# QUANTITATIVE RISK ANALYSIS
# FOR THE
# FINGER LAKES LPG STORAGE FACILITY

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QUEST

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# SECTION 1
# INTRODUCTION AND OVERVIEW

Quest Consultants Inc. was retained by Inergy Midstream to perform a quantitative risk analysis (QRA) of the Finger Lakes LPG Storage Project located in Schuyler County, NY. The Finger Lakes LPG project is designed to provide seasonal storage of liquefied petroleum gas (LPG) products (propane and butane), importing in the summer months by railcar and pipeline, and exporting in the winter months by tank truck, railcar, and pipeline. Storage is accomplished with existing underground salt caverns.

The objective of this study was to compute the level of risk posed to the public from potential releases of flammable fluids originating from the LPG facility.

The study was divided into four primary tasks.

Task 1. Determine potential releases that could result in hazardous conditions.
Task 2. For each potential release identified in Task 1, derive the annual probability of the release.
Task 3. For each potential release identified in Task 1, calculate the potentially lethal hazard zones.
Task 4. Using a consistent, accepted methodology, combine the probabilities from Task 2 with the potential release consequences from Task 3 to arrive at a measure of the "risk" the Finger Lakes LPG facility poses to the public.

Figure 1-1 illustrates the steps in the QRA procedure required to complete the four primary tasks.

## 1.1 Hazards Identification

The potential hazards associated with the Finger Lakes LPG facility are common to similar facilities worldwide, and are a function of the materials being processed, processing systems, procedures used for operating and maintaining the facilities, and hazard detection and mitigation systems provided. The hazards that are likely to exist are identified by the physical and chemical properties of the materials being handled, and the process conditions. For the facility considered in this study, the common hazards are:

- Torch fires (gas and liquefied gas releases)
- Pool fires (liquefied gas and volatile liquid releases)
- Flash fires (gas, liquefied gas, and volatile liquid releases)
- Vapor cloud explosions (gas, liquefied gas, and volatile liquid releases)

The hazards identification step is discussed in Section 3.

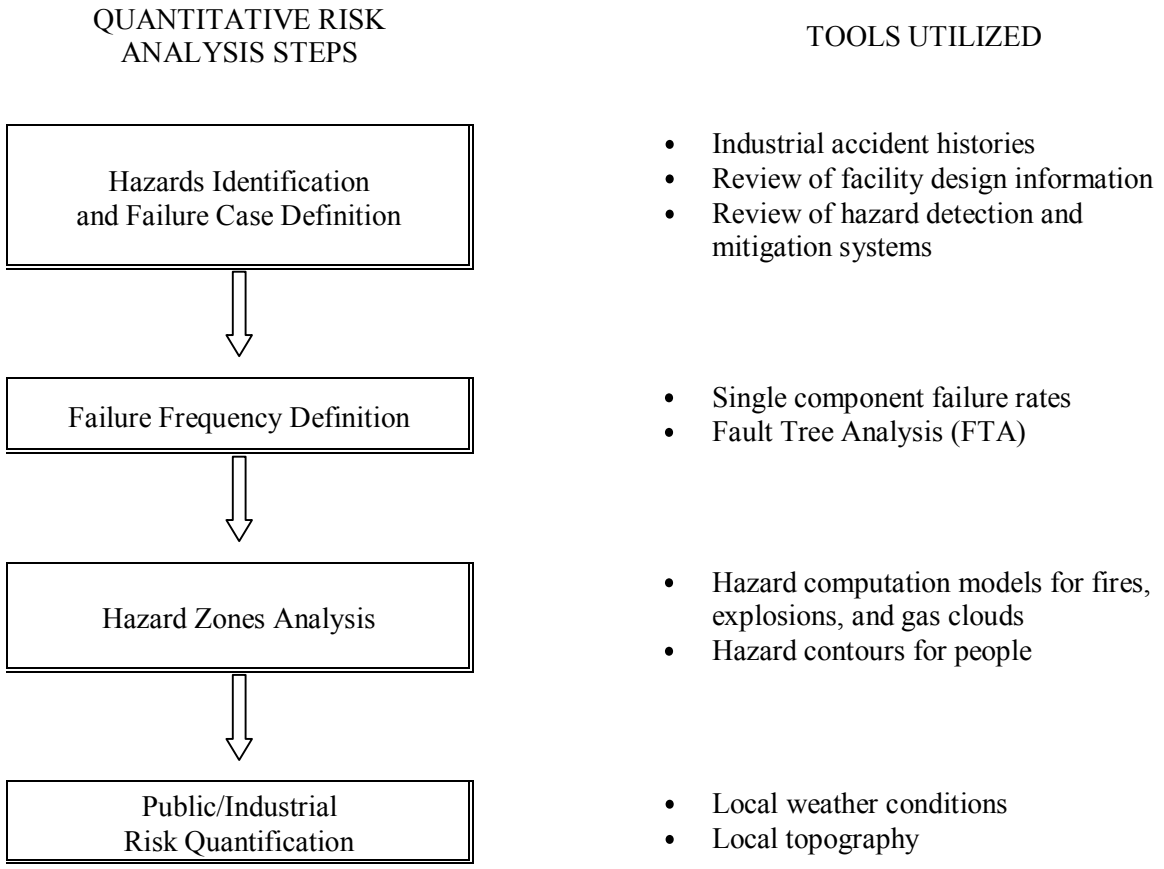


**Figure 1-1**
**Overview of Risk Analysis Methodology**

## 1.2 Failure Case Definition

The potential release sources of hazardous fluids are determined from a combination of past history of releases from similar facilities and facility-specific information, including previous reports, accident data, and engineering analysis by system safety engineers.

This step in the analysis defines the various release sources and conditions of release for each failure case. The release conditions include:

- Fluid composition, temperature, and pressure
- Release rate and duration
- Location and orientation of the release
- Type of surface over which released liquid (if any) spreads

The failure case definition step is included in Section 3.

## 1.3 Failure Frequency Definition

The frequency with which a given failure case is expected to occur can be estimated by using a combination of:

- Historical experience
- Failure rate data on similar types of equipment
- Service factors
- Engineering judgment

For single component failures (e.g., pipe rupture), the failure frequency can be determined from industrial failure rate data bases. The failure frequency step and the data base references are included in Section 4.

## 1.4 Hazard Zone Analysis

The release conditions (e.g., pressure, composition, temperature, hole size, inventory, etc.) from the failure case definitions are then processed, using the best available hazard quantification technology, to produce a set of hazard zones for each failure case. The CANARY by Quest® computer software hazards analysis package is used to produce profiles for the fire and explosion hazards associated with the failure case. The models that are used account for:

- Release conditions
- Ambient weather conditions (wind speed, air temperature, humidity, atmospheric stability)
- Effects of diking or vegetation, as applicable
- Mixture thermodynamics

The hazard zone analysis step is included in Section 3.

## 1.5 Public/Industrial Risk Quantification

The methodology used in this study has been successfully employed in many QRA studies that have undergone regulatory review in countries worldwide. This methodology is described in Section 5.

The result of the analysis is a prediction of the risk posed by the Finger Lakes LPG facility to the public. Risk may be expressed in several forms (e.g., location-specific risk contours, average individual risk, societal risk, etc.). For this analysis, the focus was on location-specific individual risk (LSIR) contours.

## 1.6 Risk Assessment

Risk indices enable decision makers (i.e., corporate risk managers and regulatory authorities) to evaluate the risks associated with the facility. The risk measures produced for the Finger Lakes LPG facility can be compared to generally-accepted risk levels or other risks that the public may be exposed to.

The results of the risk analysis are presented in Section 6.

# SECTION 2
# DESCRIPTION OF THE
# FINGER LAKES LPG STORAGE FACILITY

## 2.1 Facility Description

The following facility description is based on information available to Quest, our knowledge of hazardous materials facilities similar to those included in this study, and codes and standards that are applicable to the facility that is the subject of this study.

The Finger Lakes LPG Storage Facility will be a multi-cycle LPG storage system with a major pipeline connection and rail and truck load/unload racks. The facility will be located in Schuyler County, NY, near the Village of Watkins Glen and the Town of Reading.

The facility will consist of:

- underground storage caverns which will store the LPG;
- a rail and truck loading/unloading area with associated storage tanks, offices, and control facilities, located on NYS Route 14A;
- a new pipeline connecting to the Texas Eastern Products Pipeline Company (TEPPCO);
- a plant area that will inject LPG into the storage caverns and transfer LPG between the storage caverns and the TEPPCO pipeline or the rail and truck loading/unloading area;
- new pipelines to connect these portions of the project; and
- brine storage ponds to hold the brine displaced from the caverns as LPG is pumped in.

Figure 2-1 shows the overall site layout, including the cavern wellhead locations, cavern transfer equipment, and the surface facility where the rail siding and truck loading area will be located.

All design elements will be in accordance with applicable NFPA, OSHA (PSM), DOT and DEC guidelines or regulations.

### 2.1.1 Underground Storage Caverns

LPG, consisting of butane or propane, will be stored in separate underground caverns in the Syracuse Salt formation on company owned property. The cavern designated for propane will store a maximum of 1.5 million barrels of liquid, and the cavern designated for butane will store a maximum of 600,000 barrels. The caverns were created by solution mining salt for consumer and other uses by US Salt (and its predecessors).

Product can be delivered to the site either from the TEPPCO pipeline or railcars. The caverns will initially be full of brine. Cavern injection pumps will be used to transfer product to the caverns received from the TEPPCO pipeline or from rail cars. The cavern injection pumps will increase the LPG pressure so it can be injected into a cavern. During LPG injection, brine will be displaced out of the cavern as the LPG is pumped in. The process will be reversed during the withdrawal cycle when brine is pumped into the cavern and LPG is withdrawn. A storage cavern wellhead pressure of approximately 1,000 psi will be maintained during all modes of operation.

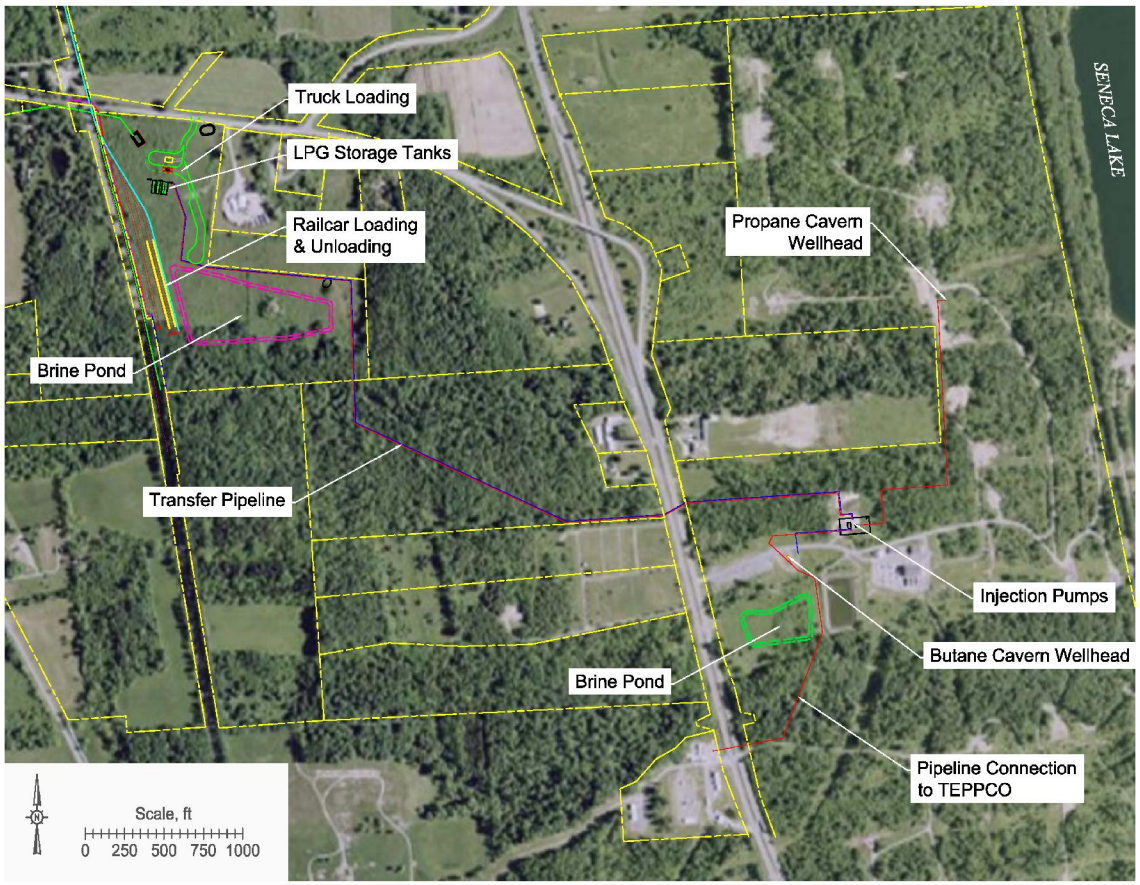


**Figure 2-1**
**Site Operations Plan**

LPG will be withdrawn as brine is injected into the cavern. The LPG will have adequate pressure to directly enter the TEPPCO pipeline. LPG is transferred to the railcars or aboveground cylindrical tanks at a controlled rate through a variable choke system with pressure over rides and shut-ins.

### 2.1.2 Rail/Truck Area

A new facility located on NYS Route 14A will be built for the rail/truck loading and unloading area. This area will include the following facilities:

- six rail spurs;
- five aboveground storage "cylindrical" tanks (30,000 gallons each) measuring 65 feet long and 8 feet in diameter and equipped with excess flow surge checks on the main liquid lines;
- three electric booster pumps to transfer product from the aboveground cylindrical tanks to the truck unloading rack or to the cavern injection pumps;
- six vapor compressors to be used in the rail car unloading process;
- an emergency shutdown system consisting of isolation valves and multiple personnel activation devices;
- a control and office building;

- a truck canopy (not fully enclosed) measuring 30 by 40 feet;
- three enclosed, heated and cooled kiosk buildings; and,
- site security including approximately 3,100 feet of chain link fence.

Product received by rail will be unloaded into aboveground storage cylindrical tanks using small vapor compressor units. Booster pumps will be installed to pump product from the storage tanks into a pipeline that connects the truck/rail area to the cavern injection pumps. During truck loading, the booster pumps will be used to pump LPG from the storage tanks into trucks through the truck loading rack. The pumps and compressors will be powered by electricity to minimize noise. The interconnecting pipelines will utilize high tensile steel pipe and fittings, with a corrosion inhibition coating in all locations where the piping is installed below grade.

The truck rack is projected to be capable of loading 30 trucks per day with 2 bays. The rail loading area is projected to be capable of loading or unloading 24 rail cars in 12 hours with space to park 32 rail cars. Surge capacity will be provided by the storage tanks. Three of the storage tanks will be dedicated to propane use and two to butane use.

### 2.1.3 Plant Area

The plant area will consist of four electrically driven pumps to be used to inject LPG into the caverns. Because of potential LPG contact with brine in the caverns, the facility will also include a separation vessel for butane and a molecular sieve drying system for propane. The molecular sieve system includes regeneration equipment consisting of a remote heater, heat exchangers, and the required process control systems.

The plant area also includes piping headers and valving to facilitate the movement of both products into and out of the caverns. The system will be equipped with automated valves to control the direction of product flow and to provide system isolation.

The site will also include a small control building and a control center (MCC).

### 2.1.4 Pipelines

There will be several sections of pipeline that will transfer LPG to and from the various portions of this facility. Approximately 10,800 feet of 8- and 10-inch diameter steel pipe will be used, consisting of:

- TEPPCO to plant area – 2,700 feet;
- plant area to two caverns – 2,500 feet; and,
- plant area to rail/truck area – 5,600 feet.

## 2.2 System Characterization

Based on the above description and the facility's technical drawings, Quest divided the facility into several sections, or nodes. Each node was selected, and defined, based on its function within the system. Due to the presence of multiple products (propane and butane) and multiple operational modes, each section could also have different properties depending on specific circumstances. For example, consider

the section which includes the railcar liquid piping manifold. This consists of two separate piping systems (one each for propane and butane) and could operate in the following modes:

- receiving propane for injection into the cavern
- receiving butane for injection into the cavern
- loading propane into railcars
- loading butane into railcars
- static mode (not loading or unloading), but containing propane
- static mode (not loading or unloading), but containing butane

Based on this type of approach, the entire facility was divided into process nodes. These divisions, along with their approximate normal pressure and temperature conditions, are listed in Table 2-1.

