was applied in the same way as described above (with a log-logistic CDF) and the fit parameters are also provided in Table A-9.

[9] HSE (2010), Failure Rate and event Data for use within Land Use Planning Risk Assessments. Health and Safety Executive, London, United Kingdom, 2010.

Table A-9
Failure Rate Data and Distribution Parameters for Process Piping

Equipment	Annual Failure Rate Per Foot of Pipe	Log-Logistic Curve Fit Parameters	
		α	β
Piping - D<2"	4.88×10^{-6}	1.84	1.04
Piping - 2"≤D<6"	1.07×10^{-6}	2.01	0.71
Piping - 6"≤D<12"	7.01×10^{-7}	5.79	0.84
Piping - 12"≤D<20"	4.79×10^{-7}	3.85	0.86
Piping - D≥20"	3.78×10^{-7}	3.04	0.96

A-3.1.3 Buried Gas Pipelines

The U.S. Department of Transportation (DOT) maintains a database of buried gas transmission and gas distribution pipeline incidents in the United States. Incident data and mileage data can be downloaded from the DOT's Pipeline and Hazardous Materials Safety Administration (PHMSA) website. The incident data provide a record of all occurrences of a pipeline-related failure, based on the DOT's reporting criteria. The data were extracted from the PHMSA incident database from 2010 to 2020[10]. That data were processed to remove offshore pipelines as well as aboveground systems. The data were also evaluated for a distribution of hole sizes when an incident occurs. Table A-10 lists the resulting TIR and the calculated α and β parameters used for hole size distribution, using the same approach as with the HCRD (see previous section).

Table A-10
Incident Rate and Cumulative Distribution Factors for Gas Transmission Pipelines

Equipment Type or Group	Calculated Total Incident Rate per Year, per Foot of Pipe	Log-Logistic Curve Fit Parameters	
		α	β
Gas Transmission Pipelines, Buried	2.42×10^{-8}	1.75	0.60

[10] PHMSA (2021), Pipeline and Hazardous Materials Safety Administration Incident Database. https://www.phmsa.dot.gov/data-and-statistics/pipeline/pipeline-incident-flagged-files

A-3.2 Ignition Probabilities

As introduced with event trees, the timing of ignition (when a flammable material is released) is an important factor in determining the eventual outcome of an LOC event. Likewise, the probability of ignition is an important factor in determining the probability of each outcome. Ignition probabilities are applied to the event frequencies as conditional probabilities, classified as immediate, delayed, or no ignition.

A-3.2.1 Immediate Ignition Probability

The immediate ignition probabilities employed in this study are calculated using exit mass flow rate, exit mass phase, and gas reactivity—based on a model presented by TNO[11], as listed in Table A-11. For this analysis, since all releases involve natural gas, the "low reactivity" option is employed.

Table A-11
Immediate Ignition Probabilities

Source Release Rate	Substance		
	Liquid	Gas (low reactivity)	Gas (average/high reactivity)
< 10 kg/s	0.065	0.02	0.2
10-100 kg/s	0.065	0.04	0.5
> 100 kg/s	0.065	0.09	0.7

[11] TNO (1999), Guidelines for Quantitative Risk Assessment (First Edition), the Purple Book. CPR 18E, The Netherlands Organization for Applied Scientific Research, Committee for Prevention of Disasters, the Hague, Netherlands, 2005.

A-3.2.2 Delayed Ignition Probability

The delayed ignition probabilities employed in this study are developed according to the methodology published by the Energy Institute[12]. The delayed ignition methodology considers the number of potential ignition sources that may be reached by a dispersing flammable vapor cloud. As the number of encountered ignition sources increases, the probability of ignition increases. Each delayed ignition probability is a function of the ignition source densities in and around the facility that are reached by the flammable cloud.

Delayed ignition probability for each accident event is found by summing the ignition probabilities due to all potential sources of ignition within the area covered by the flammable cloud produced by that accident event. The following formula is used to calculate that probability:

$$P(\textit{Delayed Ignition}) = (1 - e^{-\Sigma lnQ}) \bullet (1 - \beta)$$

where:

β = Immediate ignition probability

$\ln Q$ = $u \bullet A[(1 - a \bullet p) \bullet e^{-\lambda \bullet p} - 1]$

- u = ignition source density ($meter^{-2}$)
- p = ignition potential of active source
- a = probability of source being active
- λ = frequency at which the source becomes active
- A = area ($meter^2$)

Assumption: Material Reactivity

The probability of delayed ignition is estimated for the different areas of the facility based on the descriptions of the ignition areas defined in the ~~UKOOA~~ Energy Institute model. For delayed ignition, the flammable cloud is allowed to grow to its full extent before delayed ignition is evaluated. This approach provides a worst-case event to determine the maximum possible impact or extent of the hazard.

Table A-12 lists the parameters used in the delayed ignition calculation for each type of area, with the non-ignition probability, ln(Q), based on a 100 m^2 area for illustrative purposes. Sources that could cause delayed ignition for the Ventura site were accounted for in both the existing compressor station and Proposed Project. For areas within and around the facility, process systems, office/commercial/ residential buildings, and roadways (all vehicular movement areas) were identified to create ignition locations data sets. In the QRA calculations, each flammable vapor cloud is evaluated against the appropriate data set to determine delayed ignition potential.

[12] ~~UKOOA~~ Energy Institute (2006), Ignition Probability Review, Model Development and Look-Up Correlations, IP Research Report, January 2006.

Table A-12
Delayed Ignition Parameters

Ignition Area Type	u	p	a	λ	ln(Q)
Process – 'light' equipment level	0.0050	0.10	1.000	0	-0.0500
Office/commercial/residential (assumes inside ignition sources)	0.0020	0.05	1.000	0	-0.0100
Roadways	0.0003	0.10	0.100	0.085	-0.0006

A-3.3 Release Orientation Probabilities

As discussed in consequence modeling, this analysis evaluates two release orientations: a horizontal release and a vertical release. For this risk analysis, the probability of each orientation was assumed to be the same (p = 0.5 for each).

A-3.4 Operational Frequencies

When the compressor station is operated in different modes, corresponding to different flow rates based on the number of compressors in operation, frequency data are required. In order to assess the potential risk impacts of operating the station in different modes, two scenarios were evaluated:

- Operating at the full rated flow throughput, 100% of the year
- Operating in "combined" modes: a high flow (full rated flow) mode, low flow mode, and standby mode, according to the parameters provided in Table A-1.

The operating frequencies for the three different modes, as applied in the combined mode case, are provided in Table A-13.

Table A-13
Operational Probabilities and Parameters

Operational Mode	Combined Flow Case, Yearly Fraction
High Flow	0.50
Low Flow	0.25
Standby	0.25

APPENDIX B
CONSEQUENCE MODEL DESCRIPTIONS
CANARY by Quest®

When performing site-specific consequence analysis studies, the ability to accurately model the release, dilution, and dispersion of gases and aerosols is important if an accurate assessment of potential exposure is to be attained. For this reason, Quest uses a modeling package, CANARY Quest®, that contains a set of complex models that calculate release conditions, initial dilution of the vapor (dependent upon the release characteristics), and subsequent dispersion of the vapor introduced into the atmosphere. The models contain algorithms that account for thermodynamics, mixture behavior, transient release rates, gas cloud density relative to air, initial velocity of the released gas, and heat transfer effects from the surrounding atmosphere and the substrate. The release and dispersion models contained in CANARY have been reviewed in several studies that evaluated models on technical merit and model predictions against published field-scale test data.

CANARY also contains models for pool fire, jet fire, and fireball (BLEVE) thermal radiation. These models account for (as is appropriate to the fire type) impoundment configuration, material composition, target height relative to the flame, target distance from the flame, atmospheric attenuation (includes humidity), wind speed, and atmospheric temperature. All of the fire models are based on information in the public domain (published literature) and have been validated with experimental data.

Lastly, CANARY contains models for vapor cloud explosions. These models account for the vapor cloud's physical properties, as well as levels of confinement and congestion in the area occupied by the flammable vapor cloud.

CANARY uses fluid properties and fluid release sub-models to supply information for vapor dispersion, vapor cloud explosion (VCE), and fire radiation models. The consequence models provide a simulation of potential hazardous material release scenarios so that the inherent hazards can be quantified. The following models are discussed:

- Engineering Properties
- Fluid Release Model
- Pool Spreading and Vaporization Model
- Momentum Jet Dispersion Model
- Heavy Gas Dispersion Model

- Pool Fire Radiation Model
- Torch Fire and Flare Radiation Model
- Fireball Model
- QMEFS Vapor Cloud Explosion Model

A brief description of the capabilities, requirements, and correlations used within each mode, as found in version 4.6, is presented below. A more detailed description of the models is available upon request.

ENGINEERING PROPERTIES

The purpose of this model is to provide an accurate means of computing physical and thermodynamic properties of a wide range of chemical mixtures using a minimum of initial information. The Peng-Robinson cubic equation of state (EOS) is combined with van der Waals quadratic mixing rules and pure component data (e.g., normal boiling point) for the computation of thermodynamic properties.

The model is implemented using a properties database of approximately 250 single components which can be applied to mixtures of up to 10 components. The user supplies composition, temperature, and pressure, and the model provides thermodynamic properties (such as density, enthalpy, entropy, etc.) for liquid, vapor, and two-phase systems. These properties are used as inputs to the release and hazard models.

FLUID RELEASE MODEL

The purpose of the fluid release model is to predict the rate of mass release from a breach of containment. Specifically, the model predicts the rate of flow and the physical state (liquid, two-phase, or gas) of the release of a fluid stream as it enters the atmosphere from a breach in a pipe or vessel wall. The model also computes the amount of gas, or liquid or aerosol produced and the rate at which liquid reaches the ground.

The fluid release model takes into account the composition, temperature and pressure of the fluid before the release and identifies flow regime within the closed system before and during the release event. User-defined parameters such as normal flow rate of fluid, pipe and vessel sizes, area of the orifice, angle of release relative to horizontal, and release elevation provide a physical description of the system from which the release occurs. The model tracks the pressure profile in the system, computing the flow conditions stepwise in time until the mass is depleted or an end time is reached, while accounting for the system inventory and head pressure available. The system flow can be all vapor, all liquid, or two-phase, with checks made to determine if the fluid flow is realistic (e.g., velocity has not exceeded the sonic velocity). An orifice equation is used to calculate the time-varying velocity and mass flow rate from the breach during the release event.

The prediction of aerosol formation and amount of liquid rainout is based on the theoretical work performed for the Center for Chemical Process Safety (CCPS) by CREARE. CREARE's work has been corrected and extended by Quest. The extension to the model computes the non-aerosol drop evaporation. An example validation plot for this portion of the model is given in Figure B-1, for chlorine (Cl_2), methylamine (MMA), CFC-11, and cyclohexane aerosol test data compared to values computed by the CANARY aerosol model.

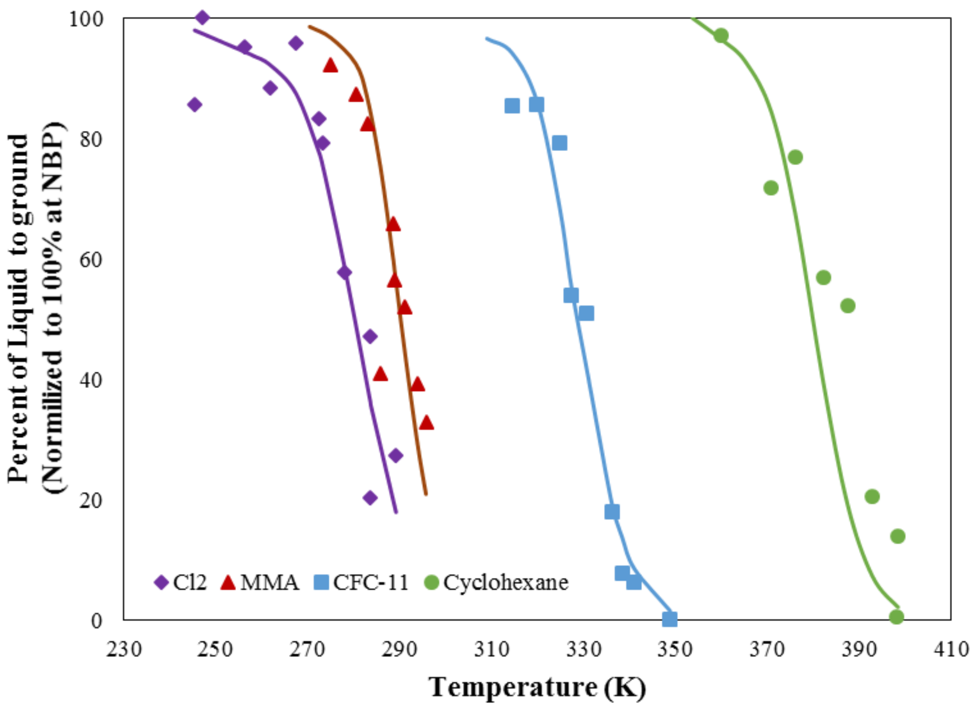

Figure B-1
Aerosol Predictions Compared to Experimental Data

Figure B-2 compares the computed and experimental gas discharge rates for the complete breach of two pipelines. Experiments included pipeline with two different internal diameters 6.2 inches (0.157 m), and 12 inches (0.305 m) respectively. These pipes were initially pressurized to 1,000 psia with air and then explosively ruptured. The experimental values were reported in a research paper for Alberta Environment, authored by Wilson [Wilson, 1981].