## 2.3 Meteorological Data

Meteorological data for wind speed, wind direction, and Pasquill-Gifford atmospheric stability class used in this study were obtained from the National Climatic Data Center in Asheville, NC, for the Ithaca, NY area. Ithaca was the closest location with full wind speed, wind direction and atmospheric stability data. A summary of the meteorological data used in this study is presented in Figure 2-2 as annual wind rose data for all stability classes. 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. Reviewing Figure 2-2 shows that the most common winds blow from northwest to southeast and from south to north. Since the weather data is developed from annual data (over many years), seasonal changes in wind magnitude, direction, etc. are already factored into the wind rose.

The data is divided up into six wind speed classes, sixteen wind directions, and six atmospheric stability classes (defined as A through F). While not all of these combinations are possible, this range of data allows the differences in hazard zones due to atmospheric conditions to be integrated into the analysis.

Annual average values of air temperature and relative humidity were obtained from www.city-data.com (using Watkins Glen, NY data) and applied to the analysis.

**Table 2-1**
**System Scenario Summary**

| Node # | Description | Operating Mode | Butane | | Propane | |
|---|---|---|---|---|---|---|
| | | | Temperature [°F] | Pressure [psig] | Temperature [°F] | Pressure [psig] |
| 01 | Rail Loading/Unloading Arm/Hose | injection | 70 | 135 | 70 | 165 |
| | | withdrawal | 60 | 245 | 60 | 245 |
| 02 | Rail Loading/Unloading Liquid Manifold | injection | 70 | 120 | 70 | 150 |
| | | withdrawal | 60 | 245 | 60 | 245 |
| | | static | 60 | 60 | 60 | 120 |
| 03 | Buried Line from Rail Manifold to Storage Tank Header | injection | 70 | 120 | 70 | 150 |
| | | withdrawal | 60 | 245 | 60 | 245 |
| | | static | 60 | 60 | 60 | 120 |
| 04 | Liquid Header to Storage Tanks | injection | 70 | 120 | 70 | 150 |
| | | withdrawal | 60 | 245 | 60 | 245 |
| | | static | 60 | 60 | 60 | 120 |
| 05 | Booster Pump Suction Header | injection | 60 | 120 | 60 | 150 |
| | | static | 60 | 60 | 60 | 120 |
| 06 | Booster Pump Discharge to Check Valve | injection | 60 | 245 | 60 | 245 |
| 07 | Booster Pump Discharge Header Above Ground | injection | 60 | 245 | 60 | 245 |
| | | withdrawal | 60 | 245 | 60 | 245 |
| | | static | 60 | 245 | 60 | 245 |
| 08 | Buried Line To/From Injection Pumps | injection | 60 | 245 | 60 | 245 |
| | | withdrawal | 60 | 515 | 60 | 515 |
| | | static | 60 | 245/515 | 60 | 245/515 |
| 09 | Buried Line to Truck Loading | withdrawal | 60 | 245 | 60 | 245 |
| | | static | 60 | 245 | 60 | 245 |
| 10 | Truck Loading Manifold and Hoses | withdrawal | 60 | 245 | 60 | 245 |
| | | static | 60 | 245 | 60 | 245 |
| 11 | Compressor Suction Header | all | 60 | 24 | 60 | 105 |
| 12 | Individual Compressor Suction Line | all | 60 | 24 | 60 | 105 |
| 13 | Individual Compressor Discharge Line | all | 170 | 135 | 95 | 165 |
| 14 | Compressor Discharge Header | all | 170 | 135 | 95 | 165 |
| 15 | Buried Compressor Discharge Line | all | 170 | 135 | 95 | 165 |
| 16 | Rail Vapor Manifold | all | 170 | 135 | 95 | 165 |

**Table 2-1 (continued)**
**System Scenario Summary**

| Node # | Description | Operating Mode | Butane | | Propane | |
|---|---|---|---|---|---|---|
| | | | Temperature [°F] | Pressure [psig] | Temperature [°F] | Pressure [psig] |
| 16a | Rail Vapor Loading Arm/Hose | injection | 170 | 135 | 95 | 165 |
| 17 | Pressure Control Area | injection | 60 | 245 | 60 | 245 |
| | | withdrawal | 60 | 515 | 60 | 515 |
| | | static | 60 | 245/515 | 60 | 245/515 |
| 18 | Injection Pump Suction Header | injection | 60 | 245/515 | 60 | 245/515 |
| | | withdrawal | 60 | 1015 | 60 | 1015 |
| | | static | 60 | 245/1015 | 60 | 245/1015 |
| 19 | Injection Pump Discharge to Check Valve | injection | 60 | 1015 | 60 | 1015 |
| 20 | Injection Pump Discharge Header | all | 60 | 1015 | 60 | 1015 |
| 21 | Wellhead | all | 60 | 1515 | 60 | 1450 |
| 22 | Butane Water Knock Out | withdrawal | 60 | 1015 | *NA* | *NA* |
| | | static | 60 | 1015 | *NA* | *NA* |
| 23 | Propane Dehydration System | withdrawal | *NA* | *NA* | 60 | 1015 |
| | | static | *NA* | *NA* | 60 | 1015 |
| 24 | Dehydration Bed Regeneration Propane Supply Line | all | *NA* | *NA* | 60 | 1015 |
| 25 | Dehydration Bed Regeneration Pump Discharge | withdrawal | *NA* | *NA* | 60 | 1115 |
| | | static | *NA* | *NA* | 60 | 1115 |
| 26 | Dehydration Bed Regeneration Heated Propane | all | *NA* | *NA* | 550 | 1065 |
| 27 | Dehydration Bed Regeneration Propane Return | withdrawal | *NA* | *NA* | 120 | 1045 |
| | | static | *NA* | *NA* | 120 | 1045 |
| 28 | TEPPCO Buried Pipeline | injection | 60 | 515 | 60 | 515 |
| | | withdrawal | 60 | 515 | 60 | 515 |
| | | static | 60 | 515 | 60 | 515 |
| 30 | Buried Lines to Wellheads | all | 60 | 1015 | 60 | 1015 |
| 31 | BLEVE of a Railcar | all | † | † | † | † |
| 32 | BLEVE of a Tank Truck | all | † | † | † | † |
| 33 | BLEVE of a Pressurized Cylindrical Storage Tank | all | † | † | † | † |

† - The temperature and pressure in a storage tank will vary during a BLEVE incident
NOTE: node 29 was omitted

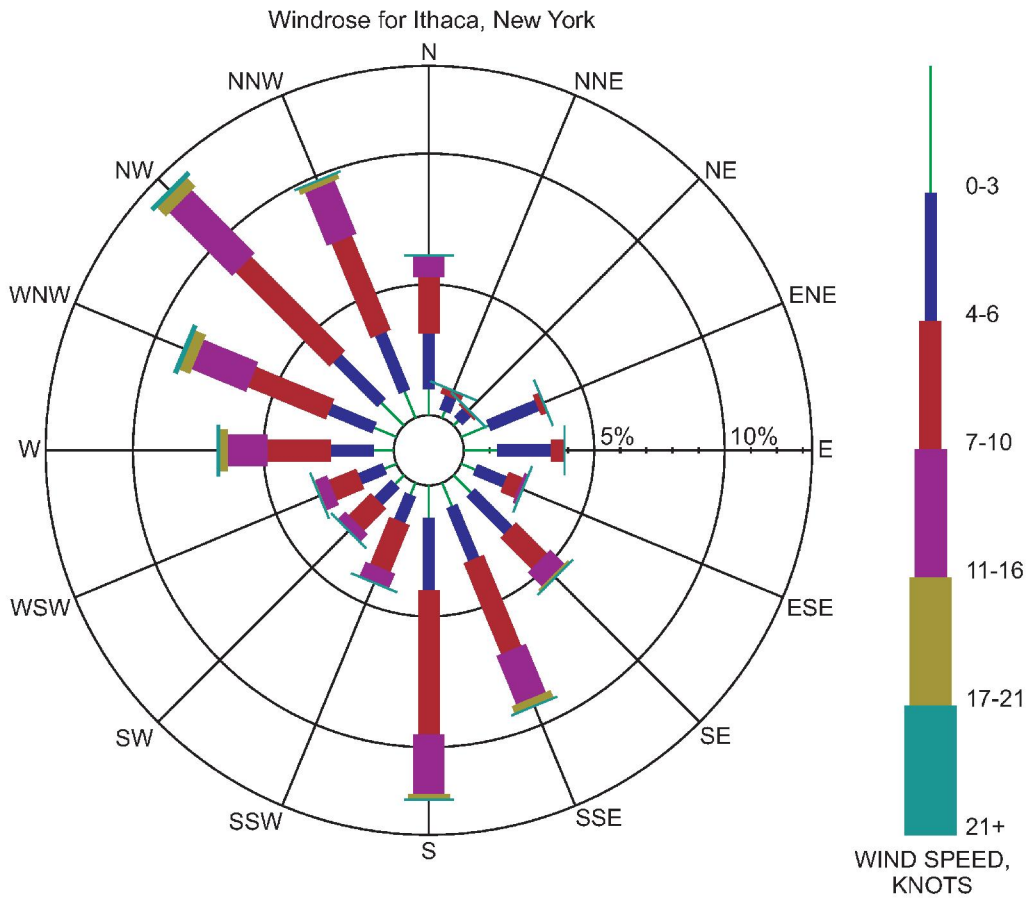


**Figure 2-2**
**Annual Wind Rose Data for All Stability Classes for Ithaca, NY**

# SECTION 3
# POTENTIAL HAZARDS

## 3.1 Hazard Identification

Quest personnel reviewed the information related to the process equipment, product transfer, and product storage in the Finger Lakes LPG Storage facility. Using that information, a review of relevant accident histories, our knowledge of and experience with similar facilities, and good engineering practices, the types of credible hazardous events that have some potential to occur in each area of the facility were determined.

For each section of the facility, releases were evaluated with regard to the potential for emergency shutdown (ESD) activation. In the case where an ESD can be activated, the release continues for no more than a set period of time (e.g., two minutes). For cases where an ESD may not be activated, the release is allowed to continue uninterrupted until the system contents are depleted, or a long-term steady-state condition is reached.

The release scenarios identified for the facility define the range of credible releases that might occur within LPG facility site. Each of the releases may create one or more of the following hazards.

1) Exposure to flammable gas cloud that could result in a flash fire
2) Exposure to explosion overpressure following the ignition of a flammable cloud
3) Exposure to thermal radiation following ignition of a flammable fluid release, in the form of a torch fire or pool fire

The remainder of Section 3 defines the techniques used to quantify these hazards.

## 3.2 Introduction to Physiological Effects of Fires, and Explosions

The QRA performed on the Finger Lakes LPG Storage facility involved the evaluation of thousands of potential hazardous material releases. Each potential release may result in one or more of the hazards listed above. In order to compare the risks associated with each type of hazard, a common measure of consequence must be defined. In risk analysis studies, a common measure for such hazards is their impact on humans. For each of the fire and explosion hazards listed, there are data available that define the effect of the hazard on humans.

For example, when comparing a fire radiation hazard to an explosive hazard, the magnitude of the hazard's impact on humans must be identically defined. It would not be meaningful to compare human exposure to nonlethal overpressures (e.g., low overpressures that break windows) to human exposure to lethal thermal radiation (e.g., 37.5 $kW/m^2$ for five seconds).

In this study, risk is defined as the potential exposure of humans to lethal hazards (i.e., flammable vapor cloud, radiant heat, or explosion overpressure) that have the potential to occur as a result of accidents originating in the LPG facility. The lethal exposure levels for the various hazards are discussed in the following sections.

## 3.3 Physiological Effects of Exposure to Thermal Radiation from Fires

The physiological effect of fire on humans depends on the rate at which heat is transferred from the fire to the person, and the time the person is exposed to the fire. Even short-term exposure to high heat flux levels may be fatal.

In the event of a flash fire (ignition of a flammable vapor cloud), persons inside a flammable vapor cloud (defined by the lower flammable limit or LFL) when it is ignited, without protective clothing are susceptible to flame exposure and short-term high radiation levels. Persons located outside a flammable cloud when it is ignited will be exposed to much lower heat flux levels. If the person is far enough from the edge of the flammable cloud, the heat flux will be incapable of causing injuries. Persons closer to the cloud, but not within it, will be able to take action to protect themselves (e.g., moving farther away as the flames approach, or seeking shelter inside structures or behind solid objects). Based on these principles, this analysis assumed 100% fatality for persons outdoors and within a flammable vapor cloud and 0% fatality for persons outdoors and outside of the flammable vapor cloud.

In the event of a continuous fire (such as a torch or pool fire) following the release of flammable fluid, the thermal radiation 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.

For exposure to thermal radiation, the probit equation is developed in the form of radiation intensity (where the variable $I$ is used for the radiation intensity) and exposure time ($t$) is in seconds. Work sponsored by the U.S. Coast Guard [Tsao and Perry, 1979] developed the following probit relationship between exposure time and incident heat flux.

$$Pr = -36.378 + 2.56 \ln\left(I^{4/3} \cdot t\right)$$

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

Table 3-1 presents the probit results for several exposure times that would be applicable for torch fires and pool fires. The mortality rates and corresponding thermal radiation levels are listed. The graphical form of the thermal radiation probit equation for different exposure times is presented in Figure 3-1.

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" $\left(I^{4/3} \cdot t\right)$ produce equal expected mortality rates. An exposure time of 30 seconds was chosen for this analysis for members of the public for torch fires and pool fires. This is considered conservative (i.e., too long) as people who are exposed to radiant hazards are aware of the hazards and know in which direction to move in a very short period of time.

**Table 3-1**
**Hazardous Thermal Radiation Levels for Various Exposure Times**
**Using the Tsao and Perry [1979] Thermal Radiation Probit**

| Exposure Time [seconds] | Probit Value | Mortality Rate* [percent] | Thermal Radiation [kW/m$^2$] |
|---|---|---|---|
| 5 | 2.67<br>5.00<br>7.33 | 1<br>50<br>99 | 27.87<br>55.17<br>109.20 |
| 15 | 2.67<br>5.00<br>7.33 | 1<br>50<br>99 | 16.57<br>32.80<br>47.39 |
| 20 | 2.67<br>5.00<br>7.33 | 1<br>50<br>99 | 9.85<br>19.50<br>38.60 |
| 30 | 2.67<br>5.00<br>7.33 | 1<br>50<br>99 | 7.27<br>14.39<br>28.47 |

*Percent of exposed population fatally affected.

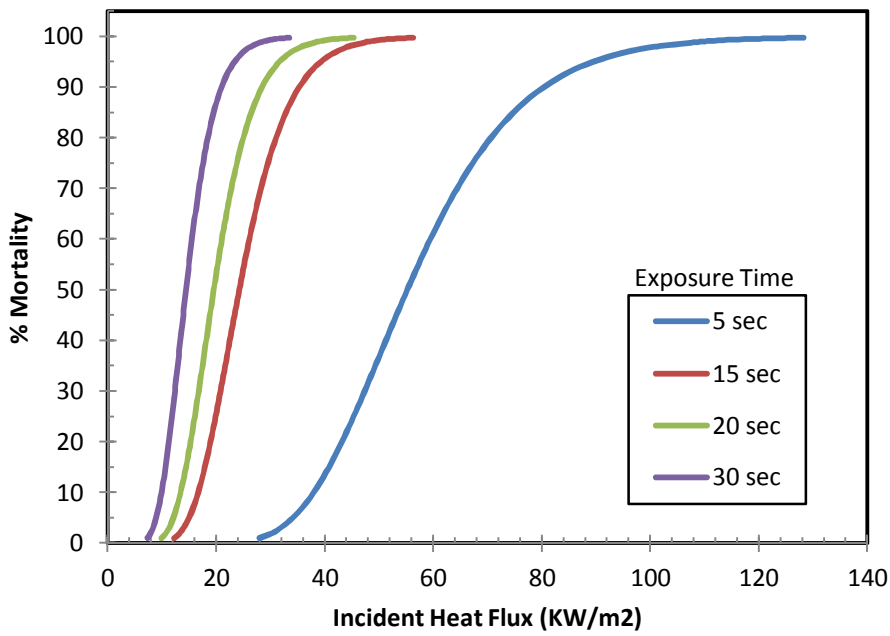


**Figure 3-1**
**Incident Radiation Probit Functions**

## 3.4 Physiological Effects of Explosion Overpressures

The damaging effect of overpressure on an object depends on the peak overpressure that reaches a given object, and its method of construction, as illustrated by Table 3-2. Similarly, the physiological effects of overpressure (to humans) depend on the peak overpressure that reaches a person. Exposure to high overpressure levels may be fatal. If the person is far enough from the source of the explosion, the overpressure is incapable of causing fatal injuries.

**Table 3-2**
**Damage Produced by Blast Waves [Clancey, 1972]**

| Overpressure [psi] | Damage |
|---|---|
| 0.02 | Annoying noise |
| 0.04 | Loud noise (143 dB) |
| 0.15 | Typical pressure for glass breakage |
| 0.3 | 10% window glass broken |
| 0.5 - 1.0 | Large and small windows usually shattered; occasional damage to window frames |
| 0.7 | Minor damage to house structures |
| 1.0 | Partial demolition of houses, made uninhabitable |
| 1.3 | Steel frame of clad building slightly distorted |
| 2.0 | Partial collapse of walls and roofs of houses |
| 2.3 | Lower limit of serious structural damage |
| 2.5 | 50% destruction of brickwork of houses |
| 3.0 | Steel frame building distorted and pulled away from foundations |
| 3 - 4 | Frameless, self-framing steel panel building demolished |
| 4.0 | Cladding of light industrial buildings ruptured |
| 5.0 | Wooden utility poles snapped |
| 5.0 - 7.0 | Nearly complete destruction of houses |
| 7.0 | Loaded railcars overturned |
| 7.0 - 8.0 | Brick panels, 8-12 inches (203-305-mm) thick, not reinforced, fail by shearing or flexure |
| 9.0 | Loaded train boxcars completely demolished |
| 10.0 | Probable total destruction of buildings |

In the event of an ignition and deflagration of a flammable gas or gas/aerosol cloud, the overpressure levels necessary to cause injury are often defined as a function of peak overpressure. Unlike potential fire hazards, persons who are exposed to overpressure have no time to react or take shelter; thus, time does not enter into the hazard relationship. Work by the Health and Safety Executive, United Kingdom [HSE, 1991], has produced a probit relationship based on peak overpressure. This probit equation has the following form.

$$Pr = -10.639 + 1.37 \ln(p)$$

where: $p$ = peak overpressure, psi

Table 3-3 presents the probit results for exposure time that would be applicable for a vapor cloud explosion. The mortality rates and corresponding overpressure levels are listed. The graphical form of the overpressure probit equation for exposure time is presented in Figure 3-2.

**Table 3-3**
**Hazardous Overpressure Levels for Various Exposure Times**
**Using the HSE [1991] Overpressure Probit**

| Exposure Time | Probit Value | Mortality Rate* [percent] | Overpressure [psi] |
|---|---|---|---|
| Instantaneous | 2.67 | 1 | 2.4 |
| | 5.00 | 50 | 13.2 |
| | 7.33 | 99 | 72.1 |

*Percent of exposed population fatally affected.

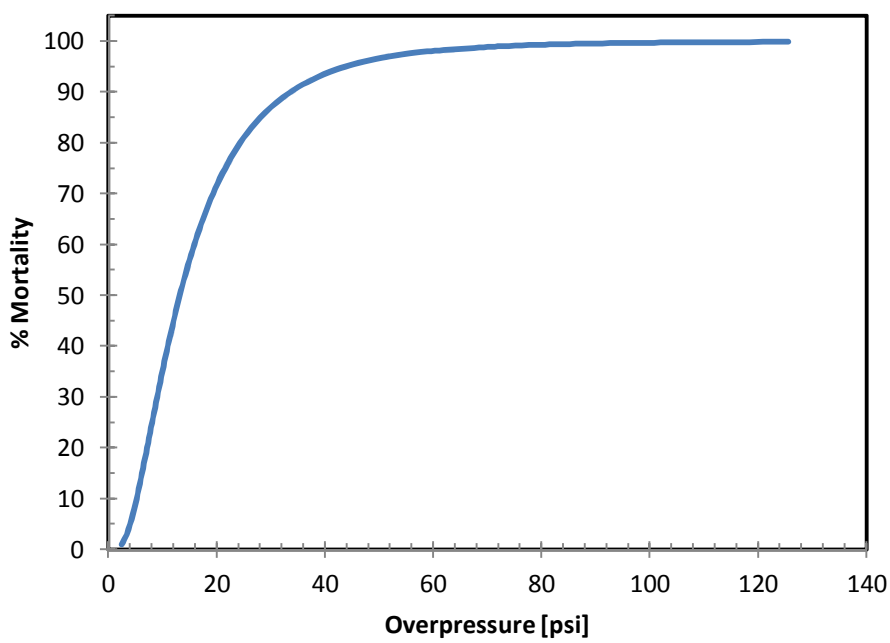


**Figure 3-2**
**Explosion Overpressure Probit Function**

## 3.5 Consequence Analysis

### 3.5.1 Consequence Analysis Models

The hazard zones resulting from the selected releases were evaluated to determine the extent and location of flammable vapor clouds, fire radiation, and explosion overpressure. 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 by Quest®, that contains a set of complex models that calculate release conditions, initial dilution of the vapor (dependent upon the release characteristics), and the 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 the QuestFOCUS package (the predecessor to CANARY by Quest) were reviewed in a United States Environmental Protection Agency (EPA) sponsored study [TRC, 1991] and an American Petroleum Institute (API) study [Hanna, Strimaitis, and Chang, 1991]. In both studies, the QuestFOCUS software was evaluated on technical merit (appropriateness of models for specific applications) and on model predictions for specific releases. One conclusion drawn by both studies was that the dispersion software tended to overpredict the extent of the gas cloud travel, thus resulting in too large a cloud when compared to the test data. This is often referred to as a conservative approach, because the hazard is generally predicted to be larger than it may actually be during a real accident scenario.

A study prepared for the Minerals Management Service [Chang, et. al,1998] reviewed models for use in modeling routine and accidental releases of flammable gases. CANARY by Quest received the highest possible ranking in the science and credibility areas. In addition, the report recommends CANARY by Quest for use when evaluating flammable gas releases. The specific models (e.g., SLAB) contained in the CANARY by Quest software package have also been extensively reviewed.

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

For vapor cloud explosion calculations, Quest uses a model that is a variation of the Baker-Strehlow-Tang (BST) method. The Quest model for estimation of flame speeds (QMEFS) [Melton & Marx, 2008] 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.

This model is based on the premise that the strength of the blast wave generated by a vapor cloud explosion (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; and 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 vapor cloud [Mercx, 1994a, 1994b, 1997; Mercx, Van den Berg, & Van Dongen, 1996]. 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 following quotations illustrate this point.

> "On the evidence of the trials performed at Maplin Sands, the deflagration [explosion] of truly unconfined flat clouds of natural gas or propane does not constitute a blast hazard." [Hirst and Eyre, 1982] (Tests conducted by Shell Research Ltd., in the United Kingdom.)
>
> "Both in two- and three-dimensional geometries, a continuous accelerating flame was observed in the presence of repeated obstacles. A positive feedback mechanism between the flame front and a disturbed flow field generated by the flame is responsible for this. The disturbances in the flow field mainly concern flow velocity gradients. Without

repeated obstacles, the flame front velocities reached are low both in two-dimensional and three-dimensional geometry." [van Wingerden and Zeeuwen, 1983] (Tests conducted by TNO in the Netherlands.)

"The current understanding of vapor cloud explosions involving natural gas is that combustion only of that part of the cloud which engulfs a severely congested region, formed by repeated obstacles, will contribute to the generation of pressure." [Johnson, Sutton, and Wickens, 1991] (Tests conducted by British Gas in the United Kingdom.)

Researchers who have studied case histories of accidental vapor cloud explosions have reached similar conclusions.

"It is a necessary condition that obstacles or other forms of semi-confinement are present within the explosive region at the moment of ignition in order to generate an explosion." [Wiekema, 1984]

"A common feature of vapor cloud explosions is that they have all involved ignition of vapor clouds, at least part of which have engulfed regions of repeated obstacles." [Harris and Wickens, 1989]

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 assumed to be filled with a flammable mixture of gas and air, and five additional parameters.

Fuel Reactivity: A fuel's reactivity is characterized by its laminar flame speed. Because the QMEFS model is based on the BST model, flame speeds correlate to the BST categories of high, medium, and low. For example, ethylene, with a flame speed of approximately 76 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 a flame speed between 40 and 45 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. As this dimension increases, the peak overpressure increases to a limiting value. This distance 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, increasing the peak overpressure that is produced. The default value, from the BST test series is 2 inches (0.0508 m).

### 3.5.2 Hazard Scenarios

A range of event scenarios was selected to cover the potential hazards identified at the Finger Lakes LPG facility. Each scenario was fully evaluated with the CANARY software and/or the QMEFS VCE model. The list of release locations (process nodes) was presented in Section 2-2. Within each node and for each mode of operation (propane or butane, and injection, withdrawal, or static) several release types are possible. The various types evaluated in this analysis are initially classified by release hole size. Four hole sizes were evaluated:

1) Small releases (leaks), characterized by ¼-inch diameter holes
2) Moderate releases (punctures), characterized by 1-inch diameter holes
3) Large releases (large hole), characterized by a 3-inch hole
4) Ruptures, characterized by a hole with diameter equal to the pipe diameter or, for process equipment, a hole with a diameter equal to the diameter of the largest attached pipe

For each hole size, two release orientations were evaluated:

1) Horizontal, for aboveground equipment and piping, or near-horizontal for buried piping
2) Upward (vertical)

For each of the above release conditions, several potential hazardous outcomes might be possible. These outcomes were identified by the construction of event trees.

### 3.5.3 Release Event Trees

For any single release from a vessel or piping system, several different potentially hazardous outcomes may develop, dependent on such factors as availability of ignition sources and the reactivity of the material (for overpressure potential). The chance that any single outcome will result from a release of material is dependent on these factors, as well as the "size" of the release.

An example of one of the event trees prepared for this study is presented in Figure 3-3. It begins with the release of flammable liquid from piping associated with the booster pump discharge header. Moving from left to right, the tree first branches into four leak sizes, each identified by the diameter of the hole through which the fluid is being released. Each of these four branches divides into two branches identifying the orientation of the release (upward or horizontal). Each of these two branches divides into three branches based upon the ignition timing and probability. At this point in Figure 3-3 only the path of the event tree for the 3-inch holes are shown. The same events are possible for the other three hole sizes.

Immediate ignition of the release results in a torch fire and/or a pool fire. When not immediately ignited, the released material develops into a vapor cloud. At this point, ignition of the released material is called delayed ignition. Delayed ignition can result in several hazards. First, the flammable vapor cloud burns back to the release source as a flash fire (vapor cloud fire). Concurrently, if the vapor cloud reached a confined or congested space as it burns, a vapor cloud explosion is possible. Lastly, a torch fire or a pool fire can result if material is still being released (torch fire) or the released material is present in the form of a liquid pool on the ground (pool fire). If the release does not ignite immediately or find an ignition source, the outcome is dissipation of the hazardous fluid. The right side of the event tree results in 24 "outcomes" that have some probability of occurring if the release occurs. The probabilities of the event outcomes are developed in Section 4.

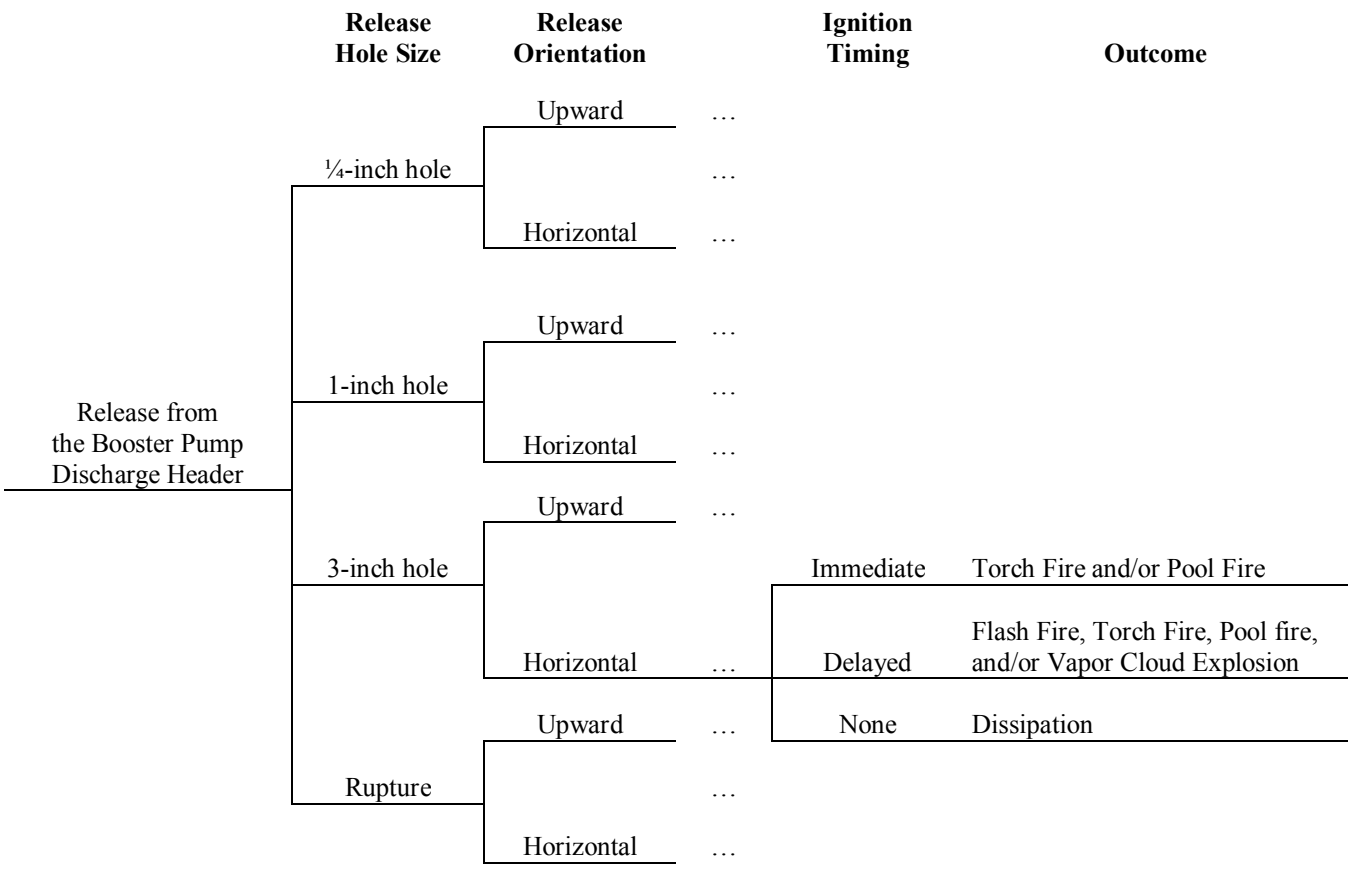


**Figure 3-3**
**Event Tree for a Flammable Release**

## 3.6 Analysis of a Superheated Liquid Release

For each potential release in the LPG facility (as defined in Section 3.5.2 above), a number of consequence analysis calculations must be performed. As an example, this section evaluates the release of butane from the booster pump discharge header. The event tree for this type of release was presented in Figure 3-3.

For this release, the following sections describe the hazard calculations.