POOL SPREADING AND VAPORIZATION MODEL

The purpose of this model is to describe the spreading and mass vaporization rate of spilled liquids. For spills of refrigerated liquids on water, the model accounts for the presence of a potential obstacle that the liquid must overcome the local wave action.

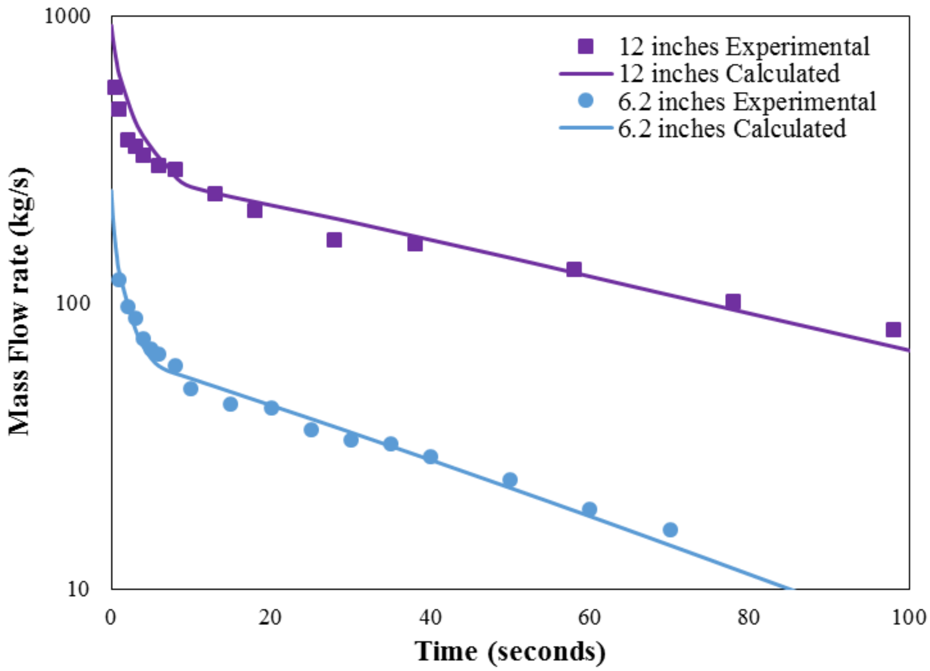

Figure B-2
Mass Release Rate Predictions Compared to Experimental Data

The pool spreading and vaporization model uses information about impoundment systems provided by the user (and can also model the unconfined case) as well as liquid flow rate information from the release model. Coupled with the material's thermodynamic properties, the time-varying pool size and vaporization rate are predicted. The output from this model is used for input as a source term in the heavy gas dispersion model.

For refrigerated liquid spills on water, the liquid will spread radially and unconfined from the release point until the liquid reaches some minimum thickness that diminishes the liquid's ability to spread due to hydrodynamic head. The speed at which the liquid pool spreads is a function of the spill rate, liquid vaporization rate, physical properties of the liquid, radius of the liquid pool, and the nature of the spill surface. For this model the viscosity and surface tension effect are considered to have negligible effects on the rate of spread. This later simplification allows the rate of liquid spreading to be found at any instant in time, by use of a simple hydrodynamic model in which the rate of spread becomes a function of spill, vaporization rate, and pool radius. Finally the numerical solution of the differential equations permits the computation of the pool size, height of the liquid pool, and the transient evaporated mass rate.

MOMENTUM JET DISPERSION MODEL

The purpose of this model is to predict the dispersion of a jet release into ambient air. It is used to predict the downwind travel of a momentum-based jet of flammable or toxic gas or aerosol. The momentum jet dispersion model incorporates the composition and properties (temperature, pressure, composition, density, etc.) of the released materials, the mass rate of release, and some geometric parameters such as angle of release relative to horizontal, height of release, and area of release. Environmental and atmospheric conditions such as wind speed, Pasquill-Gifford stability class, ambient air temperature, and surface roughness are taken into account. Velocity, concentration, and density profiles are assumed to be cylindrically symmetric about the plume axis and Gaussian in shape. Entrainment along the jet is calculated while applying equations for conservation of mass and momentum.

The momentum jet dispersion model used in CANARY was validated by comparing results obtained from the model with experimental data from field-scale tests. Data used for this comparison and the conditions used in the model were taken from an American Petroleum Institute (API) study [Hanna, 1991]. Comparisons were made with the Desert Tortoise, Goldfish, and Prairie Grass series of dispersion tests. Results of these comparisons are shown in Figure B-3.

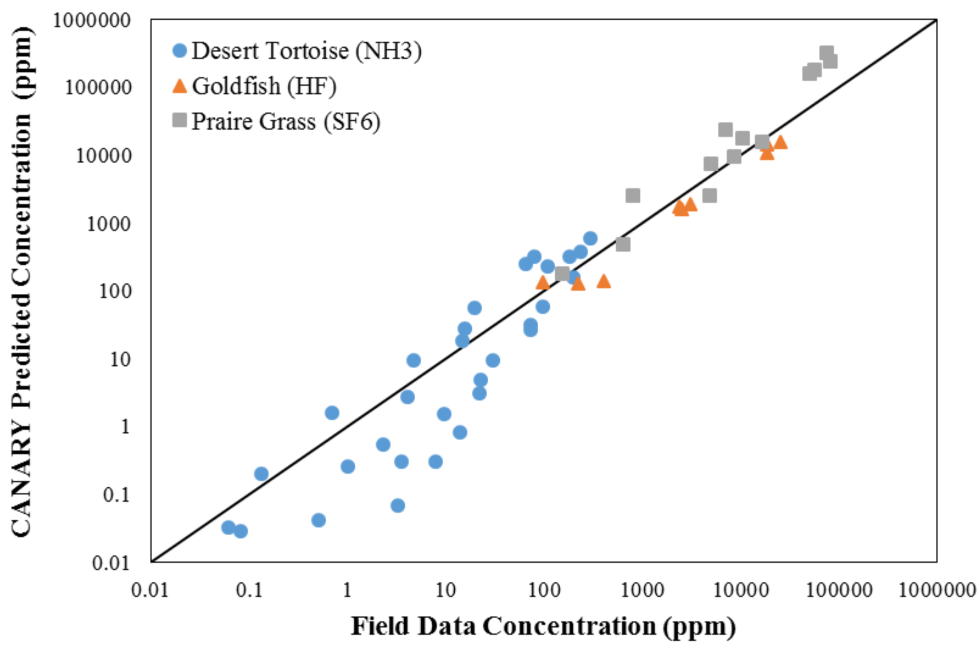

Figure B-3
Momentum Jet Dispersion Predictions Compared to Experimental Data

HEAVY GAS DISPERSION MODEL

The purpose of this model is to predict the dispersion and gravity flow of heavier-than-air gases evolving from liquid pools. The model is also employed when an initially momentum-dominated release involving heavier-than-air gases loses its momentum, and impacts grade. The model is used to predict the downwind travel of a flammable or toxic vapor cloud.

The heavy gas dispersion model incorporates the properties of the source vapor, as well as its mass rate and the size of the source area. Environmental and atmospheric conditions such as wind speed, Pasquill-Gifford stability class, ambient air temperature, and surface roughness are taken into account. Concentration and density profiles are applied about the plume axis. Entrainment along the dispersing cloud is calculated while applying equations for conservation of mass and momentum.

The heavy gas dispersion model used in CANARY was validated by comparing results obtained from the model with experimental data from field-scale tests. Data used for this comparison and the conditions used in the model were taken from the Burro, Coyote, and Maplin Sands series of dispersion tests. Results of these comparisons are shown in Figure B-4.

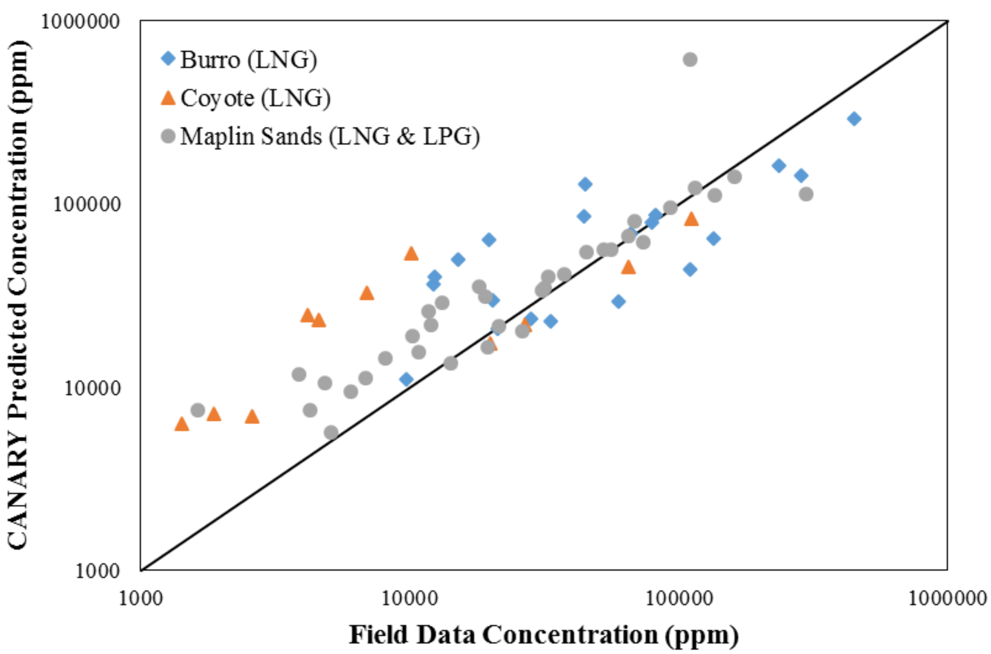

Figure B-4
Heavy Gas Dispersion Predictions Compared to Experimental Data

POOL FIRE RADIATION MODEL

The purpose of this model is to predict the impact of fire radiation emitted by flames fueled by vapors emanating from liquid pools. Specifically, the model predicts the maximum radiant heat flux incident upon a target as a function of distance between the target and the flame. Thermal radiation hazard zones can then be determined for any radiant end points of interest.

The pool fire model incorporates the composition and temperature of the liquid pool, atmospheric conditions such as wind speed, air temperature, and relative humidity. Variables such as elevation of the target, elevation of the pool, and dimensions of the free surface of the pool (rectangular or circular) are accounted for. The dimensions and tilt of the flame (due to wind) are determined using correlations based on thermodynamic properties of the pool and air as well as the size of the pool. A pool fire is divided into two zones: a clear zone in which the flame is not obscured by smoke, and a smoky zone in which a fraction of the flame surface is obscured by smoke. The Surface Emissive Power (SEP) for the clear zone can be determined by material properties, while the average SEP of the smoky zone is an area-weighted average of the surface fluxes for smoke and the clean-burning areas within the smoky zone. The model defines the flame geometry as a tilted elliptical cylinder over the pool. The surface of the flame is divided into numerous differential areas and the total radiant heat flux to a target is calculated using the SEP, view factors, and atmospheric transmittance.