### 3.6.1 Flash Fire Hazards Following Release from the Butane Booster Pump Discharge Header

The extent of the potential flash fire hazards is determined by the process conditions, hole size, wind speed, atmospheric stability, etc. Process conditions for the butane booster pump discharge header were presented in Table 2-1. A release from this portion of the facility is defined to be from one of the four hole sizes: ¼-inch, 1-inch, 3-inch, and rupture (full break of the 10-inch line). Only the results for the horizontal release are presented below. The results for the upward release orientation is developed in the same manner.

A review of the local weather data indicates that 21 of the 36 wind speed/atmospheric stability combinations exist (e.g., 23.2 mph wind speed and F stability does not occur). A release from the booster pump discharge header produces a vapor/aerosol cloud and a liquid pool on the ground for all hole sizes; however, for the two smallest hole sizes, the liquid pool is only about 5 feet in diameter and does not produce a flammable vapor cloud beyond the limits of the pool. Thus, for the smaller holes, 21 dispersion calculations to the lower flammable limit (LFL) were made; for the two largest hole sizes evaluated, 42 dispersion calculations must be made (21 for the momentum-dominated vapor cloud, and 21 for the vapor cloud evolving off of a liquid pool).

The maximum downwind extents of the LFL for each of the 84 momentum jet dispersion calculations (4 hole sizes x 21 momentum jet calculations per hole size) made are presented in Tables 3-4, 3-5, 3-6, and 3-7. Table 3-4 presents the dispersion results in a matrix for a full rupture of the butane booster pump discharge header or associated equipment. Each element in the matrix presents the distance to the LFL under the wind speed/atmospheric stability class defined. As an example, for a full rupture of the piping, under 10.4 mph winds and C stability, the momentum jet flammable cloud extends a maximum of 330 feet downwind of the release point. Tables 3-5, 3-6, and 3-7 present the momentum jet dispersion matrix results for the 3-inch, 1-inch and ¼-inch release scenarios respectively.

For vapor clouds evolving off of a liquid pool, Tables 3-8 and 3-9 present the dispersion modeling results for the maximum downwind extent of the LFL. Results are only presented for the Rupture and 3-inch hole sizes because the smaller hole sizes did not result in the formation of a significant liquid pool. These results are analogous to those presented in Tables 3-4 through 3-7, but represent heavy gas clouds evolving of the liquid pool that have no initial momentum.

**Table 3-4**
**Summary of Momentum Jet Dispersion Flash Fire Downwind Distances for a Rupture of the Butane Booster Pump Discharge Header**

Momentum jet dispersion - maximum downwind distances (flammable vapor cloud)

Endpoint: LFL = 1.87% (0.0187 mole fraction) 100% mortality

Downwind Distance in Feet to Concentration Level

| | | | | | | |
|---|---|---|---|---|---|---|
| 25.3 mph wind speed | | | 185 | 195 | | |
| 23.2 mph wind speed | | | 200 | 205 | | |
| 16.1 mph wind speed | | | 250 | 255 | | |
| 10.4 mph wind speed | | 300 | 330 | 340 | 350 | |
| 6.3 mph wind speed | 330 | 350 | 390 | 410 | 430 | 450 |
| 2.3 mph wind speed | 390 | 410 | 465 | 505 | | 595 |
| | A stability | B stability | C stability | D stability | E stability | F stability |

Note: existing wind speed/stability combinations are enclosed by the heavy line.

**Table 3-5**
**Summary of Momentum Jet Dispersion Flash Fire Downwind Distances for a 3-inch Hole in the Butane Booster Pump Discharge Header**

Momentum jet dispersion - maximum downwind distances (flammable vapor cloud)

Endpoint: LFL = 1.87% (0.0187 mole fraction) 100% mortality

Downwind Distance in Feet to Concentration Level

| | | | | | | |
|---|---|---|---|---|---|---|
| 25.3 mph wind speed | | | 185 | 190 | | |
| 23.2 mph wind speed | | | 195 | 205 | | |
| 16.1 mph wind speed | | | 245 | 255 | | |
| 10.4 mph wind speed | | 260 | 295 | 320 | 345 | |
| 6.3 mph wind speed | 265 | 260 | 300 | 340 | 385 | 380 |
| 2.3 mph wind speed | 285 | 300 | 350 | 395 | | 475 |
| | A stability | B stability | C stability | D stability | E stability | F stability |

Note: existing wind speed/stability combinations are enclosed by the heavy line.

**Table 3-6**
**Summary of Momentum Jet Dispersion Flash Fire Downwind Distances**
**for a 1-inch hole in the Butane Booster Pump Discharge Header**

Momentum jet dispersion - maximum downwind distances (flammable vapor cloud)

Endpoint: LFL = 1.87% (0.0187 mole fraction) 100% mortality

Downwind Distance in Feet to Concentration Level

| | | | | | | |
|---|---|---|---|---|---|---|
| 25.3 mph wind speed | | | 155 | 160 | | |
| 23.2 mph wind speed | | | 165 | 170 | | |
| 16.1 mph wind speed | | | 205 | 215 | | |
| 10.4 mph wind speed | | 250 | 275 | 280 | 300 | |
| 6.3 mph wind speed | 295 | 305 | 320 | 340 | 360 | 375 |
| 2.3 mph wind speed | 375 | 395 | 435 | 470 | | 550 |
| | A stability | B stability | C stability | D stability | E stability | F stability |

Note: existing wind speed/stability combinations are enclosed by the heavy line.

**Table 3-7**
**Summary of Momentum Jet Dispersion Flash Fire Downwind Distances for a ¼-inch Hole in the Butane Booster Pump Discharge Header**

Momentum jet dispersion - maximum downwind distances (flammable vapor cloud)

Endpoint: LFL = 1.87% (0.0187 mole fraction) 100% mortality

Downwind Distance in Feet to Concentration Level

| | | | | | | |
|---|---|---|---|---|---|---|
| 25.3 mph wind speed | | | 45 | 45 | | |
| 23.2 mph wind speed | | | 50 | 50 | | |
| 16.1 mph wind speed | | | 60 | 30 | | |
| 10.4 mph wind speed | | 80 | 85 | 90 | 90 | |
| 6.3 mph wind speed | 90 | 95 | 100 | 100 | 100 | 105 |
| 2.3 mph wind speed | 130 | 140 | 150 | 155 | | 170 |
| | A stability | B stability | C stability | D stability | E stability | F stability |

Note: existing wind speed/stability combinations are enclosed by the heavy line.

**Table 3-8**
**Summary of Heavy Gas Dispersion Flash Fire Downwind Distances**
**for a Rupture of the Butane Booster Pump Discharge Header**

Heavy gas dispersion - maximum downwind distances (flammable vapor cloud)

Endpoint: LFL = 1.84% (0.0184 mole fraction) 100% mortality

Downwind Distance in Feet to Concentration Level

| | | | | | | |
|---|---|---|---|---|---|---|
| 25.3 mph wind speed | | | † | † | | |
| 23.2 mph wind speed | | | † | † | | |
| 16.1 mph wind speed | | | † | † | | |
| 10.4 mph wind speed | | † | † | † | † | |
| 6.3 mph wind speed | † | † | † | 10 | 10 | 15 |
| 2.3 mph wind speed | † | 20 | 25 | 45 | | 70 |
| | A stability | B stability | C stability | D stability | E stability | F stability |

Note: existing wind speed/stability combinations are enclosed by the heavy line
† - Vapor cloud does not leave area of liquid pool; hazard confined to 10 ft from release point

**Table 3-9**
**Summary of Heavy Gas Dispersion Flash Fire Downwind Distances for a 3-inch Hole in the Butane Booster Pump Discharge Header**

Heavy gas dispersion - maximum downwind distances (flammable vapor cloud)

Endpoint: LFL = 1.84% (0.0184 mole fraction) 100% mortality

Downwind Distance in Feet to Concentration Level

| | | | | | | |
|---|---|---|---|---|---|---|
| 25.3 mph wind speed | | | † | † | | |
| 23.2 mph wind speed | | | † | † | | |
| 16.1 mph wind speed | | | † | † | | |
| 10.4 mph wind speed | | † | † | † | † | |
| 6.3 mph wind speed | † | † | † | † | † | † |
| 2.3 mph wind speed | † | 15 | 25 | 35 | | 70 |
| | A stability | B stability | C stability | D stability | E stability | F stability |

Note: existing wind speed/stability combinations are enclosed by the heavy line.
† - Vapor cloud does not leave area of liquid pool; hazard confined to 10 ft from release point

### 3.6.2 Fire Radiation Hazards Following a Release from the Booster Pump Discharge Header

The extents of the potential fire hazards following a release from the butane booster pump discharge header are determined by many of the same parameters that define the release rate for flash fire dispersion analysis. For torch fire and pool fire calculations, the atmospheric stability is not an important parameter; thus, for each hole size, 12 torch fire thermal radiation calculations are made - one for each wind speed class, for both immediate and delayed torch fires. 12 pool fire calculations are also made. For this release scenario, a total of 48 torch fire radiation calculations are made for each release point (4 hole sizes x 6 wind speeds x 2 ignition times). A total of 48 pool fire radiation calculations are also made. Unlike the vapor dispersion cases, the two smallest hole sizes do produce measurable hazards, assuming ignition of the small liquid pool.

The distinction between immediate and delayed fires is based upon the timing of the ignition of a flammable release. In general, the immediate torch fire will create a larger hazard because of the high mass flow during the initial moments of a release. If ignition of the flammable fluid is delayed to some time after the beginning of the release, the mass flow rate that feeds a torch fire is generally less. Thus, the two torch fire outcomes are evaluated for each flammable gas/aerosol release scenario and each hole size. For pool fires, the opposite is true. As the release continues, an unignited pool of liquid may continue to grow, thus creating the possibility of a larger hazard if the vapor emanating from the pool is ignited.

Results of the torch fire and pool fire radiation calculations are summarized in Tables 3-10, 3-11, 3-12, and 3-13. Since the torch and pool fire calculations are not a function of atmospheric stability, the matrix is defined differently than for vapor dispersion. All four hole sizes for immediate torch fires are represented in Table 3-10. Delayed torch fire results are shown in Table 3-11. In this example, the thermal radiation endpoints are defined by the probit analysis for a 30-second exposure and are listed in Tables 3-10 through 3-13 as 7.25 $kW/m^2$ (1% mortality), 14.35 $kW/m^2$ (50% mortality), and 28.41 $kW/m^2$ (99% mortality). Similar pool fire results are shown in Tables 3-12 and 3-13.

**Table 3-10**
**Summary of Immediate Torch Fire Downwind Distances**
**for a Release from the Butane Booster Pump Discharge Header**

Immediate torch fire – maximum downwind distances

Endpoints:

| | | |
|---|---|---|
| 7.25 kW/m$^2$ | ( 2,301 Btu/hr·ft$^2$) | 1% mortality |
| 14.35 kW/m$^2$ | ( 4,549 Btu/hr·ft$^2$) | 50% mortality |
| 28.41 kW/m$^2$ | ( 9,006 Btu/hr·ft$^2$) | 99% mortality |

Downwind Distance in Feet to Thermal Radiation Level

| | | | | |
|---|---|---|---|---|
| 25.3 mph wind speed | 290<br>255<br>230 | 195<br>175<br>175 | 170<br>150<br>150 | 55<br>50<br>50 |
| 23.2 mph wind speed | 290<br>260<br>235 | 195<br>175<br>175 | 170<br>150<br>150 | 55<br>50<br>50 |
| 16.1 mph wind speed | 295<br>260<br>230 | 195<br>175<br>175 | 170<br>150<br>150 | 55<br>50<br>50 |
| 10.4 mph wind speed | 300<br>260<br>230 | 195<br>175<br>175 | 170<br>150<br>150 | 55<br>50<br>50 |
| 6.3 mph wind speed | 300<br>255<br>215 | 200<br>175<br>175 | 170<br>150<br>150 | 55<br>50<br>50 |
| 2.3 mph wind speed | 300<br>255<br>210 | 200<br>175<br>175 | 170<br>150<br>150 | 55<br>50<br>50 |
| | **Rupture** | **3-inch hole** | **1-inch hole** | **¼-inch hole** |

**Table 3-11**
**Summary of Delayed Torch Fire Downwind Distances**
**for a Release from the Butane Booster Pump Discharge Header**

Delayed torch fire – maximum downwind distances

Endpoints:

| | | |
|---|---|---|
| 7.25 kW/m$^2$ | ( 2,301 Btu/hr·ft$^2$) | 1% mortality |
| 14.35 kW/m$^2$ | ( 4,549 Btu/hr·ft$^2$) | 50% mortality |
| 28.41 kW/m$^2$ | ( 9,006 Btu/hr·ft$^2$) | 99% mortality |

Downwind Distance in Feet to Thermal Radiation Level

| | | | | |
|---|---|---|---|---|
| 25.3 mph wind speed | 175<br>150<br>135 | 160<br>140<br>130 | 170<br>150<br>150 | 55<br>50<br>50 |
| 23.2 mph wind speed | 175<br>150<br>135 | 160<br>140<br>130 | 170<br>150<br>150 | 55<br>50<br>50 |
| 16.1 mph wind speed | 175<br>150<br>130 | 160<br>140<br>130 | 170<br>150<br>150 | 55<br>50<br>50 |
| 10.4 mph wind speed | 175<br>150<br>125 | 160<br>140<br>130 | 170<br>150<br>150 | 55<br>50<br>50 |
| 6.3 mph wind speed | 175<br>145<br>115 | 160<br>140<br>130 | 170<br>150<br>150 | 55<br>50<br>50 |
| 2.3 mph wind speed | 170<br>130<br>90 | 160<br>140<br>130 | 170<br>150<br>150 | 55<br>50<br>50 |
| | **Rupture** | **3-inch hole** | **1-inch hole** | **¼-inch hole** |

**Table 3-12**
**Summary of Immediate Pool Fire Downwind Distances**
**for a Release from the Butane Booster Pump Discharge Header**

Immediate pool fire – maximum downwind distances

Endpoints:

| | | |
|---|---|---|
| 7.25 kW/m$^2$ | ( 2,301 Btu/hr·ft$^2$) | 1% mortality |
| 14.35 kW/m$^2$ | ( 4,549 Btu/hr·ft$^2$) | 50% mortality |
| 28.41 kW/m$^2$ | ( 9,006 Btu/hr·ft$^2$) | 99% mortality |

Downwind Distance in Feet to Thermal Radiation Level

| | | | | |
|---|---|---|---|---|
| 25.3 mph wind speed | 30<br>25<br>25 | 35<br>30<br>25 | 20<br>15<br>15 | 15<br>15<br>15 |
| 23.2 mph wind speed | 30<br>25<br>25 | 35<br>30<br>25 | 20<br>15<br>15 | 15<br>15<br>15 |
| 16.1 mph wind speed | 30<br>25<br>25 | 35<br>30<br>25 | 20<br>15<br>15 | 15<br>15<br>15 |
| 10.4 mph wind speed | 30<br>25<br>25 | 35<br>25<br>25 | 20<br>15<br>15 | 15<br>15<br>10 |
| 6.3 mph wind speed | 30<br>25<br>20 | 30<br>25<br>20 | 20<br>15<br>10 | 15<br>15<br>5 |
| 2.3 mph wind speed | 25<br>15<br>10 | 25<br>20<br>15 | 15<br>10<br>5 | 10<br>5<br>5 |
| | **Rupture** | **3-inch hole** | **1-inch hole** | **¼-inch hole** |

**Table 3-13**
**Summary of Delayed Pool Fire Downwind Distances**
**for a Release from the Butane Booster Pump Discharge Header**

Delayed pool fire – maximum downwind distances

Endpoints:

| | | |
|---|---|---|
| 7.25 kW/m$^2$ | ( 2,301 Btu/hr·ft$^2$) | 1% mortality |
| 14.35 kW/m$^2$ | ( 4,549 Btu/hr·ft$^2$) | 50% mortality |
| 28.41 kW/m$^2$ | ( 9,006 Btu/hr·ft$^2$) | 99% mortality |

Downwind Distance in Meters to Thermal Radiation Level

| | | | | |
|---|---|---|---|---|
| 25.3 mph wind speed | 55<br>50<br>45 | 55<br>50<br>45 | 35<br>35<br>30 | 25<br>25<br>25 |
| 23.2 mph wind speed | 55<br>50<br>45 | 55<br>50<br>45 | 35<br>35<br>30 | 25<br>25<br>25 |
| 16.1 mph wind speed | 55<br>50<br>45 | 60<br>50<br>45 | 35<br>30<br>25 | 25<br>25<br>25 |
| 10.4 mph wind speed | 55<br>45<br>40 | 60<br>50<br>40 | 35<br>30<br>25 | 25<br>25<br>20 |
| 6.3 mph wind speed | 55<br>45<br>35 | 55<br>45<br>35 | 35<br>25<br>20 | 25<br>25<br>15 |
| 2.3 mph wind speed | 50<br>35<br>25 | 50<br>35<br>25 | 30<br>20<br>15 | 25<br>15<br>10 |
| | **Rupture** | **3-inch hole** | **1-inch hole** | **¼-inch hole** |

## 3.7 Hazard Zones Associated with Vapor Cloud Explosions

Review of the Finger Lakes LPG facility drawings, experience with similar installations, and a visual inspection of the facility's surrounding area reveals that, regardless of the size of the flammable vapor cloud, there are a number of locations in which a vapor cloud might reach a sufficiently obstructed or confined location. In such cases, if the vapor cloud is ignited, overpressures sufficient to cause damage may be created. These locations where sufficient confinement or congestion exists are typically located in and around process equipment, or in areas where other obstacles such as trees may exist. Approximately 30 confined or congested locations (potential explosion sites, or PESs) were identified for this analysis. As an example, consider the potential flammable vapor clouds associated with a release from the butane booster pump discharge header. The PESs that could be reached by this event are listed in Table 3-14, along with the maximum overpressure associated with each PES and the distances to the fatality endpoints for persons. The results presented in Table 3-14 are examples only; flammable vapor clouds vary by release hole size, orientation, wind speed, atmospheric stability, and wind direction. Because of this, presentation of explosion results are representative of potential results (generally for larger releases) but may not be a characterization of any one event.

**Table 3-14**
**Potential Explosion Overpressure Distances Due to Ignited Vapor Clouds Originating From a Release from the Butane Booster Pump Discharge Header**

| PES Description | Maximum Overpressure Achieved [psi] | Maximum Distance [ft] from Congested Area to Overpressure Level | | |
|---|---|---|---|---|
| | | 2.4 psig – 1% Lethality | 13.2 psig – 50% Lethality | 72.1 psig – 99% Lethality |
| Forest Area West of Railroad | 3.0 | 115 | † | † |
| LPG Storage Tanks/Booster Pumps Area | 1.6 | † | † | † |
| Rail Loading/Unloading Rack | 1.6 | † | † | † |

† Overpressure level not reached

## 3.8 Summary of Consequence Analysis Results

Table 3-15 presents a summary of representative releases originating from within the Finger Lakes LPG facility. The table lists the maximum ground level distances to the LFL (flash fire hazard) and to the threshold of lethality for fire radiation (based on the endpoints discussed earlier in this section), for each selected release scenario. The maximum hazard distances represent the furthest extent of hazards to people following these release scenarios; however, these values do not represent the most likely events. The maximum consequence events are normally the least likely to occur.

**Table 3-15**
**Summary of Maximum Hazard Distances**

| Node # | Description | Operating Mode | Maximum Downwind Distances [feet] to Scenario Hazard | | | |
|---|---|---|---|---|---|---|
| | | | Butane | | Propane | |
| | | | LFL | 1% Lethality, Thermal Radiation | LFL | 1% Lethality, Thermal Radiation |
| 01 | Rail Loading/Unloading Arm/Hose | injection | 570 | 195 | 635 | 240 |
| | | withdrawal | 660 | 175 | 625 | 225 |
| 02 | Rail Loading/Unloading Liquid Manifold | injection | 1000 | 360 | 1035 | 370 |
| | | withdrawal | 1310 | 440 | 1205 | 420 |
| | | static | 695 | 270 | 935 | 330 |
| 03 | Buried Line from Rail Manifold to Storage Tank Header | injection | 1020 | 365 | 1100 | 420 |
| | | withdrawal | 1330 | 470 | 1220 | 450 |
| | | static | 550 | 235 | 1036 | 405 |
| 04 | Liquid Header to Storage Tanks | injection | 1050 | 360 | 1140 | 405 |
| | | withdrawal | 1350 | 455 | 1255 | 435 |
| | | static | 595 | 210 | 1075 | 365 |
| 05 | Booster Pump Suction Header | injection | 1010 | 340 | 1135 | 385 |
| | | static | 590 | 210 | 1075 | 365 |
| 06 | Booster Pump Discharge to Check Valve | injection | 445 | 185 | 385 | 175 |
| 07 | Booster Pump Discharge Header Above Ground | injection | 595 | 300 | 890 | 365 |
| | | withdrawal | 560 | 295 | 555 | 295 |
| | | static | 680 | 215 | 915 | 335 |
| 08 | Buried Line To/From Injection Pumps | injection | 715 | 225 | 935 | 375 |
| | | withdrawal | 670 | 260 | 960 | 405 |
| | | static | 670 | 245 | 895 | 340 |

**Table 3-15 (continued)**
**Summary of Maximum Hazard Distances**

| Node # | Description | Operating Mode | Maximum Downwind Distances [feet] to Scenario Hazard | | | |
|---|---|---|---|---|---|---|
| | | | Butane | | Propane | |
| | | | LFL | 1% Lethality, Thermal Radiation | LFL | 1% Lethality, Thermal Radiation |
| 09 | Buried Line to Truck Loading | withdrawal | 575 | 240 | 505 | 260 |
| | | static | 360 | 170 | 295 | 165 |
| 10 | Truck Loading Manifold and Hoses | withdrawal | 590 | 235 | 520 | 245 |
| | | static | 105 | 35 | 90 | 165 |
| 11 | Compressor Suction Header | all | 110 | 70 | 215 | 205 |
| 12 | Individual Compressor Suction Line | all | 110 | 50 | 200 | 90 |
| 13 | Individual Compressor Discharge Line | all | 0 | 90 | 0 | 90 |
| 14 | Compressor Above Ground Discharge Header | all | 150 | 110 | 150 | 110 |
| 15 | Compressor Below Ground Discharge Header | all | 25 | 110 | 30 | 110 |
| 16 | Rail Vapor Manifold | all | 150 | 110 | 150 | 110 |
| 16a | Rail Vapor Loading Arm/Hose | injection | 0 | 90 | 0 | 90 |
| 17 | Pressure Control Area | injection | 705 | 220 | 930 | 335 |
| | | withdrawal | 630 | 275 | 940 | 390 |
| | | static | 680 | 260 | 915 | 335 |
| 18 | Injection Pump Suction Header | injection | 700 | 245 | 925 | 335 |
| | | withdrawal | 1075 | 520 | 1020 | 495 |
| | | static | 385 | 185 | 315 | 175 |
| 19 | Injection Pump Discharge to Check Valve | injection | 500 | 195 | 415 | 180 |
| 20 | Line To/From Caverns | all | 1070 | 520 | 1015 | 495 |
| 21 | Wellhead | all | 1495 | 490 | 1435 | 490 |

**Table 3-15 (continued)**
**Summary of Maximum Hazard Distances**

| Node # | Description | Operating Mode | Maximum Downwind Distances [feet] to Scenario Hazard | | | |
|---|---|---|---|---|---|---|
| | | | Butane | | Propane | |
| | | | LFL | 1% Lethality, Thermal Radiation | LFL | 1% Lethality, Thermal Radiation |
| 22 | Butane Water Knock Out | withdrawal | 1140 | 525 | *NA* | *NA* |
| | | static | 575 | 310 | *NA* | *NA* |
| 23 | Propane Dehydration System | withdrawal | *NA* | *NA* | 1075 | 505 |
| | | static | *NA* | *NA* | 770 | 500 |
| 24 | Dehydration Bed Regeneration Propane Supply Line | all | *NA* | *NA* | 550 | 285 |
| 25 | Dehydration Bed Regeneration Pump Discharge | withdrawal | *NA* | *NA* | 270 | 95 |
| | | static | *NA* | *NA* | 150 | 65 |
| 26 | Dehydration Bed Regeneration Heated Propane | all | *NA* | *NA* | 145 | 140 |
| 27 | Dehydration Bed Regeneration Propane Return | withdrawal | *NA* | *NA* | 330 | 155 |
| | | static | *NA* | *NA* | 265 | 150 |
| 28 | TEPPCO Buried Pipeline | injection | 680 | 230 | 860 | 345 |
| | | withdrawal | 680 | 230 | 860 | 345 |
| | | static | 500 | 195 | 765 | 300 |
| 30 | Buried Line to Wellhead | all | 1350 | 550 | 1195 | 520 |
| 40 | BLEVE of a Railcar | all | -- | 990 | -- | 985 |
| 41 | BLEVE of a Tank Truck | all | -- | 605 | -- | 600 |
| 42 | BLEVE of a Cylindrical Pressurized Storage Tank | all | -- | 805 | -- | 800 |

# SECTION 4
# ACCIDENT FREQUENCY

The likelihood of a particular accident occurring within some specific time period can be expressed in different ways. One way is to state the statistical probability that the accident will occur during a one-year period. This annual probability of occurrence can be derived from failure frequency data bases of similar accidents that have occurred with similar systems or components in the past.

Most data bases that are used in this type of analysis contain failure frequency data (e.g., on the average, there has been one failure of this type of equipment for 347,000 hours of service). By using the following equation, the annual probability of occurrence of an event can be calculated if the frequency of occurrence of the event is known.

$$p = 1 - e^{(-\lambda \cdot t)}$$

where: $p$ = annual probability of occurrence (dimensionless)
$\lambda$ = annual failure frequency (failures per year)
$t$ = time period (one year)

If an event has occurred once in 347,000 hours of use, its annual failure frequency is computed as follows.

$$\lambda = \frac{1 \text{ event}}{347{,}000 \text{ hours}} \bullet \frac{8{,}760 \text{ hours}}{\text{year}} = 0.0252 \text{ events/year}$$

The annual probability of occurrence of the event is then calculated as follows.

$$p = 1 - e^{(-0.0252 \cdot 1)} = 0.0249$$

Note that the frequency of occurrence and the probability of occurrence are nearly identical. (This is always true when the frequency is low.) An annual probability of occurrence of 0.0249 is approximately the same as saying there will probably be one event per forty years of use.

Due to the scarcity of accident frequency data bases, it is not always possible to derive an exact probability of occurrence for a particular accident. Also, variations from one system to another (e.g., differences in design, construction, operation, maintenance, or mitigation measures) can alter the probability of occurrence for a specific system. Therefore, variations in accident probabilities are usually not significant unless the variation approaches one order of magnitude (i.e., the two values differ by a factor of ten).

The following subsections describe the basis and origin of failure frequency rates used in this analysis.

## 4.1 Process Equipment Failure Rate Data

The equipment failure rate data was extracted from the UK Health and Safety Executive (HSE) Hydrocarbon Release Database (HCRD) [HSE HCRD, 2011]. For this study, four hole sizes were evaluated.

- ¼-inch in diameter
- 1-inch in diameter
- 3-inch in diameter
- Rupture for pipe that exceeds 3-inches in diameter

The data for the range of process equipment present at the Finger Lakes LPG facility is presented in Table 4-1. Few exceptions were made during the application of the HCR data. One exception was the modification of the failure rate for fin-fan heat exchangers. The failure rate for fin-fan heat exchangers includes 10 meters of 3-inch or smaller diameter pipe to account for the small lines connecting the inlet and outlet headers to the exchanger.

**Table 4-1**
**Summary of Equipment Failure Rate**

| Equipment | Hole Size [mm] | | | | Total |
|---|---|---|---|---|---|
| | 1/4 inch | 1 inch | 3 inch | Rupture | |
| Piping D <= 3-inch | $1.80 \times 10^{-4}$ | $3.23 \times 10^{-5}$ | $6.23 \times 10^{-6}$ | | $2.19 \times 10^{-4}$ |
| Piping 3-inch < D <= 11-inch | $4.53 \times 10^{-5}$ | $8.47 \times 10^{-6}$ | $2.73 \times 10^{-6}$ | $2.30 \times 10^{-6}$ | $5.88 \times 10^{-5}$ |
| Piping D > 11-inch | $4.04 \times 10^{-5}$ | $7.26 \times 10^{-6}$ | $5.57 \times 10^{-7}$ | $8.61 \times 10^{-7}$ | $4.91 \times 10^{-5}$ |
| Valves | $1.63 \times 10^{-4}$ | $3.04 \times 10^{-5}$ | $7.15 \times 10^{-6}$ | $1.79 \times 10^{-6}$ | $2.03 \times 10^{-4}$ |
| Flanges | $3.44 \times 10^{-5}$ | $4.84 \times 10^{-6}$ | | | $3.93 \times 10^{-5}$ |
| Centrifugal Pumps | $6.76 \times 10^{-3}$ | $6.94 \times 10^{-4}$ | | | $7.46 \times 10^{-3}$ |
| Reciprocating Pumps | $5.88 \times 10^{-3}$ | $1.87 \times 10^{-3}$ | $2.46 \times 10^{-4}$ | $1.62 \times 10^{-4}$ | $8.15 \times 10^{-3}$ |
| Centrifugal Compressors | $8.92 \times 10^{-3}$ | $2.10 \times 10^{-3}$ | $9.76 \times 10^{-5}$ | | 1.11 x 10-2 |
| Reciprocating Compressors | 7.16 x 10-2 | $9.29 \times 10^{-3}$ | $9.23 \times 10^{-5}$ | | 8.10 x 10-2 |
| Pressure Vessels | $1.29 \times 10^{-3}$ | $3.11 \times 10^{-4}$ | $9.78 \times 10^{-5}$ | $5.41 \times 10^{-5}$ | $1.75 \times 10^{-3}$ |
| Plate Heat Exchangers | $3.82 \times 10^{-3}$ | $1.02 \times 10^{-3}$ | $1.61 \times 10^{-4}$ | $6.80 \times 10^{-5}$ | $5.07 \times 10^{-3}$ |
| Heat Exchangers – Shell Side | $4.47 \times 10^{-3}$ | $1.00 \times 10^{-3}$ | $6.07 \times 10^{-5}$ | $8.39 \times 10^{-5}$ | $5.61 \times 10^{-3}$ |
| Heat Exchangers – Tube Side | $1.92 \times 10^{-3}$ | $4.29 \times 10^{-4}$ | $2.61 \times 10^{-5}$ | $3.60 \times 10^{-5}$ | $2.41 \times 10^{-3}$ |
| Fin Fan Coolers | $1.80 \times 10^{-3}$ | $3.23 \times 10^{-4}$ | $6.23 \times 10^{-5}$ | | $2.19 \times 10^{-3}$ |
| Liquid Pipelines | $2.44 \times 10^{-7}$ | $1.67 \times 10^{-7}$ | $2.37 \times 10^{-7}$ | $3.28 \times 10^{-7}$ | $9.76 \times 10^{-7}$ |
| Instrument Connections | $5.28 \times 10^{-4}$ | $1.27 \times 10^{-4}$ | | | $6.54 \times 10^{-4}$ |

Notes: Piping failure frequencies are per meter of pipe
Each Fin Fan Cooler includes 10 meters of D<= 3-inch piping

## 4.2 Cargo Transfer Hose Failure Rates

The TNO Purple Book [1999] value for hose failures is 4.0 x $10^{-6}$/hour, or 3.5 x $10^{-2}$/year, assuming continuous use. However, hoses used for loading or unloading tank trucks or railroad tank cars are not in continuous use; they are used only during cargo transfer operations. Therefore, the annual failure rate for hoses must be adjusted to account for the actual number of hours they are used during a one-year period (see Section 4.12).

The relationship between failure frequency and failure severity (i.e., size of hole in the hose) cannot be determined from the available data. In the absence of such data, we have assumed the following distribution for hose failure rates.

| | | | |
|---|---|---|---|
| Equivalent hole diameter | ≤1/4 inch | 1/4 to 1 inch | >1 inch |
| Expected failure rate | 2.0 x $10^{-6}$/hour | 2.0 x $10^{-6}$/hour | 4.0 x $10^{-6}$/hour |

## 4.3 Hazardous Liquids Pipelines Failures

The Finger Lakes LPG facility includes several sections of buried piping (TEPPCO line, between the truck/rail area and injection pumps, etc). Failure rates for this piping are expected to resemble cross-country pipeline failure rates more than process piping. Department of Transportation (DOT) data for buried hazardous liquid pipeline incidents in the United States were evaluated to determine a failure rate.