One of the most notable test series was the Montoir large liquefied natural gas (LNG) pool fires, which involved pools up to 35 meters in diameter [Nédelka, 1989]. Figure B-5 compares the radiation isopleths predicted by CANARY with the actual measurements taken in Test 2 of the Montoir series.

JET FIRE AND FLARE RADIATION MODEL

The purpose of this model is to predict the extent of fire radiation emitted by burning jets of vapor (jet fire, torch fire, flare fire). Specifically, the model predicts the maximum radiant heat flux incident upon a target as a function of distance between the target and the point of release.

The jet fire and flare radiation model incorporate the composition of the release material, the temperature and pressure of the material before release, the diameter of the release orifice, and the mass flow rate of the release. Environmental factors of wind speed, air temperature and relative humidity are accounted for, as well as geometric factors such as elevation of the target, elevation of the release point, and the angle of release.

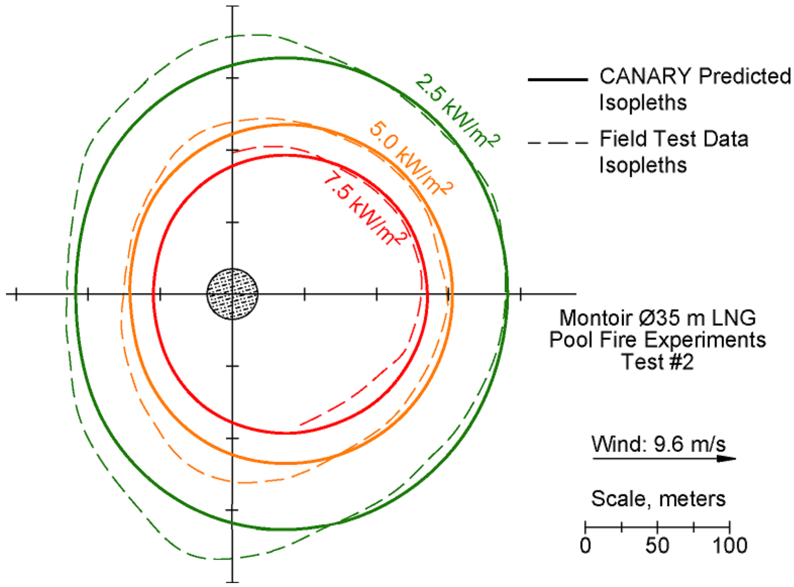

Figure B-5
CANARY Pool Fire Radiation Comparison to Montoir Test #2

Correlations for the length of the flame and flame path are applied to the user-defined parameters. These correlations account for the effects of composition of the released material, diameter of the exit hole, release rate, release velocity, wind speed, and plume buoyancy. The geometric shape of the flame is defined as a frustum of a cone with a hemisphere at the large end of the frustum. The surface of the flame is divided into numerous differential areas and the total radiant heat flux to a target is calculated using the surface emissive power, view factors, and atmospheric transmittance.

Several of the equations used in the Jet Fire Radiation Model are empirical relationships based on data from medium- to large-scale experiments, which ensures reasonably good agreement between model predictions and experimental data for variables such as flame length and flame tilt angle. Comparisons of experimental data and model predictions for incident heat flux at specific locations are more meaningful and of greater interest. Unfortunately, there are only a few reports on medium- or large-scale experiments that contain the level of detail required to make such comparisons.

Two test series that provided sufficient data for model comparison were conducted by Shell [Chamberlain, 1987], [Johnson, et.al., 1994]. It contains measured radiant heat flux data from several methane fires, in both vertical and horizontal release orientations. Variables that were examined during these tests include release diameter, release rate and velocity, and wind speed. Figure B-6 compares the predicted values of incident heat flux with experimental data from the three series of tests presented in the abovementioned publications.

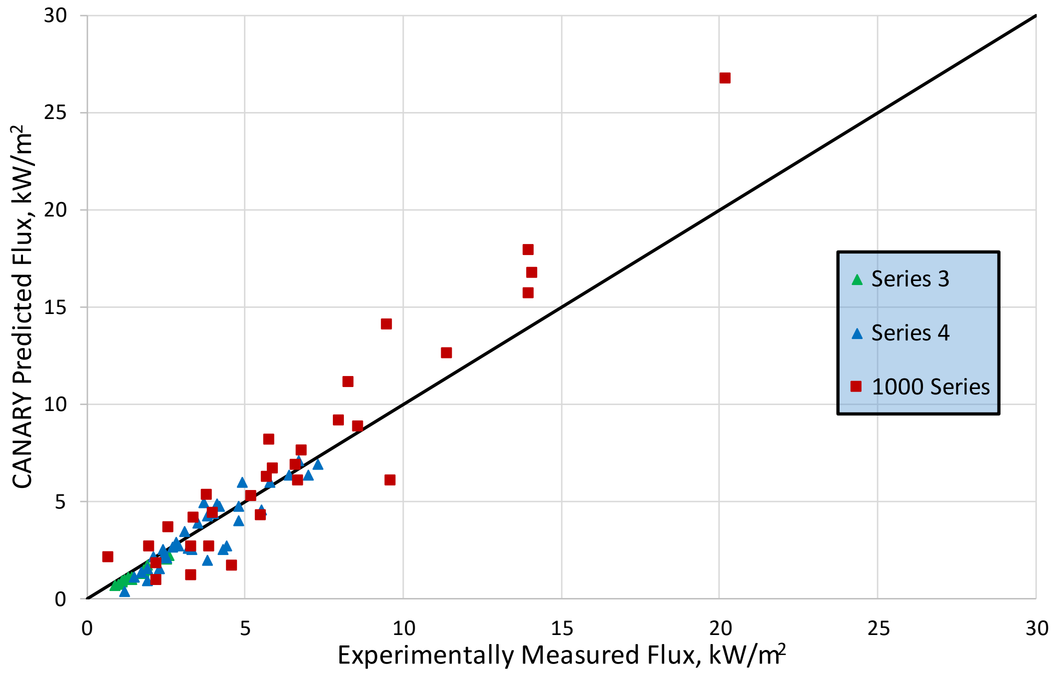

Figure B-6

CANARY Jet Fire Radiation Comparison to Shell Tests

FIREBALL MODEL

The purpose of the fireball model is to predict the impact of thermal radiation emitted by fireballs that result from catastrophic failures of pressure vessels containing superheated liquids. This event is called a Boiling Liquid Expanding Vapor (BLEVE). Specifically, the model predicts the average radiant heat flux incident upon a grade-level target as a function of the horizontal distance between the target and the center of the fireball. The fireball model incorporates the composition, mass, temperature and pressure of the flammable liquid contained in the pressure vessel before release. Air temperature and relative humidity are also incorporated to determine the radiant heat flux reaching a target.

The maximum diameter and the duration of the fireball can be calculated from the mass of fuel using empirical correlations. The maximum SEP is computed using the heat of combustion and adjusted for the pressure at the point of the release. The model simulates the fireball as a sphere that grows in time, then lifts off from grade level, with a decreasing SEP as it moves upwards vertically. The view factor between the fireball and a target is determined analytically. The radiant heat flux at a target location is computed using the SEP, view factor, and atmospheric transmittance. Impacts from the fireball are expressed as absorbed energy, average incident flux, and integrated dosage over the duration of the fireball.

Comparisons of experimental data and model predictions for average incident heat flux, absorbed energy, or dosage are needed for model validation. Unfortunately, very few reports on BLEVEs contain the level of detail required to make such comparisons, and no such data are available for large-scale experiments. One of the most complete sources of test data for medium-scale fireball tests is a report by Johnson, Pritchard, and Wickens [Johnson, 1990]. It contains data on five BLEVE tests that involved butane and propane, in quantities up to 2,000 kg. Figure B-7 compares the CANARY predicted values of absorbed energy with experimental data from those five BLEVE tests.

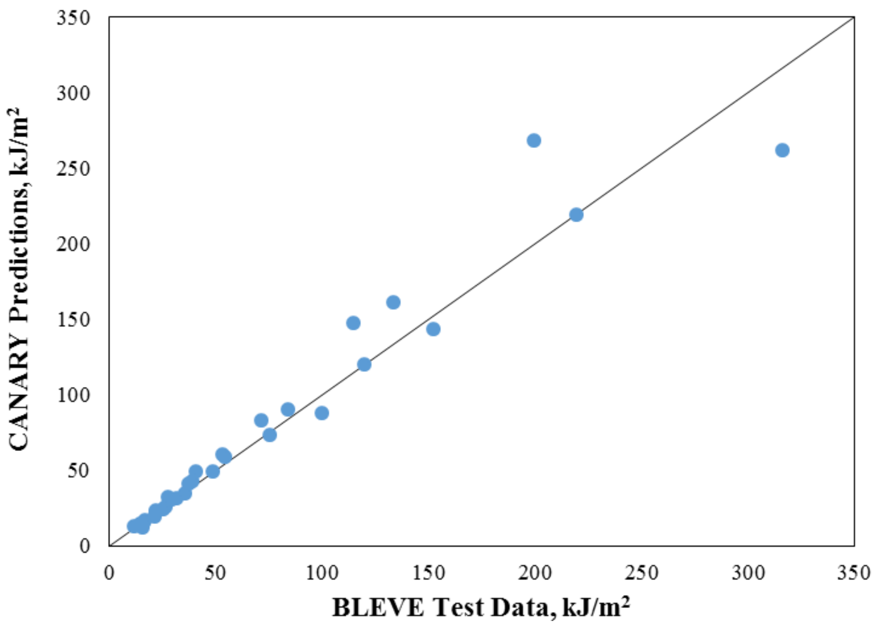

Figure B-7

CANARY Absorbed Energy Comparison to Johnson, Pritchard, and Wickens [1990]

QMEFS VAPOR CLOUD EXPLOSION MODEL

For VCE calculations, Quest uses QMEFS, which is a variation of the Baker-Strehlow-Tang (BST) method. QMEFS [Marx & Ishii, 2017] is based on experimental data involving vapor cloud explosions, and is related to the amount of confinement and/or obstruction present in the volume occupied by the vapor cloud. Quest's QMEFS model is based on the premise that the strength of the blast wave generated by a VCE is dependent on the reactivity of the flammable gas involved, the presence (or absence) of structures such as walls or ceilings that partially confine the vapor cloud, the spatial density of obstructions within the flammable cloud [Baker, et al., 1994, 1998], the average size of those obstacles, and the overall size of the confined or congested space [Mercx, et al., 1997, 2000]. This model reflects the results of several international research programs on vapor cloud explosions, which show that the strength of the blast wave generated by a VCE increases as the degree of confinement and/or obstruction of the cloud increases.

The strength of the blast wave predicted by the QMEFS VCE model is directly related to the size of the obstructed or partially confined volume that is filled with a flammable mixture of gas and air, and five additional parameters.

Fuel Reactivity: A fuel's reactivity is characterized by its laminar burning velocity (LBV). Because the QMEFS model is based on the BST model, certain LBVs match the BST categories of high, medium, and low. For example, ethylene, with an LBV of approximately 75 cm/s, was explicitly defined as a high reactivity fuel in the BST test series that defined that model. Most other fuels (propane, natural gas) have an LBV around 43 cm/s, making them medium reactivity fuels.

Volume Blockage Ratio (VBR): The density of obstacles within the flammable cloud influences the peak overpressure due to the generation of turbulence along the flame front. VBR is defined as the fraction of a particular volume that is occupied by obstacles.

Number of Confining Planes: The number of confining planes affects the strength of an explosion, potentially limiting the expansion of the flame front. The number of planes can be any number from 0 to 6, but is typically limited to values of 1 ("3-D" flame expansion with ground reflection), 2 ("2-D" expansion, or what occurs between flat, parallel surfaces), or 1.5 ("2½-D", for situations that begin as 2-D and quickly transition to 3-D, or have one confining plane that is semi-porous or frangible).

Flame Run-up Distance: This dimension is a descriptor for the maximum distance which a flame front can travel within the burning cloud. This value is typically limited to the longest horizontal dimension of the congested area.