Incident data and mileage data for hazardous liquids pipelines were downloaded from the DOT's Pipeline and Hazardous Materials Safety Administration (PHMSA) website [DOT, 2011]. The incident data provide a record of all occurrences of a pipeline-related failures, based on the DOT's reporting criteria. This data was reviewed and the following entries in the database were eliminated:

- Incidents involving offshore pipelines
- Incidents where no liquid was spilled
- Incidents where the failure involved a specific non-pipe component (i.e., valves, scraper launchers, instrumentation, above ground storage tanks, etc.)

The analysis retained all incidents involving pipe, joints, seams, welds, and repair sleeves. Combining the onshore incidents involving spills from a hazardous liquids pipeline and the number of miles of active pipeline results in a failure rate of 1.57 x $10^{-3}$ failures/mile/year, or 9.75 x $10^{-7}$/year/meter of pipe.

These data sets are not sufficiently detailed to allow a determination of the failure frequency as a function of the size of the release (i.e., the size of hole in the pipeline). Due to this lack of data, an average hole size distribution was taken from the process piping data presented in Section 4.1. Based on the DOT data sets and this hole size distribution, the expected failure rates for a hazardous liquid pipeline, per meter of pipe, are assumed to be as follows.

| Equivalent hole diameter | ≤ ¼-inch | ¼-to 1-inch | 1-inch to 3-inch | > 3-inch |
|---|---|---|---|---|
| Expected failure rate | 7.51 x $10^{-7}$/m/yr | 1.41 x $10^{-7}$/m/yr | 4.53 x $10^{-8}$/mi/yr | 3.81 x $10^{-8}$/m/yr |

## 4.4 Catastrophic Failures

The catastrophic failure of a pressure vessel that contains a superheated liquid is generally referred to as a BLEVE (Boiling Liquid Expanding Vapor Explosion). The most common type of BLEVE is the heat-induced BLEVE, which results from a fire external to the vessel causing the shell of the vessel to weaken to such an extent that the vessel ruptures at the full-open-pressure of the pressure relief valves. In such an event, the superheated liquid within the vessel will be released at a temperature that is well above ambient temperature and it will nearly always be ignited by the external fire, resulting in a short-lived fireball.

### 4.4.1 BLEVEs of Pressurized Tank Trucks

Data published by the U.S. Bureau of Transportation Statistics [BTS, 2010] provides the total volume of hazardous materials transported in tank trucks in the United States. Data is available from commodity surveys in 1997, 2002, and 2007. From this data, approximately 16 billion gallons of flammable gases (this includes propane and butane transported as a liquefied gas) were transported by truck each year. Assuming each truck moved an average of 10,000 gallons per trip, there have been 1.6 million loaded trips each year. Since each loaded trip requires one cargo loading event and at least one unloading event, there would be at least 3.2 million cargo transfers per year. To the best of our knowledge, during the past 40 years (the time period from 1970 to 2010), there have been only three BLEVEs of pressurized tank trucks in the United States while cargo was being transferred into or out of the truck's tank – one at Tewksbury, Massachusetts, in 1972; one in Jacksonville, Florida, in 1977; and one in Tacoma, Washington, in 2007. (Other BLEVEs of tank trucks have occurred, but they did not occur at loading or unloading facilities.)

Three BLEVEs in 40 years is equivalent to a frequency of one BLEVE per 42.7 million cargo transfers, or a probability of $2.4 \times 10^{-8}$ per cargo transfer. For a given facility, the annual probability of a tank truck BLEVE is the product of this probability and the number of cargo transfers that occur at that facility each year.

### 4.4.2 BLEVEs of Pressurized Railcars

Data published by the U.S. Bureau of Transportation Statistics [BTS, 2010] provides the total volume of hazardous materials transported by railcar in the United States. From commodity surveys in 1997, 2002, and 2007, approximately 7.6 billion gallons of flammable gases (this includes propane and butane transported as a liquefied gas) were transported by railcar each year. Assuming each railcar moved an average of 33,000 gallons per trip, there have been about 230,000 loaded trips each year. Since each loaded trip requires one cargo loading event and one unloading event, there would be at least 460,000 cargo transfers per year. To the best of our knowledge, during the past 40 years (the time period from 1970 to 2010), there has been only one BLEVE of a pressurized railcar in the United States while cargo was being transferred into or out of the railcar – at Kingman, Arizona, in 1973. (Other BLEVEs of rail tank cars have occurred, but they did not occur at loading or unloading facilities.)

One BLEVE in 40 years is equivalent to a frequency of one BLEVE per 18.3 million cargo transfers, or a probability of $5.45 \times 10^{-8}$ per cargo transfer. For a given facility, the annual probability of a railcar BLEVE is the product of this probability and the number of cargo transfers that occur at that facility each year.

### 4.4.3 BLEVEs of Pressurized Storage Tanks

A government organization in the Netherlands estimated the frequency of BLEVEs for stationary LPG storage tanks to be 4.0 x $10^{-7}$ per year per tank, for tanks at "depots" (marketing terminals) [TNO, 1983]. If there are two or more tanks present at one site, then the probability of a BLEVE at that site is approximately equal to the product of the number of tanks and the annual probability of a BLEVE for one tank.

## 4.5 LPG Cavern Failures

The failure of underground hydrocarbon storage caverns is addressed in a research report published by the United Kingdom's Health and Safety Laboratory, for the Health and Safety Executive [HSE, 2008]. The report evaluated historical data and previous analyses concerning hydrocarbon storage in salt caverns and depleted hydrocarbon production formations.

The report finds that cavern failures have an annual probability of approximately 1.0x $10^{-5}$/year. However, these failures are attributed to cavern or reservoir structural failure, including those in geologically active areas. These types of structural failures result in small leaks into the surrounding soil and are quickly diluted and do not pose a flammable hazard at the surface.

The report also noted that the risk from underground storage is dominated by the surface and shallow sub-surface equipment (valves, piping, etc.). The risk dominance is due to the much higher release rates possible from this equipment (as compared to diffusion from cavern structural issues). The report recommends applying failure frequencies for wellhead equipment according to the database presented in Section 4.1 above. This approach was adopted in this study.

## 4.6 Common Cause Failures

Components that are exposed to a common working environment may be susceptible to common cause failures if they contain a common design error (e.g., wrong materials of construction specified) or a common manufacturing defect (e.g., improper welding technique). Thus, within a particular unit or facility, the failure rates of components, such as pipes, valves, pump seals, gaskets, etc., may be higher than the rates obtained from typical failure rate data bases, if the components are susceptible to common cause failures. However, common cause failures seldom exert a large influence on the actual failure rate of a specific type or class of component. Design reviews, quality control and quality assurance programs, process hazards analyses, accident investigations, etc., will generally reveal the sources of common cause failures either before such failures occur, or after only one or two such failures have occurred. The susceptible components are then respecified, repaired, or replaced, as required.

Failures of sensing and control devices seldom lead directly to an accident. In most cases, the failure of such a device would lead to an accident only if other events occur simultaneously or sequentially. The contribution of such failures to the frequency of specific accidents can sometimes be estimated by techniques such as fault tree analysis. The presence of common cause failures in a fault tree will increase the complexity of the analysis.

In the analysis that is the subject of this report, each accident of interest involves the failure of a physical component of a process system. Available data bases for component failures include failures that occurred as the result of common causes. Hence, the expected frequencies of occurrence of the accidents

of interest can be based directly on component failure rates obtained from historical data bases, and there is no need to resort to fault tree analysis or to adjust the estimated failure rates to account for common cause failures.

## 4.7 Human Error

The probability of occurrence of any specific accident can be influenced by human error. However, in most situations, it is not possible to quantify this influence. Fortunately, it is seldom necessary to attempt such quantification.

There are two general forms in which human error can contribute to the failure of a component or system of components. The first form, which is implicit in nature, includes poor component design, improper specification of components, flawed manufacturing, improper selection of materials of construction, and similar situations that result in the installation and use of defective components or the improper use of nondefective components. The second form, which is explicit in nature, includes improper operation and improper maintenance.

Most of the available equipment failure rate data bases do not categorize the causes of the failures. Whether the rupture of a pipe is due to excessive corrosion, poor design, improper welding procedure, or some other cause, the rupture is simply added to the data base as one "pipe failure." Thus, since implicit human errors manifest themselves in the form of component failures, they are already included in the failure rate data bases for component failures.

Many types of explicit human errors also manifest themselves in the form of component failures. Therefore, like implicit human errors, component failures caused by explicit human errors are already included in the failure rate data bases for component failures. For example, if a pump seal is improperly installed (improper maintenance) and it begins to leak after several hours of operation, it would simply be recorded in a failure rate data base as one "pump seal failure." Similarly, if an operator responds improperly (improper operation) to a high pressure alarm and the pressure continues to increase, ultimately resulting in the rupture of a pipe, the event is recorded in a failure rate data base as a "pipe rupture."

Except in rare cases, there is little reason to believe that equipment failures due to implicit or explicit human errors will occur more often or less often in a specific facility than in the facilities that contributed failure rate data to the data bases. Therefore, component failure rates obtained from historical data bases can nearly always be used without being modified to account for human error.

Accidents that are the result of explicit human errors, but do not involve failures of components, are not included in typical failure rate data bases. Examples of such accidents include overfilling a tank (resulting in a liquid spill), opening a flanged connection on a piping system that has not been properly drained and purged (resulting in a leak of gas or liquid), opening a water-draw-off valve on an LPG tank and then walking away (resulting in a release of LPG), etc.

The contribution of explicit human error to the frequency of accidents that do not involve the failure of components can sometimes be estimated by techniques such as fault tree analysis or event tree analysis. These techniques are used to illustrate how the occurrence of an accident is the result of a chain of events or the simultaneous occurrence of several events. These events can be component failures or human failures. Using these techniques, the probability of occurrence of the accident can be quantified IF the probability of occurrence of EVERY event that contributes to the accident can be quantified. In many cases, there is insufficient historical data for some of the events. (This is particularly true for human error

events.) Thus, assumed values must often be used. This inevitably leads to questions regarding the accuracy or applicability of the estimated probability of occurrence of the accident.

In the analysis that is the subject of this report, the accidents of interest all involve the failure of a physical component of a process system. Thus, frequencies of occurrence of these accidents (which are based on component failure rates obtained from historical data bases) need not be increased or decreased to account for human error.

## 4.8 Hazardous Events Following Fluid Releases

A release of hazardous fluid to the atmosphere may create one or more hazardous conditions, depending on events that occur subsequent to the release. For a flammable fluid the possibilities are:

a) No ignition. If a flammable vapor cloud forms but never ignites, there is no hazard.
b) Immediate ignition. If ignition occurs nearly simultaneously with the beginning of the release, the hazard may be thermal radiation from a torch fire (pressurized release) or a pool fire.
c) Delayed ignition. If there is a time delay between the start of the release and ignition of the release, a flammable vapor cloud will form. After ignition, there will be a vapor cloud fire (flash fire), possibly followed by a pool fire or torch fire. If the flammable vapor cloud is contained, or partially contained, within a confined or congested space, then subsequent to ignition, the vapor cloud deflagrates, producing local overpressure.

Each of these three possibilities has some probability of occurring, once a release has occurred. The sum of these three probabilities must equal one.

### 4.8.1 Immediate Ignition

The immediate ignition probabilities employed in this study are taken from the TNO Purple Book [1999] which presents a model for direct (immediate) ignition of flammable releases, based on the reactivity of the material and the release rate. Larger releases and more reactive materials are more likely to ignite during the initial moments of a release. Table 4-2 is adapted from the the ignition probabilities presented by TNO. As seen in the table, the maximum value for immediate ignition is 0.7, or 70%. The LPG products in this facility would be classified as average reactivity, thus falling in the average/high category. Please note that while the substance categories are referred to as liquid or gas, the gas category includes substances such as liquefied gases, like LPG.

**Table 4-2**
**Immediate Ignition Probabilities from TNO [1999]**

| Release Rate | | Substance | | |
|---|---|---|---|---|
| [kg/s] | [lb/s] | Non-volatile Liquid | Gas, Low Reactivity | Gas, Average/High Reactivity |
| < 10 | < 22 | 0.065 | 0.02 | 0.2 |
| 10-100 | 22-220 | 0.065 | 0.04 | 0.5 |
| > 100 | > 220 | 0.065 | 0.09 | 0.7 |

### 4.8.2 Delayed Ignition

The delayed ignition probabilities employed in this study are developed according to the methodology published by the Energy Institute [UKOOA, 2006]. The delayed ignition methodology considers the number of potential ignition sources in the path of the dispersing cloud. As the number of encountered ignition sources increases, the probability of ignition increases. The ignition sources in and around the Finger Lakes LPG facility fall into three general classifications:

- Process areas
- Roadways and rail lines
- Direct ignition sources

The proposed layout of the LPG facility and the areas surrounding the site(s) were evaluated to determine where ignition sources may be present. Roadways and railroads were assigned a value according to the UKOOA model, as were the process areas. Process areas included the following:

- The cavern injection pumps area
- The natural gas processing facility near the injection pumps area
- The storage tanks, booster pumps, and compressors at the truck/rail loading/unloading area
- The rail loading manifold
- The truck loading manifold

There was one direct ignition source included – the fired heater used in the propane drying mole sieve regeneration system, located approximately 100 feet from the cavern injection pumps.

### 4.8.3 Conditional Probabilities

The set of conditional probabilities for any one release scenario includes not only the ignition (or non-ignition) values, but a value for the fraction of the year that that equipment group is in a particular service. The various classifications of service were listed in Table 2-1 with each process node. These service modes determine the operational conditional probability applied to each release scenario. These operational conditional probabilities must sum to 1.0 for any process node. For example, a section of the process could be in cavern injection mode, cavern withdrawal mode, or in static mode. Each mode has its own probability based on product throughput, and its own properties (temperature, pressure, flowrate) depending on the system operation. Table 4-3 lists many of the values used in developing the operational conditional probabilities for this analysis.

### 4.8.4 Event Trees

The application of failure frequencies (by hole size) and for ignition probability are best illustrated by event trees, with a release of fluid as the initial event. An example of an event tree was presented in Figure 3-3. Event trees like that in Figure 3-3 were used to develop the event probabilities for all scenarios evaluated in this analysis. Within the risk mapping program, event trees were constructed for each release of LPG. This methodology incorporates the failure frequency for each hole size (as derived using the data in Table 4-1), release orientation probabilities, weather probabilities, and ignition probabilities. Ignition probabilities are dependent on the following factors:

**Table 4-3**
**Operational Conditional Probabilities**

| Operation | Yearly Volume [bbl/yr] | Product Movement | | Percent of Movement | Annual Fraction |
|---|---|---|---|---|---|
| | | Flowrate [gpm] | Flowrate [bbl/yr] | | |
| Propane In by Pipeline | 1.50E+06 | 1,200 | 1.50E+07 | 90 | 0.0899 |
| Propane In by Rail | | 500 | 6.26E+06 | 10 | 0.0240 |
| Propane Out by Truck | 1.50E+06 | 500 | 6.26E+06 | 75 | 0.1798 |
| Propane Out by Rail | | 500 | 6.26E+06 | 10 | 0.0240 |
| Propane Out by Pipeline | | 1,200 | 1.50E+07 | 15 | 0.0150 |
| Butane In by Pipeline | 6.00E+05 | 1,200 | 1.50E+07 | 25 | 0.0100 |
| Butane In by Rail | | 500 | 6.26E+06 | 75 | 0.0719 |
| Butane Out by Rail | 6.00E+05 | 500 | 6.26E+06 | 90 | 0.0863 |
| Butane Out by Truck | | 500 | 6.26E+06 | 10 | 0.0096 |
| TEPPCO Pipeline Idle | | | | | 0.8851 |
| Propane Pipeline Idle | | | | | 0.7723 |
| Butane Pipeline Idle | | | | | 0.8322 |

- The type of fluid released (in this analysis, all were medium reactivity "gases")
- The fluid release rate
- The development of a ground-level flammable vapor cloud
- The presence of ignition sources

Thus, for each unique release scenario, an immediate and a delayed ignition probability was assigned at the time of hazard mapping, depending on the above factors. In general, small releases are the most likely to occur and the least likely to be ignited (small probability of reaching an ignition source). The largest releases are the least likely to occur and the most likely to be ignited (highest probability of reaching an ignition source). The outcome probabilities from the event trees are combined with consequence outcomes in the risk mapping analysis, which is described in Section 5.1.

To illustrate how failure frequencies and conditional probabilities are used in this analysis, consider a release from the booster pump discharge header (the example release described in Section 3.6). The failure frequency is derived from the group of equipment which contains the same fluid with common fluid properties. The booster pump discharge header equipment group contains a butane mixture at approximately 60°F and 230 psig. The equipment associated with this release point is summarized in Table 4-4.

**Table 4-4**
**Summary of Failure Rate Data Associated with a Release from the Booster Pump Discharge Header**

| Equipment | Count | Annual Failure Rate by Hole Size [inches], for all Pieces of Equipment | | | | Total Annual Failure Rate |
|---|---|---|---|---|---|---|
| | | ¼ | 1 | 3 | Rupture | |
| Piping 3-inch < D < 11-inch | 55 | $2.49 \times 10^{-3}$ | $4.66 \times 10^{-4}$ | $1.50 \times 10^{-4}$ | $1.27 \times 10^{-4}$ | $3.23 \times 10^{-3}$ |
| Instrument Connections | 6 | $3.17 \times 10^{-3}$ | $7.62 \times 10^{-4}$ | | | $3.93 \times 10^{-3}$ |
| Valves | 9 | $1.47 \times 10^{-3}$ | $2.74 \times 10^{-4}$ | $6.44 \times 10^{-5}$ | $1.61 \times 10^{-5}$ | $1.82 \times 10^{-3}$ |
| Flanges | 18 | $6.19 \times 10^{-4}$ | $8.71 \times 10^{-5}$ | | | $7.06 \times 10^{-4}$ |
| Total Failure Rate | | $7.75 \times 10^{-3}$ | $1.59 \times 10^{-3}$ | $2.15 \times 10^{-4}$ | $1.43 \times 10^{-4}$ | $9.70 \times 10^{-3}$ |

Note: Piping counts are in units of meters

The total failure rate for this location $9.70 \times 10^{-3}$ failures/year. This failure rate must then be modified by the fraction of the year the discharge header is in a certain mode of operation. During cavern injection mode (receiving from rail cars and pumping product to the injection pumps), this value is 0.0719, or 7.19% of a year. Truck loading (0.0096) and static mode (0.9185) account for the remainder of the probability for this node. The resulting total failure rate for the butane booster pump discharge header in cavern injection mode is $6.98 \times 10^{-4}$ failures/year. This is the failure rate that would be located at the beginning of the event tree presented in Figure 3-3. The fractional contributions of each hole size can be determined from Table 4-3.

The next branch in the event tree defines the fraction of each release that is oriented upward or horizontal. For this study, the orientation fractions were assumed to be upward = ½ and horizontal = ½.

The release-specific event tree continues to be populated as the path proceeds from left to right. Several of the conditional probabilities, such as delayed ignition, can only be calculated once the flammable cloud is overlaid upon the LPG facility and surrounding area. This is due to the delayed ignition probability being a function of the wind direction, wind speed, atmospheric stability, and the number of ignition sources encountered in the cloud travel path.

# SECTION 5
# RISK QUANTIFICATION

The Finger Lakes LPG facility poses no health hazards to the public as long as flammable materials are not released into the environment. In the event of an accident that results in a release of LPG, persons near the release point may be at risk due to the hazards posed by the release. The objective of this quantitative risk analysis (QRA) is to calculate the level of risk to the public due to the inherent hazards involved with storing, processing, and transporting LPG.

## 5.1 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 releases from the Finger Lakes LPG facility.

Conceptually, performing a risk analysis is straightforward. For example, 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 credible events that would create a flammable vapor cloud, vapor cloud explosion, torch fire, or pool 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 of each unique event are:

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

Step 2. Determine the frequency of occurrence of each hazardous event (f(acc)), and for each event, all possible outcomes. The 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 event outcome is calculated using event trees. Each outcome's

unique frequency is based on the release event frequency and conditional probabilities of ignition and weather conditions.

Step 3. Calculate the size of each potentially fatal hazard zone created by each of the releases identified in Step 1.

i. The hazards of interest are:
   a. Thermal radiation from flash fires, torch fires, and pool fires,
   b. Overpressure from vapor cloud explosions.

ii. The size of each hazard zone is a function of one or more of the following factors.
   a. Orientation of the release (upward, horizontal, downward)
   b. Wind speed
   c. Atmospheric stability
   d. Local terrain
   e. Composition, pressure, and temperature of fluid being released
   f. Hole size
   g. Vessel inventories
   h. Diameter of the liquid pool
   i. Presence of regions of confinement or congestion

Step 4. Determine the risk to the public in the vicinity of the LPG facility.

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 (person), relative to the release location
   c. Wind direction

ii. Determine the exposure (as defined by the hazard endpoints for the public) to each potential hazard zone.
   a. Perform flash fire and vapor cloud explosion hazard zone calculations for all wind directions, wind speeds, atmospheric stabilities, hole sizes, and release orientations.
   b. Perform torch fire and pool fire hazard zone calculations for all hole sizes, release orientations, wind speeds, and wind directions. (Fire radiation hazard zones are not dependent on atmospheric stability.)

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(mode) = mode of operation of the process node
   b. P(orientation) = probability that hazardous fluid is released into the atmosphere in a particular orientation.
   c. 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 5-1 represents a typical wind speed versus stability distribution for the site.
   d. P(ii) = probability of immediate ignition (i.e., probability that ignition occurs nearly simultaneously with the release).
   e. P(di) = probability of delayed ignition (i.e., probability that ignition occurs after a vapor cloud has formed).

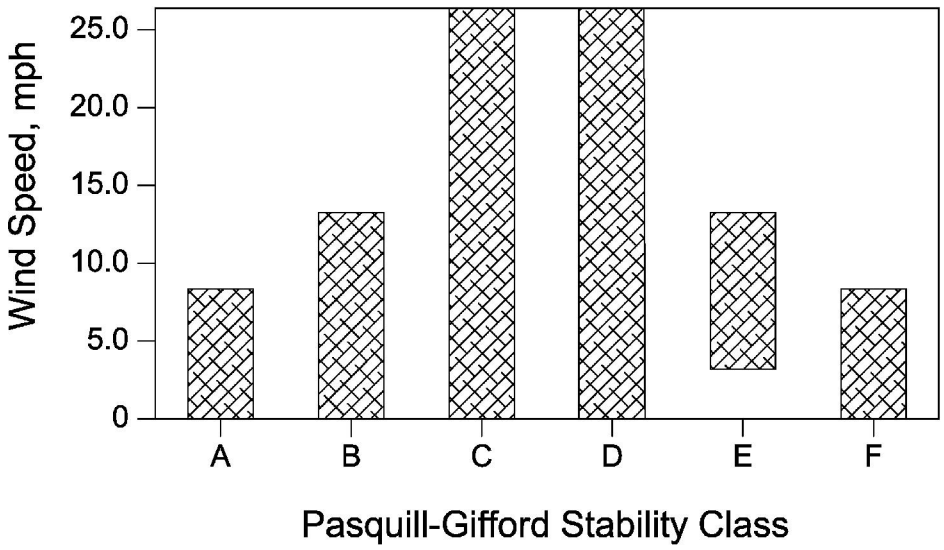


**Figure 5-1**
**Representative Range of Wind Speed/Atmospheric Stability Categories for the Finger Lakes LPG Site**

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 flash fire is f(acc)*P(mode)*P(orientation)* P(ws,wd,stab)*P(di).

## 5.2 Risk Presentation

Professionals in risk analysis realize there is no single measure that completely describes the risk a project poses to the public or workers. The most common measures that have been used by risk analysts include hazard footprints, risk contours, and *f/N* curves. This analysis calculated hazard footprints and location-specific individual risk (LSIR) or risk contours.

### 5.2.1 Hazard Footprints and Vulnerability Zones

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

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

for each potential release that is included in the study. For each potential release, a combination of these factors results in a unique accident.

A hazard footprint can be defined as the area over which a given unique accident is capable of producing some level of undesirable consequences (e.g., 1% mortality, 3.0 $kW/m^2$, etc.). 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 5-2 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. However, vulnerability zones do not provide any data related to the risk associated with the event.

### 5.2.2 Risk Contours

The risks due to all possible unique accidents can be combined to produce a measure of the overall risk presented by the subject of the study. 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 5-3. 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 define the summation of all hazard zones for each unique accident combined with their respective probabilities. The set of risk contours in Figure 5-3 represents the variation of annual probability of fatal exposure with location within and around the facility, due to releases from the butane booster pump discharge header (for all modes of operation). When the risk contours are based on continuous exposure (person located in a fixed position 24 hours per day, 365 days per year) the risk contours are defined as location-specific individual risk (LSIR) contours. This measure defines the risk to a *person's location*, not necessarily to an individual. LSIR may be conservatively used to estimate the risk to the public since it overpredicts the risk by assuming the public is continuously present. LSIR does not effectively represent the risk to the workers in the LPG facility since these workers move throughout the facility and are not present at a specific location for long periods of time (e.g., when they are off work or moving throughout the facility).

**Figure 5-2**
**Example Hazard Footprint and Vulnerability Zone for a Flammable Vapor Cloud**

**Figure 5-3**
**Example of Location-Specific Risk Contours for the Butane Booster Pump Discharge Header**

# SECTION 6
# RESULTS AND CONCLUSIONS

This section presents the results of the quantitative risk analysis and discusses the results with regard to various risk criteria. The results are the combination of the consequences of each unique event (described in Section 3) and the frequencies of those events (described in Section 4) put together by risk mapping (described in Section 5).

## 6.1 Hazard Footprints and Vulnerability Zones

For each release within the terminal, one particular combination of conditions will create the largest potentially lethal hazard zone for that release. For the example release used throughout this report, a release of fluid from the butane booster pump discharge header, the largest flammable vapor cloud (to the lower flammable limit [LFL] of the mixture, 1.87 mol%) is associated with a rupture of the header. Under worst-case atmospheric conditions, the LFL vapor cloud extends 595 feet from the point of release. The hazard zone associated with this unique event is illustrated in two ways in Figure 6-1. One method presents it as a circular vulnerability zone with a radius of 595 ft. This presentation is misleading since all locations within this circle cannot be simultaneously exposed to a potentially lethal hazard (exposure to a flash fire) from any single accident. When the vulnerability zone (the circle) on Figure 6-1 is presented, there is no associated probability since the cloud cannot cover the entire area at one time. In addition, there are many other possibilities of cloud formation from the same accident scenario.

A more realistic presentation of the maximum potential hazard zone associated with the line rupture is the cross-hatched area in Figure 6-1, which is the hazard footprint that would be expected if the liquid line were to rupture during cavern injection mode, and the release is horizontal, and the wind is blowing from the southwest, and the wind speed is low (2.3 mph), and the atmosphere is stable (Pasquill F), and the cloud did not ignite immediately upon release. The probability of the simultaneous occurrence of these conditions is $4.91 \times 10^{-9}$ per year, or about one chance in 204,000,000 per year that the flammable cloud will form exactly as shown.

This risk analysis considered 21 wind speed/atmospheric stability combinations and 64 wind directions (developed from the 16 that were provided in the data set). These conditions are combined with four release hole sizes, two release orientations, and several event outcomes (flash fire, VCE, torch fire, and pool fire). The cross-hatched hazard footprint shown in Figure 6-1 is just one of many possible outcomes from this single system failure scenario. Thus, hazard footprints are also not a meaningful measure of risk because they simply provide information about one possible unique accident, but provide no information about the probability of exposure.

## 6.2 Study Results

Once each release event has been fully assessed for its frequency of occurrence and the corresponding consequences, the results can be added together and presented in a concise manner. There are several methods available to present the risk associated with the potential release of flammable fluids. Most methods define the level of exposure of the surrounding population in terms of probability of exposure (e.g., fatality) on an individual or societal basis.

**Figure 6-1**
**Hazard Footprint and Vulnerability Zone for a Flammable Vapor Cloud Following a Release from the Butane Booster Pump Discharge Header**

### 6.2.1 Terminology and Numerical Values for Representing Risk Levels

The risk a member of the public is potentially exposed to by events that originate in the Finger Lakes LPG facility can be represented by a numerical measure. This numerical measure 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 x $10^{-6}$/year (or $10^{-6}$ in shorthand notation) represents one chance in 1,000,000 (one million) per year of being fatally affected by a release originating in the facility. Table 6-1 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. If a 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 <u>any</u> potential release from the facility's equipment. The concept of a person being in the same location for a full year (24 hours/day, 365 days/year) is referred to as continuous occupancy. Risk predictions are generally made based on continuous occupancy, but can be adjusted for different occupancies if that data is known. For example, if a person (or certain population) is known to be in an area for 10% of a year, then the predicted risk to that person (or people) is adjusted to 10% of its former value. In this example, a 1.0 x $10^{-5}$/year risk would become 1.0 x $10^{-6}$/year.

**Table 6-1**
**Risk Level Terminology and Numerical Values**

| Numerical Value | Shorthand Notation | Chance per Year of Fatality |
|---|---|---|
| $1.0 \times 10^{-3}$ | $10^{-3}$ | One chance in 1,000 of being killed per year |
| $1.0 \times 10^{-4}$ | $10^{-4}$ | One chance in 10,000 of being killed per year |
| $1.0 \times 10^{-5}$ | $10^{-5}$ | One chance in 100,000 of being killed per year |
| $1.0 \times 10^{-6}$ | $10^{-6}$ | One chance in 1,000,000 of being killed per year |
| $1.0 \times 10^{-7}$ | $10^{-7}$ | One chance in 10,000,000 of being killed per year |
| $1.0 \times 10^{-8}$ | $10^{-8}$ | One chance in 100,000,000 of being killed per year |

### 6.2.2 Risk Levels Produced by the Finger Lakes LPG Facility

The risk posed by the LPG facility is represented by location-specific individual risk (LSIR), or risk contours. Figures 6-2 and 6-3 present the LSIR contours for the areas near and outside the LPG facility, for the west and east areas, respectively. Each set of contours illustrate the annual risk to members of the public near the facility as a function of their distance from the facility. Any level of risk shown by a risk contour is the risk of lethal exposure to any of the hazards associated with a release from within the LPG facility (which is comprised of many possible release scenarios, including those from pipelines). For example, the contour labeled $10^{-6}$/yr in Figure 6-2 represents one chance in one million per year of being exposed to a fatal hazard from <u>any</u> of the possible releases of flammable material from the western portions of the facility or its associated pipelines. Because the risk contours are based on annual data, this level of risk is dependent on a member of the public being in the location where the $10^{-6}$ contour is shown for 24 hours a day, 365 days per year (continuous occupancy).

If any member of the public were to be exposed to a fatal hazard originating in the LPG facility, their annual risk of exposure would be defined by their location relative to the equipment handling LPG. Most public risk levels outside the facility boundaries are less than $1.0 \times 10^{-4}$ per year. Regarding the western portions of the facility, the following observations can be made (see Figure 6-2):

- Only two areas outside of the facility boundary experience risk levels greater than $1.0 \times 10^{-4}$/year. One is a uninhabited and undeveloped area to the west of the railroad tracks, while the second is onto property owned by an LPG tucking company.
- The $1.0 \times 10^{-6}$/year contours extend a maximum of 870 feet past the west facility boundary (the main railroad line), 320 feet to the north of the facility boundary (Highway 14A), and approximately 300 feet on either side of the propane and butane pipelines connecting to the eastern portion of the facility.
- There are no residences impacted by a risk level of $1.0 \times 10^{-6}$/year or greater. To the west, south, and north, the land is uninhabited; to the east, the $1.0 \times 10^{-6}$/year reaches the LPG trucking company and a waste transfer station that is currently unused, but neither of these properties includes a residence.