Average Obstacle Diameter: As the size of obstacles decreases, the turbulence generated in a burning cloud increases, which increases the peak overpressure that is produced. The default value, from the BST test series, is 2 inches (0.0508 m).

One of the basic principles in application of the QMEFS explosion model is that after a flame front exits a congested or confined space, the deflagration decays to a lower burning velocity and does not significantly contribute to the creation of overpressure. This behavior has been demonstrated in test programs [Van den Berg and Mos, 2005]. Even if a flammable cloud can fill two or three distinct congested/confined locations (PESs), free space between them may prevent the concurrent generation of overpressure from all locations, and each PES can be considered independent. In practice, this limits the volume of flammable gas involved in a unique deflagration event.

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APPENDIX C
FAILURE CASE INITIAL CONDITIONS

The failure cases and their initial conditions considered in the existing Ventura Compressor Station (EXS) and the proposed Ventura Compressor Station Modernization (CSM) Project are provided in Table C-1.

Table C-1
Failure Case Conditions

Failure Case Designation	Release from	Pipe size [inches]	Initial Conditions		
			Temperature [°F]	Pressure [psia]	Operational Mode
EXS01	Compression Station Inlet	[redacted]	[redacted]	[redacted]	High Flow
EXS02	Compression Inlet Header	[redacted]	[redacted]	[redacted]	High Flow
EXS03	Single Compressor Inlet	[redacted]	[redacted]	[redacted]	High Flow
EXS04	Single Compressor Discharge	[redacted]	[redacted]	[redacted]	High Flow
EXS05	Gas Cooler	[redacted]	[redacted]	[redacted]	High Flow
EXS06	Cooled Gas Discharge Header	[redacted]	[redacted]	[redacted]	High Flow
EXS07	Compression Station Outlet	[redacted]	[redacted]	[redacted]	High Flow
EXS08	Fuel Gas Supply	[redacted]	[redacted]	[redacted]	High Flow
EXS09	Fuel Gas Feed to Compressors	[redacted]	[redacted]	[redacted]	High Flow
EXS11	Compression Station Inlet	[redacted]	[redacted]	[redacted]	Low Flow
EXS12	Compression Inlet Header	[redacted]	[redacted]	[redacted]	Low Flow
EXS13	Single Compressor Inlet	[redacted]	[redacted]	[redacted]	Low Flow
EXS14	Single Compressor Discharge	[redacted]	[redacted]	[redacted]	Low Flow
EXS15	Gas Cooler	[redacted]	[redacted]	[redacted]	Low Flow
EXS16	Cooled Gas Discharge Header	[redacted]	[redacted]	[redacted]	Low Flow
EXS17	Compression Station Outlet	[redacted]	[redacted]	[redacted]	Low Flow
EXS18	Fuel Gas Supply	[redacted]	[redacted]	[redacted]	Low Flow
EXS19	Fuel Gas Feed to Compressors	[redacted]	[redacted]	[redacted]	Low Flow

Failure Case Designation	Release from	Pipe size [inches]	Initial Conditions		
			Temperature [°F]	Pressure [psia]	Operational Mode
EXS21	Compression Station Inlet	[redacted]	[redacted]	[redacted]	Standby
EXS22	Compression Inlet Header	[redacted]	[redacted]	[redacted]	Standby
EXS23	Single Compressor Inlet	[redacted]	[redacted]	[redacted]	Standby
EXS24	Single Compressor Discharge	[redacted]	[redacted]	[redacted]	Standby
EXS25	Gas Cooler	[redacted]	[redacted]	[redacted]	Standby
EXS26	Cooled Gas Discharge Header	[redacted]	[redacted]	[redacted]	Standby
EXS27	Compression Station Outlet	[redacted]	[redacted]	[redacted]	Standby
EXS28	Fuel Gas Supply	[redacted]	[redacted]	[redacted]	Standby
EXS29	Fuel Gas Feed to Compressors	[redacted]	[redacted]	[redacted]	Standby
CSM01	Compression Station Inlet - Buried	[redacted]	[redacted]	[redacted]	High Flow
CSM02	Compression Inlet Header	[redacted]	[redacted]	[redacted]	High Flow
CSM03	Single Compressor Feed	[redacted]	[redacted]	[redacted]	High Flow
CSM04	Single Compressor Inlet	[redacted]	[redacted]	[redacted]	High Flow
CSM05	Single Compressor Discharge	[redacted]	[redacted]	[redacted]	High Flow
CSM06	Compressor Discharge Header	[redacted]	[redacted]	[redacted]	High Flow
CSM07	Cooled Gas to Station Outlet	[redacted]	[redacted]	[redacted]	High Flow
CSM08	Compression Station Outlet - Buried	[redacted]	[redacted]	[redacted]	High Flow
CSM09	Fuel Gas Supply	[redacted]	[redacted]	[redacted]	High Flow
CSM10	Fuel Gas Feed to Compressors	[redacted]	[redacted]	[redacted]	High Flow
CSM11	Compression Station Inlet - Buried	[redacted]	[redacted]	[redacted]	Low Flow
CSM12	Compression Inlet Header	[redacted]	[redacted]	[redacted]	Low Flow
CSM13	Single Compressor Feed	[redacted]	[redacted]	[redacted]	Low Flow
CSM14	Single Compressor Inlet	[redacted]	[redacted]	[redacted]	Low Flow
CSM15	Single Compressor Discharge	[redacted]	[redacted]	[redacted]	Low Flow
CSM16	Compressor Discharge Header	[redacted]	[redacted]	[redacted]	Low Flow

Failure Case Designation	Release from	Pipe size [inches]	Initial Conditions		
			Temperature [°F]	Pressure [psia]	Operational Mode
CSM17	Cooled Gas to Station Outlet	[redacted]			Low Flow
CSM18	Compression Station Outlet - Buried				Low Flow
CSM19	Fuel Gas Supply				Low Flow
CSM20	Fuel Gas Feed to Compressors				Low Flow
CSM21	Compression Station Inlet - Buried				Standby
CSM22	Compression Inlet Header				Standby
CSM23	Single Compressor Feed				Standby
CSM24	Single Compressor Inlet				Standby
CSM25	Single Compressor Discharge				Standby
CSM26	Compressor Discharge Header				Standby
CSM27	Cooled Gas to Station Outlet				Standby
CSM28	Compression Station Outlet - Buried				Standby
CSM29	Fuel Gas Supply				Standby
CSM30	Fuel Gas Feed to Compressors				Standby

APPENDIX D
HAZARD EXTENTS

The various hazards extents associated with releases of natural gas from the existing Ventura Compressor Station (EXS) and the proposed Ventura Compressor Station Modernization (CSM) Project are provided in this appendix. Table D-1 shows the maximum downwind extents of the various failure case scenarios for lower flammable limit (LFL) and thermal radiation impacts. These are based on the fatality endpoints for outdoor persons in Appendix A. Tables D-2 and D-3 present the distances to explosion overpressure levels for each of the potential explosion sites (PESs) chosen for this analysis.

Table D-1
Maximum Distances [feet] to Lethal Hazard Levels

Failure Case Designation	Release from	Lower Flammable Limit (LFL)	Thermal Radiation		
			28.4 kW/m²	14.3 kW/m²	7.3 kW/m²
EXS01	Compression Station Inlet	180	375	380	385
EXS02	Compression Inlet Header	<10	<10	<10	<10
EXS03	Single Compressor Inlet	<10	<10	<10	<10
EXS04	Single Compressor Discharge	<10	<10	<10	<10
EXS05	Gas Cooler	45	95	100	110
EXS06	Cooled Gas Discharge Header	<10	<10	<10	<10
EXS07	Compression Station Outlet	280	570	575	625
EXS08	Fuel Gas Supply	10	15	15	20
EXS09	Fuel Gas Feed to Compressors	<10	<10	<10	<10
EXS11	Compression Station Inlet	185	375	385	385
EXS12	Compression Inlet Header	<10	<10	<10	<10
EXS13	Single Compressor Inlet	<10	<10	<10	<10
EXS14	Single Compressor Discharge	<10	<10	<10	<10
EXS15	Gas Cooler	45	95	100	110
EXS16	Cooled Gas Discharge Header	<10	<10	<10	<10
EXS17	Compression Station Outlet	280	570	575	625

Failure Case Designation	Release from	Lower Flammable Limit (LFL)	Thermal Radiation		
			28.4 kW/m²	14.3 kW/m²	7.3 kW/m²
EXS18	Fuel Gas Supply	<10	10	10	10
EXS19	Fuel Gas Feed to Compressors	<10	<10	<10	<10
EXS21	Compression Station Inlet	185	380	385	385
EXS22	Compression Inlet Header	<10	<10	<10	<10
EXS23	Single Compressor Inlet	<10	<10	<10	<10
EXS24	Single Compressor Discharge	<10	<10	<10	<10
EXS25	Gas Cooler	60	20	25	25
EXS26	Cooled Gas Discharge Header	<10	<10	<10	<10
EXS27	Compression Station Outlet	280	570	575	625
EXS28	Fuel Gas Supply	10	<10	<10	<10
EXS29	Fuel Gas Feed to Compressors	<10	<10	<10	<10
CSM01	Compression Station Inlet - Buried	15	270	330	390
CSM02	Compression Inlet Header	120	235	235	265
CSM03	Single Compressor Feed	120	235	235	260
CSM04	Single Compressor Inlet	<10	<10	<10	<10
CSM05	Single Compressor Discharge	<10	<10	<10	<10
CSM06	Compressor Discharge Header	95	200	220	245
CSM07	Cooled Gas to Station Outlet	115	205	225	255
CSM08	Compression Station Outlet - Buried	20	465	540	615
CSM09	Fuel Gas Supply	15	25	25	30
CSM10	Fuel Gas Feed to Compressors	<10	<10	<10	<10
CSM11	Compression Station Inlet - Buried	15	280	340	400
CSM12	Compression Inlet Header	135	255	260	295
CSM13	Single Compressor Feed	130	255	255	290
CSM14	Single Compressor Inlet	<10	<10	<10	<10
CSM15	Single Compressor Discharge	<10	<10	<10	<10
CSM16	Compressor Discharge Header	75	125	140	160
CSM17	Cooled Gas to Station Outlet	90	135	150	175

Failure Case Designation	Release from	Lower Flammable Limit (LFL)	Thermal Radiation		
			28.4 kW/m²	14.3 kW/m²	7.3 kW/m²
CSM18	Compression Station Outlet - Buried	20	465	540	615
CSM19	Fuel Gas Supply	15	15	20	25
CSM20	Fuel Gas Feed to Compressors	<10	<10	<10	<10
CSM21	Compression Station Inlet - Buried	15	280	340	405
CSM22	Compression Inlet Header	135	260	260	295
CSM23	Single Compressor Feed	135	255	260	290
CSM24	Single Compressor Inlet	<10	<10	<10	<10
CSM25	Single Compressor Discharge	<10	<10	<10	<10
CSM26	Compressor Discharge Header	110	45	50	60
CSM27	Cooled Gas to Station Outlet	130	50	60	70
CSM28	Compression Station Outlet - Buried	10	80	90	110
CSM29	Fuel Gas Supply	35	10	10	15
CSM30	Fuel Gas Feed to Compressors	<10	<10	<10	<10

Table D-2
Maximum Overpressure Impacts [feet] Associated with the Existing Compressor Station

#	PES Designation	72.0 psi	13.1 psi	2.4 psi
1	Gas Metering Area	†	†	†
2	Existing Compressor House	†	†	†
3	Existing After Coolers	†	†	†

† - Overpressure endpoint not reached

Table D-3
Maximum Overpressure Impacts [feet] Associated with the Proposed Compressor Station

#	PES Designation	72.0 psi	13.1 psi	2.4 psi
1	Inlet Filter Area	†	†	†
2	Suction/Discharge Header Area	†	†	†
3	New Compressor House	†	†	†
4	Air Intake/Exhaust Area	†	†	†
5	Outlet Coolers	†	†	†
6	Utility Tank Area	†	†	†
7	New PDC Room	†	†	†
8	Gas Metering Area	†	†	†

† - Overpressure endpoint not reached

APPENDIX E
RISK QUANTIFICATION METHODOLOGY

The risk posed by a hazardous materials facility is often expressed as the product of the probability of occurrence of a hazardous event and the consequences of that event. Therefore, in order to quantify the risk associated with hazardous fluids, it is necessary to quantify the probabilities of accidents that would release fluids into the environment, and the consequences of such releases. The release frequencies and potential consequences must then be combined using a consistent, accepted methodology that accounts for the influence of weather conditions and other pertinent factors.

Generalized Risk Quantification Methodology

The risk posed by hazardous materials is often expressed as the product of the probability of occurrence of a hazardous event and the consequences of that event. Therefore, in order to quantify the risk associated with hazardous fluids, it is necessary to quantify the probabilities of accidents that would release the fluids into the environment, and the consequences of such releases. The event outcome probabilities and associated consequences must then be combined using a consistent, accepted methodology that accounts for initiating event frequencies, conditional probabilities, the influence of weather conditions, and other pertinent factors.

The risk quantification methodology used in this study has been successfully employed in QRA studies that have undergone regulatory review in several countries worldwide. The following is a brief description of the steps involved in quantifying the risk to the due to the hazardous fluids in a facility. For releases of hazardous fluids, the analysis can be divided into the following steps.

Step 1. Within each area of the facility being considered in the study, determine the potential failure cases that would create a flammable gas cloud, vapor cloud explosion, or jet fire. Potential release sources are determined from a combination of historical accident data, site-specific information, and engineering analyses by process safety engineers. Some of the factors that contribute to the selection and definition of each failure case are:

a. Fluid composition, temperature, and pressure
b. Fluid inventory in the process
c. Release location
d. Process controls and emergency shutdown systems

Step 2. Determine the frequency of occurrence of each accident scenario (f(acc)), and for each scenario, all possible outcomes. The initial frequency of occurrence is a summation of the failure frequencies of all portions of the process where a release of hazardous fluid would result in a similar hazard. Individual failure frequencies are based on historical experience, failure rate data for similar equipment, service factors, emergency shutdown systems, and engineering judgment. The frequency of occurrence for each scenario outcome is calculated using event trees.

Step 3. Calculate the size of each potentially fatal hazard zone for each population (workers indoors) created by each of the events identified in Step 1.

i. The hazards of interest are:
   a. Thermal radiation from jet fires
   b. Overpressure from vapor cloud explosions
   c. Flash fires due to flammable infiltration
ii. The size of each hazard zone is a function of one or more of the following factors.
   a. Composition, pressure, and temperature of fluid being released
   b. Hole size
   c. System inventory
   d. Orientation of the release (upward, horizontal, downward)
   e. Wind speed
   f. Atmospheric stability
   g. Local terrain (including impoundment)
   h. Presence of regions of confinement or congestion
   i. Process controls and emergency shutdown systems

Step 4. Determine the risk posed by the facility in the vicinity of potential failure cases.

i. The potential exposure to a specific hazard zone depends on the following factors.
   a. Size (area) of the hazard zone
   b. Location of the receptor (building), relative to the release location
   c. Wind direction
ii. Determine the exposure (as defined by the hazard endpoints) to each potential hazard zone.
   a. Perform flammable vapor cloud (flash fire) and vapor cloud explosion hazard zone calculations for all wind directions, wind speeds, atmospheric stabilities, hole sizes, and release orientations.
   b. Perform jet fire and pool fire hazard zone calculations for wind directions, wind speeds, hole sizes, and release orientations. (Fire radiation hazard zones are not dependent on atmospheric stability.)

c. Perform BLEVE calculations for each liquefied gas storage vessel.
d. Perform building infiltration calculations for flammable and toxic vapor cloud exposure.

iii. Modify each frequency of occurrence f(acc) identified in Step 2 by the applicable conditional probabilities. The conditional probabilities are divided into the following groups.
a. P(orientation) = probability that hazardous fluid is released into the atmosphere in a particular orientation.
b. P(wd,ws,stab) = probability that the wind blows from a specified direction (wd), with a certain wind speed (ws), and a given atmospheric stability class, A through F (stab). Meteorological data are generally divided into sixteen wind directions, six wind speed classes, and six Pasquill-Gifford atmospheric stability categories. Although all 576 combinations of these conditions do not exist, a significant number will exist for each meteorological data set. Figure E-1 represents a typical wind speed versus stability distribution.
c. P(ii) = probability of immediate ignition (i.e., probability that ignition occurs nearly simultaneously with the release).
d. P(di) = probability of delayed ignition (i.e., probability that ignition occurs after a vapor cloud has formed).
e. P(con)=conditional probability based on non-continuous use or other factors. If there are no applicable factors, P(con)=1.0.

iv. Sum the potential exposures from each of the hazards for all releases identified in Step 1. This summation involves applying the frequency of each potential hazard zone to the areas covered by that zone. For example, the frequency of a specific vapor cloud explosion is f(acc)*P(orientation)* P(ws,wd,stab)*P(di)*P(con).

v. Develop measures of risk based on the cumulative total impact of all event outcomes for all failure cases at all locations in and around the facility, that may be affected by each unique event outcome. These may include:
a. Location-specific individual risk (LSIR) contours, based on continuous occupancy;
b. Individual risk per annum (IRPA), based on LISR and expected occupancies in varied areas in and/or around the facility; or
c. Societal risk in the form of F/N curves, based on the expected number of persons at various locations in and/or around the facility

Figure E-1
Representative Range of Wind Speed/Atmospheric Stability Categories

Hazard Footprints and Vulnerability Zones

When conducting a quantitative risk analysis, it is necessary to determine the consequences of each possible combination of:

- hole size;
- release orientation;
- release outcome (hazard);
- wind speed;
- atmospheric stability; and
- wind direction.

for each potential failure case that is included in the study. Within each failure case, combinations of these factors result in a set of unique accidents.

A hazard footprint can be defined as the area over which a given unique accident is capable of producing some level of undesirable consequences. A vulnerability zone is defined as the area within the circle created by rotating a hazard footprint around its point of origin. Any point within that circle could, under some set of circumstances, be exposed to a hazard level that equals or exceeds the endpoint used to define the hazard footprint. However, except for accidents that produce circular hazard zones (e.g., explosions), only a portion of the area within the vulnerability zone can be affected by a unique accident. This is illustrated in Figure E-2 by an example of a flammable vapor cloud hazard footprint (cross-hatched area) and its vulnerability zone. In addition, many "smaller" accidents might be capable of producing hazard footprints that would affect parts of the vulnerability zone associated with a "large" accident.

Vulnerability zones can be used to define the size and shape of the area around a release within which there is a finite probability of exposure to a fatal hazard. Persons located outside this area would not be at risk from that unique accident scenario.

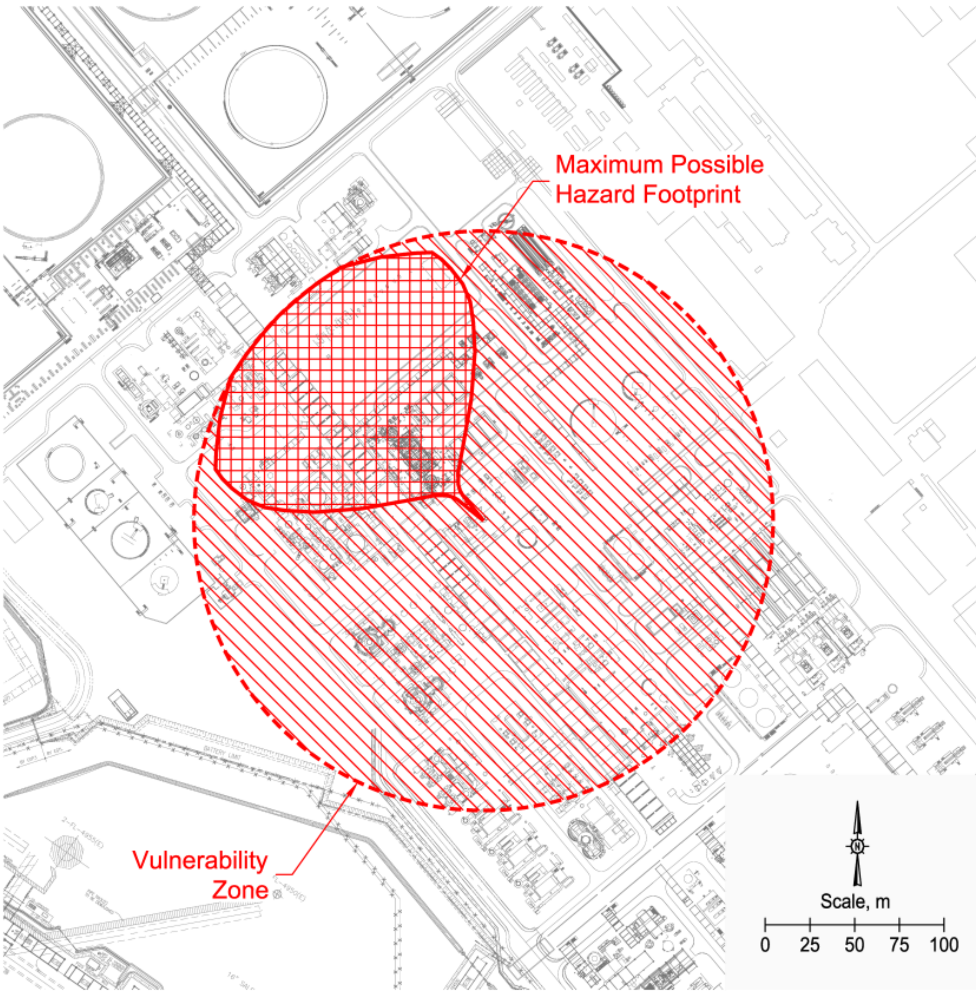

Figure E-2
Example Hazard Footprint and Vulnerability Zone for a Flammable Vapor Cloud

When the hazard vulnerability zone (the circle) on Figure E-2 is presented, there is no associated probability since the cloud cannot cover the entire area at one time. In addition, there are other possibilities of cloud formation from the same release scenario that would fill a portion of the vulnerability zone. This risk analysis considered 21 combinations of wind speed and atmospheric stability and 64 wind directions for each unique release. These conditions were used when evaluating five release hole sizes and several event outcomes (flash fire, explosion overpressure, jet fire, and pool fire). The hazard footprint presented in Figure E-2 is just one of the thousands of possible outcomes following a release. Thus, vulnerability zones are not a meaningful measure of risk. Vulnerability zones simply provide information about which areas could potentially be exposed to one unique accident, but provide no information about the probability of exposure.

Risk Contours

The risks due to all possible unique accidents can be combined to produce a measure of the risk that describes the entire facility. The measure of risk must be in a form that is easy to interpret and can be compared to the appropriate risk criteria for the activity.

One presentation method that meets these criteria is the use of risk contours. An example set of risk contours is presented in Figure E-3 for the example accident presented in Section 3. If early fatality is the measure of risk, then each risk contour is the locus of points where there exists a specific probability of being exposed to a fatal hazard, over a one-year period, to any of the acute hazards associated with many possible releases. Because the risk contours are based on annual data, the risk level for a given contour is the risk to an individual who remains at a specific location 24 hours a day, for 365 consecutive days. It is important to note that the risk contours are generally independent of the local population density and distribution. Thus, whether there are 2, 20, or 200 persons at a specific location (for the entire year), the risk of exposure to a fatal hazard would be the same for each of the persons at that location.

Risk contours predict the potential exposure for an individual to by events that originate in a facility, a portion of a facility, or from one specific failure case. The predicted numerical measure of risk represents the chance, or probability, that an individual will be exposed to a fatal hazard during a year-long period. For example, a value of 1.0×10^{-6}/year (or 10^{-6} in shorthand notation) represents one chance in 1,000,000 (one million) per year of being fatally affected by any of the releases included in the analysis. If this risk level is predicted to occur at a particular location, it represents the annual chance of fatality at that location, assuming a person stays in that location for the full year, due to any potential release from the system. This assumption is referred to as continuous occupancy and was applied to this study.