Regarding the eastern portions of the facility, the following observations can be made (see Figure 6-3):

- The $1.0 \times 10^{-4}$/year risk contours are contained on the property owned by US Salt.

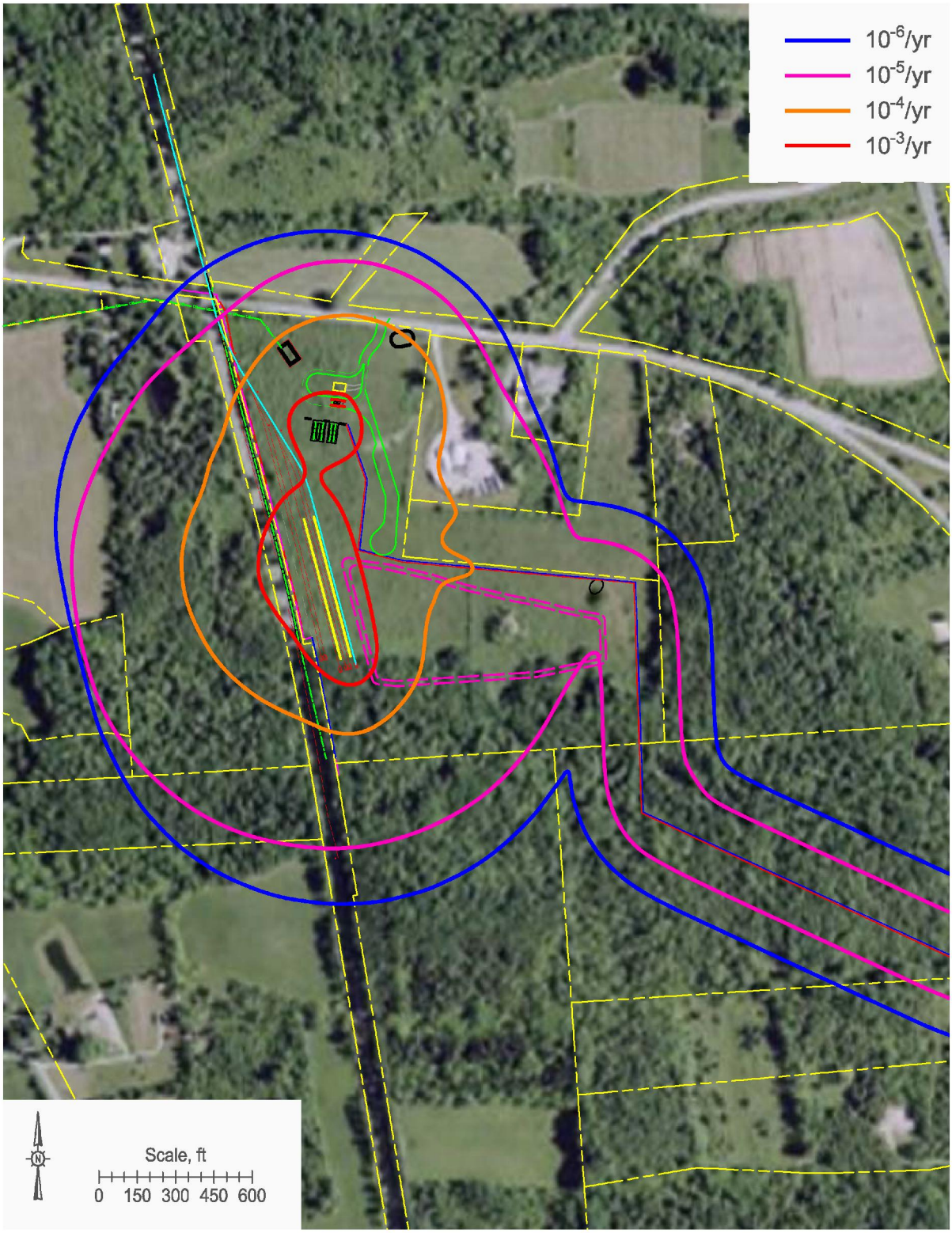


**Figure 6-2**
**Location-Specific Risk Contours for the Finger Lakes LPG Facility, Western Area**

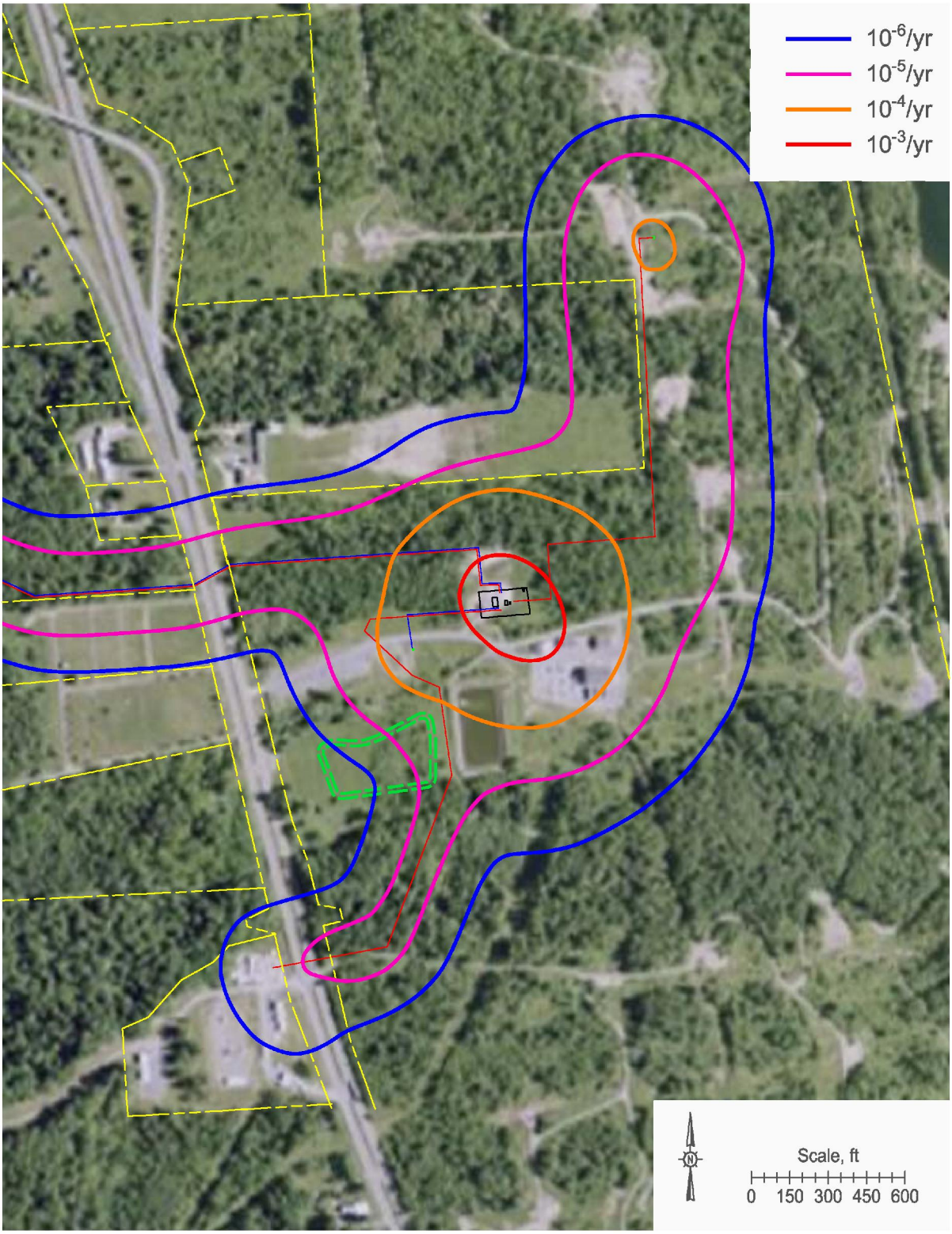


**Figure 6-3**
**Location-Specific Risk Contours for the Finger Lakes LPG Facility, Eastern Area**

- The 1.0 x $10^{-6}$/year contours extend to approximately 250 feet around the TEPPCO connection pipeline, 900 to 1,000 feet from the injection pumps area, and 475 feet from the propane storage cavern and its transfer pipeline.
- The 1.0 x $10^{-6}$/year contour reaches a portion of one residential property – a location along Highway 14 to the north of the pipeline connecting the east and west portions of the facility. In all other locations, there are no residences within the 1.0 x $10^{-6}$/year risk contour.

### 6.2.3 Transient Populations

Because the measures of risk produced by this analysis are based on continuous occupancy, it is useful to consider the implications for members of the public that are not permanently located near the facility. Transient populations may include agricultural workers, passing traffic on Highways 14 and 14A, or landowners who are on undeveloped portions of their land (e.g., forested sections).

As discussed in section 6.2.1, the expected annual occupancy can be used to modify a predicted level of risk. Even at a residential location (a home), the inhabitants are not expected to be in that location continuously. For agricultural or forested areas, the occupancy should be very low, likely less than 10%. For traffic passing by on Highways 14 or 14A, the risk from the LPG facility is extremely low. The time it takes to pass by this facility will result in only a miniscule amount of risk being imposed upon those persons. In addition, a vehicle offers protection from flammable vapor clouds and fires, further reducing the risk.

## 6.3 Comparison of QRA Study Results

There have been a few attempts to define acceptability criteria for public risk. In general, the risk criteria have been developed to help regulatory agencies define where permanent housing should be developed near industrial areas. Currently, there are no applicable regulatory criteria for either New York or the USA. Regulatory bodies in the United Kingdom, Australia, and the Netherlands define risk levels less than 1.0 x $10^{-6}$ per year as acceptable for public residential areas. Risk levels of 1.0 x $10^{-6}$ per year and higher are generally seen as unacceptable for public areas where there are residences, schools, or other high-density populations. Please note that these general criteria are based upon continuous occupancy. There are no criteria for public areas that are unoccupied or used for agricultural purposes.

Another way to evaluate the risk imposed by the facility on the public is by using fatality rates from other activities or accidental events. Table 6-2 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. An examination of Table 6-2 reveals that there are many potential causes of death (including agricultural accidents, motor vehicle accidents, falls, and accidental drowning) that have similar or higher probability of fatality, when compared to the risk of fatality imposed by the Finger Lakes LPG facility in locations beyond the facility's property lines.

**Table 6-2**
**Odds of Early Fatality Data from the National Safety Council's *Injury Facts, 2010 Edition***

| 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 |
|---|---|---|---|
| Agricultural Accidents | 623† | 3,374† | $2.96 \times 10^{-4}$ |
| Cancer | 50,334 | 5,928 | $1.68 \times 10^{-4}$ |
| Motor vehicle accidents | 45,316 | 6,584 | $1.52 \times 10^{-4}$ |
| Accidental poisoning | 27,531 | 10,837 | $9.23 \times 10^{-5}$ |
| Falls | 20,823 | 14,329 | $6.98 \times 10^{-5}$ |
| Pedestrian (motor-vehicle accident) | 6,162 | 48,420 | $2.07 \times 10^{-5}$ |
| Accidental choking | 4,332 | 68,874 | $1.45 \times 10^{-5}$ |
| Accidental drowning | 3,579 | 83,365 | $1.20 \times 10^{-5}$ |
| Exposure to smoke, fire, or flames | 3,109 | 95,968 | $1.04 \times 10^{-5}$ |
| Complications of medical and surgical care | 2,521 | 118,351 | $8.45 \times 10^{-6}$ |
| Exposure to forces of nature (heat, cold, storms, earthquakes, etc.) | 1,340 | 222,659 | $4.49 \times 10^{-6}$ |
| Lightning | 47 | 6,348,148 | $1.58 \times 10^{-7}$ |

† Agricultural accidents are based on the agricultural worker population, not overall population; odds of fatality are for agricultural workers only.

## 6.4 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 releases from the project components. Thus, Quest believes that 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.

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 risk calculations assume that people are present, 24 hours a day, 365 days a year, at locations surrounding the LPG facility. The population data available show that there are no continuously occupied public buildings (e.g., houses, schools, etc.) in close proximity to the facility. Thus, the risk to any member of the public is extremely small since there are no members of the public continuously present near the facility.
- **Overprediction of Flammable Cloud**: If a release did not ignite immediately upon release, the flammable cloud was assumed to not ignite until the maximum downwind distance was achieved.

This results in a significant overprediction of the risk since every flammable hazard is allowed to reach its maximum size in the analysis.

- **Ideal Dispersion Conditions**: For all vapor dispersion cases, the models are inherently based on vapors moving downwind, over flat, level terrain. Sloped terrain and large obstacles (such as trees) cannot be accounted for with current dispersion modelling techniques. These features may inhibit the downwind extent of flammable vapors. The end result is that the flammable vapor cloud travel distances are overpredicted.
- **Ignoring Human Response Time**: For persons exposed to fire radiation from a pool fire or torch 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 thirty 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.

## 6.5 Conclusions

Quest Consultants Inc. performed a quantitative risk analysis on the proposed Finger Lakes LPG Storage facility located in Schuyler County, NY. The study was composed of four distinct tasks.

Task 1. Determine potential releases that could result in hazardous conditions outside the boundaries of the LPG facility.
Task 2. For each potential release identified in Task 1, derive the annual probability of the release.
Task 3. For each potential release identified in Task 1, calculate the potentially lethal hazard zones.
Task 4. Using a consistent, accepted methodology, combine the annual probabilities from Task 2 with the potential release consequences from Task 3 to arrive at a measure of the risk the facility poses to the neighboring public.

The first task identified 113 accident scenarios. Each scenario is a unique combination of an operating mode and a specific product (propane or butane) for one portion of the system. Each of these scenarios was further expanded to include four release hole sizes and two release orientations.

The second task, calculation of accident frequencies, relied on historical data available from the sources identified in Section 4.

The third task involved quantification of the hazards posed by the individual accident scenarios. Each scenario identified in task 1 was evaluated under a range of weather conditions, and for multiple hazard types. The results of these calculations limited the overall analysis to areas within about 1,500 feet of any potential release source. This was the maximum extent, under the worst-case weather conditions, that a flammable hazard created by a release of LPG from the facility could travel. All other offsite hazard zones were smaller for all other potential accidents. Because most releases sources are away from the property lines, potential impacts outside of the facility boundaries are less than this maximum extent.

The fourth task undertaken in this work was the calculation of the risk posed to the public. The risk was quantified and presented graphically. The potential impact to the public was compared to generally-accepted levels of risk and common modes of fatality that members of the public may experience.

The following conclusions can be drawn from this analysis.

a) The risk to the public, measured as Location-Specific Individual Risk (LSIR, the risk to a single person) is dependent upon that individual's location. The maximum risk of fatality, for a member

of the public who is located near the western boundary of the west portion of this facility (the truck/rail loading/unloading area), and remains in that location for a full year (365 days, 24 hours per day), is between $1.0 \times 10^{-4}$ and $1.0 \times 10^{-3}$/year.

b) The risk beyond about 1,500 feet of any of the facility's components is zero, because there are no fatal impacts that can reach that distance. This limits any level of risk from any part of the project to within approximately 1,100 feet of a property line. This is, however, strongly dependent upon the specific location around the facility.

c) Most offsite areas that are exposed to risk from this facility are exposed to risk levels in the range of $1.0 \times 10^{-5}$ to $1.0 \times 10^{-6}$/year.

d) The hazards associated with this facility are common to (and already exist) for the TEPPCO facility on Highway 14, to which this facility has a connecting pipeline. These hazards are also known and understood by employees of the LPG trucking company east of the truck loading area (one of the areas of highest offsite risk).

e) The risk associated with the Finger Lakes LPG facility is not unusual for industrial activities handling flammable materials.

In summary, the hazards and risk associated with the Finger Lakes LPG facility are similar to those from LPG storage, transport and processing facilities worldwide. While the offsite risk associated with the operation of the LPG facility is not zero, the offsite areas impacted by the higher risk levels ($1.0 \times 10^{-4}$ and greater) are limited to a few uninhabited locations, and most offsite areas are found to be exposed to low levels of risk. In addition, this analysis is conservative in nature, so should provide an overprediction of the true risk imposed by this facility.

# SECTION 7
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