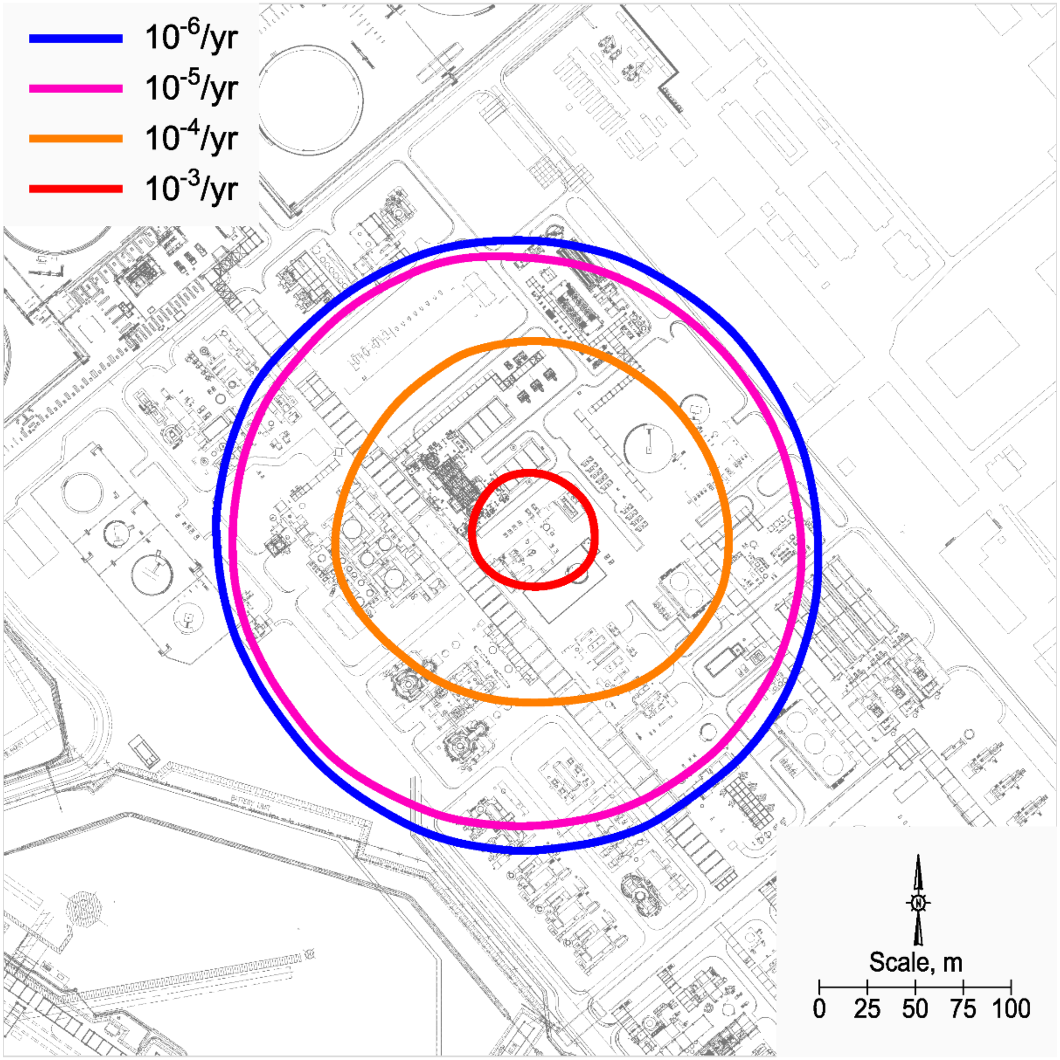

Figure E-3
Example Location-Specific Individual Risk (LSIR) Contours

Risk contours define the summation of all hazard zones for each unique accident combined with their respective probabilities. An example of risk contours in Figure E-3 represents the variation of annual probability of building exposure resulting in occupant fatality. Thus, a building within the 10^{-6} contour will have a one in a million chance of the building experiencing hazards that may result in an occupant fatality.

Appendix S-2

QMEFS Reference Document

Revisions to the QMEFS Vapor Cloud Explosion Model

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Revisions to the QMEFS Vapor Cloud Explosion Model

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Keywords: vapor cloud explosion (VCE), Baker-Strehlow-Tang (BST) model, estimating flame speeds

Abstract

The Quest model for estimating flame speeds (QMEFS) was introduced in 2007, has since been published, and has been used by Quest and other companies to provide a detailed method for vapor cloud explosion (VCE) predictions. QMEFS provides a set of parameters that predict a flame speed, which then is used with the Baker-Strehlow-Tang (BST) blast curves to predict overpressure and impulse. The original intent of the QMEFS model was to provide better characterization of confined or congested areas, as well as fuel reactivities, which fit between the low, medium, and high categories offered by the BST model, so that the large differences in predictions between categories could be eliminated. In this way it provided a more refined system for predicting the consequences of a VCE, while remaining anchored within the flame speeds provided by the BST matrix.

In the years since QMEFS' publication, Baker has added to the BST flame speed matrix. In addition, use of the model has highlighted some of the areas where the model could be improved. This paper shows several ways in which the model has been enhanced to encompass a wider range of conditions than are covered by the BST model.

1 Introduction

Any release of a flammable fluid in a petrochemical facility has the potential to generate a flammable vapor cloud that, if ignited, could produce a vapor cloud explosion (VCE). Most VCEs that generate damaging levels of overpressure originate in what is called a potential explosion site (PES), where confinement and congestion contribute to flame acceleration and the generation of overpressure. When flammable vapors enter the PES and are ignited, the possibility of human injury/death, asset damage, or event escalation becomes a concern. The concern for human injury or death is most often addressed in the form of a building siting study. Because people are somewhat less likely to be injured or killed when outside, as compared to when inside a building, the siting study focuses on the potential impacts to buildings within and around petrochemical facilities. It then becomes the task of process safety professionals to estimate the potential for VCE events, and their resulting overpressure impacts on buildings.

The Baker-Strehlow-Tang (BST) model and the TNO Multi-energy (ME) model use blast curves to estimate the overpressure impacts generated by an exploding vapor cloud. Both approaches require the user to estimate the strength of the explosion as a function of the reactivity of the flammable material and the degree of confinement or congestion present in the cloud. This information is then used to determine which strength curve (in the case of the TNO model) or flame speed curve (in the case of the BST model) is used to calculate the overpressure of the explosion as a function of distance from the center of the explosion. It is not clear, however, how best to choose the correct curve when modeling an explosion.

There have been several papers published regarding blast curve selection for the ME model. These methods are generally presented as a qualitative ruleset which acts as an index into which of the 10 curves should be used. The BST model provides a simple set of guidelines that result in a selection of a flame speed, which corresponds to an overpressure vs. distance relationship. Three parameters are used to determine the flame speed: reactivity of the flammable gas, the degree of confinement of the flammable cloud, and the degree of obstruction due to obstacles within the flammable cloud. These parameters are represented by a set of what are effectively low, medium, and high choices for each parameter.

While the BST model provides reasonable guidance on choosing the explosion parameters, there are still areas that could be improved. One problem is that the BST flame speed matrix includes large jumps in flame speed between categories of confinement, reactivity, or congestion. This was first addressed by Baker in a 1998 paper [1] where a new confinement category, 2½-D, was added for those situations that were more confined than the 3-D case, but less so than the 2-D case. The flame speeds used for the 2½-D confinement were simply the arithmetic average of the flame speeds for the 2-D and 3-D cases for a given reactivity and congestion class. Even with this extension, large discontinuities remained among the categories for flame speed according to the prescribed methodology. These discontinuities drive the need for a new method to determine flame speed based upon quantifiable properties of the flammable gas and its surroundings that varies smoothly across the range of conditions that are found in actual process plants.

The creation of the QMEFS model [2] improved upon the basic BST scheme by combining it with the GAMES correlations [3] and providing a numerical resolution to the BST matrix. Integration of the GAMES model allows the strength of the explosion to be defined by numeric input parameters and avoids the low/medium/high categorizations.

2 Parameters Affecting Flame Speed

With the incorporation of the GAMES correlations, the resulting explosion flame speed is characterized by five parameters:

- Laminar burning velocity (LBV) is used as the characteristic property for fuel reactivity

- Volume blockage ratio (VBR) and average obstacle diameter define the level of congestion
- Confinement is characterized as the number of confining planes, or walls, that are available to confine the expanding gases.
- Flame run-up distance is used to characterize the flame acceleration path

The last part of explosion characterization is the explosive energy of the fuel/air mixture, which is defined by the gas concentration, the combustion energy of the fuel, and the volume occupied by the fuel/air mixture.

2.1 Reactivity

Fuel reactivity is a measure of the propensity of the flame front to accelerate and create overpressures or potentially undergo a deflagration-to-detonation transition (DDT). The BST model originally classified reactivity as high, medium, or low based on the fuel in the fuel-air mixture. The original rule set [1] defined propylene oxide, ethylene oxide, and hydrogen (or materials with a 0.8 m/s LBV or larger) as high reactivity; methane and carbon monoxide were classified as low reactivity, and everything else as medium reactivity. According to the current BST model, materials having a laminar flame speed greater than 0.75 m/s are considered high reactivity (to accommodate ethylene being high reactivity) while those having a laminar flame speed below 0.4 m/s are considered low reactivity [1], although some BST publications list the low boundary as 0.45 m/s. In 2016, the BST categories were expanded to include a very-low category for fuels like ammonia, which has an LBV in the range of 0.07 m/s to 0.15 m/s [4].

In the experimental studies that form the basis of the BST model, ammonia, methane, propane, and ethylene were used to define the very low, low, medium, and high reactivity categories. These categories produce confusion due to how they create boundaries between the BST categories. For example, the LBV of ethylene, depending on the cited reference, ranges between 0.64 and 0.83 m/s. With the current definition of 0.75 m/s as the high reactivity boundary, this makes ethylene a “borderline” fuel – one that may either be defined as medium or high reactivity. However, ethylene is explicitly categorized as a high reactivity material, as their experimental work used ethylene as the high reactivity material [5]. This then begs the question: what about ethylene oxide (LBV 1.0 m/s) or acetylene (LBV 1.6 m/s)? These two materials are clearly more reactive than ethylene, but are still categorized as high reactivity. The BST model effectively says that an ethylene explosion will be as severe as an acetylene explosion, when all other parameters are held constant.

2.2 Congestion

In the original BST model, low obstacle density was defined as having an area blockage ratio (ABR) of less than 10%, while high obstacle density was defined as an ABR of 40% or greater, and everything in between is considered medium [6]. Later BST guidelines have used the volume blockage ratio (VBR) as the parameter for classifying obstruction [5]. In practice both blockage ratios will affect how fast a flame accelerates, but, for a uniform obstacle field, the two are related simply by the pitch-to-diameter ratio of the obstacles. If the obstacles included in an ABR are not repeated quasi-uniformly throughout the obstacle field, then their effect would be more accurately portrayed by VBR.

The classifications of low, medium, and high are often too coarse for proper assignment of congestion to a particular PES. In the experimental programs that helped to define the BST model, VBRs of 1.5%, 4.3%, and 5.7% were used to represent the low, medium, and high categories. As with other VCE parameters, the differences between these categories leaves significant room for variation between the categories. In addition, no definition of 0% VBR is provided, nor is any relationship to VBRs higher than 5.7%.

2.3 Confinement

The effect of the confinement of the flammable cloud is taken into account by determining the number of dimensions in which the burning gas may expand. 3-D expansion allows the burning cloud to expand freely in all directions and results in the slowest flame acceleration and lowest overpressures. 2-D expansion, such as a flame between two flat plates, generates higher overpressures because the combustion gases have fewer directions in which to expand resulting is a higher flame acceleration.

Confinement is included in the BST model by identifying the number of dimensions that are available to the products of combustion for expansion. Expansion into free space (except for the plane of the ground) is considered 3-D expansion, expansion between two parallel planes is considered 2-D expansion, and expansion in a pipe is considered 1-D expansion. The 1-D case was removed in the more recent publications discussing the BST model [5]. To handle the case of a frangible or partially-confining plane, such as a very closely spaced pipe rack, the BST model added a 2.5-D classification which simply averaged the 2-D and 3-D flame speed results [5].

While the classification is fairly straightforward, especially after the 2.5-D category was added, some situations are still difficult to define. These include partial walls, pieces of equipment that may form more confinement than congestion, or surfaces that are porous such as grated decks.

2.4 Other Factors

Several researchers [5, 7, 8] have acknowledged that the overall dimensions of the flammable vapor cloud before ignition directly affect the final flame speed and consequent overpressures of the vapor cloud explosion. Since a flame will accelerate until it reaches a maximum sustainable value (or undergoes a deflagration to detonation transition, a DDT), the maximum dimension of a flammable cloud is expected to be an important variable in the creation of overpressure. As a point of reference, the length available for flame acceleration in the more recent BST tests was 15 meters [5].

In addition, research [7, 8] suggests that the scale of obstacles within the congested area also affects the maximum flame speed that may be achieved. As a flame front moves around and past obstacles, the turbulence that is generated can increase the flame surface area and accelerate combustion. The characteristic obstacle diameter for the BST tests was 2 inches (0.0508 meters); other test series (including the MERGE/EMERGE tests, varied the average obstacle diameter).

2.5 Parameters Comparison

The BST parameters discussed above are listed in Table 1, along with the corresponding numerical values that are equivalent to those applied in the QMEFS model. When the numerical values in Table 1 are applied in the QMEFS model, the results will match the predictions of the BST model.

Table 1. BST Flame Speed Parameters

BST Parameter	BST Category	Model Parameter	Corresponding Parameter Value
Reactivity	Very-Low (e.g., Ammonia)	S_l	0.08 m/s
	Low (e.g., Methane)		0.37 m/s
	Medium (e.g., Propane)		0.43 m/s
	High (e.g., Ethylene)		0.75 m/s
Obstacle Density	Low	*VBR*	0.015
	Medium		0.043
	High		0.057
Expansion	3-D	*nPlanes*	1
	2.5-D		1.5
	2-D		2

3 Model for Estimating Flame Speed

The QMEFS model was created to overcome some of the limitations described above. By incorporation of the GAMES correlations and the overpressure/impulse curves from the BST method, a model that provides the capability for more detailed descriptions of explosion scenarios has been created. Thus, QMEFS incorporates the modeling methodologies and experimental data sets that have been used in both the BST model and in the GAMES project.

3.1 Fundamental Correlations

The fundamental correlation is based on correlations developed from the GAMES project [3]. These correlations related overpressure to parameters based on the MERGE and EMERGE experiments [7,8]. These correlations can be combined with acoustic theory to relate flame speed to explosion parameters [2] to produce the equations below.

For no confining surfaces other than the ground (3D expansion):

$$2.4 * \frac{M_f^2}{1+M_f} * p_0 = 0.84 * \left(\frac{VBR*L_f}{D}\right)^{2.75} * S_l^{2.7} * D^{0.7} \quad (1)$$

For confinement between two flat planes (2D expansion):

$$2.4 * \frac{M_f^2}{1+M_f} * p_0 = 3.38 * \left(\frac{VBR*L_f}{D}\right)^{2.25} * S_l^{2.7} * D^{0.7} \quad (2)$$

where:

- VBR = volume blockage ratio
- L_f = maximum distance a flame may propagate in the obstructed region (i.e., the run-up distance), m
- D = average obstacle diameter, m
- S_l = laminar burning velocity (LBV) of the flammable gas, m/s
- p_0 = the ambient pressure, bara
- M_f = the flame speed relative to a fixed observer, expressed as a Mach number

To correct the flame speed to account for confinement in spaces other than one or two planes, a curve fit of the ratio of burned cloud to unburned cloud radii versus the number of confining planes was made. A curve fit was generated with an expansion ratio (α) equal to 7, a typical expansion ratio for common hydrocarbon fuels in air. This is also the value assumed in the derivation of portions of the BST model [9]. The equation resulting from this curve fit is:

$$NPF = \frac{1}{0.5035 - 0.0757 \cdot nPlanes} - 1.338 \quad (3)$$

where:

- NPF = flame speed correction factor
- $nPlanes$ = number of confining planes

For true 3-D spherical expansion, *nPlanes* = 0. For a typical explosion at grade level, *nPlanes* = 1. For 2-D expansion, such as a flame propagating between a floor and a ceiling, *nPlanes* = 2. For 1-D expansion, such as a flame front in a pipe, *nPlanes* = 4. Planes that are not completely solid or rigid may be accounted for using a fraction of a plane.

The flame speed correction factor, *NPF*, does not fully account for increases in flame speed as the number of confining planes increases. This is accomplished by applying the following factor to the flame speed when *nPlanes* is equal to 2:

$$\beta = \frac{M_{f,2D}}{M_{f,3D} \cdot NPF(nPlanes = 2)} \quad (4)$$

This can be implemented for nPlanes =1 to nPlanes = 4:

nPlanes = 1

$$M_f = M_{f\,3D} * NPF \quad (5)$$

1 > *nPlanes* < 2

$$M_f = M_{f\,3D} * NPF * \beta \quad (6)$$

nPlanes >= 2

$$M_f = M_{f\,3D} * NPF * [1 + (\beta - 1) * (nPlanes - 1)] \quad (7)$$

3.2 Flame Speed Limits

The equations above are implemented in the QMEFS model to define the flame speed (M_f) and then coupled with the latest BST flame speed matrix [4]. One limitation to the GAMES correlations is that they can predict unrealistic flame speeds. This is a direct result of the correlations fitting the data within the scope of the MERGE and EMERGE tests, and not being designed to extend beyond that scope. By coupling with the BST model, this problem is partially resolved because the BST matrix provides a set of upper limits to flame speeds (and by extension, the explosion strength).

Upon examination, it can be seen the GAMES correlations will predict higher and higher flame speed values as parameters such as L_f or S_l, increase. In reality, for a given obstacle configuration, geometry, and flammable gas mixture, there is a limit to the flame speed that can be achieved. This flame speed may be either subsonic or the cloud may undergo a deflagration-to-detonation transition (DDT) in which the flame front becomes a detonation propagating at roughly the Chapman-Jouguet (C-J) detonation velocity for the flammable mixture. For most common flammable hydrocarbons in air, this speed is roughly 1800 m/s or $M_f = 5.2$. For purposes of this model, any flame that accelerates to a calculated velocity greater than $M_f = 3.0$ is considered to have undergone DDT [10, 11] and the flame speed is set to the C-J velocity, $M_f = 5.2$.

The flame speeds suggested by the latest BST model are applied as the upper limit flame speeds to be used in this model, as they have been “scaled up” to account for industrial scale flammable clouds [5] and account for DDTs.

The result of these correlations is a model that estimates the flame speed based on *VBR*, *D*, S_l, L_f and the number of confining planes. The resulting flame speed is compared to the published BST model, which provides a matrix of flame speeds as a function of reactivity, obstacle density, and flame expansion. The BST matrix values are used as maximum flame speed values for the set of parameters given in Table 1. Values between the BST matrix elements are calculated by linear interpolation (as was done for Baker’s 2½-D flame expansion category). This methodology provides an extended, systematic approach for estimating flame speeds resulting from the combustion of a flammable cloud in an obstructed and/or confined region. Predicted flame speeds are used with the existing BST blast curves to produce estimates of overpressure at a distance from the explosion source.

3.3 Expansion of the BST Matrix

The range of the QMEFS model is limited by the upper and lower bounds of the BST matrix elements for congestion, confinement, and fuel reactivity. Through application of this model to various petrochemical projects, the need to expand the matrix became obvious. As described above, the model is built to provide predictions for the *nPlanes* (confinement) parameter in the range of 1.0 to 4.0 (the model is not validated nor trusted above this value). Values of average obstacle diameter and flame run-up distance are built into the GAMES correlations, so naturally are accounted for within reasonable limits. This leaves the congestion (VBR) and fuel reactivity parameters as places to potentially expand the model.

The intent of model expansion is to widen the range of congestion and reactivity inputs so that it removes questions about its use in the “below low” and “above high” regions. With proper expansion of the model described above, the predicted flame speed following ignition of a flammable cloud may then be used with the BST blast curves to estimate the overpressure impacts in the area surrounding a vapor cloud explosion.

To accomplish this expansion, additional categories were added to the BST matrix for congestion and reactivity. This follows Baker’s own expansion into the **very-low reactivity** category when ammonia explosion experimental results were published [4].

For a **very-high reactivity** category, hydrogen was assumed as the characteristic fuel, and represents a true upper bound for LBV. Expansion to the very-high category, for parts of the matrix with high flame speeds is simple because DDTs are expected in these conditions already. For other areas, published data was required for the basis of the expansion.

In the case of the **very-low congestion** category, open air (3-D flame expansion) explosion tests were performed by Harris and Wickens [12] as well as Sato and Iwabuchi [13] for a variety of materials. The **very-high congestion** category, several of the BFETS series of tests were used [14] due to their use of a VBR in the 10% range.

The expanded matrix applied in the new QMEFS model is presented in Table 2. The latest BST flame speed matrix values are outlined by bold lines in Table 2. Values outside these areas have been added as part of the QMEFS expansion.

While a 1-D confinement is not expected to be applied in large-scale industrial scenarios, the *nPlanes* = 5 (1-D) confinement category is included in this model to provide an interpolation point beyond *nPlanes* = 2 (2-D flame expansion).

Table 2. Expanded Flame Speed Matrix

Confinement	Reactivity	Congestion				
		Very-Low	Low	Medium	High	Very-High
1D	Very-High	DDT	DDT	DDT	DDT	DDT
	High	DDT	DDT	DDT	DDT	DDT
	Medium	1.029	1.029	1.765	2.265	DDT
	Low	0.5	0.5 *	1.029	2 *	DDT
	Very-Low	0.023	0.023	0.124	0.168	0.303
2D	Very-High	DDT	DDT	DDT	DDT	DDT
	High	0.588	0.588	DDT	DDT	DDT
	Medium	0.47	0.47	0.66	1.6	DDT
	Low	0.079	0.079	0.47	0.66	1.244
	Very-Low	0.008	0.008	0.049	0.069	0.130
3D	Very-High	0.5	DDT	DDT	DDT	DDT
	High	0.06	0.36	DDT	DDT	DDT
	Medium	0.03	0.11	0.44	0.5	1.084
	Low	0.025	0.026	0.23	0.34	0.678
	Very-Low	0.003	0.003	0.024	0.036	0.073

* Values adjusted from BST publication for model consistency

4 Application

It is helpful to test the QMEFS model outside of the published BST matrix, in the areas where the QMEFS matrix has been expanded. Large scale hydrogen experiments were performed in a hemispherical test rig with no congestion. The test volume was 300 m^3 with a base of 10.4 meters diameter [13] and center ignition. The tests were modeled with the latest BST model and the expanded BST model. The model parameters listed in Table 3 were applied to these calculations. Figure 1 presents the overpressure in relation to distance from center of the fuel-air mixture, for the test results and both BST and QMEFS predictions. The BST model does not have a category for a hydrogen vapor cloud with no congestion, thus the scenario falls into the high fuel reactivity and low congestion portion of the matrix. The result is an underprediction of the overpressure. The BST high fuel reactivity works well for fuel such as ethylene (LBV = 0.76 m/s), but will often underpredict the impacts of a hydrogen (LBV = 3 m/s) explosion. The expanded matrix allows a higher fuel reactivity category and a lower congestion category, and consequently a better prediction of the explosion impacts. As seen in Figure 1, the QMEFS result is a slight overprediction of the overpressure.

Table 3. Modeling Parameters for an Unconfined Hydrogen Explosion

Parameter	BST	Expanded QMEFS
Volume [m^3]	300	300
nPlanes	1	1
Reactivity	High	Very-High
VBR	N/A	0
Congestion	low	N/A
Run-up distance [m]	N/A	5.2

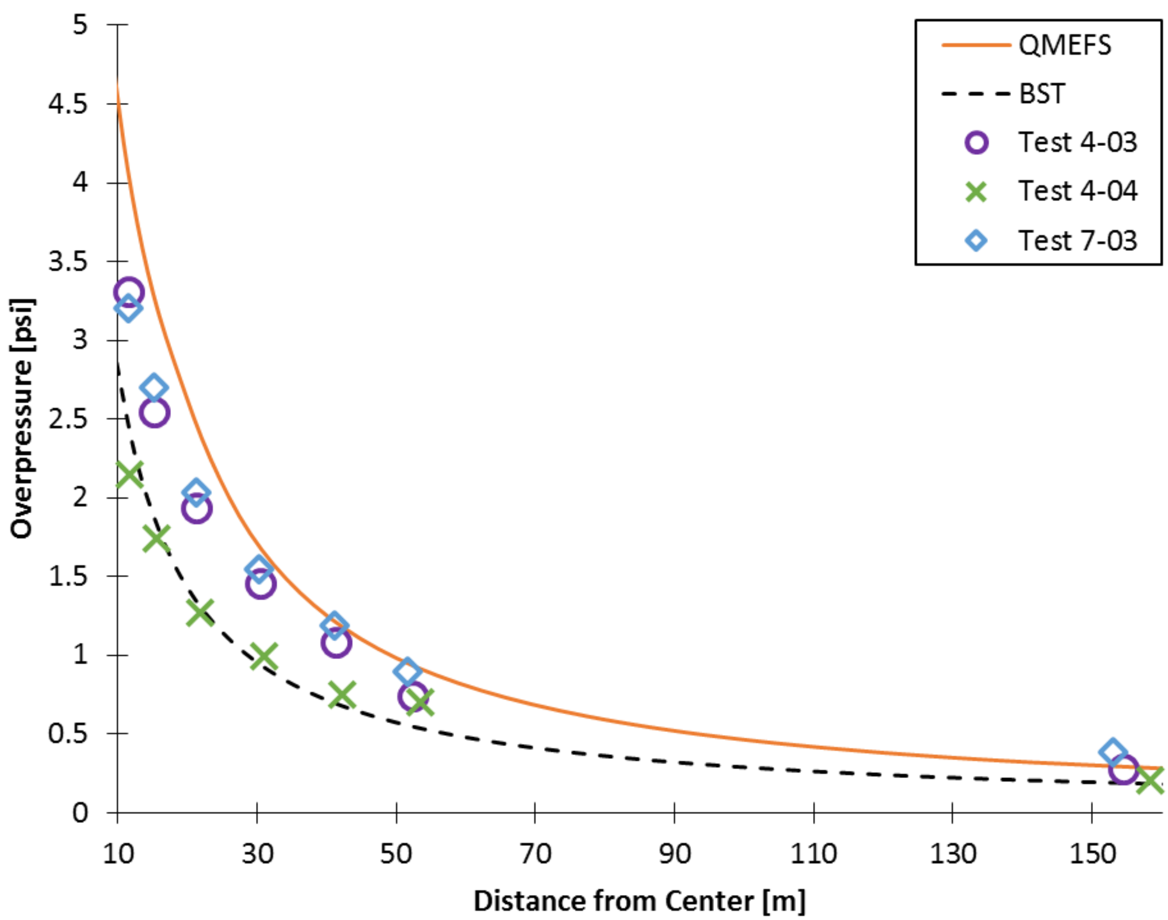

Figure 1. Overpressure vs. Distance for Open-Air Hydrogen Tests

As discussed in the paper, the distance that is available for the flame to accelerate, i.e. the run-up distance, can have a significant effect on the flame speed attained in a flammable gas cloud. The flame speeds presented in the original Baker-Strehlow (BS) model [6] were generated in a test rig whose largest dimension was less than 6 feet (1.8 meters) [5]. The flame speeds presented in the 2005 BST paper are based on tests where the largest dimension was 48 feet (14.6 meters) with the published flame speed results "scaled up" to account for the maximum size of a typical industrial plant [5]. One test of the QMEFS model is to determine the flame speed versus run-up distance for the test configurations used in the newest BST model when specific parameters are varied.

Figure 2 shows the results for the 3-D flame expansion (*nPlane*s = 1), medium reactivity (S_l = 0.43 m/s) case. The curves plotted in Figure 2 show six VBR values – the high (5.7%), medium (4.3%), and low (1.5%) congestion values used in the BST experiments, one intermediate value to show how the model behaves as the VBR is adjusted, a fifth value (1%) below the BST low category to demonstrate the behavior in the "less-than-low" congestion range, and the sixth value (10%) above the BST high category to demonstrate the behavior in the "higher-than-high" congestion range.

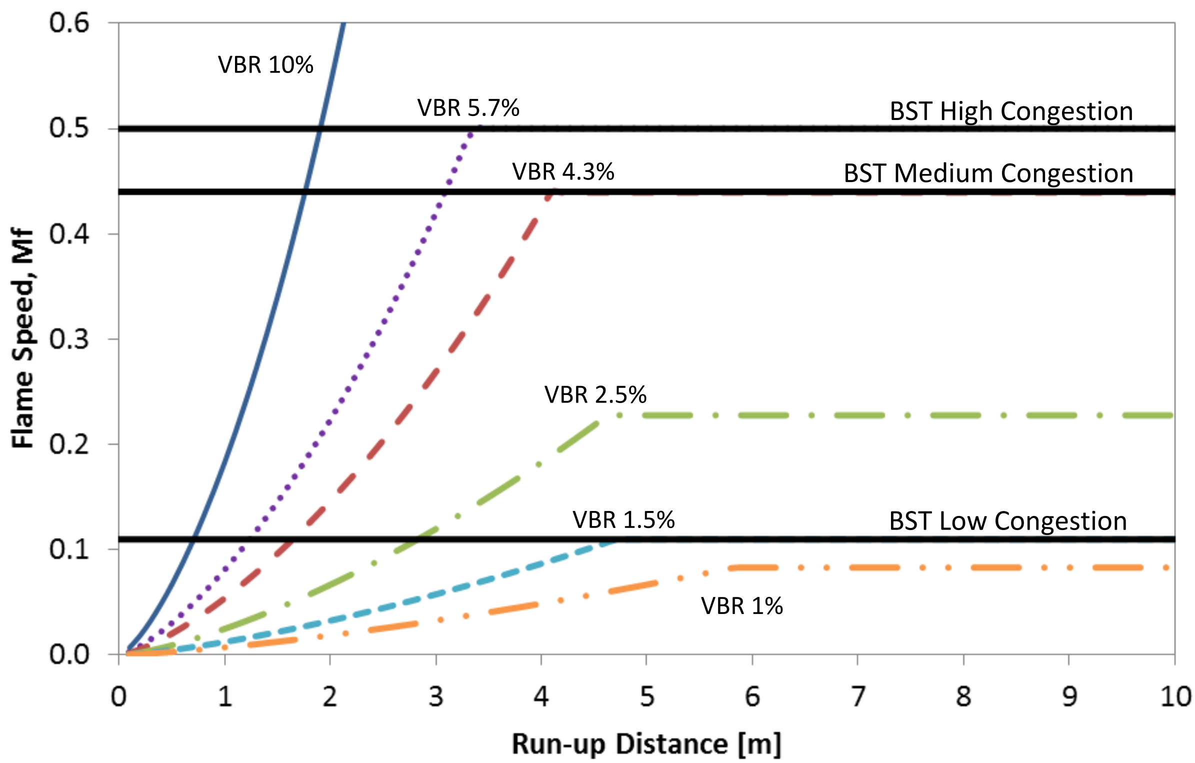

Figure 2. Flame Speed vs. Run-Up Distance; 3-D, Propane, D = 2"

Figure 3 demonstrates how flame speed varies with *nPlane*s and LBV. The basis of the figure is an explosion involving a medium VBR (0.043) and a 4-inch average obstacle diameter. The *nPlane*s parameter is varied between 1.0 (3-D flame expansion) and 4.0 (the maximum value recommend for use in the QMEFS model). The curves plotted in Figure 3 show five materials with various LBV values – ammonia (0.08 m/s), methane (0.37 m/s), propane (0.43 m/s), ethylene (0.76

m/s) and ethylene oxide (0.91 m/s). In the BST model ethylene oxide and ethylene are grouped together into the high category, but these two fuels have different burning properties as can be seen with their LBV values. Thus, by accounting for the LBV of the fuel, the new model provides a finer resolution for flame speed. In addition, as seen in Figure 3, the QMEFS model provides more resolution for the flame expansion parameter through the use of the *nPlanes* variable.

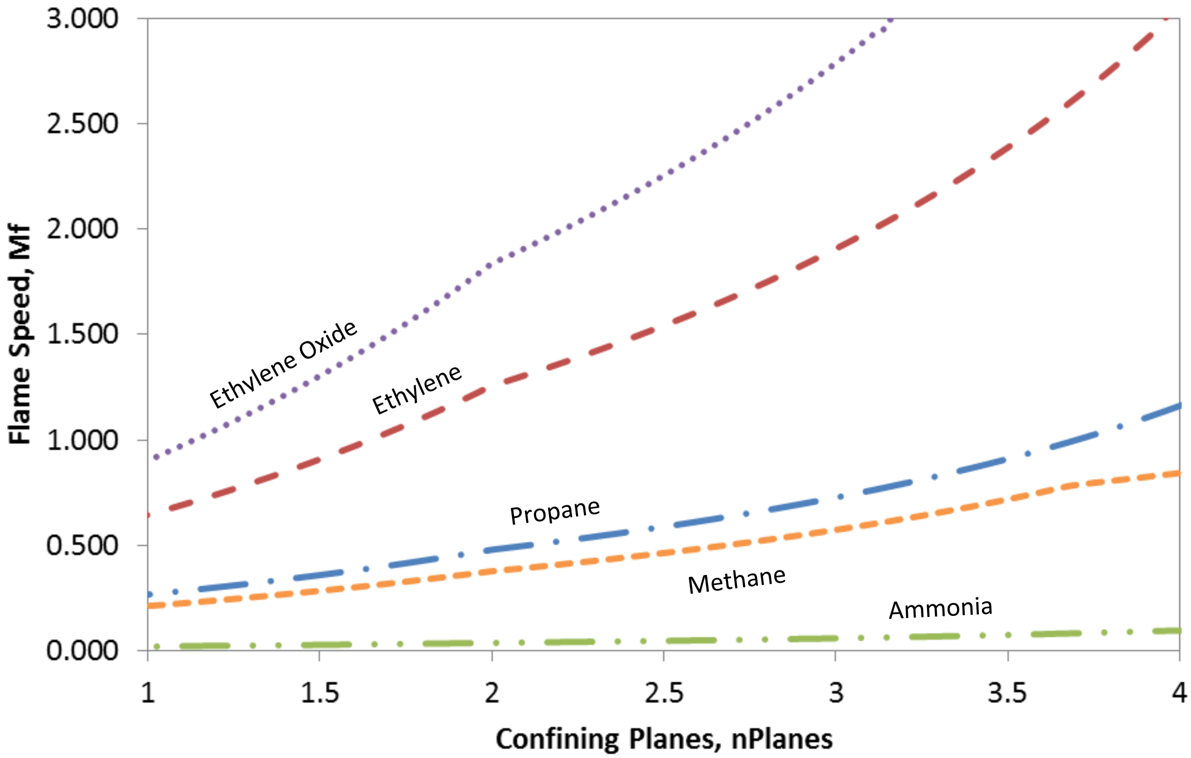

Figure 3. Flame Speed vs. Confining Planes; Medium VBR, D = 4"

5 Conclusions

The model described in this paper provides an improved method to describe the characteristics of a vapor cloud explosion over a wide range of conditions. It combines elements of the work conducted by Baker to develop the BST model, as well as the European MERGE/EMERGE projects; thus incorporating data from the two largest, modern vapor cloud explosion test projects.

Because the BST categories are resolved into numeric ranges, a higher resolution solution space and a clearer set of measureable inputs are achieved. With the ability to model the reactivity of a flammable gas cloud based on laminar flame speed instead of a low, medium, or high classification, the model is able to more accurately describe a wide range of flammable gases and mixtures. Expansion of the constraining flame speed categories to very-low and very-high then provides an even wider range of possibilities.

With the QMEFS matrix expanded to congestion (VBR) categories of very-low and very-high, the model provides a wider range of predictive capability for explosion scenarios. These expansions and enhancements are still confined by the flame speeds in the BST system, and are applied within the set of curves for overpressure and impulse. Thus, with the QMEFS model presented here, process safety experts have a more versatile tool to predict VCE impacts in petrochemical plants.

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